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Faculty of Civil Engineering
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On Influence of Plants on the Quality of Indoor Environment from the Point of View of Building's Operation and Ventilation

DOCTORAL THESIS

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DECLARATION

Ph.D. student’s name: Ondřej Franek

Title of the doctoral thesis: **On Influence of the Plants on the Quality of Indoor Environment from the Point of View of Building’s Operation and Ventilation**

I hereby declare that this doctoral thesis is my own work and effort written under the guidance of the tutor Čeněk Jarský.
All sources and other materials used have been quoted in the list of references.

The doctoral thesis was written in connection with research on the projects:
SGS20/005/OHK1/1T/11Research of the plants impact in the indoor buildings environment, with respect on operating costs in the field of ventilation in terms of CO_2 concentration
SGS21/007/OHK1/1T/11 The plants impact on the quality of the indoor building environment from the perspective of its operation

In Prague on ……………… ………………………………………
signature

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ABSTRACT

The present paper deals with unique research on the effect of plants on the quality of the indoor building's environment with a positive impact on operational savings in building ventilation aspects. The present paper contains a number of theoretical simulations and unique verifying of practical measurements that are necessary for understanding the issue of implementing plants into the internal environment of buildings and their operation. Theoretical simulations deal with variable parameters of the required quality of the indoor environment C_{req} and the quality of the supplied air C_{sup} from the point of view of CO_2 and VOC (Volatile Organic Compounds) with variable lighting. Based on the provided calculation, it was shown that for a sample office indoor environment with a volume of 74.7 m^3, occupancy of 3 people and the implementation of 3 m^2 of green leaves, when lighting 40 % green plant leaves PPFD (Photosynthetic Photon Flux Density) = 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 60 % green leaves 80 $\mu mol \cdot m^{-2} \cdot s^{-1}$, brings potential saving of 0.31 % to 1.44 % on building ventilation and PPFD = 100 / 60 $\mu mol \cdot m^{-2} \cdot s^{-1}$ potential savings of 0.15 % to 0.98 %.

Using provided theoretical simulations, it was shown that VOC is a minority compared to CO_2, but plants can still contribute significantly to reducing its concentration.

Using practical measurements, it was found that for plant illumination, it is advisable to place them near openings with direct access to natural light, since in the model office, only artificial lighting used for office lighting showed insufficient illumination values in the PPFD range of 0 to 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$, whereas after sunrise and illumination of the workplaces with natural light, the measured values in the autumn-winter-spring period ranged from 0 to 647 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD.

In this thesis, the actual performance of selected cultivars of Ficus Benjamina and Aloe Vera was practically measured in an enclosed model space simulating light conditions and the respective CO_2 concentrations of the indoor environment. The measurements of the cultivar Ficus Benjamina (C_3 - the most common metabolic pathways for carbon fixation in photosynthesis) significantly exceeded the theoretical assumptions when, with a leaf area of ~ 0.26 m^2, and a PPFD light level of ~ 139 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at the upper level of the plant canopy, it was able to reduce the CO_2 concentration on average by 0.526 $g \cdot m^{-2} \cdot h^{-1}$, and at

PPFD ~ 49 μmol · m^{-2} · s^{-1} by 0.421 g · m^{-2} · h^{-1}, whereas the theoretically calculated value at more suitable light conditions of PPFD 300 / 80 μmol · m^{-2} · s^{-1} was only 0.307 g · m^{-2} · h^{-1} and 0.150 g · m^{-2} · h^{-1}, respectively, in the case of PPFD 100 / 60 μmol · m^{-2} · s^{-1}. For the Aloe Vera cultivar (CAM - carbon fixation pathway that evolved in some plants as an adaptation to arid conditions), the values were less favourable as expected, with an average of 0.022 g · m^{-2} · h^{-1} assimilated by the plant at PPFD ~ 90 μmol · m^{-2} · s^{-1} and 0.005 μmol · m^{-2} · s^{-1} at PPFD ~ 50. The last part of the work takes into account the monitoring of the behaviour of employees in a real office environment with the monitoring of the CO_2 concentration evolution for one working week, where habits and potential opportunities with an impact on savings in the field of building ventilation can be appropriately identified.

Overall, this work confirms the current limited understanding of the issue of plant implementation in the indoor environment of buildings and points to a completely new scientific field that needs to be further developed and researched.

KEYWORDS:

Indoor Environment, Indoor Air Quality, Plant, Green Wall, CO2, VOC, Ventilation, Climate Change, Energy Efficiency, Energy Consumption

CONTENT

Abbreviations

A_c	Circadian index
CAS	CAS Registry Number (assigned by the Chemical Abstracts Service)
CAM	Crassulacean acid metabolism
CO_2	Carbon dioxide
CRI	Color rendering index
ESA	The European Space Agency
HVAC	Heating, ventilation and air conditioning
IDA	Indoor Air Quality
LCP	Light compensation point
LED	Light (light-emitting diode)
NASA	The National Aeronautics and Space Administration
ODA	Outdoor Air Quality
PAR	Photosynthetic Active Radiation
PPFD	Photosynthetic Photon Flux Density
T_{cp}	Color temperature
VOC	Volatile organic compounds

Expressions

Bake-out: This is the use of heat in building construction for removal volatile organic compounds.

Biofiltration: This is a biological-based technique that is employed to treat contaminated air.

BREEAM: (Building Research Establishment Environmental Assessment) This is an assessment method carried out by independent licensed specialists using science-based sustainability metrics and indices that cover a range of environmental issues.

C_3: (C_3 carbon fixation) is the most common metabolic pathways for carbon fixation in photosynthesis.

C_4: (C_4 carbon fixation) is a next known photosynthetic processes of carbon fixation in plants.

CAM: This is a carbon fixation pathway that evolved in some plants as an adaptation to arid conditions that allows a plant to photosynthesize during the day, but only exchange gases at night.

CDD: (Cooling degree day) is a measurement designed to quantify the demand for energy needed to cool buildings.

Flush-out: This is a technique whereby air is forced through a building after construction and prior to occupancy in order to remove or reduce pollutants, such as VOCs and particulate matter, inadvertently introduced indoors during construction. Can be air flush or buildung flush.

HDD: (Heating degree day) is a measurement designed to quantify the demand for energy needed to heat a building.

LEED: (Leadership in Energy and Environmental Design) This is a green building certification program used worldwide, developer by the U.S. Green Building Council in 1998.

SBToolCZ: This is a sustainable building certification scheme developed as a localization of International Initiative for a Sustainable Built Environment's SBTool. Czech version is fully localized for national conditions and priorities and is fully harmonized with national and European standards.

WELL: This is certification global rating system that recognizes buildings designed and constructed to support health and well-being of their occupants.

1. Introduction

The quality of the internal environment of buildings is still a less intensively solved issue. One of the key parameters for assessing the quality of the indoor environment is the quality of the indoor air itself and the level of concentrations of harmful substances – pollutants. Thanks to ventilation, most pollutants can be relatively effectively kept within the relevant limits. Theoretically it can be stated that with the increased amount of changed air, the concentrations of pollutants in the indoor air will approach the values of the outdoor air, which can be mostly considered as the "less harmful".

Because of the two conflicting requirements, the present topic is closely related to the energy efficiency of buildings. One of them are the requirements of building's users, which is receiving of maximum air quality in the indoor environment, i.e., a high requirement for ventilation and air filtration. The second one are the requirements of the building manager, which is minimizing of operating costs, i.e., the potential effort to minimize ventilation and air filtration. The energy requirement of building ventilation consists primarily in adjusting of supplying air to internal quality parameters, in this case primarily in temperature.

In the case of air filtration, it is necessary to check filters regularly and change them, which has a negative impact on operating costs.

It is known that in the case of the user's presence in the building, ventilation must take place almost continuously to keep the concentration of pollutants within acceptable limits. Among the most monitored pollutant is a concentration of CO_2.

The present topic is relevant for buildings that are operated in Central Europe, but it acquires real significance for buildings that are operated in climate zones with large or long-lasting temperature differences between the internal and external environment, i.e., in polar, subpolar, subtropical, and tropical climate zones. Therefore, it is appropriate to investigate alternative operating methods leading to the reduction of pollutant concentrations in the indoor environment of buildings, which have the potential to save operating costs and at the same time improve indoor air quality.

The basic aim of the present research is to verify the possibility of implementing plants into the internal environment of buildings, as an active element used to reduce pollutants, in order to save costs for operational ventilation of buildings, or to achieve a higher quality of the internal environment in terms of air quality. The submitted thesis presents examples of solutions based on the concrete examples.

The first part contains detailed research of the investigated issue and the results of research that are known and were published in foreign journals and books. Next part deals with determining the methods for ensuring the own measurement, specifically, determining the ability of selected plants to reduce the concentration of CO_2 in the indoor environment based on variable lighting. The work also includes measurements of typical lighting values in the indoor environment in an office building and CO_2 production in a real office based on the presence of workers.

The final part of the paper shows measurements that are summarized and used in further simulations in sample environments. Based on the provided own measurements in the real environment and own calculations, the thesis achieves a unique view of the topic, compares them with partial results of foreign researches and establishes recommendations for the implementation of plants in the interior environment of buildings.

2. The current state of the issue

2.1 Definition of the solved issue

The present topic deals with the quality of the internal environment of buildings from the perspective of the occurrence of selected pollutants and individual elimination methods leading to reduction of pollutants in the indoor air. Ventilation of the internal environment is known as a basic possible and currently used method leading to a permanent reduction of pollutants. It can be provided by both variants as forced or natural. On a limited scale, air filtration can be partially used to reduce pollutants, especially for dust particles and volatile organic substances.

However, the carbon dioxide concentration cannot be reduced too much by the air filtration that is commonly installed in residential or administrative buildings. The concentration of CO_2 must therefore be reduced purely by ventilating.

A lot of research has been done in recent years, which explores the ability of individual plants to bind selected pollutants [1; 2; 3; 4; 5] and it is therefore assumed that plants have the potential to significantly contribute to the reduction of pollutants in the indoor environment of buildings.

2.2 Importance and significance of solving issue

The issue is closely related to the ever-increasing requirements for the safety and health protection of the indoor environment of buildings and the quality level of the air in the indoor environment itself. It is necessary to mention that pollutants are generated in the building throughout its life cycle, i.e., both during construction and during operation.

During the building's operation, mainly carbon dioxide (CO_2) is produced due to the users' breathing. Also, volatile organic substances are brought in together with the built-in materials and during the operation of the building. There are proven cases when so many pollutants were entered into the building during construction, that the building was uninhabitable and unhealthy for several months after its construction [6].

It is known that increased concentrations of pollutants in the indoor environment can have a negative effect on the human health of building users [7], in general it can be stated that the long-term exposure of a user in an environment with higher concentrations of pollutants has an impact on its health, this fact is relatively appropriately described as a sick building syndrome [8]. Another study, based on measurements, proved that the level of carbon dioxide concentration has a direct impact on work performance [9], while the measurements were based on normal concentrations, within the limits of the legal limit. [10; 11]

Indoor air quality classes were solved by (already cancelled) Czech technical standard [12] in very good way, which established 4 basic IDA (Indoor Air Quality) classes. The newer Czech technical standard, which replaced the original technical standard, no longer solves indoor air quality classes in such a deep detail [13].

Finally, it is also appropriate to mention the building certification systems, which also monitor the level of concentrations of pollutants in the indoor environment. The implementation of various measures leading to the reduction of pollutant concentrations in the indoor environment, or the results of specific measurements of pollutant concentration levels are directly reflected in the final environmental assessment of the building. These are primarily the globally widespread certification systems WELL [14], BREEAM [15] and LEED [16], among less widespread certification systems then SBToolCZ [17].

In Czech legislation, air quality in the indoor environment of buildings is currently assessed according to the concentration of carbon dioxide [10; 11], while in living rooms the maximum concentration limit is set at 1500 ppm, which corresponds to a concentration of 0.15%. The concentration of dust particles, the chemistry of the environment and the occurrence of pathogenic units, including microorganisms, are also intensively monitored in school buildings [18]. There is a constant demand for increasing the energy efficiency of buildings and related technological devices that are used for buildings ventilation. On the other hand, the research of the other ways of eliminating carbon dioxide and other investigated pollutants in the indoor environment of buildings is completely overlooked, whereas the newly investigated methods could have a significant positive impact on the amount of ventilated air, thus also on the operating costs.

It can be concluded that with the increasing efficiency of air ventilation systems, the costs of ventilating buildings and the associated with it modifications of the supply air to the appropriate indoor temperature are still high worldwide known.

The requirement to adjust the outside air to the desired temperature is especially relevant in places with a high difference between the inside and outside air temperature (except for the Czech Republic, where high costs are considered for air treatment both in the winter and summer months). It is an assumption that even a minimal reduction in the amount of air supplied has the potential for truly significant savings in operating costs on a global scale. To maintain high user requirements for the quality of the indoor environment and at the same time to reduce the energy demand of buildings, it is necessary to find new ways of eliminating pollutants, which will make possible to reduce the amount of ventilated air while maintaining the required air quality in the indoor environment, and which correspond to the level of knowledge of the 21st century.

The presented issue is currently intensively researched, especially abroad. These are primarily places with a high level of air supply pollution, where the effort is to find any technology that would bring even minimal savings. Currently, there are only recommendations for placing plants in the indoor environment in general [15], but specific measurements that would point to the specific ability of plants to reduce pollutants in the indoor environment in a real case are still only in the research and verification phase. Reducing the concentration of harmful substances in the indoor environment of buildings can currently be solved either by replacing contaminated air by newly supplied air from the outside environment treated by air conditioning or by treating the existing indoor air, while treating the supply air from the outside environment is rather energy intensive. It is also possible to exchange air naturally through windows without the use of air conditioning equipment, however, when exchanging air on hot or cold days, the ventilation causes thermal discomfort to the users of the building, which is undesirable. It is necessary to mention that there is an increasing number of buildings without the possibility of natural ventilation, when windows cannot be opened in such buildings and the quality of the indoor environment is directly dependent on the quality of ventilation regulation using air-conditioning devices. In the case of natural window ventilation, it must be mentioned that open windows cannot be equipped with effective filtration in the case of contaminated outside air. In case that living rooms are located near sources of acoustic noise (e.g. roads, railways), there is also a problem with meeting hygiene limits or acoustic requirements in the case of ventilation directly using open windows. It has been proven that the selected plants have a significant potential to reduce the concentration of the treated pollutants [1], and it is therefore appropriate to investigate the possibilities of incorporating them into the internal environment of buildings in order to naturally reduce the monitored pollutants. Selected plants can reduce carbon dioxide and other pollutants contained in the environment in which the plants are located, while the ability of plants to reduce pollutants depends primarily on temperature, lighting and the concentration of the pollutant [1; 2; 19].

With the increasing concentration of carbon dioxide in the indoor environment
the plant's ability to bind carbon dioxide increases slightly, with decreasing levels of illumination the plant's ability to fix carbon dioxide is falling significantly [2; 20; 21]. However, the plant's ability to increase its ability to bind carbon dioxide is directly dependent on increasing temperature, while without lighting, the plant's ability to bind carbon dioxide is significantly suppressed. In the indoor environment, which can be classified as a relatively stable temperature environment with a difference of only a few degrees Celsius, and at the same time the lighting is limited and relatively constant, therefore a significant difference in the ability to bind a larger amount of carbon dioxide cannot be assumed, as the temperature and lighting are rather similar even at increased concentration. Of course, the light can be slightly

variable depending on the location of the plant within the space and depending on the combination and intensity of artificial and natural lighting. However, it is not customary for indoor lighting values to be at the same levels as in outdoor environments.

2.3 Influence of the quality of the indoor environment on the user's performance

According to the latest foreign research, which monitored the performance of workers in detail according to the amount of carbon dioxide in the indoor environment [22], 3 basic researched environments were determined - a normal environment corresponding to the standards [23], i.e. ordinary buildings, an environment with increased quality corresponding to the LEED standard, i.e. green buildings, and an environment corresponding to the LEED standard [16] with an increased amount of external air supply, marked as green building plus (+). The range of carbon dioxide concentration in individual environments was in the average range of 486–1420 ppm.

The measurement took place over a period of 6 days, on 24 people in the age range of 20 - 70 years, the participants were both men and women. The evaluation for a total of 9 investigated activities is shown in Figure 2-1 [22].

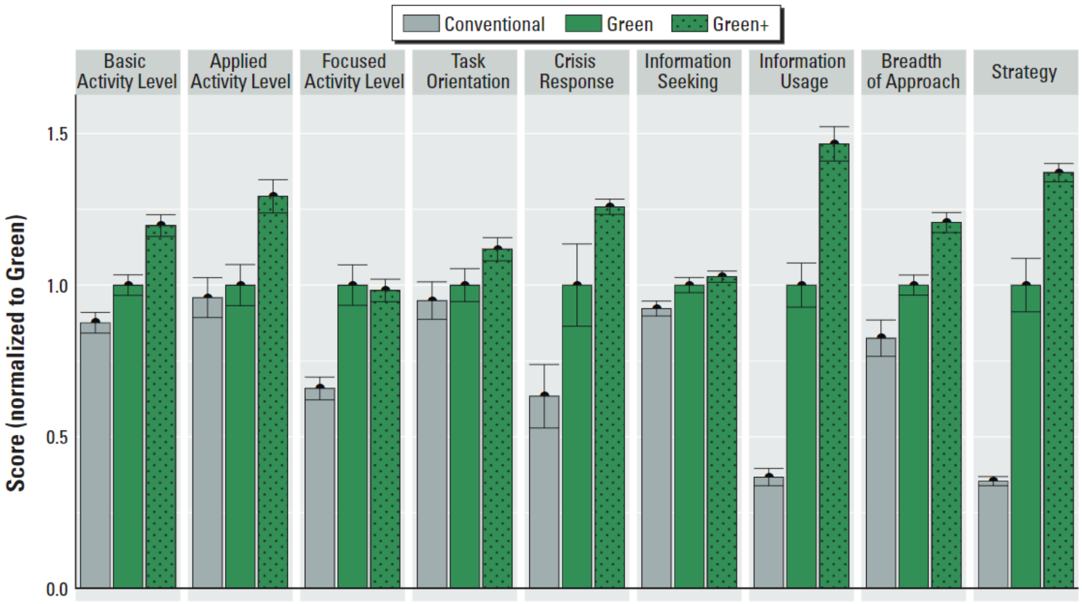

Figure 2-1 The influence of the quality of the indoor environment measured by CO_2 concentration on the work efficiency of users

Figure 2-1 shows a significant difference in the efficiency of users located in the individual researched environments. From the conducted research, it can be concluded that, compared to conventional buildings, the efficiency of workers is 61% higher in green buildings, and 101% higher on average in green buildings with an increased amount of supplied air. During this experiment, the concentrations of VOCs (volatile organic compounds) in the indoor environment were also measured at the same time. It is assumed that the combination of an increased concentration of carbon dioxide and various VOCs can intensify the fatigue effect, however, research cannot specifically determine the synergistic effect of individual VOCs, and it is considered that the majority effect on reducing the performance of users is primarily an increased concentration of carbon dioxide.

Another similar research, which studied the performance of users even for a higher concentration of carbon dioxide, specifically up to values of 2500 ppm, achieved similar results [9], which confirms the negative effect of carbon dioxide on the performance of users in an indoor environment. The differences in performance between users working in high and low CO_2 environments are significant for most cases, as shown in Figure 2-2 [9].

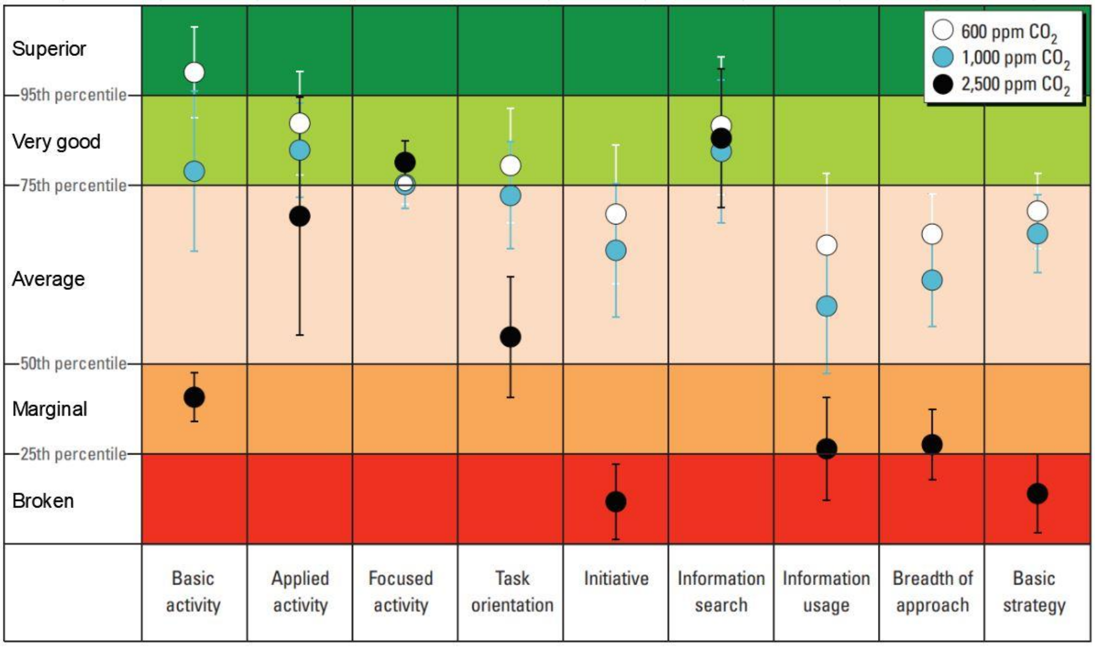

Figure 2-2 The influence of CO_2 concentration in the indoor environment on the work performance of users

It is clear from Figure 2-1 and Figure 2-2 that the most fundamental difference in user performance is recorded in the case of activities requiring a high degree of concentration and thinking. In the case of high concentrations, evident disfunction is noted in activities consisting in strategic decision-making and initiative activities, borderline are activities related to information processing and creating a comprehensive overview. It is important to point out the ability to make decisions in crisis situations (so-called crisis reactions) in which, in the case of a high concentration of CO_2 in the internal environment, human function is suppressed by approximately a half. Crisis activities can include professions requiring immediate reactions and high concentration, such as surgeons, flight dispatchers, emergency call centres workers, etc.

For these professions that work in crisis situations and require an operative solution to stressful situations, it is necessary to permanently ensure a high quality of the internal environment and not limit the ability of cognitive functions. [24; 25; 26] Not ensuring sufficient quality of the internal environment can contribute to the failure of the performed activity due to insufficiently fast and accurate reactions.

The specific effect of individual VOCs on the performance of users has not yet been thoroughly researched, however, negative effects on human health have been proven, especially with long-term exposure. Among the main negative effects are carcinogenicity, irritated mucous membranes and respiratory tract, negative effect on immunity and weakening of the organism [7; 27; 28]. The risk depends on the type of active substance, the amount of concentration, the time of exposure in the contaminated environment and the susceptibility of the specific user. As were mentioned above, some research reports a synergistic ability to suppress human cognitive functions with simultaneously increased CO_2 concentration in the indoor environment of buildings. [9; 22; 29; 30; 31]

2.4 Sources of pollutants in buildings

The origin of pollutants in the indoor environment can be divided into 2 basic groups. The first basic source are the materials used in the internal environment, i.e. the materials incorporated and used during construction, renovation or during the retrofitting of the internal environment itself. VOCs are mainly emitted from this group. [32; 33] The second major source of pollutants in the indoor environment are users of the building themselves, i.e., pollutants introduced during the operation of the building. Carbon dioxide, which is a product of human activity due to breathing, is emitted to the greatest extent here. However, building users also produce VOCs in the form of personal materials or perfumes brought in, as well as during cleaning using cleaning agents, or during operation of copying machines and printers. [34; 35; 36; 37]

Currently, the only effective way to maintain the concentration of pollutants at sustainable limits in the indoor environment is ventilation of buildings and possibly filtration. While most VOCs can be filtered relatively effectively, carbon dioxide cannot be captured by common filter media installed in air handling devices and must be distributed to the external environment, where reduction is already ensured by the naturally occurring external greenery thanks to photosynthesis.

New constructions and buildings after renovations are significantly risky buildings for the occurrence of harmful substances. If a significant number of pollutants are introduced into the building, it may take several months before the concentration is reduced to the permissible limit due to ventilation [6; 38]. The so-called Flush-out method can be partially effective [14; 16], which currently ventilates above-limit concentrations of harmful substances after the construction of the building, and subsequently only permanent ventilation is maintained with the help of the air-conditioning system. A significant source of pollutants entered into the indoor environment of buildings is the finishing processes during construction. In the cited research, it was decided whether it is possible to accelerate the evaporation of pollutants from building materials [39; 40]. Based on provided measurements, it has been proven that, in the case of using the bake-out method (or heat treatment) [41; 42], it is possible to significantly increase the leakage of volatile substances from building materials and thus to ventilate the contaminated air more efficiently. The bake-out method uses negative pressure or elevated temperature to facilitate the transport of volatile substances from materials to the environment in which the material is located. [43; 44] However, this method is mainly suitable as a measure immediately after construction, due to the use of higher temperatures exceeding 30 °C or the creation of negative pressure in the space, this method cannot be used during normal operation of the building, as it could cause some discomfort to users in the building. An interesting result was obtained by measuring the occurrence of pollutants in Sweden, which compared the concentration of pollutants in 20 new passive buildings compared to 21 conventional buildings. It has been found that passive houses contain a higher number of VOCs on average [45]. This can be attributed to poorer air circulation compared to conventional houses, which normally have a much lower level of airtightness to the outside environment.

2.5 Application of green walls and the effect on the quality of the indoor environment

Green walls are increasingly being designed for the interior of buildings, mainly for administrative and school buildings. The fundamental advantage of green walls is the use of vertical surfaces in the interior, instead of the use of horizontal surfaces. From this point of view, green walls are space efficient compared to regular flowerpots placed on the floor. It is a relatively new application, and the necessary measurements are still being made, although they are already actively applied in the commercial sector, mainly thanks to certification systems that allow to earn bonus points in case of using these innovative solutions. [14; 15; 16; 46] Examples of already implemented green walls are shown in Figure 2-3 [47].

Figure 2-3 Green wall in the André Hoffmann Atrium, David Attenborough Building, Cambridge

Scientific laboratory studies mention that plants have the ability to reduce selected VOCs in two basic ways, namely direct reduction (absorption) and indirect (biotransformation or with the help of microorganisms) [48]. It is proven that with increasing light intensity, the ability to reduce VOCs increases.

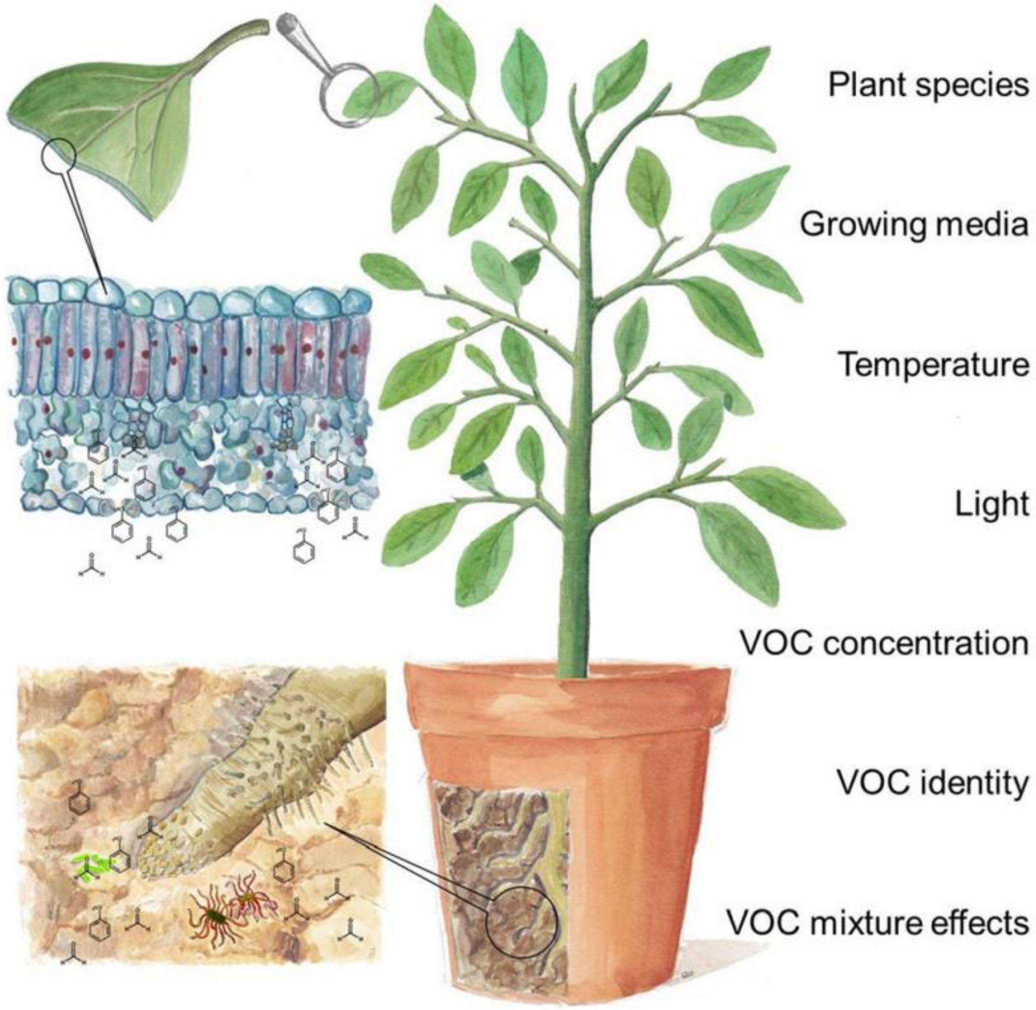

Figure 2-4 Schematic representation of VOC elimination by a plant

Figure 2-4 [48] shows the way in which VOCs are stored by the plant, which depends primarily on the type of plant, peat, temperature, lighting, concentration and type of pollutant [48]. The plant captures VOCs in the stomata of the leaf and further transports the substance to the root system, where it is stored. However, pollutants are also captured in the bronchi, where they can remain.

To clarify the question of what specific effect the shown above green walls can have on the biofiltration of the internal environment, initial measurements were carried out as part of foreign research. One case study [49] was performed in a closed container, where a total of 9 VOCs were monitored, among which benzene and toluene were also investigated. The measurement dealt with the effectiveness of the plant in reducing pollutants in the flowing supply air, so the air in the space was not static. It has been found that green walls can reduce ethanol and acetone quite effectively, by an average of more than 75%, from the supplied air through such a wall. According to measurements, the investigated substances as benzene and toluene can be reduced significantly less in flowing air, on average between 20% for toluene and 30% for benzene [49]. In further research the specific effect of air flow speed was monitored on the ability of green walls to reduce carbon dioxide, together with the intensity of lighting in the given space [50]. It has been confirmed that for the ability to reduce carbon dioxide in the indoor environment, lighting is the majority parameter, while air flow speed has a minimal, almost negligible effect [50]. From the provided measurements can be concluded, that in the case of suitable lighting conditions and an increased concentration of carbon dioxide, the plant is able to reduce carbon dioxide more with increasing air flow speed.

The ability to reduce carbon dioxide directly depends on the type of plant and the specific metabolic cycle of the plant, while within the same metabolic cycle of one plant, the ability to bind carbon dioxide under reduced light conditions in the internal environment can be significantly lower compared to ideal conditions in the external environment [51]. It is therefore not possible to precisely determine the specific behavior of individual cultivars without appropriate measurements for the given plant. [51]

Current knowledge divides plant metabolic cycles into C_3, C_4 and CAM (Crassulacean acid metabolism). C_3 metabolism covers approximately 90% of all plant representatives worldwide, it is common for them to occur in colder, temperate to partially subtropical conditions. However, they are mostly represented in the temperate climate zone.

These plants are able to bind carbon dioxide up to an average of 25 °C, above this temperature the ability begins to stagnate and subsequently weakens. These plants are typically resistant to colder and humid climates, photosynthesis usually takes place up to a temperature of 0 °C. In the case of frost-resistant species, which include, for example, conifers and grasses, the absorption of carbon dioxide is measurable even in the case of temperatures below freezing, approximately down to -7 °C.

It is assumed that plants with a C_3 metabolic cycle are evolved into plants with a C_4 metabolic cycle. They are usually found in drier places; they can withstand higher temperatures and stronger sunlight. The ability to bind carbon dioxide increases on average up to a temperature of 40 °C, after which the ability to bind carbon dioxide weakens [52]. The last basic known metabolic cycle is CAM, which was evolved from plants with C_4 metabolism. They are able to survive even in very dry environments, in the natural environment during hot dry days they do not open their pores and fix the carbon dioxide that they have accumulated during the night - this means that these plants do not mostly create carbon dioxide during the night, as in the case with the C_3 metabolic cycles and C_4. At the same time, it is proven from observation that some plants with a CAM metabolic cycle can function in the same way as plants with a C_3 metabolic cycle under suitable conditions, while the ability to fix according to the CAM cycle does not lose during their life and they can apply it again if it is from a natural point of view more favourable for plant survival purposes [52].

Figure 2-5 [2] shows the average fixation of carbon dioxide according to the plant's metabolic cycle and temperature [2]. Plants with the CAM metabolic cycle have the ability to fix carbon dioxide even during the night hours, but during the day in the case of favourable temperature and light conditions, they fall significantly behind the C_3 and C_4 metabolic cycles.

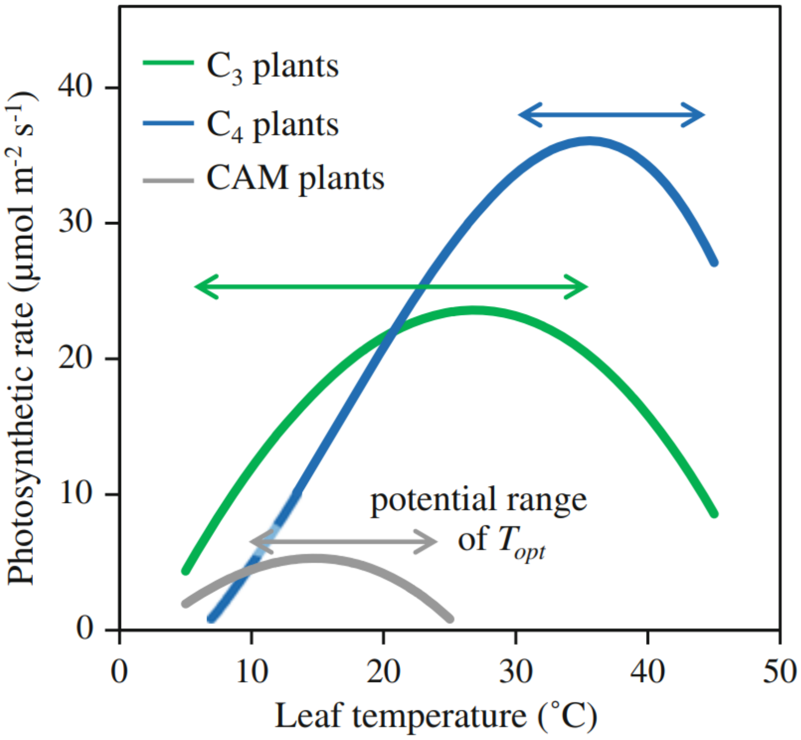

Figure 2-5 The ability of plants to bind CO_2 according to the metabolic cycle and leaf temperature

Each metabolic cycle has pros and cons in terms of use in the indoor environment. Research has shown that with the right combination of plants with different metabolic cycles, the overall effect on the reduction of monitored pollutants can be favorably enhanced [53]. In the absence of a light source in front of the plants, the efficiency of some metabolic cycles is greatly reduced (C_3 and C_4), and it is worth considering in such environments to choose the CAM metabolic cycle. In case of ensuring a suitable temperature and light environment however, it is a prerequisite for significantly higher efficiency in plants with a C_3 and C_4 metabolic cycle.

The behavior of plants at night is closely related to the issue of lighting, or the level of the light compensation point (i.e., the point when the plant does not produce or reduce carbon dioxide). Plants are known to sequester carbon dioxide during the day when light is sufficient (i.e., the potential to reduce the concentration in the study environment), while at night when the light is dimmer, they produce it again (i.e., the potential to increase the concentration in the study environment). However, the amount of carbon dioxide produced by plants during the night hours is an order of magnitude lower than the amount reduced during the day. This parameter is appropriately discussed in a study that investigated the ability to bind carbon dioxide in the indoor environment according to light conditions and which is shown in Figure 2-6. [54]

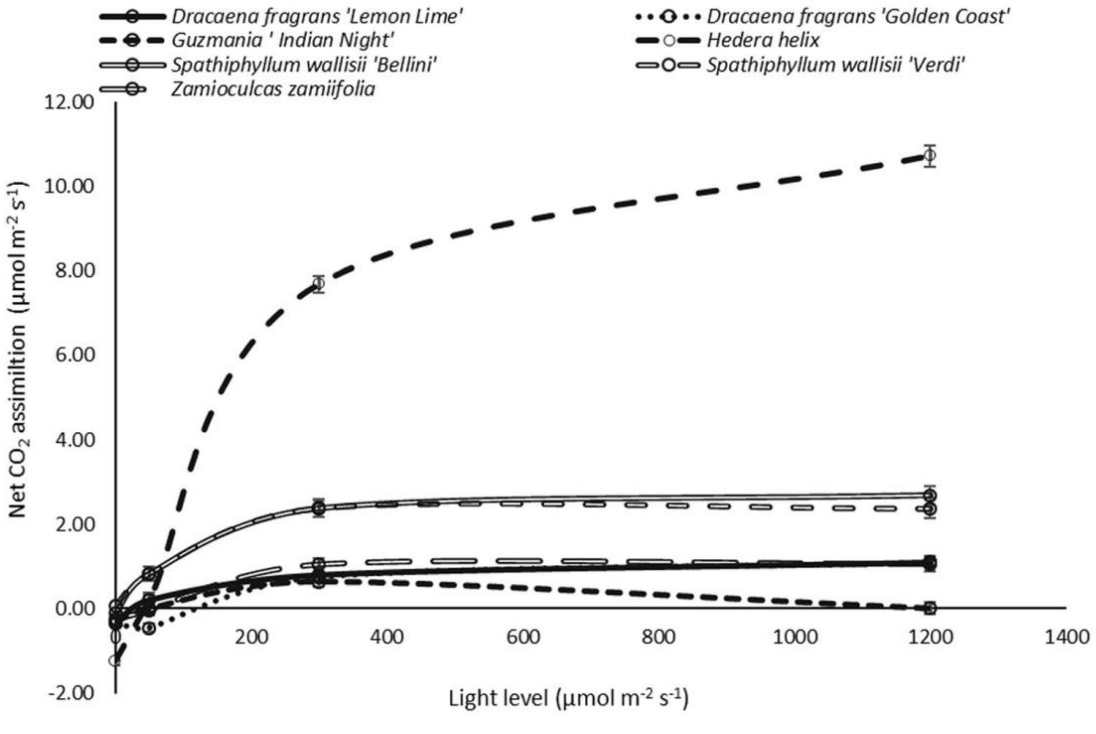

Figure 2-6 The ability to bind CO_2 by selected plants according to the level of illumination

It can be seen from Figure 2-6 that the investigated plants have several times more potential to reduce carbon dioxide than to produce it. With the exception of Dracaena fragrans, the compensation point of photosynthesis ranges from 0 to 50 [$\mu mol \cdot m^{-2} \cdot s^{-1}$], and these lighting values can normally be reached without problems even in an indoor environment. In case of longer duration of conditions without sufficient intensity of lighting, the plant usually suffers, then withers and dies. [54] Therefore, it cannot be assumed that the investigated plants would produce more CO_2 during their life cycle than they reduce it. In the mentioned study, it was further investigated whether the humidity of the substrate influences the ability to bind carbon dioxide, and it was concluded that the humidity of the substrate has a negligible effect under the conditions of the indoor environment [54].

Further research [55] points to the risk of microbial contamination of the internal environment in the case of the presence of stagnant water in green walls, the presence of which is mainly caused by inadequate watering of green walls. The measurement points out that although biofiltration is effective, i.e. VOC reduction is taking place, however, due to the formation of bacteria, it recommends the use of forced ventilation of the indoor environment and the use of greenery mainly in the exterior. This also results in recommendations for the choice of plants for the indoor environment, namely those that do not require a large amount of irrigation and can survive without problems even in drier conditions or dry substrates. There is also the possibility of working with breakthrough irrigation technologies such as hydroponic irrigation, which sufficiently irrigates the root system with minimal water consumption. [56; 57; 58] This results in relatively low substrate moisture, but sufficient moisture for the plant's survival needs. At the same time, it is necessary to mention other research that points to the probable ability to reduce VOCs also by microbial organisms that are created in the substrate and around plants, while there are still not enough measurements to definitively determine the effectiveness of this secondary ability of these organisms [59].

Furthermore, it is necessary to note that the wrong choice of plants can cause allergic reactions in users, especially due to the production of aromatic substances [60]. However, such substances are overwhelmingly produced mainly from plant flowers, so it is advisable to take such a factor into account when choosing plants for indoor use. Similarly, to plants, a well-maintained air-conditioning system [61] can also be a source of allergens, and such a system can itself be a source of other pollutants, especially dust particles and microbiological pollution.

Another feature of green walls and the placement of plants in the indoor environment is that plants in green walls can also bind airborne dust in the indoor environment [62], while the ability to reduce airborne dust increases proportionally with increasing airborne particles. This is also why green walls are suitable as a kind of biofiltration in an infested environment. It is also worth mentioning the positive effect of green walls on the reduction of heat islands and areas that are burdened by solar radiation and thus cause local discomfort [63]. This property can be suitably used both in external and internal environments. The presence of greenery in the indoor environment also offers a certain potential from the point of view of passive cooling and maintaining the temperature stability of the indoor environment, thanks to the transpiration of water vapour through the leaves. In the external environment, in order to reduce the risk of temperature islands in the urban area, it can be assumed to ensure a more stable environment from the point of view of temperature fluctuations, research describes a significant positive benefit, especially in the external environment, as part of planting greenery on the envelope of a building or roof. [64; 65; 66; 67] From the point of view of the indoor environment, it can be assumed that with reduced light intensity, transpiration will decrease at the same time, and thus the cooling performance in the indoor environment will also decrease. Plant transpiration should be set correctly together with the air handling system to avoid extreme uncontrollable humidity in the indoor environment. While in the winter months during the heating season the increase in humidity in the indoor environment can be perceived rather positively, in the summer months there is an effort to reduce the humidity. [68] However, the issue of passive cooling using plants is still in the research and observation phase. However, it is advisable to pay attention to this fact as well.

It is known that the placement of plants in the indoor environment of buildings generally has a rather positive impact on the psychological well-being of building users and the related performance of users [69]. As part of foreign research, user satisfaction was investigated for rooms containing non-aromatic, slightly aromatic and strongly aromatic plants, and the size of the plants was also considered. The evaluation of the conducted research clearly demonstrated that small, slightly aromatic plants are considered optimal in the indoor environment by the majority of users [69].

2.6 Operating costs for building ventilation

An important aspect for the ventilation of buildings and the quantity of supplied air is the quality of the outside air itself [70]. While pollutants from the VOC group can be relatively effectively filtered within reasonable financial limits, carbon dioxide cannot be filtered without the use of special and expensive technologies. The requirement for the amount of supplied air to achieve a certain, predetermined, quality of the building's internal environment is therefore directly dependent on the concentration of carbon dioxide in the supplied air. Research was conducted in Shanghai, which dealt with the operating costs of ventilation of administrative buildings. It has been shown that buildings next to roads in their immediate closeness need to ventilate on average 20% - 30% more to achieve the required indoor concentration, compared to buildings within pedestrian areas [71]. At the same time, in this research, carbon dioxide concentrations were measured near roads and in the closeness of pedestrian areas. While an average concentration of 435 ppm was measured in the closeness of pedestrian areas, it was an average of 550 ppm in the closeness of roads.

Operating costs for building ventilation therefore depend significantly on the required indoor air quality, or targeted concentration of pollutants, and according to the quality of the supply air. [72; 73] Depending on the amount of changed air, the requirement for the amount of temperature-controlled air also increases, and the amount of costs incurred is directly related to this.

Figure 2-7 shows the global energy consumption in the world for the operation of residential and office buildings in 2010 [74]. In the graph, energy consumption is divided into sub-areas of consumption, namely indoor heating, water heating, lighting, cooling, electrical appliances, cooking and others. The statistics are based on a study from 2010, and due to the constantly increasing demands for comfort and ensuring the overall comfort of users, it can be assumed that the total energy consumption will continue to increase. This assumption is also supported by the fact that the amount of population is still increasing, which is closely related to the requirement for the construction of additional new buildings to ensure the basic needs of individual people, and with this the absolute value of the consumed energy will probably increase as well.

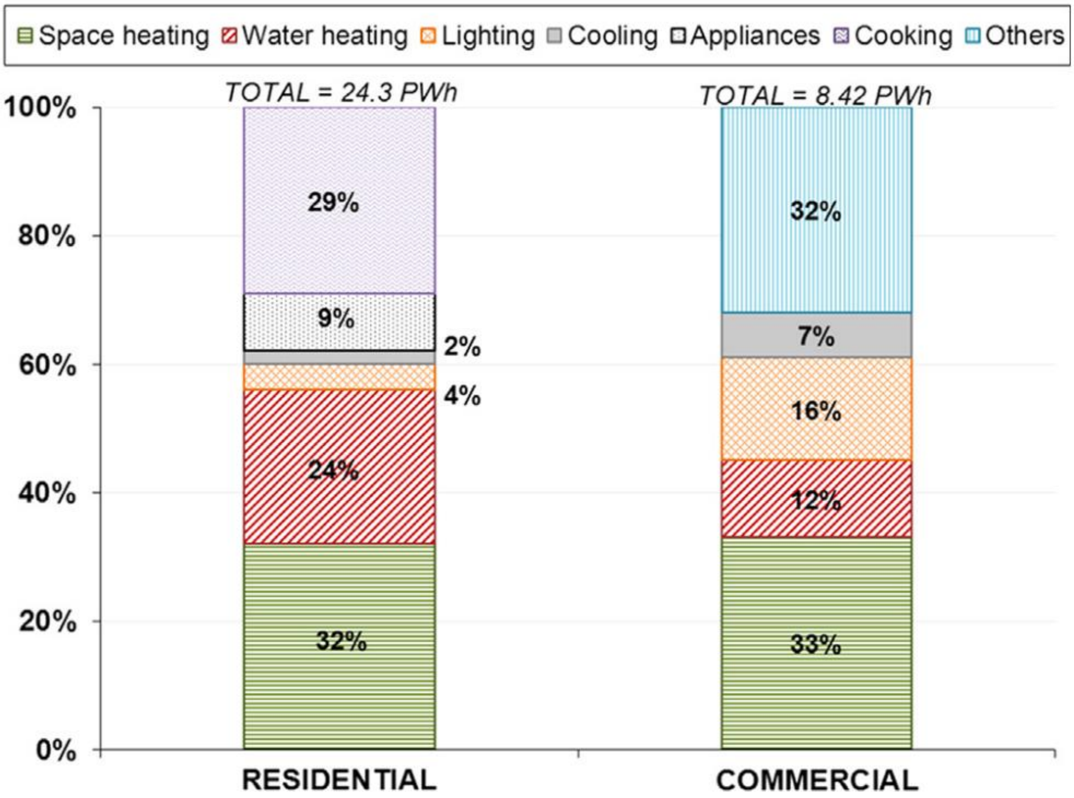

Figure 2-7 Global balance of energy supplied to residential and administrative buildings in 2010, divided into sub-consumptions

Figure 2-7 shows that residential buildings use an average of 34% of the total energy supplied to the building for heating and cooling, commercial buildings an average of 40%. Losses of heat and cold in the exhaust air depend on the efficiency of the ventilation system and the efficiency of recovery, which for non-industrial buildings ranges on average between 60% - 85% under the most favourable conditions, while the actual values are often less favourable because the air handling systems are not always operated at optimal performance, they are further influenced by several variable factors such as the air tightness of the system itself and the related losses. It can therefore be stated that, due to ventilation, a considerable amount of energy is spent worldwide on conditioning the supply air and ensuring the required thermal comfort in the indoor environment. Despite increasing the efficiency of recuperation within the air handling systems, the theoretical 100% efficiency will probably never be achieved, due to the losses of the air handling system, and it will be necessary to supply a high amount of energy annually for the temperature treatment of the air in the future.

2.7 Expected development and potential impact of climate change on building ventilation

Based on current research, a continuing global warming trend is expected. [74; 75; 76] This results in favourable expectations from the point of view of building heating, where a reduction in the energy demand of buildings can be expected due to a reduction in the demand for heat supply. Unfavourable expectations are, however, in the field of cooling, where climate change can significantly increase the demand for the supply of cold to buildings. Figure 2-8 show the expected trend of percentage change of climate change. Figure 2-8 show the changes for the period between 2021 – 2040 compared to the period 1981 – 2000. Figure 2-8 part a) shows the expected percentage change in the individual world metropolises for the demand for heat supply during the model year, Figure 2-8 part b) shows the percentage change for the demand of cooling deliveries during the model year. It is clear from Figure 2-8 part a) that for heat supply, a decrease in energy supply is expected in the observed period in the range of absolute values − 5% to − 50%, the most frequently represented expectation is − 10% to − 20%. It is clear from Figure 2-8 part b) that for the supply of cold, an increase in the supply of energy is expected in the monitored period in the range of absolute values of + 10% to + 100% and more, the most common represented expectation is + 20 to + 60%. [75] From the point of view of building operations the mentioned predictions can be evaluated rather as negative, because the expected costs of cooling the building have a significant potential to exceed the expected cost savings that were achieved from a lower heating requirement several times over. It can be assumed that building operators will be significantly forced to look for all operating savings and find experimental solutions, thanks to which they can achieve even minimal savings, which can be significant when considering the total delivered energy. [77; 78; 79]

However, climate change does not only consist in the issue of expected temperature changes, but also in the undesirable development of the quality of the external environment from the point of view of CO_2 concentration. The concentration of CO_2 in the external environment has already increased significantly during the last century, when in the years 1900 - 2000 the concentration was in the range of 280 – 400 ppm, and only since 2000 have values exceeding 400 ppm become common, while today the concentration of CO_2 in typically around 410 ppm in the external environment. [80] In 2020, the average CO_2 concentration in the atmosphere was 414 ppm [81].

Based on conducted studies, it was assumed, that the concentration of CO_2 in the external environment will continue to rise, when in 2050 it is estimated to be 550 ppm, in 2100 to 670 ppm [82], which represents a 57% increase compared to the situation in 2020.

Upon this finding, a potential problem arises in the future with maintaining the required quality of the indoor environment from the point of view of the CO_2 concentration during the economic sustainability of operation, especially in environments with a requirement for a high quality of the indoor environment, i.e. in environments with a CO_2 concentration moving around values of 600 ppm. In principle, it can be stated that if in the future the air supplied to the indoor environment has a higher concentration of CO_2 than the required value, it will not be possible to ventilate the environment with such air. The facts mentioned in this chapter will bring about major complications from the point of view of the operation of the building, which will be very difficult to solve. It is therefore entirely appropriate to investigate to a high degree the possibilities and solutions of how to support the ventilation of buildings in the future with regard to energy solutions. The stated reasons only emphasize the importance of this work. A model variability of climate trends in energy demand for heating and cooling shows Figure 2-8. [75]

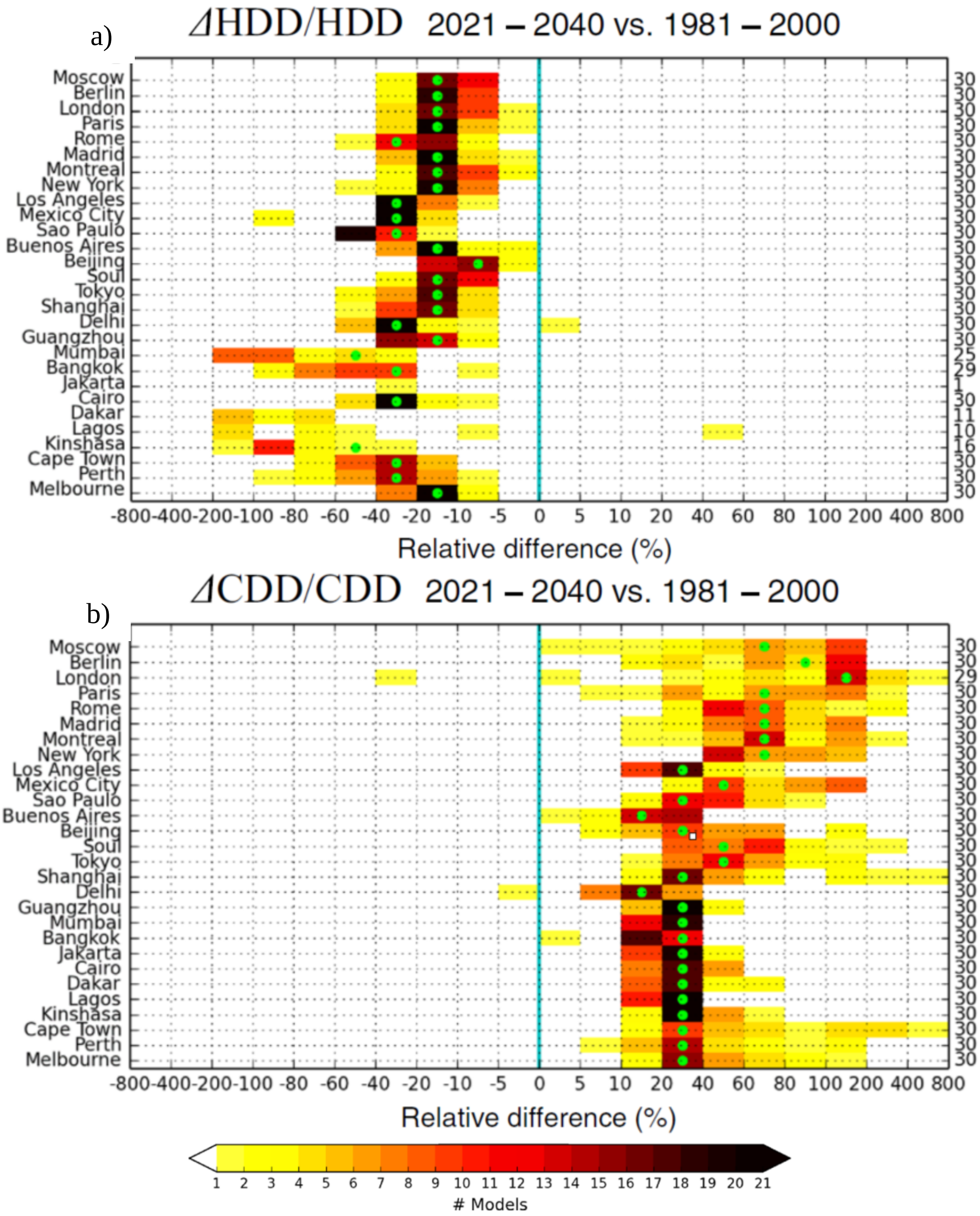

Figure 2-8 Model variability of climate trends in energy demand for heating and cooling of buildings in selected cities

2.8 Evaluation of the current state of the issue

From the previous chapters, it follows that plants have the potential to reduce pollutants in the indoor environment of buildings, depending on the lighting, temperature, metabolic cycle of the plant and the concentration of the monitored pollutant. The risks proven by the placement of plants in the indoor environment, consisting in the risks of the symptoms of allergies in users and microbiological pollution of the indoor environment, must also be considered with combination of conventional ventilation methods, i.e., even regularly maintained air ducts can be sources of dust particles, VOCs, and microbial pollution. The research mainly deals with the fact whether plants can effectively filter harmful substances in the indoor environment, especially CO_2, with respect to poor lighting conditions compared to the external 32nvironmentt. Economic potential for building operation savings is not deeply solved in this research. Other measures are also related to the operational side of the building, such as the maintenance of greenery in the case of its application and maintenance of any lighting fixtures. In order for the proposed experimental method to be applied, it must first be verified whether the experimental method is profitable from the point of view of building operation. Apart from the effect on the quality of the indoor environment, it is also appropriate to assess the effect on total energy consumption and the financial potential of savings in case of application of the experimental method.

2.9 Examples of the similar current research in the world

At least a few other universities in the world are actively dealing with the effect of plants on the quality of the indoor environment. In Great Britain, with the collaboration of the University of Reading, the Royal Horticultural Society and the University of Birmingham, it has been shown, based on calculations and measurements, that plants can have a beneficial effect on reducing CO_2 in the indoor environment of buildings. At the same time, the connection between the ability to reduce CO_2 and the rate of water vapour transpiration, i.e., the increase of humidity in the indoor environment, was monitored. Research has shown that in indoor conditions the effect of substrate humidity is negligible [54].

In the USA, in cooperation with Utah State University and NASA, the influence of radiation intensity and its wavelength on the plant’s growth ability and therefore also its ability to reduce CO_2 is being investigated in great detail [75; 76; 80]. It has been proven that for the proper growth of plants in the indoor environment, it is necessary to take into account the wavelength of the radiation (i.e. the composition of the spectrum). At the same intensity of visible light radiation measured with a lux meter, different growth potentials of plants can be observed with different types of lighting, as it is more appropriate to examine the intensity of radiation using a Quantum-Flux meter in PPFD units [$\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$]. The issue is also intensively researched from the economic point of view, especially which sources of artificial lighting can be used for optimal plant growth and at the same time regarding cost minimization.

The specific composition of plants from the point of view of the possibility of reducing VOCs in the indoor environment is currently being intensively researched by the University of Sydney, where it is proven that adjusting the composition of plants in the indoor environment influences the resulting reduction of harmful substances, especially of specific types of chemicals [81]. The influence of green plants in classrooms and their effect on the quality of the indoor environment from the point of view of the presence of harmful substances is also being investigated by scientists from the Technische University Wien, while the results so far indicate that plants in the indoor environment have a positive effect on the relative humidity of the air in the winter months, but it is also monitored for a long time gradual reduction of CO_2 in the examined room [67; 68].

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3. Main goals of doctoral thesis

3.1 Own scientific contribution compared to current knowledge and benefit for practice

This thesis presents the possibilities of an experimental method that deals with the influence of plants on the quality of the indoor environment, where the reduction of pollutants by placing plants in the indoor environment of buildings is considered. The research is mainly focused on comparing the performance of existing operational methods (i.e., ventilation of the indoor environment) against new, experimental methods or their combinations. Furthermore, the thesis explores the possibilities of implementing the experimental method into practice, i.e., for the normal operation of buildings.

Carbon dioxide CAS 124-38-9 (CAS Registry Number by the Chemical Abstracts Service) is one of the most basic researched and also mainly known pollutant in the indoor environment. The research is fully devoted to this substance, the thesis also deals with intensive measurements and theoretical simulations. Between other pollutants that are included into present research belong the volatile organic substances: namely benzene CAS 74-43-2, trichloroethylene CAS 79-01-6 and toluene CAS 108-88-3. In the present research we spoke about secondary substances which are in the case of active ventilation for minimizing the concentration of CO_2 in the indoor environment, much more effectively reduced, the present research deals only with theoretical simulations and does not deal with detailed measurements in a real environment.

The scientific contribution of the work is to verify the above-mentioned assumptions, derived based on previous measurements carried out in the field of biology. It will be investigated whether the established experimental method, specifically the use of plants in the internal environment of buildings, can positively affect the concentration of monitored pollutants and thus bring savings in the operation of buildings in the area of ventilation. The basic contribution compared to the current knowledge will be the creation of an own computational model, based on which it will be possible to compare the individual methods. The computational model will enable the monitoring of the development of the concentration for both CO_2 and VOC. Furthermore, knowledge will be expanded by carrying out selected measurements of the actual ability of selected plants to reduce carbon dioxide in the indoor environment, measuring the development of carbon dioxide concentration in a real office ventilated in accordance with the regulations that are valid in the Czech Republic based on the presence of workers, and in the same office, lighting intensity measurement is ensured. The presented thesis thus applies the theoretical foundations found so far from individual related fields of biology and the internal environment of buildings to the actual operating conditions of buildings and extends them with unique measurements from the perspective of the real environment within the operation of buildings regarding real lighting, real development of CO_2 concentration in the internal environment and real ability of selected plants to reduce CO_2.

3.2 Main goals of the doctoral thesis

The main goal of the present paper is to research the ability of selected plants to reduce selected pollutants in the indoor environment of buildings, taking into account the conditions that are typical for the indoor environment, especially at reduced lighting values. From a research point of view, in the thesis a computational model for the theoretical equivalent efficiency of plants for reducing CO_2 and selected VOCs in the indoor environment will be created. The theoretical model will be based on practical measurements in a real environment, specifically on measurements monitoring the development of CO_2 concentration in the office based on the presence of workers, further on measurements monitoring the intensity of lighting in the investigated office and measurements monitoring the ability of selected plants to reduce CO_2 based on the level of lighting corresponding to the indoor environment.

The individual goals of the thesis can therefore be defined as follows:

1. Determination of a computational model for a theoretical comparison of the equivalent effectiveness of individual elimination methods.
2. Theoretical comparison of the equivalent effectiveness of individual elimination methods – a simulation calculation showing the requirement for ventilated air into an environment with plants versus an environment without plants, based on the established calculation model established in point 1.
3. Determination of procedures for practical measurement of elimination methods.
4. Practical measurement of the actual effectiveness of elimination methods.
5. Evaluation of the effectiveness of experimental methods based on theoretical calculation.

6. Evaluation of the effectiveness of experimental methods based on practical measurement.
7. Comparison of theoretical calculated results with practical measurement.
8. Conclusions and recommendations for the operation of buildings based on calculations and measurements.

Based on the achieved results of the present thesis, it will be possible to understand better the possibilities of implementing plants in the internal environment of buildings for the purpose of operational optimizations and thus develop this promising field.

4. Methods used to achieve the goals

To achieve the stated goals of the dissertation, the following methods are expected to be used:

a) Determination of the calculation model for the theoretical comparison of the equivalent effectiveness of individual elimination methods

The computational model must adequately compare the required performance of the individual methods, i.e., the ability to reduce the concentration of pollutants in the indoor environment of buildings using ventilation compared to the ability to reduce the concentration of pollutants using plants. While the amount of incoming and outgoing air can usually be effectively regulated, i.e. increase or decrease the air flow per unit of time, the ability of plants to bind pollutants is directly determined by the area of the green leaves of the plant and the physical conditions of the environment. The equivalent level should therefore indicate the ability of plants to influence the amount of air exchanged. The calculation will be based on the potential of the plants to reduce the requirement for the amount of changed air while maintaining the same level of indoor air quality, i.e., to achieve the same concentration. The derivation of the computational model will be determined since already performed measurements of the ability of selected plants to reduce CO_2 and VOC, which were carried out as part of previously conducted research.

6) Theoretical comparison of the equivalent effectiveness of individual elimination methods – calculation based on the established calculation model

Based on the established calculation model in point a) a theoretical comparison of the equivalent efficiency of the investigated methods will be performed from the point of view of the effect of CO_2 and VOC.

It is assumed that plants can significantly influence the quality of indoor air and therefore bring savings in ventilation costs in the order of percent, however, under current conditions and technology, they cannot completely replace the ventilation of buildings. The evaluation will be carried out on the basis of a simulation calculation showing the requirement for the amount of ventilated air to the environment with plants versus the environment without plants, based on the established calculation model set out in paragraph a) of this chapter.

c) Determination of procedures for practical measurement of elimination methods

Practical measurement is assumed in a model environment – a closed box. For research into the real effect of plants in a model environment on the ability to reduce pollutant concentrations miniature showing the interior environment will be designed and constructed. Practical measurements are expected to be made only for CO_2, for which it is assumed that plants have the most significant impact on the reduction, and trends in the development of the concentration can thus be adequately measured even when deviations are considered. At the same time, carbon dioxide is the most commonly solved pollutant in the indoor environment of buildings.

The implementation of practical measurement for VOC will not be addressed due to toxicity, significant technological complexity of the research and the probability of high deviations in the measurement of trends to produce the test model.

d) Practical measurement of the actual effectiveness of elimination methods

Measurements will be made on the model made according to c), which will show the effect of plants on the ability to reduce carbon dioxide in the indoor environment under increased pollutant concentrations, reduced levels of lighting and a range of temperatures corresponding to the indoor environment. It is assumed that a histogram with the data will be created from the measurement.

e) Evaluation of the effectiveness of experimental methods based on theoretical calculation

From the calculated data according to point b), an evaluation of the effectiveness of the experimental methods will be carried out.

f) Evaluation of the effectiveness of experimental methods based on practical measurement

The effectiveness of experimental methods will be evaluated from the measured data according to point d).

g) Comparison of theoretical calculated results with practical measurement

The results achieved from the theoretical calculation will be compared with the results obtained by practical measurement, thus only the results for carbon dioxide will be compared. It is assumed that the results obtained from practical measurements will have a slight deviation compared to the results obtained from theoretical calculations. It is not assumed that the results obtained from the theoretical calculation part would be significantly different compared to the results obtained from the practical measurement.

h) Conclusions and recommendations for the operation of buildings based on calculations and measurements.

Based on the performed calculations and measurements, conclusions will be drawn regarding the experimental methods. Preliminary recommendations for the operation of buildings will be established.

5. Results of the thesis

5.1 Determination of the computational model for the theoretical comparison of the equivalent effectiveness of individual elimination methods

For a relevant expression of the capabilities of individual methods, in this thesis a computational model was created thanks to which it is possible to simulate design states and display the effectiveness of the investigated methods. The calculation model is based on a comparison of the quantity requirement of ventilated air for spaces without plants with the quantity requirement of ventilated air for the space where experimental plants are placed. The model is able to work with variables expressing the initial concentration of the investigated pollutant, the continuous production of the pollutant in the indoor environment and the required final value of the concentration, the so-called concentration targeted by the operator. Based on the requirement for the final concentration and degree of infestation, it is necessary to adjust the amount of ventilated air in the monitored time. In the case of the placement of plants, a supporting effect of reducing the pollutant concentration is assumed, which has the potential to slow down the rate of increase in pollutant concentration and thereby reduce the current quantity requirement of ventilated air and the total requirement per unit of time. According to the calculated results, it is then possible to determine the percentage difference between the individual model cases, from which the performance is derived.

The minimum air exchange requirement depending on the volume of the room and the knowledge of the concentrations in the supply and exhaust air and the knowledge of the concentration required per unit of time can be used by derived relation (1):

$$C_{req} = \frac{V_{in} \cdot C_{in}}{V_{in}} - \frac{Q_h \cdot C_{in}}{V_{in}} + \frac{Q_h \cdot C_{out}}{V_{in}} \tag{1}$$

$$C_{req} = C_{in} - Q_h \frac{C_{out} - C_{in}}{V_{in}} \tag{1a}$$

$$C_{req} - C_{in} = Q_h \frac{C_{out} - C_{in}}{V_{in}} \tag{1b}$$

Equation (1) indicates the relationship between the current concentration of the monitored pollutant in each environment, the amount of discharged contaminated air and supplied air with a certain concentration, and the desired resulting concentration.

After the basic mathematical adjustments shown in steps (1a) and (1b), equation (2) can be derived from equation (1) showing the requirement for the total amount of air exchanged according to the respective concentrations:

$$Q_h = V_{in} \frac{\left(C_{req} - C_{in}\right)}{\left(C_{sup} - C_{in}\right)} \tag{2}$$

For equations (1) and (2) it applies: Q_h [m³] is the supply air quantity requirement, where, where $Q_h \geq 0$ [m³], V_{in} [m³] is the volume of air in the monitored indoor environment, C_{req} [g · m^{-3}] where $C_{req} \in (C_{sup}, C_{in})$, is the required resulting concentration of the pollutant, C_{in} [g · m^{-3}] is the current concentration of the pollutant in the indoor environment, C_{sup} [g · m^{-3}] is the concentration of the pollutant in the air supplied to the indoor environment.

In order to express the demand for the amount of supplied air according to a previously known time period, it is necessary to implement the variable t showing the development over time into equation (1) and (2). The relationship is shown in the relationship (3):

$$q_h = \frac{V_{in}}{t} \frac{\left(C_{req} - C_{in}\right)}{\left(C_{sup} - C_{in}\right)} \tag{3}$$

For the equation (3) applies: q_h [m³ · h^{-1}] is the volume flow rate of the supply air, where $q_h = \frac{V}{t_1}$, whereas $V \in \langle 0, \infty)$ a $t_1 = 1$; V_{in} [m³] is the volume of air in the monitored indoor environment, C_{req} [g · m^{-3}] where $C_{req} \in (C_{sup}, C_{in})$, is the required resulting concentration of the pollutant, C_{in} [g · m^{-3}] is the current concentration of the pollutant in the indoor environment, C_{sup} [g · m^{-3}] is the concentration of the pollutant in the air supplied to the indoor environment, t [h] is the time period over which air is supplied, whereby $t = t_1$.

The development of the pollutant concentration over time in the indoor environment is determined based on the initial concentration of the pollutant, the amount produced, and the amount reduced during the specified time frame. The following equation is defined to calculate the current concentration over time (4), (5), (6):

$$C_{in} = m_{ori} + m_{pro} - m_{red} \tag{4}$$

$$m_{pro} = m_{per} + m_{oth1} \tag{5}$$

$$m_{red} = m_{pla} + m_{vent} + m_{oth2} \tag{6}$$

For the equation (4), (5), (6) applies: C_{in} [g · m^{-3}] is the current pollutant concentration inside the indoor environment, m_{ori} [g · m^{-3}] is the initial indoor pollutant mass, m_{pro} [g · m^{-3}] is the total mass production of pollutants in the indoor environment, m_{red} [g · m^{-3}] is the total mass reduction of pollutants in the indoor environment, m_{per} [g · m^{-3}] is the indoor pollutant mass excess due to person activity, m_{pla} [g · m^{-3}] is the indoor pollutant mass loss due to plant reduction, m_{vent} [g · m^{-3}] is the indoor pollutant mass loss due to air ventilation, m_{oth1} [g · m^{-3}] a m_{oth2} [g · m^{-3}] is the total mass production or reduction of pollutants in the indoor environment by other means, including losses.

In the case of calculation with the volume concentration of the pollutant, it can be converted to the mass concentration of the pollutant using the equation (7):

$$V = \frac{m \cdot R \cdot T}{M \cdot p} \tag{7}$$

For the equation (7) applies: V [dm^3] is the volume of the gas, m [g · dm^{-3}] is the mass of the gas, R [J · K^{-1} · mol^{-1}] is the molar gas constant, T [K] gas temperature, M [kg · mol^{-1}] molar mass of the gas, p [Pa] gas pressure.

In order to express the specific ability of the plant to reduce the pollutant, showing the absolute mass versus the net assimilation of the pollutant from the leaf area per unit time of 1 hour, the relation (8) was derived.

$$A_{P_g} = A_{P_{mol}} \cdot M_{Poll} \cdot 3600 \tag{8}$$

For the equation (8) applies: A_{P_g} [g · m^{-2} · h^{-1}] is the level of net mass assimilation of the investigated pollutant per 1 m^2 of green leaf, $A_{P_{mol}}$ [µmol · m^{-2} · s^{-1}] is the level of net molar assimilation of the investigated pollutant from 1 m^2 of green leaf, M_{Poll} is the molar mass of the tested pollutant. The relationship (8) can be used especially for cases of research on the photosynthetic reaction by a plant from the point of view of CO_2 reduction.

The level of net photosynthesis based on light intensity can be expressed from the relationship (9) [83; 84]:

$$P_n = P_{g_{max}} \left(1 - e^{\frac{-PPFD}{P_{g_{max}}}} \right) - R_d \tag{9}$$

For the equation (9) applies P_n [μmol · m^{-2} · s^{-1}] is net photosynthesis, $P_{g_{max}}$ [μmol · m^{-2} · s^{-1}] is light-saturated gross photosynthesis, $PPFD$ [μmol · m^{-2} · s^{-1}] is photosynthetic photon flux density and R_d [μmol · m^{-2} · s^{-1}] is dark respiration.

With the help of equations (1) to (9), it is possible to simulate and monitor the development of the concentration of pollutants in the internal environment of buildings, and it is therefore possible to perform the necessary theoretical calculations. To simulate the interaction of the parameters and monitor the development over time, the function of the spreadsheet (MS Excel) is used, where the calculation parameters were defined.

5.2 Theoretical comparison of the equivalent effectiveness of individual elimination methods

For a theoretical comparison of the effectiveness of individual elimination methods, i.e., the theoretical influence of plants on the ability to influence the quality of the indoor environment, it is necessary to perform a theoretical simulation on a specific model case based on a real environment. The simulations are performed on a specified computational model based on the theoretical formulas presented in chapter 5.1.

An office room (Figure 5-1) with a total area of 24.1 m², a height of 3.1 m and a total volume of 74.7 m³ is considered as a model environment. For simulation purposes, it is assumed that this room is forcibly ventilated by a central air-handling system, while the amount of supplied air is controlled according to the current CO_2 concentration in the room, based on the CO_2 concentration sensor. Permanent positions for 3 employees are being considered in the office room. It is assumed that the presence of employees during working hours is between 8:00 a.m. - 4:00 p.m. The production of CO_2 by one employee is 31.5 [g · m^{-2} · s^{-1}]. [23] The temperature of the internal environment can generally be considered stable in administrative buildings, for the purposes of the model environment a temperature range of 19–25 °C is considered, the relative humidity of the internal environment is 30% to 50%. Atmospheric pressure is set at 101.3 kPa. There are considered 2 lighting levels for 2 cases of implemented plants, where a PPFD value of 100 [μmol · m^{-2} · s^{-1}] in the first case and PPFD 300 [μmol · m^{-2} · s^{-1}] is considered for the entire simulation time.

In the simulated environment, the placement of the Hedera helix plant is considered, and in another case, Ficus Benjamin, the placement of 1 m² of green leaves per 1 person is considered, i.e., 3 m² in total. The internal environment is schematically shown in Figure 5-1.

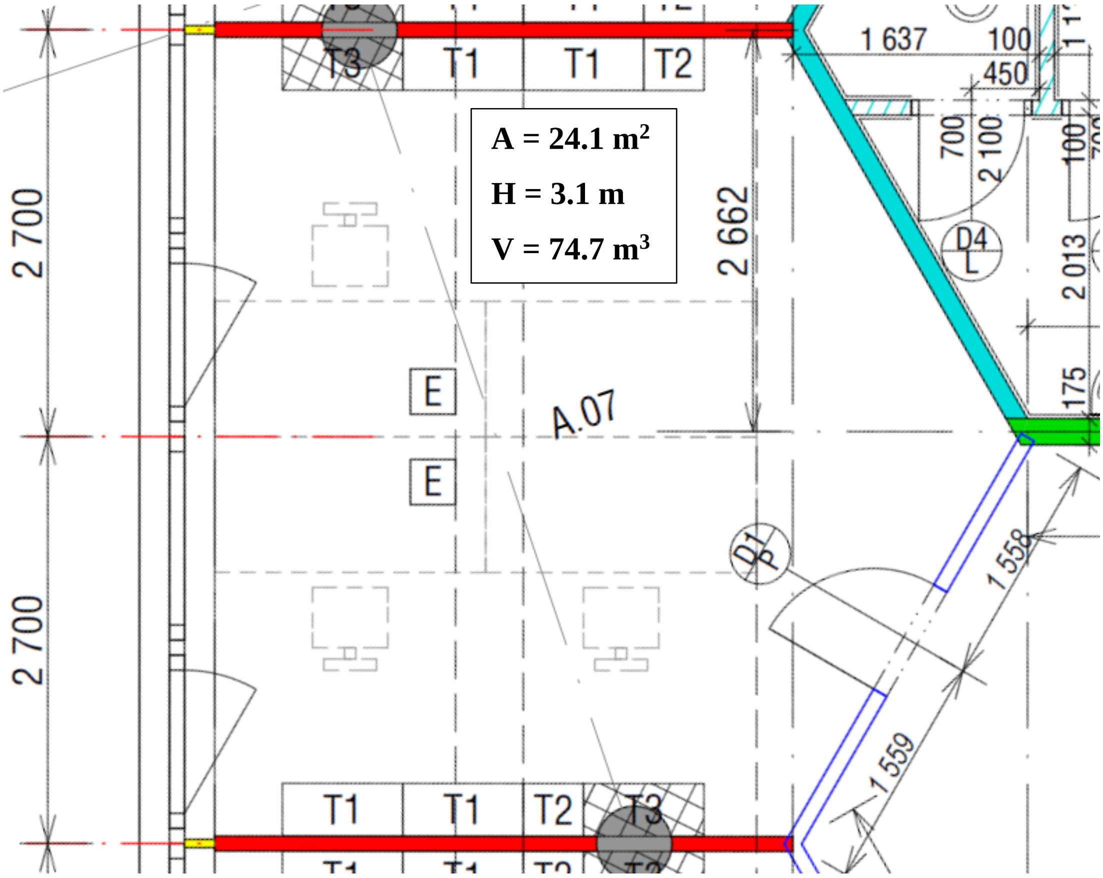


Figure 5-1 A scheme of the office space

5.2.1 The theoretical influence of plants on the reduction of carbon dioxide

In the first phase, the simulation compares the 2 states of the maximum permissible CO_2 concentration. The first limit state requires a maximum concentration of CO_2 in the indoor environment of 1000 ppm, when this concentration is generally considered acceptable for performing administrative work. The second limit state requires a maximum concentration of CO_2 in the indoor environment of 1500 ppm, this concentration is considered the maximum permissible from the point of view of the ability to perform administrative activities. At the time of commencement of work administrative workers consider an initial concentration corresponding to the specified modelling limit. Air supply to the indoor environment is considered using an air distribution system, while for the modelling purposes, variable values of the quality of the supplied air from the external environment are considered differently according to the expected development of the CO_2 concentration in the Earth's atmosphere. A value of 419 ppm is considered for the year 2023, 550 ppm is considered for the year 2050, and 670 ppm is considered for the year 2100. [85; 86; 82]

For the simulation purposes, the effect of the local negative influence of the supplied air is neglected. Such effects in the real environment can occur especially in cases where intake air from the external environment is near traffic routes for cars or located in polluted industrial zones and locations. Air penetration due to leaks in the building envelope or office operation is also neglected.

For the purposes of the simulation, the plant cultivars Hedera helix and Ficus benjamina are used, which are listed in the Table 5-1. [83]

Table 5-1 Net CO_2 assimilation per m² of plant's leaf with PPFD 100 and PPFD 300

Cultivar	**LCP (Light compensation point) [μmol · m^{-2} · s^{-1}]**	**Dark respiration R_d [μmol · m^{-2} · s^{-1}]**	**Net CO_2 assimilation PPFD 100 [μmol · s^{-1} m^{-2}]**	**Net CO_2 assimilation PPFD 300 [μmol · s^{-1} m^{-2}]**
Hedera helix	8.0	-0.55	3.97	6.56
Ficus benjamina	22.0	-0.46	1.32	3.28

Table 5-1 shows the cultivar Hedera helix, which can be characterized as a super cultivar for use in the indoor environment of buildings, which has a significant performance from the point of view of CO_2 assimilation and a very low value of light compensation point at the level of 8.0 [μmol · m^{-2} · s^{-1}]. The second Ficus benjamina cultivar ranks among the more efficient cultivars, but compared to the first cultivar, it has a significantly lower ability to assimilate CO_2 and the light compensation point is at the level of 22.0 [μmol · m^{-2} · s^{-1}]. An important aspect for the purposes of theoretical modeling is the degree of shading of the leaves inside the crown of individual cultivars by their own leaves and the percentage of the area illuminated by the design PPFD value and the percentage of the shaded area illuminated by a different PPFD value. In a practical environment, due to the shape of the plants, it is almost impossible to target the exact area of the green leaves of the plant illuminated by the exact value of the PPFD illumination, therefore it is necessary to determine the areas exactly for the purposes of the simulation. It is considered that 40% of the sheets are fully illuminated by the design value, i.e. PPFD 300 or PPFD 100 [μmol · m^{-2} · s^{-1}], the remaining 60% of the leaf area is considered with illumination of PPFD 80 or PPFD 60 [μmol · m^{-2} · s^{-1}]. At the same time, plants are living creatures and fully adapted plants to the environment in which they are placed, they direct the main surface of the leaves towards the light source, and it can therefore be expected that the plant itself will be optimized in a certain way in terms of survival efficiency.

Based on the calculation relations (1) to (9) mentioned in the previous chapter, the reduction values of the selected cultivars were calculated for the purpose of reducing the CO_2 concentration in the indoor environment based on the design lighting corresponding to the model environment. These values can be seen from Table 5-2 and Table 5-3.

Table 5-2 Overview of the calculated performance of selected cultivars for CO_2 assimilation purposes in the indoor environment PPFD 300 and PPFD 80

Area of plant	**Description**	**Cultivar [leaf area 3 m²]**	
		Hedera Helix	**Ficus Benjamina**
40% area of plant	Net CO_2 assimilation of 1 m² PPFD 300 [μmol · m^{-2} · s^{-1}]	6.56	3.28

	Leaf area [m²]	1.20	1.20
60% area of plant	Net CO_2 assimilation of 1 m² PPFD 80 [µmol · m^{-2} · s^{-1}]	3.36	1.02
	Leaf area [m²]	1.80	1.80
Leaf area summary	Net CO_2 assimilation summary [µmol · leaf area · s^{-1}]	13.92	5.76
	Net CO_2 assimilation summary [g · leaf area · h^{-1}]	2.20	0.92

Table 5-3 Overview of the calculated performance of selected cultivars for CO_2 assimilation purposes in the indoor environment PPFD 100 and PPFD 60

Area of plant	**Description**	**Cultivar [leaf area 3 m²]**	
		Hedera Helix	**Ficus Benjamina**
40% area of plant	Net CO_2 assimilation of 1 m² PPFD 100 [μmol · m^{-2} · s^{-1}]	3.97	1.32
	Leaf area [m²]	1.20	1.20
60% area of plant	Net CO_2 assimilation of 1 m² PPFD 60 [μmol · m^{-2} · s^{-1}]	2.63	0.69
	Leaf area [m²]	1.80	1.80
Leaf area summary	Net CO_2 assimilation summary [μmol · leaf area · s^{-1}]	9.50	2.82
	Net CO_2 assimilation summary [g · leaf area · h^{-1}]	1.50	0.45

Table 5-2 shows that with a design PPFD of 300 [μmol · m^{-2} · s^{-1}] for 40% of the design leaf area (1.2 m²) and a PPFD of 80 [μmol · m^{-2} · s^{-1}] for the remaining 60% of the design leaf area (1.8 m²), is the ability of the proposed plants to assimilate a total of 2.20 [g · h^{-1}] CO_2 in the case of the cultivar Hedera Helix, and 0.92 [g · h^{-1}] CO_2 in the case of the cultivar Ficus Benjamina. At the lower illuminance values shown in Table 5-3, where PPFD 100 [μmol · m^{-2} · s^{-1}] is considered for 40% and PPFD 60 [μmol · m^{-2} · s^{-1}] is considered for the remaining 60% assimilation capacity CO_2 decreases significantly, namely in the case of the cultivar Hedera Helix 1.50 [g · h^{-1}] CO_2 and 0.45 [g · h^{-1}] CO_2 in the case of the cultivar Ficus Benjamina.

In the next step, it is necessary to determine the ventilation rate q_h [m^3 · h^{-1}] that must be considered in the case of a requirement for a specific CO_2 concentration in the indoor environment. 2 cases as concentrations in the indoor environment are proposed, namely the requirement for a concentration of 1000 ppm and 1500 ppm. Also 3 cases of indoor air quality are proposed, namely 419 ppm, 550 ppm, 670 ppm.

Infiltration and mixing of exhaust air with supply air in the ventilation duct is neglected, if infiltration is considered, it would be necessary to adjust the CO_2 concentration in the supply air adequately according to the operator. The value of the concentration at the beginning of the simulation is considered as a permissible limit, i.e., 1000 ppm and 1500 ppm respectively. The level of ventilation is determined based on the calculation relationship (2) or (3). The amount of supplied air for individual cases without the influence of plants is shown in Table 5-4.

Table 5-4 The level of ventilation of the model indoor environment according to the specific requirement for the concentration of CO_2 in the indoor environment and the known concentration of CO_2 supplied from the outside environment.

CO_2 concentration				
C_{req} [ppm]	**C_{sup} [ppm]**	**Year prediction**	**Rate of ventilation [$m^3 \cdot h^{-1}$]**	**Ventilation rate / Space RATIO**
1000	670	2100	50.627	0.68
1000	550	2050	45.315	0.61
1000	419	2023	40.658	0.54
1500	670	2100	34.014	0.46
1500	550	2050	31.531	0.42
1500	419	2023	29.204	0.39

Table 5-2 shows that with a design PPFD of 300 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] for 40% of the design leaf area (1.2 m^2) and a PPFD of 80 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] for the remaining 60% of the design leaf area (1.8 m^2), is the ability of the proposed plants to assimilate a total of 2.20 [$g \cdot h^{-1}$] CO_2 in the case of the cultivar Hedera Helix, and 0.92 [$g \cdot h^{-1}$] CO_2 in the case of the cultivar Ficus Benjamina. At the lower illuminance values shown in Table 5-3, where PPFD 100 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] is considered for 40% and PPFD 60 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] is considered for the remaining 60% assimilation capacity CO_2 decreases significantly, namely in the case of the cultivar Hedera Helix 1.50 [$g \cdot h^{-1}$] CO_2 and 0.45 [$g \cdot h^{-1}$] CO_2 in the case of the cultivar Ficus Benjamina.

In the next step, it is necessary to determine the ventilation rate q_h [$m^3 \cdot h^{-1}$] that must be considered in the case of a requirement for a specific CO_2 concentration in the indoor environment. 2 cases as concentrations in the indoor environment are proposed, namely the requirement for a concentration of 1000 ppm and 1500 ppm. Also 3 cases of indoor air quality are proposed, namely 419 ppm, 550 ppm, 670 ppm.

Infiltration and mixing of exhaust air with supply air in the ventilation duct is neglected, if infiltration is considered, it would be necessary to adjust the CO_2 concentration in the supply air adequately according to the operator. The value of the concentration at the beginning of the simulation is considered as a permissible limit, i.e., 1000 ppm and 1500 ppm respectively. The level of ventilation is determined based on the calculation relationship (2) or (3). The amount of supplied air for individual cases without the influence of plants is shown in Table 5-4.

Table 5-4 shows that the level of ventilation is highly dependent on the quality of the supplied air. The highest requirement for supplied air is in case a), when the quality of the supplied air is relatively low, corresponding to the assumption of the outside air in the year 2100, and at the same time the maximum permissible concentration of CO_2 in the indoor environment is required here 1000 ppm. From the point of view of the model office, the ventilation level corresponds to 0.68 times the exchange of the total air volume of the office. The smallest level of ventilation is evident for an indoor air quality requirement of a maximum of 1500 ppm with a supply air of 419 ppm, which corresponds approximately to the 2023 outdoor air quality.

In the next step, it is necessary to compare the requirement for ventilation in the case of an environment with plants versus an environment without plants. Here it is necessary to express the total amount of CO_2 produced by the proposed workers against the total amount of CO_2 reduced by plants and express the level of ventilation in the case of an environment without plants against an environment with plants. These facts can be expressed using theoretical relations (2) to (8).

Table 5-5 and Table 5-6 show the degree of influence of plants on the quantitative level of ventilated air.

Table 5-5 Effect of plants with PPFD 300 and PPFD 80 on the total amount of the supplied air to the indoor environment to ensure the same CO_2 *concentration as in an identical space without plants*

Concentration [ppm]		**Rate of ventilation air flow for office** $[m^3 \cdot h^{-1}]$ **with set PPFD 300;80** $[\mu mol \cdot m^{-2} \cdot s^{-1}]$			**Difference [%]**	
C_{req}	C_{out}	**Without plants**	**With Hedera Helix**	**With Ficus Benjamina**	**Hedera Helix**	**Ficus Benjamina**
1000	670	50.627	50.2403	50.4679	0.76	0.31
1000	550	45.315	44.8934	45.1415	0.93	0.38
1000	419	40.658	40.2205	40.4779	1.08	0.44
1500	670	34.014	33.5773	33.8339	1.28	0.53
1500	550	31.531	31.1016	31.3537	1.36	0.56
1500	419	29.204	28.7848	29.0305	1.44	0.59

Table 5-6 The effect of plants with PPFD 100 and PPFD 60 on the total amount of air supplied to the indoor environment to ensure the same CO_2 *concentration as in an identical space without plants*

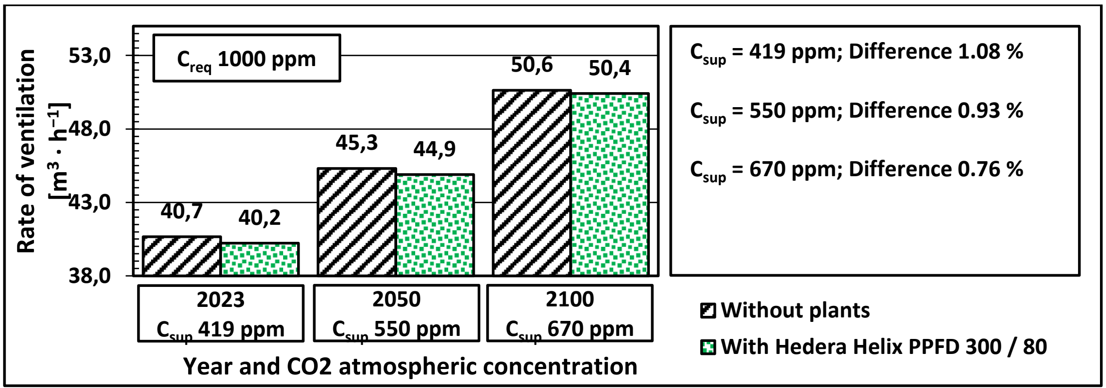
Concentration [ppm]		**Rate of ventilation air flow for office** $[m^3 \cdot h^{-1}]$ **with set PPFD 100;60** $[\mu mol \cdot m^{-2} \cdot s^{-1}]$			**Difference [%]**	
C_{req}	C_{out}	**Without plants**	**With Hedera Helix**	**With Ficus Benjamina**	**Hedera Helix**	**Ficus Benjamina**
1000	670	50.627	50.3644	50.5495	0.52	0.15
1000	550	45.315	45.0286	45.2306	0.63	0.19
1000	419	40.658	40.3607	40.5703	0.73	0.22
1500	670	34.014	33.717	33.9262	0.87	0.26
1500	550	31.531	31.2388	31.4445	0.93	0.27
1500	419	29.204	28.9185	29.1191	0.98	0.29

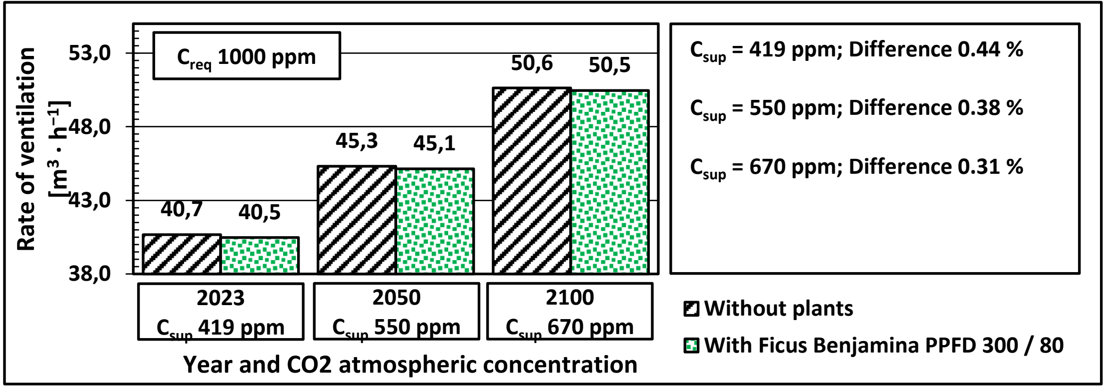
Table 5-5 and Table 5-6 show the theoretical potential for savings due to the implementation of plants in the indoor environment, while the cultivar itself and the value of the design PPFD play an important role here.

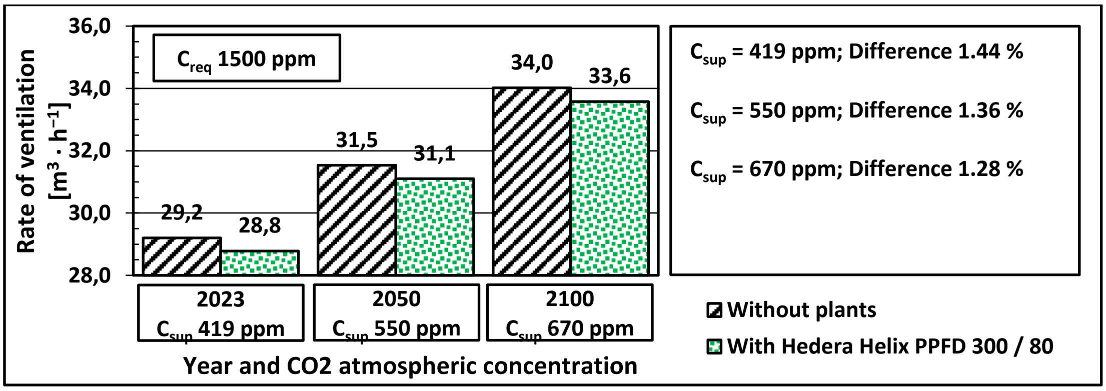
Table 5-5 shows, as expected, the most significant effect of the implementation of plants in the case of increased illumination PPFD 300 and PPFD 80 [μmol · m^{-2} · s^{-1}], at the same time the minimum requirement for the internal concentration C_{req} = 1500 ppm and with relatively good quality of the supplied air C_{sup} = 419 ppm, when in the case of the Hedera Helix cultivar possible to reduce the requirement for the amount of supplied air by up to 1.44%, in the case of the cultivar Ficus Benjamina by 0.59%. The least importance for the implementation of plants is the demand for an increased quality of the indoor environment C_{req} = 1000 ppm and with a lower supply air quality C_{sup} = 670 ppm, where Hedera Helix will reduce the supply air requirement by up to 0.76% and Ficus Benjamina by 0.31%. From

Table 5-6, at lighting values of PPFD 100 and PPFD 60 [μmol · m^{-2} · s^{-1}], the importance of plant implementation is significantly lower. The model case with the quality of the supplied air C_{sup} = 670 ppm and at the same time the increased requirement for the quality of the indoor environment C_{req} = 1000 ppm had the smallest effect on the quantity of supplied air, when Hedera Helix will reduce the requirement for the quantity of supplied air by 0.52% and Ficus Benjamina by 0.15%. A more suitable result was achieved by the model case with a higher quality of the supplied air C_{sup} = 419 ppm and a lower quality of the indoor environment C_{req} = 1500 ppm, where Hedera Helix will reduce the requirement for supplied air by 0.98% and Ficus Benjamina by 0.29%. At the same time, the overall results of the simulation are clearly displayed in Figure 5-2 and Figure 5-3.

Despite the fact that this is a relatively minimal effect on the intensity of ventilation in the indoor environment, it is necessary to emphasize that the theoretical operating savings for the operation of the ventilation system, moving around the value of 1%, are quite interesting from a global point of view. Furthermore, it must be emphasized that relatively poor lighting conditions were used in the simulation, which can be significantly improved by placing the plants closer to the window opening fillings, where the lighting values can significantly exceed the levels in the simulation. The lowest light intensity is in the Northern Hemisphere during the winter solstice, greatest levels during the summer solstice. Even during the winter months, during the winter solstice, when the sky is partly cloudy, PPFD values of 300 [μmol · m^{-2} · s^{-1}] can be exceeded, it can be assumed that in spring, summer, and autumn, when the sky is clear, PPFD values of 1000 [μmol · m^{-2} · s^{-1}] can also be exceeded. Such facts are seasonal and dependent on the current weather. However, they can significantly shift the resulting values of the simulation on the influence of the ventilation level by up to several percent. Another positive fact is the fact that most of the working hours in administrative buildings are during the day, when there is enough light from the outside environment. The plants therefore have the highest performance precisely at the time when the largest amount of CO_2 is produced by the workers.







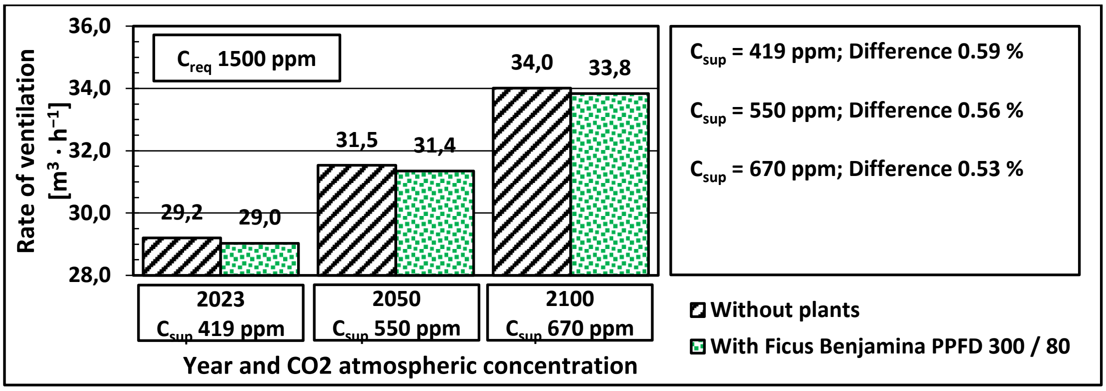
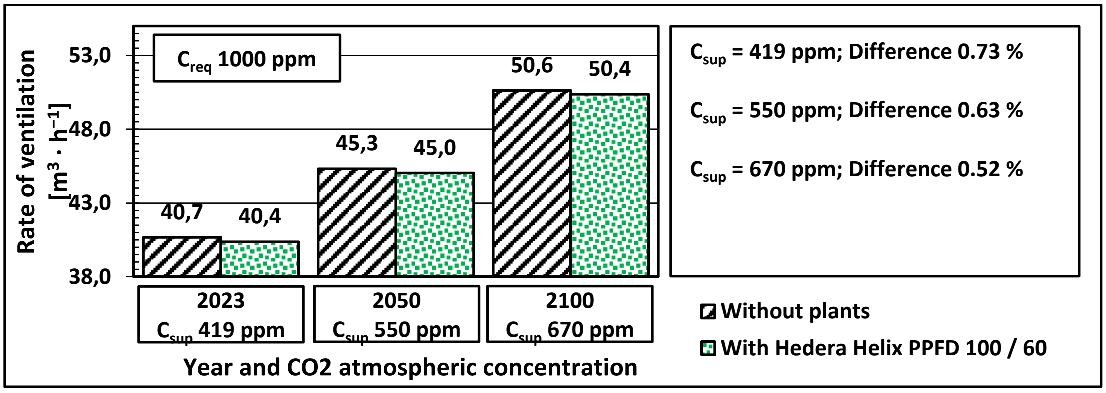
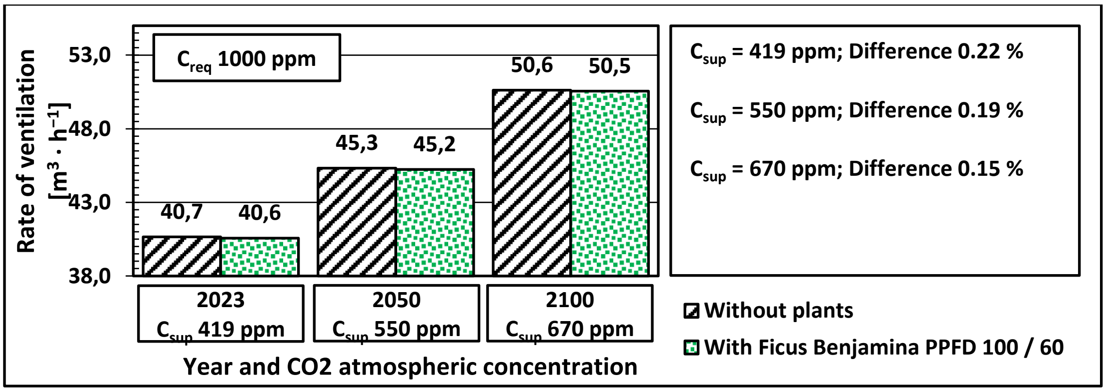
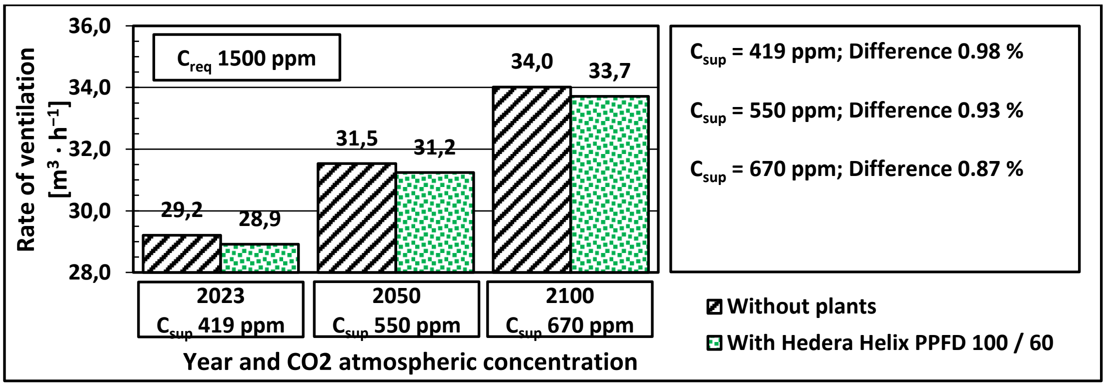


Figure 5-2 Simulation results of the influence of the implementation of selected plants in the indoor environment at PPFD 300 / 80 on the ability to reduce the amount of supplied air to ensure the same quality of the environment from the point of view of CO_2 concetration







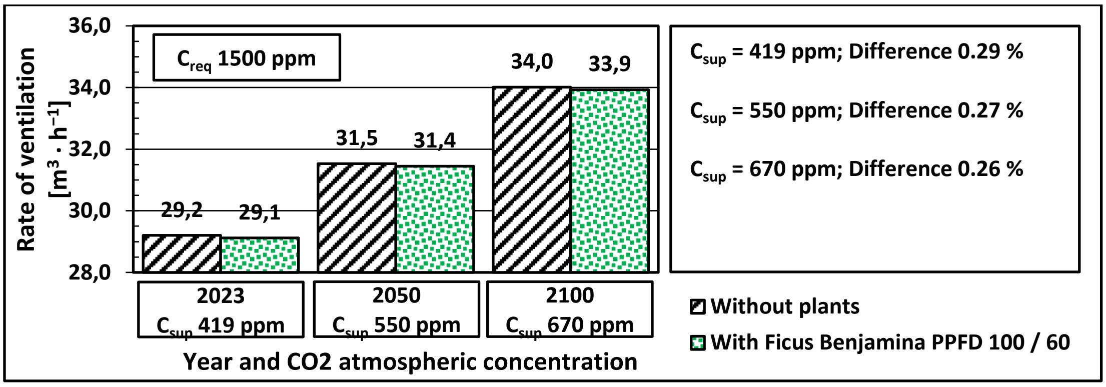


Figure 5-3 Simulation results of the influence of the implementation of selected plants in the indoor environment at PPFD 100 / 60 on the ability to reduce the amount of supplied air to ensure the same quality of the environment from the point of view of CO_2 concetration

5.2.2 Theoretical influence on the reduction of selected volatile organic substances

In general, the risk of the occurrence of VOCs and their effect on health is more significant in buildings without forced ventilation, i.e., without an air-conditioning system. The basic and general assumption is that if, in the case of the presence of workers, the space is sufficiently ventilated to reduce the CO_2 concentration, the VOC concentrations are also relatively effectively reduced at the same time. This is because the load on the indoor environment in the presence of users is the majority from the point of view of constantly produced CO_2 and the risk of a rapid increase in the current CO_2 concentration. Although VOCs can be emitted from building materials, or introduced into the indoor environment, however, with forced ventilation to reduce the CO_2 concentration, VOC concentrations are effectively reduced to a minimum.

For the purposes of the simulation, similar design conditions are used as for the simulation for the comparison of efficiency from the perspective of CO_2, which is dealt with in the previous chapter. Let us consider 3 workers and the implementation of 3 m^2 of plants, i.e. 1 m^2 of green leaves per 1 worker. The following concentrations of selected VOCs in the indoor environment at the beginning of the sea simulation are considered: benzene 5.6 [$\mu g \cdot m^{-3}$], toluene 240.0 [$\mu g \cdot m^{-3}$], trichlorethylene 120.0 [$\mu g \cdot m^{-3}$], such concentrations represent 80% of the permissible limit according to the applicable legal regulations for workplace in the Czech Republic [87]. During the monitored period of time, the following production of pollutants m_{sup} in the indoor environment is considered for the monitored VOC, the production of 1% of the original initial concentration is considered, i.e., benzene 0.056 [$\mu g \cdot m^{-3} \cdot h^{-1}$], toluene 2.40 [$\mu g \cdot m^{-3} \cdot h^{-1}$], trichlorethylene 1.20 [$\mu g \cdot m^{-3} \cdot h^{-1}$]. In the supply air, the concentrations for the examined VOCs are not considered, it is assumed that the supplied air does not contain these substances or is ventilated. In the simulation, it is required that in a permanently ventilated space the concentration is maintained at a maximum of m_{req} 5% of the initial concentration, i.e., 0.28 [$\mu g \cdot m^{-3} \cdot h^{-1}$], toluene 12.0 [$\mu g \cdot m^{-3} \cdot h^{-1}$], trichlorethylene 6.0 [$\mu g \cdot m^{-3} \cdot h^{-1}$]. The initial increased concentration in the indoor environment represents the ability of the indoor environment to accumulate selected pollutants during the evening and night time, when most cleaning takes place and during which there is an increased probability of VOC emission into the indoor environment. At the same time, in the evening and night hours, when the presence of workers is not considered, the amount of supplied air is often significantly reduced by the building management, and the accumulated VOCs are often significantly ventilated only in the morning when the air handling system is switched on again in the main mode. The ability of plants to reduce VOCs is dependent on lighting, temperature and the gas concentration itself in the indoor environment, but significantly less than in the case of the ability of plants to reduce CO_2. From the current knowledge, it is not completely clear how significant the lighting values have on the ability to absorb selected VOCs, it is assumed that simultaneously during CO_2 assimilation and transpiration by the plant, plants are able to absorb VOCs together with CO_2, i.e. they absorb the surrounding air, thus basically functioning like a certain mechanical air filter. In general, although there are still not enough measurements establishing the exact influence of the lighting value on the rate of absorption of specific VOCs, the professional public has opinions, that the ability to capture VOCs increases in proportion to the vents that are open. [39; 53; 88] It follows that with a small value of transpiration or with lighting levels moving below the break point, a significant influence on the absorption of VOCs cannot be assumed. [89]

To simulate the effectiveness of plants on the ability to reduce selected VOCs, measured data from foreign research that dealt with this issue was taken. [1]

In the source research, the plants were illuminated by artificial light sources with values of photosynthetic active radiation PAR = 5.45 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] corresponding approximately to the values of combined lighting in the indoor environment of buildings. It is not possible to determine exactly what PPFD value was used in this research, as there is no exact relationship for the conversion of these two quantities. For the purposes of this research, however, it is sufficient to consider that lighting can be suitably achieved in an indoor environment and can therefore be adequately based on the data.

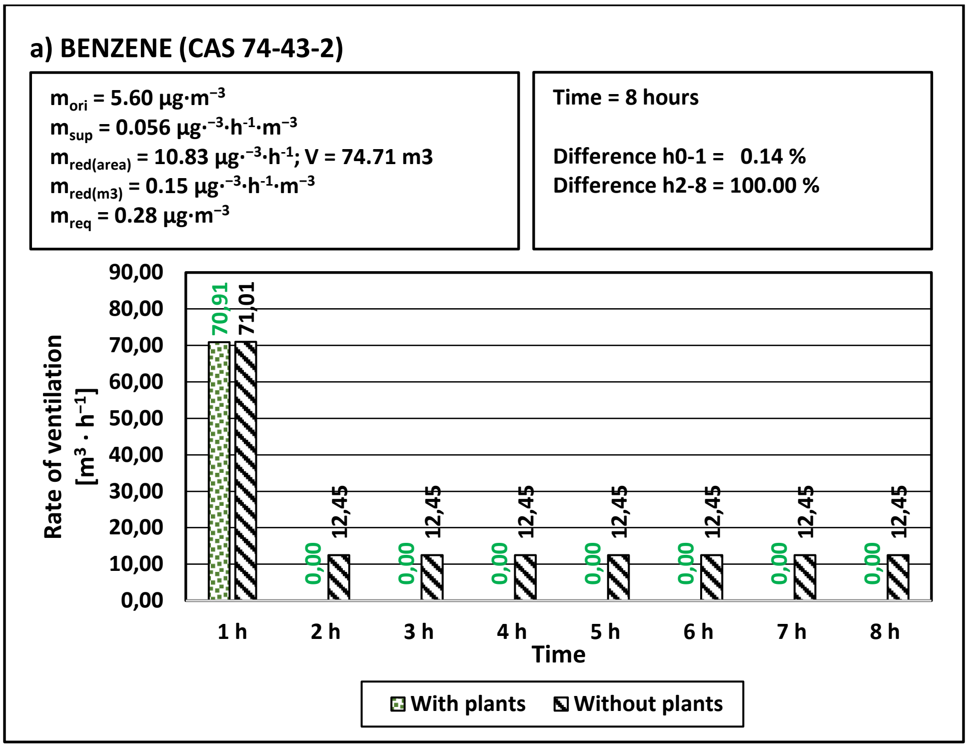
Table 5-7 [1] shows the specific ability of the selected plants to reduce the investigated VOCs.

Table 5-7 Ability of selected cultivars to reduce VOC at PAR 5.45 $[\mu mol \cdot m^{-2} \cdot s^{-1}]$

Cultivar	**Average ability to absorb monitored substances** $[\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}]$		
	Benzene	**Toluene**	**Trichlorethylene**
Hemigraphis Alternata	5.54	9.63	11.08
Hedera Helix	3.63	8.25	8.07
Ficus Benjamina	1.66	5.06	4.74
AVERAGE	3.61	7.65	7.96

It is clear from Table 5-7 that the ability to reduce the researched VOCs is significantly variable depending on the selected cultivar. While Hemigraphis Alternata and partially Hedera Helix can be described as a super cultivar from the point of view of VOC absorption, the Ficus Benjamina cultivar is slightly behind in its ability to reduce selected VOCs. It is necessary to point out that some cultivars achieve even significantly worse results, these are not considered here, as they are obviously unsuitable for the purposes of VOC reduction in the indoor environment. For the purposes of the simulation, it was assumed that 3 m^2 of the mentioned plants will be implemented in the indoor environment, where each cultivar will be represented in an area of 1 m^2, which will significantly suppress any deviations from the initial research as the model will consider the average ability to reduce VOCs for several cultivars.

Based on the theoretical relationships presented in chapter 5.1, it is possible to simulate the effect of plants on the ability to reduce VOCs in the indoor environment and display the effect on the total difference in the amount of supplied air to the indoor environment. The resulting simulation values are shown in Figure 5-4, Figure 5-5 and Figure 5-6.

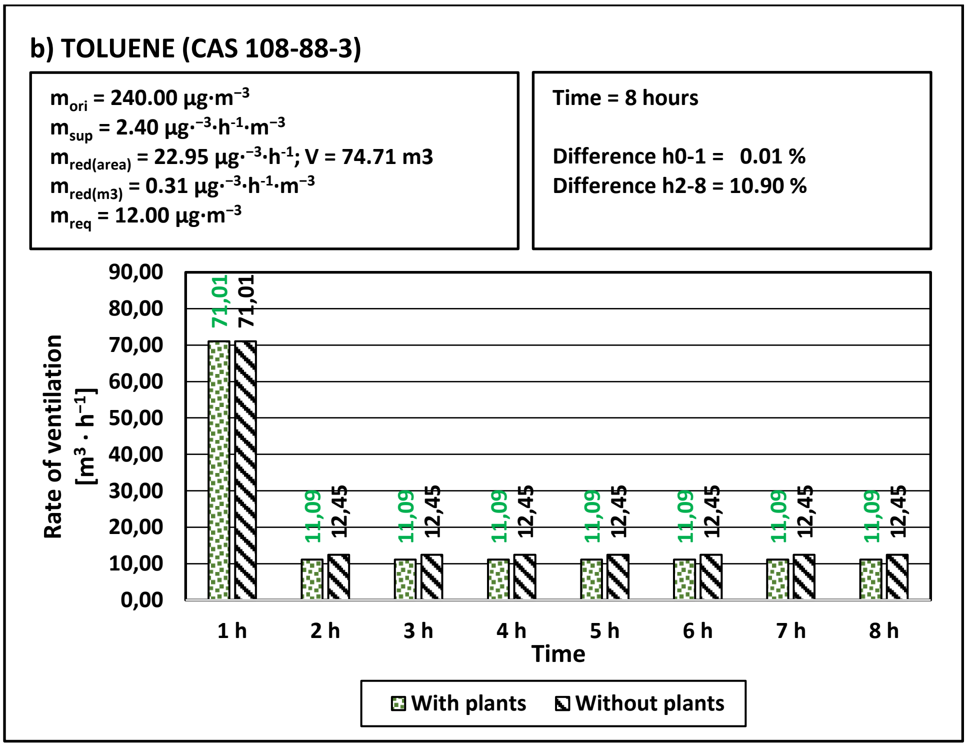


m_{ori} = 5.60 µg·m^{-3}
m_{sup} = 0.056 µg·$^{-3}$·h^{-1}·m^{-3}
$m_{red(area)}$ = 10.83 µg·$^{-3}$·h^{-1}; V = 74.71 m3
$m_{red(m3)}$ = 0.15 µg·$^{-3}$·h^{-1}·m^{-3}
m_{req} = 0.28 µg·m^{-3}

Time = 8 hours

Difference h0-1 = 0.14 %
Difference h2-8 = 100.00 %

Figure 5-4 The ability of selected cultivars to reduce the requirement for the amount of ventilated air due to the ability to reduce selected VOCs from the indoor environment - a) Benzene.



m_{ori} = 240.00 µg·m^{-3}
m_{sup} = 2.40 µg·$^{-3}$·h^{-1}·m^{-3}
$m_{red(area)}$ = 22.95 µg·$^{-3}$·h^{-1}; V = 74.71 m3
$m_{red(m3)}$ = 0.31 µg·$^{-3}$·h^{-1}·m^{-3}
m_{req} = 12.00 µg·m^{-3}

Time = 8 hours

Difference h0-1 = 0.01 %
Difference h2-8 = 10.90 %

Figure 5-5 The ability of selected cultivars to reduce the requirement for the amount of ventilated air due to the ability to reduce selected VOCs from the indoor environment - b) Toluene.

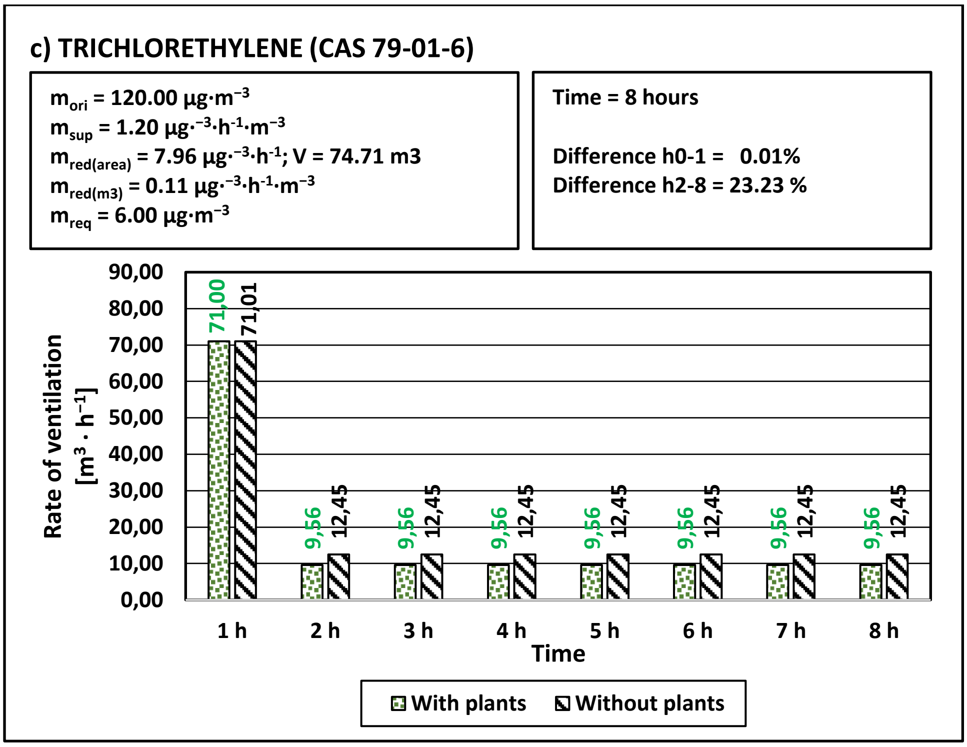


Figure 5-6 The ability of selected cultivars to reduce the requirement for the amount of ventilated air due to the ability to reduce selected VOCs from the indoor environment - c) Trichlorethylene.

It is clear from Figure 5-4, Figure 5-5 and Figure 5-6 that under the model conditions of the simulation, plants have the majority ability to influence the level of ventilation only at lower VOC concentrations. In any case, it was necessary to ventilate during the first hour or change the indoor air so that the concentrations reach on the required mass concentration without unnecessary delay m_{req}. Both for benzene, toluene and trichlorethylene, the influence on the level of ventilation in the first hour was completely negligible, when the potential for reducing the amount of exchanged air under model conditions was 0.14% for benzene, 0.01% for toluene and trichlorethylene. This is due to the fact that plants are not primarily intended for immediate effectiveness, the effect of plants is slower and they need a longer period of time to eliminate harmful substances. Therefore, plants do not have the potential to immediately improve the quality of the indoor environment, and, from this point of view, they cannot even replace sudden ventilation. However, an interesting fact is the progress in the model environment in the next 7 hours of working time, when plants in the model environment have the potential to have a significant influence the level of supplied air to the indoor environment while maintaining the required quality of the indoor environment. In the case of benzene, the implemented plants were completely able to replace ventilation to reduce the amount of pollutant emitted in the indoor environment and the level of reduction in the amount of ventilated air was 100%, in the case of toluene and trichlorethylene the plants significantly reduced the requirement for the amount of supplied air compared to the environment without plants, namely for toluene 10.90 %, trichlorethylene 23.23%. From the above, it follows that plants really have the potential to bring savings for building ventilation area by the reducing selected VOCs. However, their potential does not lie in immediate shock ventilation, but in the gradual and long-term reduction of harmful substances or maintaining the required concentration values.

5.2.3 Comparison of theoretical equivalent efficiency from a CO_2 and VOC perspective

For easier clarity, this section additionally compares the actual equivalent efficiency of individual elimination methods, namely conventional methods consisting in environmental ventilation with experimental methods consisting in the implementation of plants. For comparison, all combinations were taken from the CO_2 area, i.e. the cultivar Hedera Helix and Ficus Benjamina at the leaf illumination level in the area 40% PPFD 300, 60% PPFD 80, and also at the leaf illumination level in the area 40% PPFD 100, 60% PPFD 60. The results can be seen from Table 5-8.

Table 5-8 Equivalent effectiveness of individual elimination methods from a CO_2 perspective

CO_2 concentration [ppm]		**Only ventilation**	**Only plants**			
			Hedera Helix [m²]		**Ficus Benjamina [m²]**	
			PPFD [µmol · m^{-2} · s^{-1}]		**PPFD [µmol · m^{-2} · s^{-1}]**	
C_{req}	**C_{sup}**	**Rate of ventilation [$m^3 \cdot h^{-1}$]**	**300 / 80**	**100 / 60**	**300 / 80**	**100 / 60**
1000	670	50.627	128.61	188.39	309.64	633.18
1000	550	45.315				
1000	419	40.658				
1500	670	34.014				
1500	550	31.531				
1500	419	29.204				

It is clear from Table 5-8 that if plants will be completely replaced by ventilation systems, it would have to be quite extensive areas of greenery, which in principle would be beyond the limit of feasibility for the lighting shown in the model example in some cases.

At the same time, Table 5-8 appropriately shows that if plants will be fully replaced by the ventilation system, it would basically be a separate closed biosystem that would be independent of the quality of the external environment. Therefore, the equivalent area of green leaves remains the same for different qualities of air supplied to C_{sup}.

The cultivar Hedera Helix offers the smallest area for maintaining the required initial concentration, as expected, with illumination of 40% / 60% of the leaf area PPFD 300 / 80, with a total leaf area of 128.61 m^2. On the contrary, the largest leaf area is required at low lighting values of 40% / 60% of the leaf area PPFD 100 / 60, for the Ficus Benjamina cultivar with a total leaf area of 633.18 m^2.

As it was mentioned, it is unlikely that in the near future, plants would completely replace the ventilation systems in the buildings. On the other hand, plants can suitably supplement ventilation systems and thus bring operational savings.

By the expressing the equivalent theoretical efficiency of the individual methods from the point of view of the solved VOCs, the first hour of the simulation from the 8-hour time period was discarded in the overview, because it is a case where the sudden airing of the space, which is significantly infested with a pollutant, is almost irreplaceable and the plant would take a very long time to reduce the level of concentration of the pollutant to an acceptable level for a long time.

Table 5-9 Efficiency of individual elimination methods from the point of view of selected VOCs

		Only ventilation	**Only plants Hemigraphis Alternata + + Hedera Helix + Ficus Benjamina [m²]**
VOC	**m_{req} [µg · m^{-3}]**	**Rate of ventilation [$m^3 \cdot h^{-1}$]**	**PAR 5.45 [µmol · $m^{-2} \cdot s^{-1}$]**
Benzene	0.28	12.45	1.16
Toluene	12.00		23.44
Trichlorethylene	6.00		11.26

From

Table 5-9 it is clear that at the set model values, when the required mass concentration m_{req} was set at 1% of the 80% limit for each VOC substance, that the same amount of air is always proportionally required for ventilation. However, it is necessary to note here the significant effectiveness of plants in case they should replace ventilation. In the case of benzene, ventilation can be effectively replaced with 1.16 m^2, which is realistically achievable in the working environment. More difficult to achieve is the placement of several plants instead of ventilation for the reduction of toluene 23.44 m^2 and trichlorethylene 11.26 m^2.

It is important to mention that such plant efficiency is secondary if sufficient indoor air quality in terms of CO_2 concentration is not ensured. Ventilation due to the elimination of CO_2 is assumed to be in different orders compared to VOC, and it can therefore be assumed that if the space is effectively ventilated due to CO_2, it is also sufficiently ventilated from the point of view of VOC. This of course applies on the assumption that there is no significant source of VOCs in the indoor environment, which would emit the resolved VOCs to an extreme extent, far exceeding the values indicated in the simulation.

5.3 Determination of procedures for practical measurement of elimination methods

For the purposes of the research, it was necessary to carry out several diverse measurements consisting in ascertaining the actual performance of the selected plants from the point of view of the ability to reduce the concentration of CO_2 in the indoor environment, considering the conditions characteristic of the indoor environment. In the indoor environment, the intensity of lighting is significantly lower, which can be considered as a disadvantage from the point of view of performance, on the contrary, there is a relatively constant temperature and humidity, which is considered as an advantage. To determine the approximate values of the light intensity, additional PPFD measurements were performed in a real model office for several days during different seasons.

5.3.1 Description of the procedure for measuring CO_2 reduction by selected plants

A test chamber consisting of a closed box was created to measure the potential performance of selected plants to reduce CO_2 in the indoor environment, into which selected cultivars were gradually placed. The chamber was equipped with lighting bodies with the possibility of adjusting their lighting height, which made it possible to change the PPFD in the area where plant leaves appeared. Furthermore, the chamber was equipped with a CO_2 dispenser and a CO_2 probe for monitoring the current CO_2 concentration over time. The chamber was created from a growing box (growbox) with a high level of emissivity of the inner surface. The chamber has external dimensions: width 60 cm, depth 60 cm, height 170 cm. The total volume of the chamber is 0.612 m^3. Test chamber is shown in Figure 5-7. The test chamber was located in an interior room with stable temperature in range 21 – 23 °C and relative humidity in range 50 – 60 %.

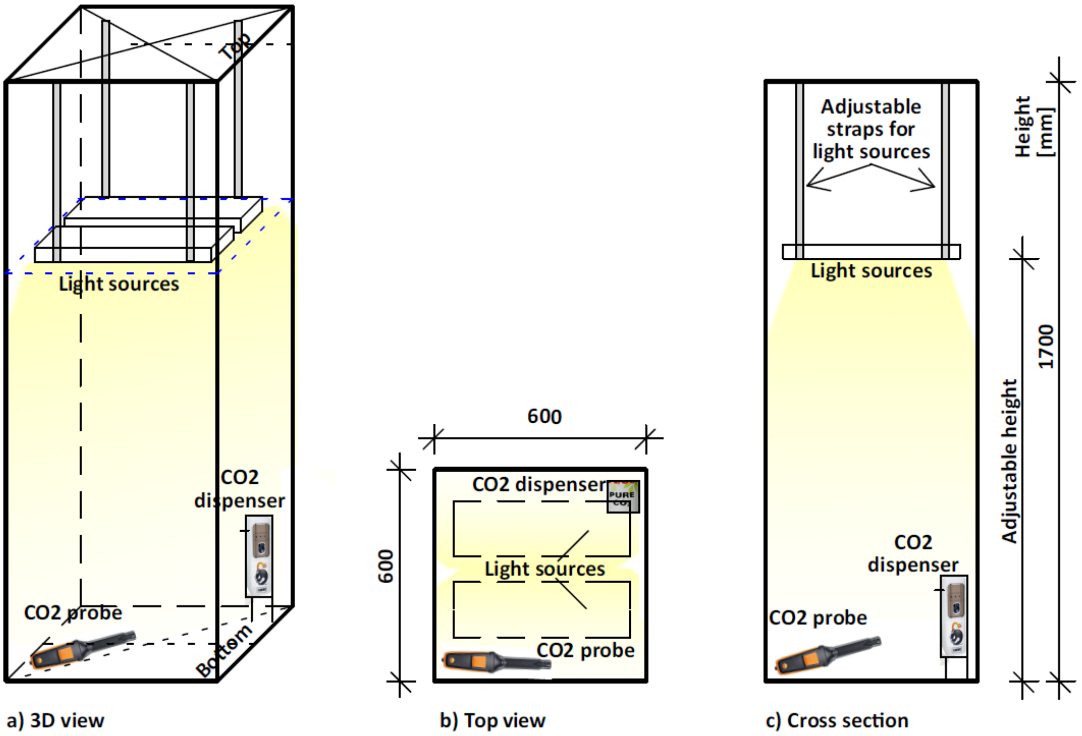


Figure 5-7 - Test chamber dimensions

To reduce the amount of air exchanged between the chamber and the environment, the chamber was additionally covered in several layers with a transparent industrial film. Fluorescent lamps with improved spectrum delivery were placed in the chamber, the suspension allowed changing the height of the suspension, so that the PPFD intensity could be changed for individual measurements. The lamps had the following parameters: 4 fluorescent tubes T5, 24 W, 1700 lm, power supply 230 V, 50 Hz, total power consumption of the installed lamps 96 W, total luminous flux 6800 lm. Chromaticity temperature Tcp 6500 K. Stated color rendering index Ra 93, Stated Circadian Activation Effect Index Ac 95. The actual measured spectrum rendering of the light source using the UPRtek MK350S Premium Spectometer is shown in Figure 5-8.

Figure 5-8 Presentation of the spectrum of the artificial light source installed in the test chamber

At the bottom of the chamber in one corner, a CO_2 dispenser of the Airboomz brand was placed for remote control, which is able to ensure the initial onset of the desired CO_2 concentration at the start of the measurement, and it can then be turned off. A probe was placed on the bottom of the chamber in the other corner to measure the current CO_2 concentration, temperature, and humidity. Parameters of the CO_2 probe: Testo brand, CO_2 measuring range 0 – 10000 ppm, accuracy ± (50 ppm + 3% of the measured value for 0 to 5000 ppm), ± (100 ppm + 5% of the measured value for 5001 to 10000 ppm). The location of the equipment in the test chamber can be seen in Figure 5-9.

Figure 5-9 The location of the equipment in the test chamber

The measurement monitored the potential of selected cultivars to reduce CO_2 in the test chamber during a defined period of time based on different PPFD values. Before starting the measurement with the respective cultivars, a so-called initial calibration measurement was performed to determine the actual loss of CO_2 concentration to the environment outside the test chamber. This involved closing the chamber, achieving the appropriate initial CO_2 concentration inside the chamber, and monitoring the trend of the CO_2 concentration inside the chamber over a set period. Afterwards, the selected cultivar was inserted into the chamber, again with the help of a remote-controlled CO_2 dispenser, the appropriate concentration of CO_2 was achieved inside the chamber and for a set period. After measuring one cultivar, another tested cultivar was inserted into the chamber and the procedure was repeated. After the measurement of the cultivars was completed, a so-called final calibration measurement was performed, when the CO_2 concentration development trend was verified again, which basically describes the net losses through the chamber construction at the end of the measurement. Structural losses can be described as a certain type of infiltration that cannot be excluded in a practical environment. After the end of the measurement at the specified light intensity, the light intensity was adjusted using a rectifiable suspension and then the entire procedure was repeated, i.e., input calibration measurement, measurement with cultivars, output calibration measurement.

Before and after placing the plants, the intensity of the PPFD lighting in the test chamber was measured at the individual levels of the chamber, as a significant influence of the shading of the own leaves by the plant itself was assumed, due to the fact that the light is directional from above. For the purpose of measuring the intensity of PPDD illumination in the test chamber, an Apogee Instruments quantum meter with an MQ-500 probe was used, spectral range 398 – 692 nm ± 5 nm, measurement Range 0 – 4000 [$\mu mol \cdot m^{-2} \cdot s^{-1}$], field of view 180°, spectral error for Cool White Fluorescent (T5) 0.1%. The device is shown on Figure 5-10.

Ficus Benjamina (C_3 photosynthetic plant) and Aloe Vera (CAM photosynthetic plant) cultivars were chosen for the measurement purposes. The total area of leaves from the underside of Ficus Benjamina in the tested cultivar is approximately 0.24 m^2, considering the growth and shape, a deviation of ± 5% is considered for the total area of the leaves. The total area of the spherical leaves from the bottom and the top of the Aloe Vera cultivar is approximately 0.32 m^2 ± 5%. The Ficus Benjamina cultivar was always thoroughly watered (not overwatered) before the measurement, the soil can be labeled as wet. The Aloe Vera cultivar had not been irrigated for a long time for several months before the measurement, all the time it thrives only on-air humidity in the indoor environment, its soil can be described as super dry. For the purposes of measurement, the time period was considered to be 8 hours.

Figure 5-10 Quantum Flux Apogee Intruments MQ-500

5.3.2 Description of the procedure and measurement of PPFD in the office space

An important aspect of the indoor environment was the lighting intensity values expressed in PPFD. The light conditions were determined in the office that is considered (full office description is on chapter 5.2). The PPFD lighting intensity was measured in a real office environment, that is the same that was considered for the theoretical comparison of the equivalent efficiency of the individual methods, described in chapter 5.2. In this office, PPFD measurements were provided during the day, between 8:00 a.m. and 4:00 p.m. The measurement took place in the month of December, when the worst light conditions for plants can be expected in the Northern Hemisphere from the point of view of PPFD due to the winter solstice, and the measurement was carried out in the month of April, when solar radiation in the Northern Hemisphere already has a much more significant intensity.

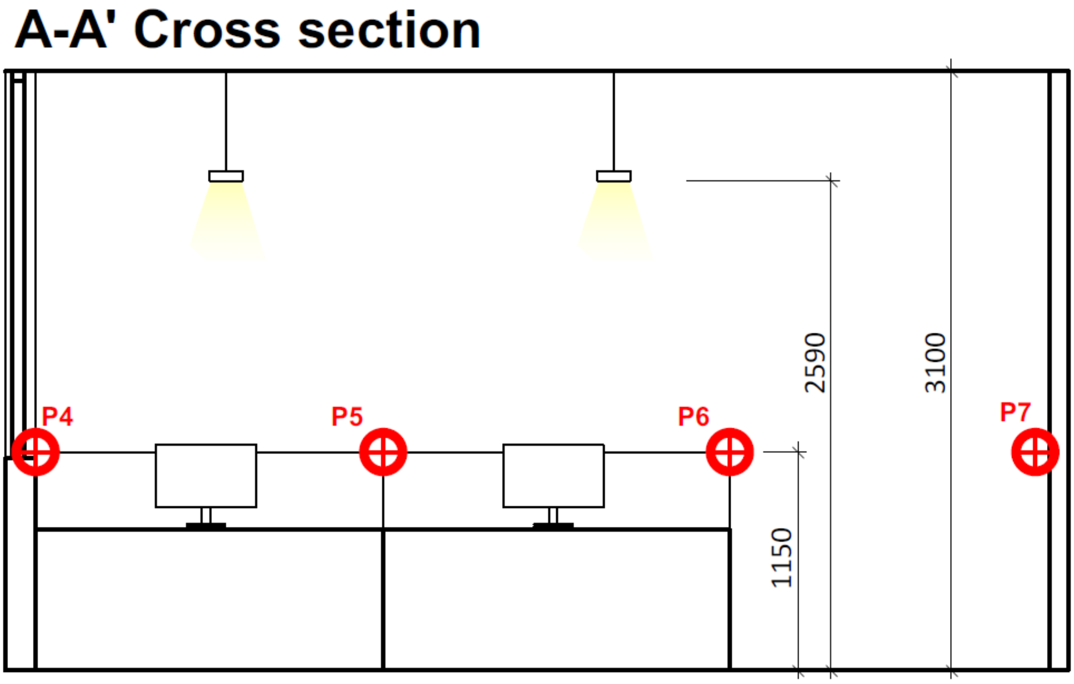


Figure 5-11 - Cross section of the office

Within the model environment, measurement points were determined at which PPFD values were measured at regular intervals using an Apogee instruments MQ-500 quantum meter at specific times. The scheme of the office with the determination of the points can be seen in Figure 5-12. Regarding the space, it should be mentioned that the windows are oriented to the north-east, the sunlight in the office is therefore only in the morning hours and the lighting conditions can generally be described as somewhat deteriorated.

It is clear from Figure 5-12 that 10 points P1 to P10 were determined. It was assumed that the most suitable lighting conditions would be achieved at points P1, P4 and P8, due to their immediate proximity to the window fillings. On the contrary, the assumption of the worst lighting is at point P7, then at points P3, P6 and P10, because the points are located significantly further from the window fillings and therefore have less natural light.

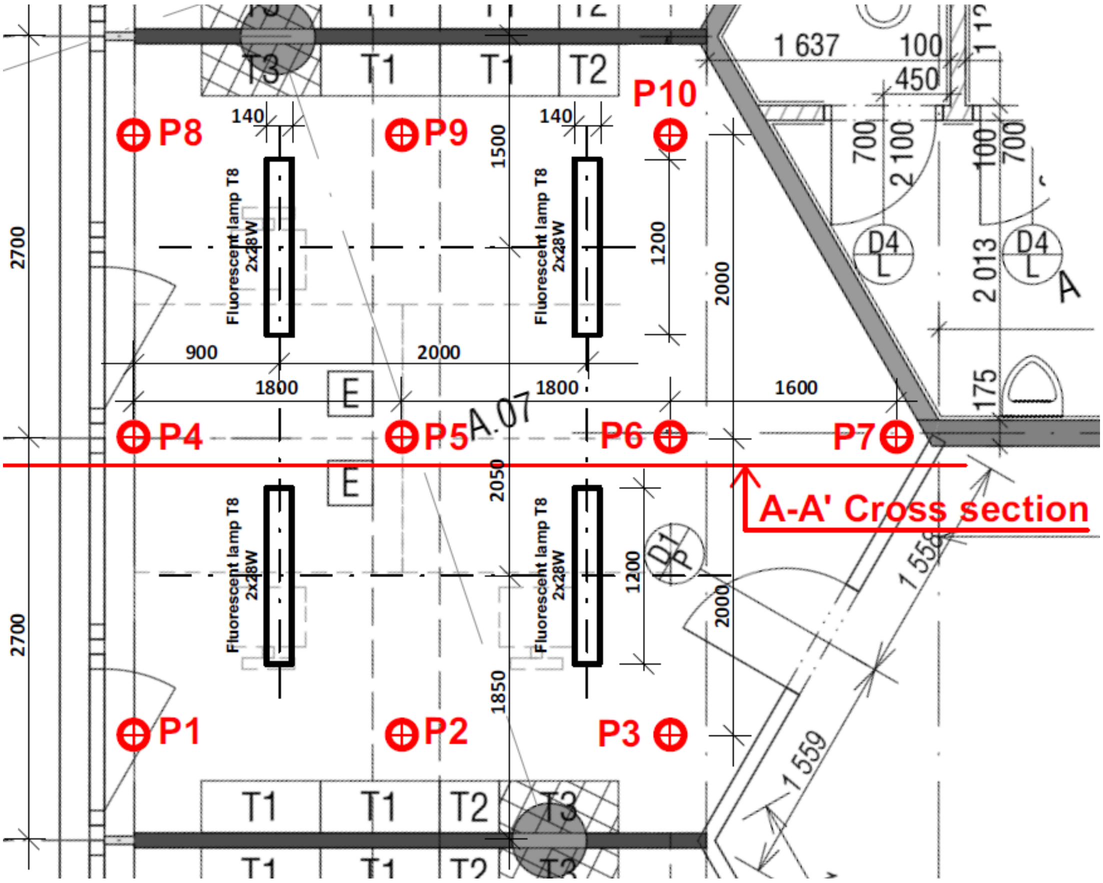


Figure 5-12 Dot network scheme in the office for measuring PPFD values

All readings at points P1 to P10 were taken at a height of 115 cm above the floor, the probe was directed perpendicular to the floor, i.e., the photodiode was directed perpendicular to the ceiling as shown in Figure 5-13. During the measurement, the lighting of the ceiling lights was not taken into account, as it turned out that the installed fluorescent ceiling lights have a completely negligible effect on the PPFD values at the measured height level, this is also proven in Table 5-10.

For completeness, the presentation of the spectrum by office lights is shown in Figure 5-14.

Figure 5-13 Direction of the Apogee MQ-500 probe in the investigated environment

Figure 5-14 Presentation of the spectrum of fitted office lights

Table 5-10 Effect of switched-on ceiling lights on PPFD values at measurement points at a height of 115 cm above the floor

		Time			
		Lighting OFF		**Lighting ON**	
Day	**Point**	**8:30**	**16:00**	**8:30**	**16:00**
20. December	Point 1	9	1	9	2
	Point 2	2	0	5	3
	Point 3	2	0	6	4
	Point 4	6	1	8	1
	Point 5	2	0	5	4
	Point 6	1	0	6	7
	Point 7	1	0	1	3
	Point 8	10	1	7	1
	Point 9	1	0	6	5
	Point 10	1	0	7	4

From Table 5-10, it is clear that even with the ceiling lights on, the difference in PPFD values is almost negligible, and it is clear that the more significant PPFD values in the model environment are made up of light from the external environment that passes through the window fillings. It can be seen from the table that in the twilight period ceiling lights have the possibility to increase the PPFD only in the order of few measure units, which in principle are almost negligible for the plant function from the point of view of CO_2 elimination, since these lights do not have the possibility to shift the PPFD values enough to reach the breakpoint for starting CO_2 sequestration by the plant. Therefore, the effect of ceiling lighting installed in the investigated environment can be neglected. During the measurement, the meteorological situation was continuously monitored, especially the course of cloudiness, precipitation and atmospheric pressure at a nearby meteorological station under the administration of the Czech Hydrometeorological Office. From this station, records of current climatic conditions were recorded continuously. The results of measuring PPFD values in the mentioned office environment in the month of April are shown in Table 5-11, in the months of December and January are shown in Table 5-12, the meteorological situation at the time of measurement is shown in Table 5-13 [90].

Table 5-11 Measured values of PPFD in the office area on the examined days in the month of April

		Time				
Day	**Point**	**8:30**	**10:00**	**12:00**	**14:30**	**16:00**
22. April	Point 1	647	187	126	123	97
	Point 2	93	58	37	44	33
	Point 3	44	22	17	24	16
	Point 4	446	191	127	134	121
	Point 5	88	60	46	53	52
	Point 6	44	31	22	35	31
	Point 7	21	15	14	21	16
	Point 8	381	187	128	133	118
	Point 9	40	26	25	36	27
	Point 10	24	17	16	25	20
23. April	Point 1	345	889	345	125	81
	Point 2	39	103	39	37	29
	Point 3	16	49	16	17	13
	Point 4	201	811	201	139	92
	Point 5	53	96	53	57	36
	Point 6	31	52	31	28	29
	Point 7	19	26	19	21	16
	Point 8	212	870	212	151	82
	Point 9	79	39	36	38	26
	Point 10	17	27	17	20	18

Table 5-12 Measured values of PPFD in the office area on the examined days in the months of December and January

		Time				
Day	**Point**	**8:30**	**10:00**	**12:00**	**14:30**	**16:00**
16. December	Point 1	4	20	65	33	2
	Point 2	3	8	15	8	1
	Point 3	5	6	12	4	0
	Point 4	4	22	75	34	3
	Point 5	4	11	19	8	1
	Point 6	6	9	11	5	1
	Point 7	1	2	5	2	0
	Point 8	4	21	78	37	1
	Point 9	5	10	10	8	0
	Point 10	4	9	8	3	0
20. December	Point 1	9	60	91	17	1
	Point 2	2	19	19	4	0
	Point 3	2	11	7	1	0
	Point 4	6	70	83	14	1
	Point 5	2	19	24	3	0
	Point 6	1	13	16	2	0
	Point 7	1	6	5	1	0
	Point 8	10	59	81	17	1
	Point 9	1	11	21	6	0
	Point 10	1	10	7	4	0
2. January	Point 1	33	87	113	32	4
	Point 2	11	23	36	6	2
	Point 3	4	13	14	2	0
	Point 4	29	86	108	33	3
	Point 5	5	25	39	8	3
	Point 6	3	12	20	4	2
	Point 7	2	7	14	2	1
	Point 8	25	87	104	31	4
	Point 9	4	20	33	8	1
	Point 10	2	10	15	2	0

Table 5-13 A meteorological situation during the critical days

Day	Meteorologic indicator	Time 8:00	10:00	12:00	14:00	16:00
22. April	Atmospheric pressure [hPa]	985.9	986.2	986.4	n/a	n/a
	Precipitation [mm]	0	0	0	n/a	n/a
	Cloudiness	Partly cloudy 4/8	Cloudy 6/8	Cloudy 5/8	n/a	n/a
23. April	Atmospheric pressure [hPa]	991.4	991.4	991.4	991.4	n/a
	Precipitation [mm]	0	0	0	0	n/a
	Cloudiness	Clear skies 1/8	Cloudy 6/8	Cloudy 6/8	Cloudy 6/8	n/a
16. December	Atmospheric pressure [hPa]	973.4	975.0	975.1	976.0	n/a
	Precipitation [mm]	0.3	n/a	n/a	n/a	n/a
	Cloudiness	Overcast 8/8	Overcast 8/8	Overcast 8/8	Overcast 8/8	n/a
20. December	Atmospheric pressure [hPa]	991.2	990.9	990.0	988.8	988.1
	Precipitation [mm]	0	0	0	0	0
	Cloudiness	Close overcast 7/8	Close overcast 7/8	Close overcast 7/8	Close overcast 7/8	Close overcast 7/8
2. January	Atmospheric pressure [hPa]	986.6	987.1	986.6	986.4	986.9
	Precipitation [mm]	0	0	0	0	0
	Cloudiness	Close overcast 7/8	Close overcast 7/8	Cloudy 5/8	Close overcast 7/8	Cloudy 6/8

From

Table 5-11, Table 5-12 and Table 5-13, it is seen that significant PPFD values can be achieved in the internal environment of the office even in relatively unfavourable conditions, when office spaces with windows are oriented mainly to the north, even when the sky is completely cloudy. According to assumptions, it has been confirmed that the most suitable conditions can be achieved by plants near transparent window coverings, ideally under a clear sky and at a time with a higher intensity of solar radiation, i.e. the summer season. While in the month of April, values in the order of several hundred PPFD units were measured at points P1, P4, P8, which are close to the windows, even when the sky was partly cloudy, in the months of December and January, i.e. around the winter solstice when it was cloudy or partly cloudy skies were maxima only in the tens of PPFD units. Significant values were reached in the month of April, when the maximum was 889 PPFD (P1) in the morning hours even when the sky was partly cloudy. In the months of December and January, the maximum was 113 PPFD (P1) at high noon, when the cloudiness was partly dissolved. According to the assumptions, deeper into the space, i.e. further from the window fillings, the PPFD values decrease significantly, when in the month of April they range in the lower tens of PPFD, in the months of December and January in the lower tens up to units of PPFD.

With regard to the very unfavourable climatic conditions at the time of the measurement, it can be stated that the measurement took place in almost worst possible conditions. On no measurement day there was a completely clear sky throughout the day, and especially through midday, which could significantly increase the PPFD values in the indoor environment even in winter at the time of the winter solstice. At the same time, values were not measured here in the summer period, when significantly higher PPFD values can be assumed, probably exceeding 1000 PPFD, and at the same time a higher number of days with clear skies, as well as a longer period of light intensity. It is important to mention that while in winter there are approximately 8 hours of daylight at the time of the winter solstice, in the summer there are 16 hours of daylight at the time of the summer solstice. It is also appropriate to point out the values in Table 5-13 marked as n/a, these parameters could not be determined as part of the research. For the purposes of this research, we can start from the data focused in the month of April, which can be considered as suitable data stated between the completely cloudy sky in the winter months and the completely clear sky in the summer months. Even though the measured days in April are not exactly in the middle of the interval between the winter and summer solstice, the conditions were again rather unsatisfactory, as the sky was partly cloudy for most of the measurement time. The lighting conditions are thus rather underestimated in this research compared to reality.

The points closest to the window fillings P1, P4, P8 can therefore be characterized as ideal for placement from the point of view of the plants, values in the range of 201 - 647 PPFD at 8:30, 187 - 889 PPFD can be expected here in the morning even with partly cloudy sky in the month of April at 10:00 a.m., 126 - 345 PPFD at 12:00 p.m., 123-151 PPFD at 2:30 p.m., 81 - 121 PPFD at 4:00 p.m. For the placement of plants, it is advisable to use the area of the walls in the immediate vicinity of the window inlays. However, due to the ability of plants to optimize the tilt of the leaf to capture the maximum amount of radiation, the actual values can be expected to be even significantly higher. The MQ-500 probe was oriented perpendicular to the ceiling for the sake of measurement uniformity. Significantly better results would be achieved if MQ-500 probe were optimally turned towards the light source from the exterior. However, such a measurement could be misleading and might not be accurate, due to the decomposition of the components of solar radiation in the earth's atmosphere into direct and diffuse (sky), from which global (total) is formed. Such a measurement would be particularly challenging in a room oriented to the northeast, where there is a significant component of direct radiation in the morning, and especially diffuse radiation in the afternoon.

5.4 Measuring the actual efficiency of plants from the point of view of CO_2 reduction

5.4.1 Measurement of light conditions in the chamber

Ficus Benjamina and Aloe Vera cultivars were chosen as part of the measurements. For the practical measurement of the actual efficiency of plants in a closed chamber, it was necessary to start from the light intensity that was measured in the previous chapter, where it was shown that PPFD can be significant even in an indoor environment. For the measurement purposes, were considered two lighting conditions of the selected cultivars in the test chamber. The first condition for Ficus Benjamina was assumed with lighting at a level of 1050 mm, which stimulated 139 PPFD on the highest leaves in the upper part of the crown of the plant at a height of approximately 900 mm. In the case of Aloe Vera, it was 90 PPFD at the height of the tallest leaf of 700 mm. Due to the number of sheets and their different inclinations, deviations within millimetres can be safely neglected. This state is shown in Figure 5-15. This state reflects more favourable lighting conditions in the indoor environment. In the second case, to reflect the less favourable conditions in the indoor environment, lighting was placed up to a height of 1500 mm, due to which the cultivars were less illuminated. Specifically, lighting induced approximately 49 PPFD at a height of Ficus Benjamina cultivar 900 mm, 50 PPFD at a height of Aloe Vera cultivar 700 mm. This state is shown in Figure 5-18.

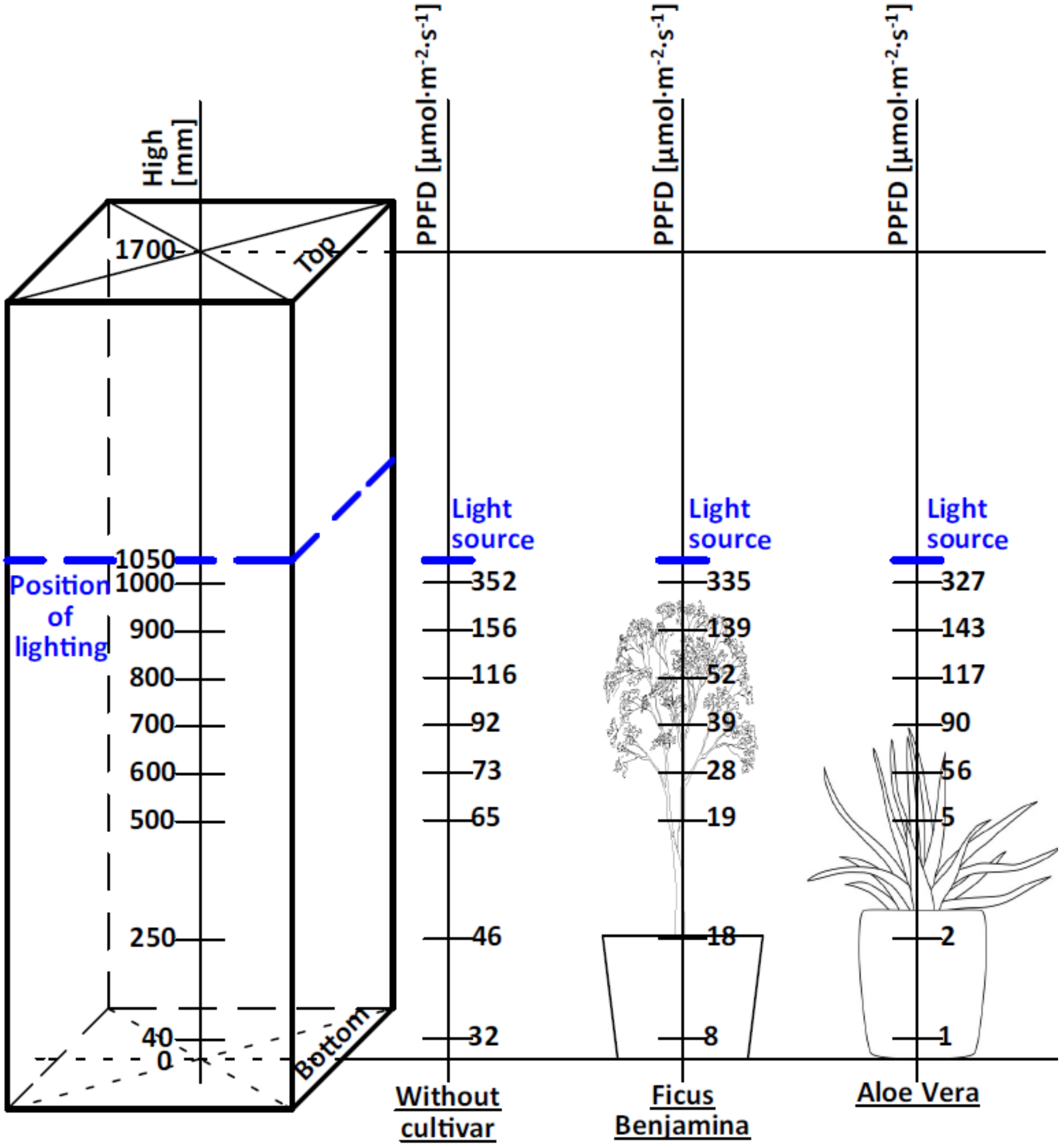


Figure 5-15 Measured PPFD values in the chamber at a light level of 1050 mm for the cases without cultivar, with Ficus Benjamina and with Aloe Vera

From Figure 5-18 it can be seen that the leaves on the upper side of the crown of the plant significantly shade, or they prevent the passage of light to the lower positions of the crown. This phenomenon is conveniently apparent in case of comparing measurements of the state with Ficus Benjamina with the state of the chamber without the cultivar. Already at a distance of 50 mm from the light source, the PPFD value is reduced from 352 to 335 due to the reduction of reflectivity from the lower side of the chamber. The majority drop can then be observed at the level of 800 mm, where the PPFD value is reduced from 116 to 52 due to leaves. In the case of Aloe Vera, the difference is even more striking, it is most conveniently observed at the level of 500 mm, where due to the dense crown of the deciduous plants, the plant does not allow too much radiation to the lower positions. The PPFD value is reduced from 65 to 5 in this tier. Within the metabolism of succulents, the value of PPFD in the lower levels of the plant is not monitored as much, as they have a better ability to adapt to extreme conditions.

Figure 5-16 and Figure 5-17 show the cultivars in the test chamber before starting the measurement.

Figure 5-16 Cultivar Ficus Benjamina in a test chamber at an illumination height of 1050 mm

Figure 5-17 Aloe Vera cultivar in a test chamber at a lighting height of 1050 mm

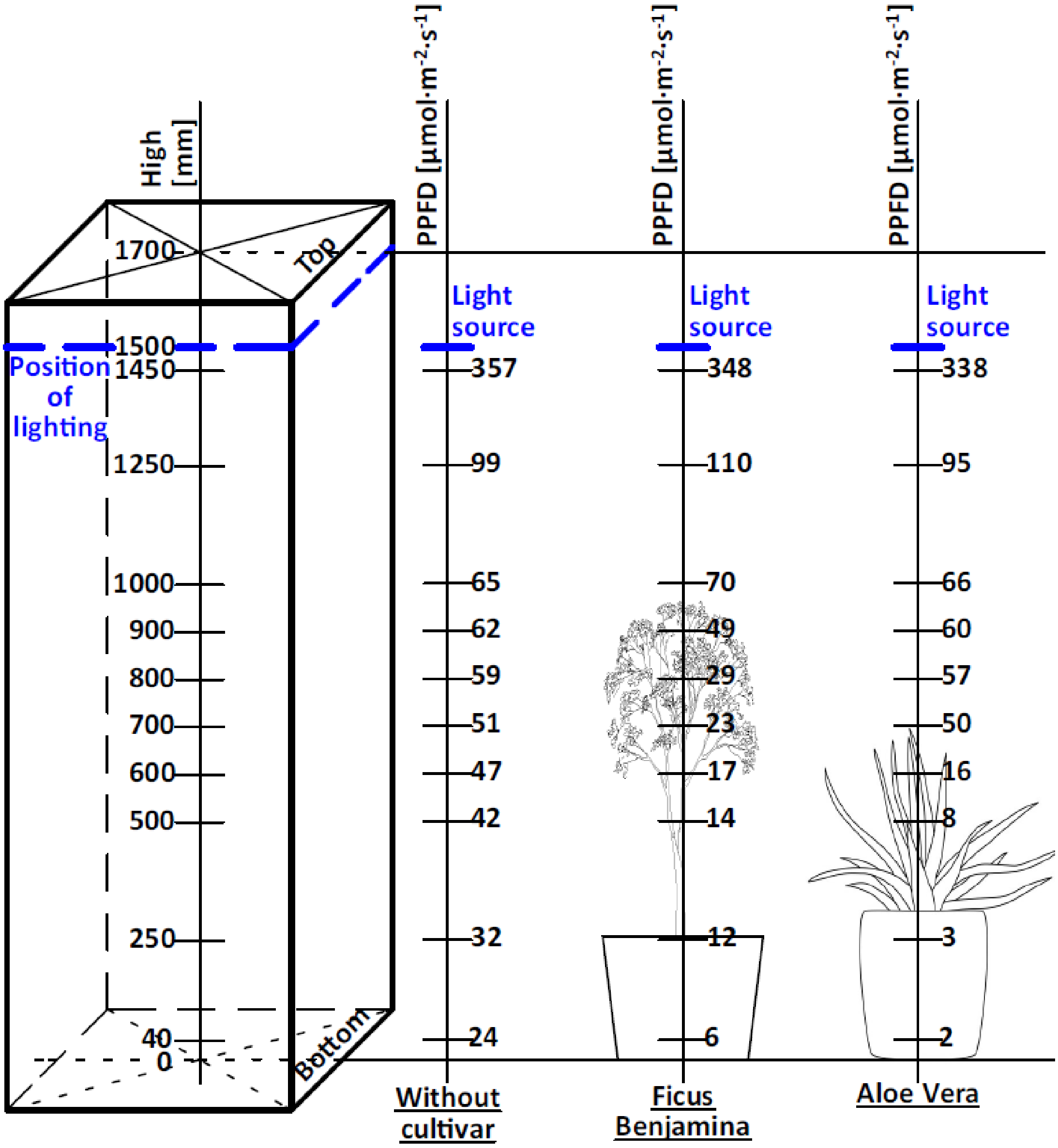


Figure 5-18 Measured PPFD values in the chamber at a light level of 1500 mm for the cases without cultivar, with Ficus Benjamina and with Aloe Vera

From Figure 5-18, a similar trend is evident as in the case of Figure 5-15, where the leaves in the upper layer of the crown of the plant significantly overshadow the leaves located in lower positions. However, due to the lower absolute value of PPFD at the level of the upper crown of the plants, the differences are less profound. In the case of Ficus Benjamina, it is possible to observe a drop at the height level of 800 mm from a PPFD value of 59 in the case of a chamber without a cultivar to a value of 29 in the case of a chamber with a cultivar. In the case of Aloe Vera, there is again a significant decrease due to shading by thick leaves at the level of 600 mm, from a value of 47 to a value of 16.

Figure 5-19 and Figure 5-20 show the cultivars in the test chamber before starting the measurement.

Figure 5-19 Cultivar Ficus Benjamina in a test chamber at an illumination height of 1500 mm

Figure 5-20 Aloe Vera cultivar in a test chamber at a lighting height of 1500 mm

It should be noted that the lower part of the Ficus Benjamina plant in case 2 as shown in Figure 5-20 is already below the level of the light compensation point, which is around the value 22. In case 1 that is shown in Figure 5-18, the Ficus Benjamina plant is located above the level of the light compensation point. Due to the different metabolic cycle, Aloe Vera has a different behavior because of lighting, when, on the contrary, in some cases it is able to reduce CO_2, especially when lighting is below of the level of the light compensation point, the behavior of succulents is significantly more difficult to predict.

5.4.2 Measurement of plant performance from the point of view of CO_2 reduction in a test chamber

After measuring the PPFD values in the chamber where the plants were placed, the process of practical measurement of the evolution of the CO_2 concentration inside the chamber was started. In the first phase, an initial measurement was made to determine the CO_2 decrease trend without the contribution of plants. Subsequently, Ficus Benjamina and Aloe Vera cultivars were placed separately in the test chamber. After measuring the trends of CO_2 decrease due to the presence of plants, the output measurement was performed again to determine the decrease trend without the contribution of plants, based of which a similar or even identical tightness of the test chamber was verified again. At each measurement, a CO_2 concentration exceeding 5000 ppm was induced using a remote-control CO_2 dispenser, targeting between 5000 and 6000 ppm. This value was chosen by the research because a gradual dilution of the air inside the chamber was assumed, where the concentration settled after 1 to 2 hours from the start of CO_2 dosing, and it was therefore impossible to achieve an exactly determined value from the beginning, even in the order of hundreds of ppm.

After the relative stabilization of the CO_2 concentration, it was possible to start monitoring trends with the reading of absolute values. The recording interval of the CO_2 probe was set to 1 minute for the measurement. The measurement results are clear from Figure 5-21 and Figure 5-22.

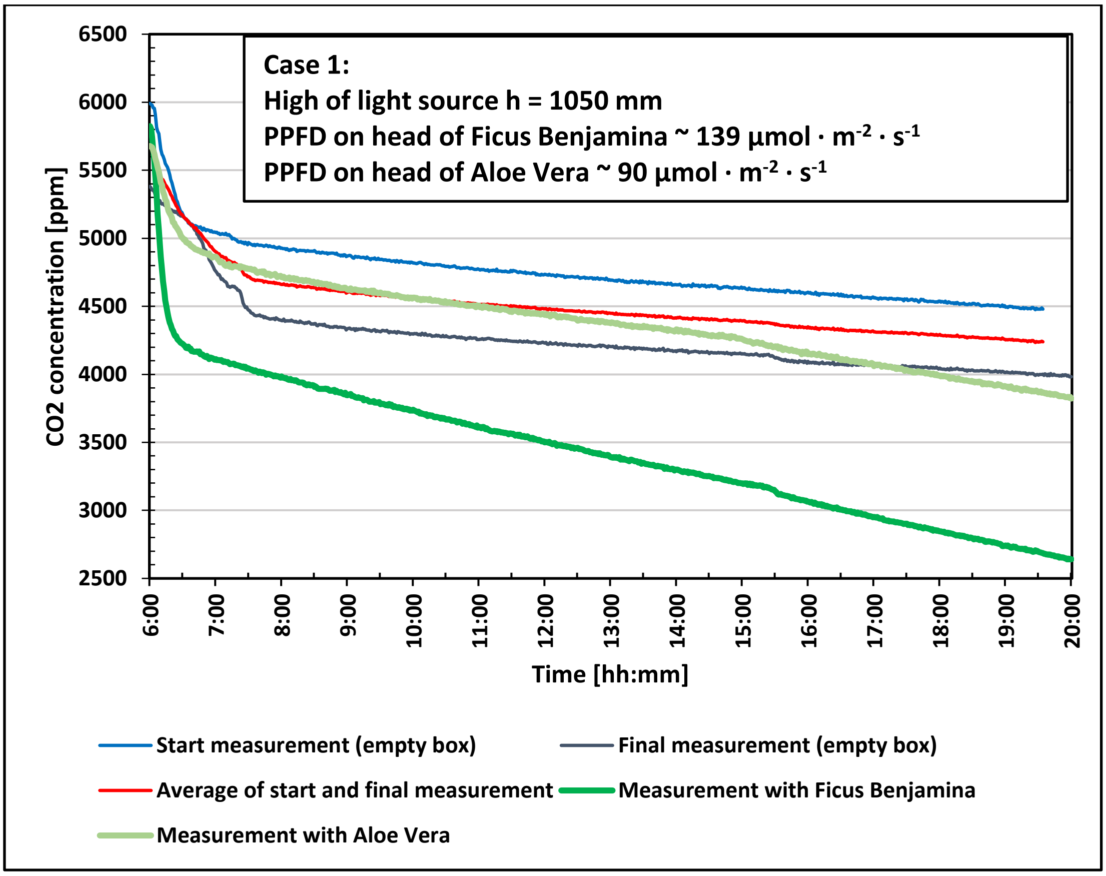


Figure 5-21 Summarized results of plant performance trend measurement for lighting case 1 at a height of 1050 mm.

Figure 5-21 and Figure 5-22 show the measured values of the development of the CO_2 concentration in a closed chamber, while the recording was started from the peak of the CO_2 concentration at the beginning of the measurement. In Figure 5-21 and Figure 5-22, therefore, the initial ramp-up to the desired CO_2 concentration is missing, as this ramp-up has no value for research purposes. From Figure 5-21 it can be seen that, the trend of both Ficus Benjamina and Aloe Vera cultivars to reduce CO_2 in the model environment of the chamber is quite evident, compared to the calibration curve, which was achieved by averaging the measurements of the empty model environment before placing the cultivars and then again the empty model environment after removing the cultivars. The mentioned trends shown in Figure 5-21 and Figure 5-22 clearly confirm that plants significantly contribute to CO_2 reduction, even in poor light conditions. According to assumptions, Ficus Benjamina with a C_3 metabolic cycle is more efficient compared to the Aloe Vera cultivar with a CAM metabolic cycle.

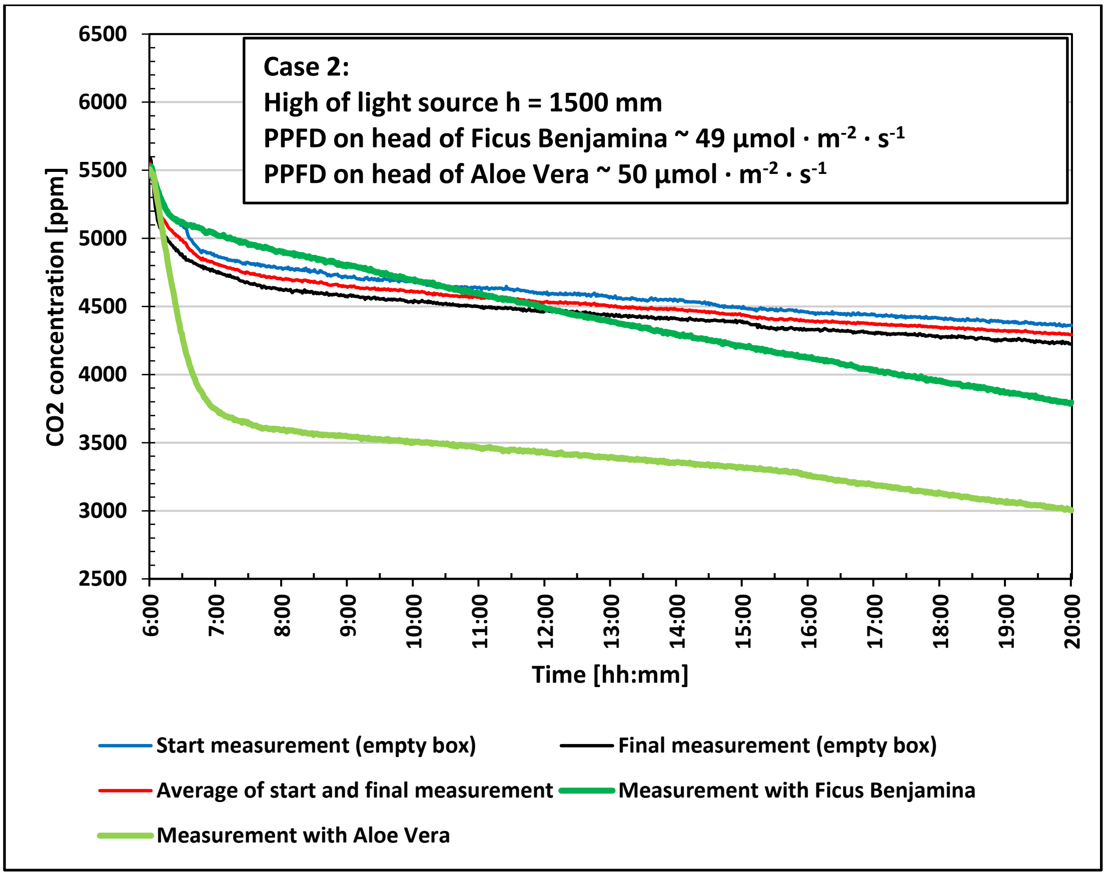


Figure 5-22 Summarized results of plant performance trend measurement for lighting case 2 at 1500 mm height

For the numerical comparison, it was necessary to start from a steady value of the CO_2 concentration in the chamber. Based on Figure 5-21 and Figure 5-22, it can be stated with a high degree of certainty that a relatively stable environment from the point of view of air mixing inside the chamber and the achievement of the actual CO_2 value on the gauges occurs after approximately 1 to 2 hours. The research therefore considers the calculation of values from the 2nd hour of measurement, followed by the analysis of a continuous 12-hour cycle. In Figure 5-21 and Figure 5-22, this corresponds to the time 8:00 - 20:00.

The exact evaluation of measurements according to hourly CO_2 reductions is shown in Table 5-14 and Table 5-15. The CO_2 concentration loss values in Table 5-14 and Table 5-15 were calculated based on the measured values by so-called smoothing of the value, where an arithmetic mean consisting of 5 measured values before a specific hour and 5 measured values including and after a specific hour was used to reach the value. The given calculation can be suitably described by the relation:

$$\bar{x} = \frac{1}{n}\sum_{i=t_i}^{n} x_i \tag{10}$$

where $\bar{x}$ [ppm] is the smoothed value of the measured CO_2 reduction for a specific time; n [-] is the number of measured values before and after a specific time, where n=10; and x_i are specific measured values of CO_2 reduction for selected consecutive times t_i [hh:mm] where $t_i \in \langle$hh:mm-00:05,hh:mm+00:05) $\wedge$ t_i=08:00 ∨ 09:00 ∨ 10:00 ∨ 11:00 ∨ 12:00 ∨ 13:00 ∨ 14:00 ∨ 15:00 ∨ 16:00.

Based on the calculated values according to relation (10), the real reduction by the plant in model conditions according to lighting was then calculated, that from the measured values for individual cultivars containing in the measured reduction also losses due to infiltration, the stated values of infiltration losses were subtracted.

Table 5-14 Measured reductions of CO_2 cultivars for the case of illumination at a height of 1050 mm

Time	**Measurement reduction [ppm · h^{-1}]**			**Real reduction [ppm · h^{-1}]**	
	Average losts by infiltration	**Ficus Benjamina including infiltration**	**Aloe Vera including infiltration**	**Ficus Benjamina**	**Aloe Vera**
6:00	not considered				
7:00	not considered				
8:00	58	126	87	68	29
9:00	47	120	68	73	21
10:00	43	120	61	77	18
11:00	35	108	60	73	25
12:00	33	109	61	77	28
13:00	32	98	57	66	25
14:00	23	99	65	76	42
15:00	49	133	102	84	53
16:00	31	114	82	83	52

Table 5-15 Measured reduction of CO_2 cultivars for the case of illumination at a height of 1500 mm

Time	**Measurement reduction [ppm · h^{-1}]**			**Real reduction [ppm · h^{-1}]**	
	Average losts by infiltration	**Ficus Benjamina including infiltration**	**Aloe Vera including infiltration**	**Ficus Benjamina**	**Aloe Vera**
6:00			not considered		
7:00			not considered		
8:00	55.8	98.4	48.3	43	-7.5
9:00	37.3	109.0	42.2	72	4.9
10:00	42.3	99.6	41.9	57	-0.4
11:00	37.3	104.7	34.9	67	-2.4
12:00	27.2	98.5	36.6	71	9.4
13:00	24.7	95.5	37.2	71	12.5
14:00	39.7	86.7	36.9	47	-2.8
15:00	44.8	83.2	56.3	38	11.6
16:00	22.6	93.2	69.2	71	46.6

According to assumptions, a significant drop in the ability of the investigated cultivars to reduce CO_2 under reduced light conditions is evident from Table 5-14 and Table 5-15. While in Table 5-14, at a greater intensity of PPFD and a height of the light source of 1050 mm, there are clear positive values for Ficus Benjamina in the range of 66-84 [ppm · h^{-1}] with an average value of 75 [ppm · h^{-1}], in Table 5-15, at a height of the light source of 1500 mm, the values for Ficus Benjamina in the range of 38 – 72 [ppm · h^{-1}], with an average value of 60 [ppm · h^{-1}]. The Aloe Vera cultivar reacted in a very interesting way, when in the first case in Table 5-14, at a light source height of 1050 mm, the ability of the cultivar to reduce CO_2 was in the range of 18 – 53 [ppm · h^{-1}], and at an average value of 33 [ppm · h^{-1}], at a light source height of 1500 mm, it was the ability to reduce CO_2 in the range of −8 – 46.6 [ppm · h^{-1}], with an average value of 8 [ppm · h^{-1}]. From Table 5-15, however, in the case of the cultivar, a certain ability to adapt to an unsuitable environment and the work of the plant with changes in metabolic cycles is evident, when the process of binding CO_2 through the metabolic cycle C_3 or CAM. The ability to assimilate CO_2 by the plant converted to the potential output of 1 m² of leaf area is shown in Figure 5-23.

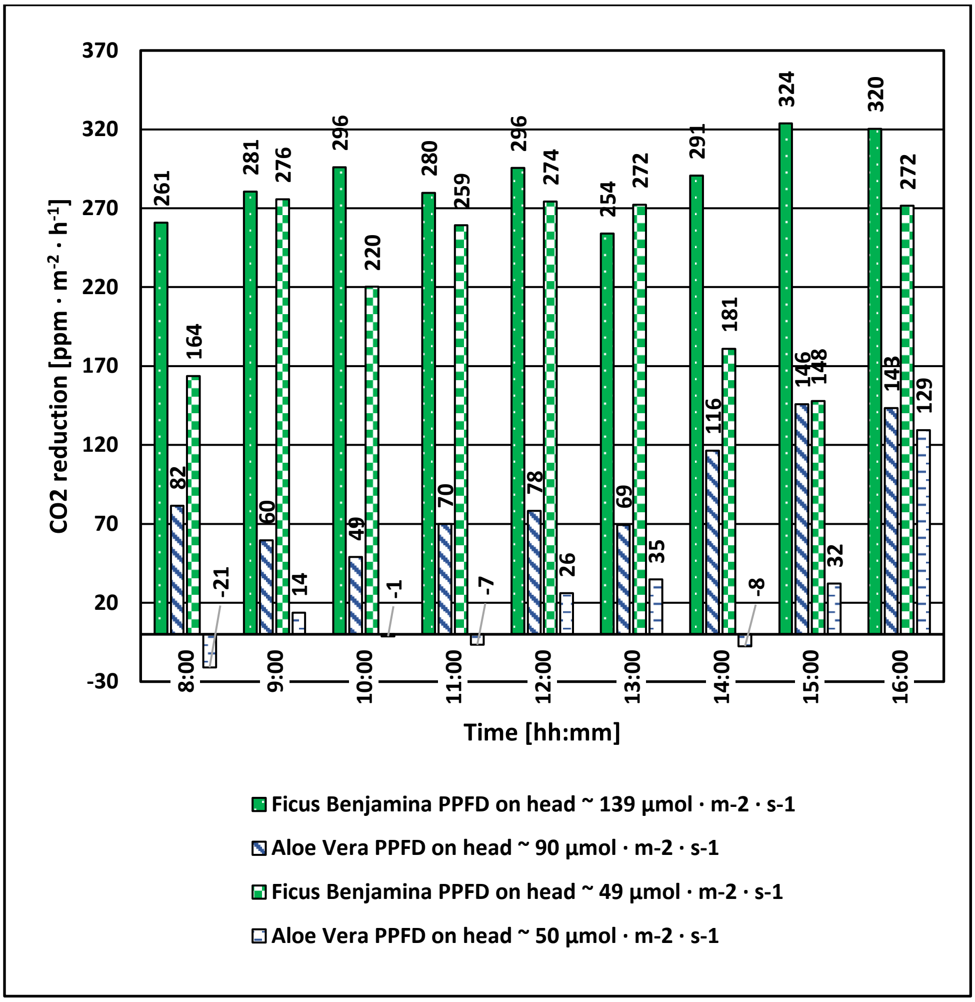


Figure 5-23 The ability to assimilate CO_2 by selected cultivars converted to 1 m^2 of green leaf

Figure 5-23 shows the significant dominance of the Ficus Benjamina cultivar under low light conditions compared to the Aloe Vera cultivar. The values in Figure 5-23 are converted proportionally from the leaf area of the measured cultivars, i.e. 0.26 m^2 for Ficus Benjmaina and 0.36 m^2 for Aloe Vera, to a total reference leaf area of 1 m^2.

5.5 Evaluation of the effectiveness of experimental methods based on practical measurements

5.5.1 Results of practical measurements of plant performance in terms of CO_2 assimilation in the indoor environment

Based on the measurements of the ability of the selected cultivars to reduce CO_2 in the environment under poor light conditions, it was shown that even under conditions corresponding to the indoor environment, a certain efficiency of plants in terms of CO_2 assimilation can be considered. The cultivar Ficus Benjamina, with a leaf area of 0.26 m^2 (calculated only from the underside of the leaf), was able to reduce an average of 75 [$ppm \cdot h^{-1}$] at PPFD values of ~ 139 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] at the top of the plant canopy, and 60 [$ppm \cdot h^{-1}$] at PPFD values of ~ 49 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] at the top of the plant canopy. The Aloe Vera cultivar with a leaf area of 0.36 m^2 (calculated over the entire leaf circumference, i.e. from the top and bottom) was able to reduce an average of 33 [$ppm \cdot h^{-1}$] at PPFD values of ~ 90 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] at the top of the plant crown, and 8 [$ppm \cdot h^{-1}$] at PPFD values of ~ 50 [$\mu mol \cdot m^{-2} \cdot s^{-1}$] at the top of the plant crown. These values are valid without the necessary acclimatization in the indoor environment and may be variable during longer time period. This variable effect due to acclimatisation is suitably detectable within the Aloe Vera cultivar in the case of the second measurement under significantly reduced light conditions, where the CO_2 assimilation capacity stagnated during the first 6 hours and then broke down significantly in the following hours, probably due to a modification of the metabolic cycle function.

The above values of CO_2 assimilating capacity need to be converted into appropriate units to determine the equivalent efficiency of the experimental method, i.e. plant implementation. The CO_2 reduction capacity values measured and expressed in units of [$ppm \cdot m^{-2} \cdot h^{-1}$] are converted to units of [$g \cdot m^{-2} \cdot h^{-1}$] using the mathematical relationships (7) and (8) presented in Section 5.1.

Table 5-16 Average CO_2 reduction capacity of measured cultivars according to illumination values and converted to 1 m² of green leaf area

Cultivar	**Active leafs area [m²]**	**PPFD on head of cultivar [µmol · m^{-2} · s^{-1}]**	**Average CO_2 assimilation [ppm · active leafs $area^{-1}$ · h^{-1}]**	**Average CO_2 assimilation [g · m² · h^{-1}]**
Ficus Benjamina	0.26	139	75	0.526
		49	60	0.421
Aloe Vera	0.36	90	33	0.022
		50	8	0.005

Table 5-16 shows that, as expected, the most significant CO_2 assimilation in the case of the Ficus Benjamina cultivar, PPFD at the top of the plant canopy is ~139 [μmol · m^{-2} · s^{-1}], where 1 m² of the plant is able to assimilate 0.526 [g · m^{-2} · h^{-1}] of CO_2. On the contrary, the lowest CO_2 assimilation capacity is evident in the case of the Aloe Vera cultivar at a PPFD at the top of the plant crown of ~ 50 [μmol · m^{-2} · s^{-1}], when the cultivar is only able to assimilate 0.005 [g · m^{-1}].

5.6 Comparison of theoretical calculated results with practical measurements

In the case of the Aloe Vera cultivar, based on previous research, a minimal impact on the ability to assimilate CO_2 in the indoor environment under lower light conditions could reasonably be expected due to the different metabolism of the CAM type. These findings were generally confirmed by measurements and the cultivar cannot be considered attractive in the short term in terms of CO_2 assimilation. However, its considerable advantage may be its significant ability to survive and adapt to the environment, where it can survive and even thrive in the long term without irrigation and without increased light requirements. This can be an advantage especially in locations where wet conditions or the presence of moist substrates cannot be assumed.

On closer analysis, however, a very interesting finding is the behaviour of the Ficus Benjamina cultivar, which significantly exceeded the predicted expectations from previous research.

This may be due to several factors that cannot be clearly quantified. Obviously, the adaptation of cultivars to their environment and their ability to thrive in such an environment over long time may play a significant factor in the measurement of cultivars, as well as the composition of the light spectrum and the size of the cultivar itself, where from a certain cultivar size onwards there is a significant shading of the lower green leaves in the case of directional light. This behaviour cannot be significantly detected, especially in young plants or plants with sparse density, where the leaves do not cause significant shading to lower positions. The theoretically calculated results in the case of the Ficus Benjamina cultivar shown in Table 5-2 and Table 5-3 in Chapter 5.4 indicate the ability of the plant to assimilate CO_2 at 0.307 [g · m^{-2} · h^{-1}] under illumination of 40% of the leaf area with a PPFD value of 300 and 60% of the leaf area with a PPFD value of 80, and at 0.150 [g · m^{-2} · h^{-1}] under illumination of 40% of the leaf area with a PPFD value of 100 and 60% of the leaf area with a PPFD value of 60. Practically, the measured results for the Ficus Benjamina cultivar shown in

Table 5-16 in Section 3.5 indicate the ability of the plant to assimilate CO_2 at 0.526 [$g \cdot m^{-2} \cdot h^{-1}$] under illumination at PPFD 139 at the top of the canopy and PPFD 19 below the lower canopy level, and at 0.421 [$g \cdot m^{-2} \cdot h^{-1}$] under illumination at PPFD 49 at the top of the canopy and PPFD 14 below the lower canopy level. The illumination levels for the practical measurement case are shown in Figure 5-15 and Figure 5-18 in Section 5.4

It can be concluded that the practical measurements yielded significantly more favourable results in terms of the plant's ability to assimilate CO_2 than the theoretical calculation based on foreign studies. Despite the fact that in both measured cases the overall values of illuminance expressed in PPFD were significantly lower, the actual plant efficiency measured was 0.526 [$g \cdot m^{-2} \cdot h^{-1}$] corresponding to 1.7 times the efficiency theoretically calculated 0.307 [$g \cdot m^{-2} \cdot h^{-1}$] based on measurements from other research. In the second case, at even worse illumination values, the actual measured plant efficiency was 0.421 [$g \cdot m^{-2} \cdot h^{-1}$] corresponding to 2.8 times the theoretically calculated efficiency of 0.150 [$g \cdot m^{-2} \cdot h^{-1}$]. This is a significant difference, and the reason for such a difference in plant efficiency seems to be in the degree of adaptation of the plant to the environment, its size and age, or other influences or combinations thereof.

These results obtained from practical measurements confirm the fact that this is a very young field of science, which is still relatively understudied and requires further intensive research for a more detailed understanding of the behaviour of plants in the indoor environment and their ability to influence the quality of the indoor environment.

5.7 Office environment from the perspective of CO_2 evolution during the working day

In order to potentially implement plants in the interior of the building in order to reduce the concentration of selected pollutants, especially CO_2, it is also necessary to provide measurements mapping trends from the point of view of the development of the CO_2 concentration in the actual office. A typical office can be ventilated either mechanically naturally by windows that are controlled by individual users, then mechanically by means of a constant supply of air using an air handling device and finally autonomously based on a CO_2 sensor that adjusts the amount of supplied air.

The space can also be ventilated by a combination of the above, i.e. by means of opening windows in combination with air conditioning equipment. Opening window ventilation is generally considered less economical due to significant heat losses, and for the purpose of large workplaces in administrative buildings, the option of ventilation using an air handling system combined with the ability of users to open windows is generally preferred. The impossibility of opening a window in the workplace can cause some workers to feel cramped, which can have a negative effect on their work performance, therefore it is recommended for architects to always leave openable windows in buildings in their design to ensure user comfort.

For the purposes of research on the development of CO_2 concentration during the working day in an office environment, the same room was chosen, which was considered in this research for the theoretical comparison of the equivalent efficiency of elimination methods in chapter 5.2 and for the measurement of lighting intensity in chapter 5.3. In addition, this is a room permanently mechanically ventilated using an air-conditioning device, where the proposed air exchange is 25 [$m^3 \cdot h^{-1} \cdot person^{-1}$], which corresponds to the valid technical regulations of the Czech Republic, and a total of 100 [$m^3 \cdot h^{-1}$] is supplied to the room. Measurements of the CO_2 concentration evolution in this environment were carried out for 5 working days during working hours. A Testo 400 instrument including a CO_2 probe was used to measure the concentration evolution, as described in Section 5.3. The CO_2 probe was placed in the indoor environment so that it was at least 2 m away from all permanent workplaces, air exhalations, opening windows and doors, to minimize unnecessary deviations during the measurement. The workstation closest to the CO_2 probe was unoccupied for a long period of time at the time of measurement. The sensor was placed at a height of 1.2 m above the floor. The location of the CO_2 probe in the office is shown in Figure 5-24.

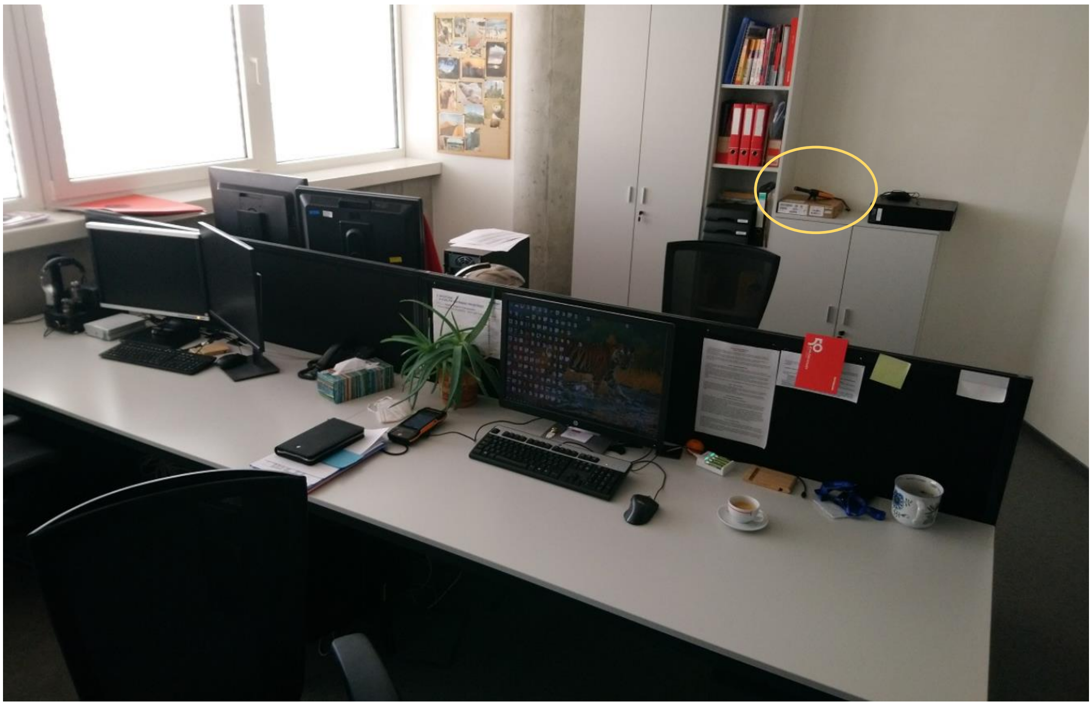


Figure 5-24 Measured office and location of CO_2 sensor in the room

CO_2 concentrations in the environment were measured at 15 s intervals, with sequential data storage. Staff presence was recorded manually, and each arrival and departure was recorded in writing. Any door opening longer than 180 seconds was also recorded, as was any window ventilation. The time interval monitored for the evolution of CO_2 concentration in the office was from 08:15 to 16:15, during which time the workers are working. Measurements were taken during 1 working week from Monday to Friday. Based on the measurements made on 22 March 2021 to 26 March 2021, the CO_2 concentration levels in the office environment were found to be highly variable throughout the day, mainly due to the different number of workers on different days and at different times, the measured values can be seen in Figure 5-25, Figure 5-26, Figure 5-27, Figure 5-28 and Figure 5-29.

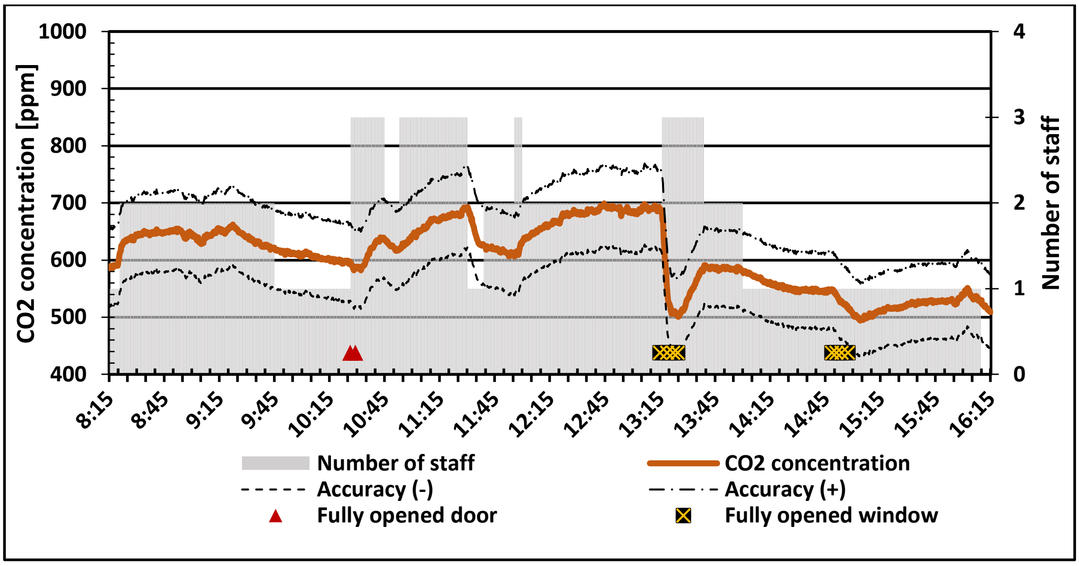


Figure 5-25 Evolution of CO_2 concentration in the measured environment on Monday 22.3.2021

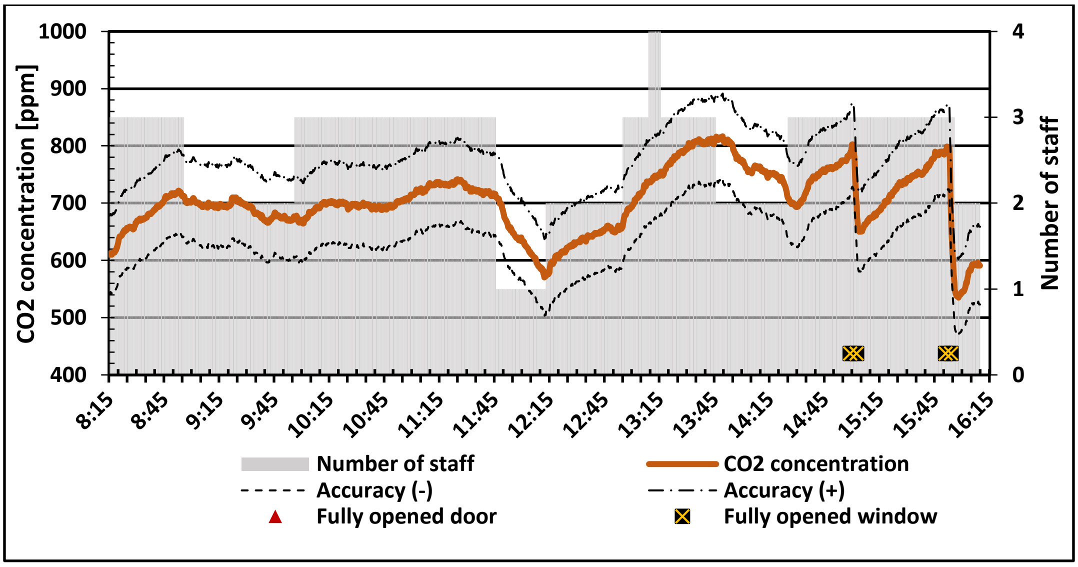


Figure 5-26 Evolution of CO_2 concentration in the measured environment on Tuesday 23.3.2021

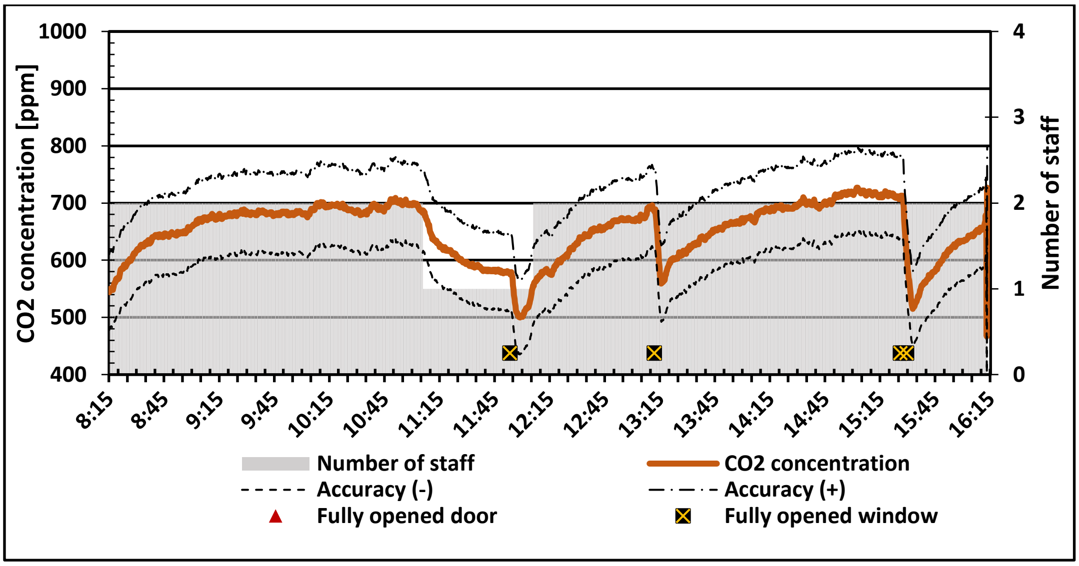


Figure 5-27 Evolution of CO_2 concentration in the measured environment on Wednesday 24.3.2021

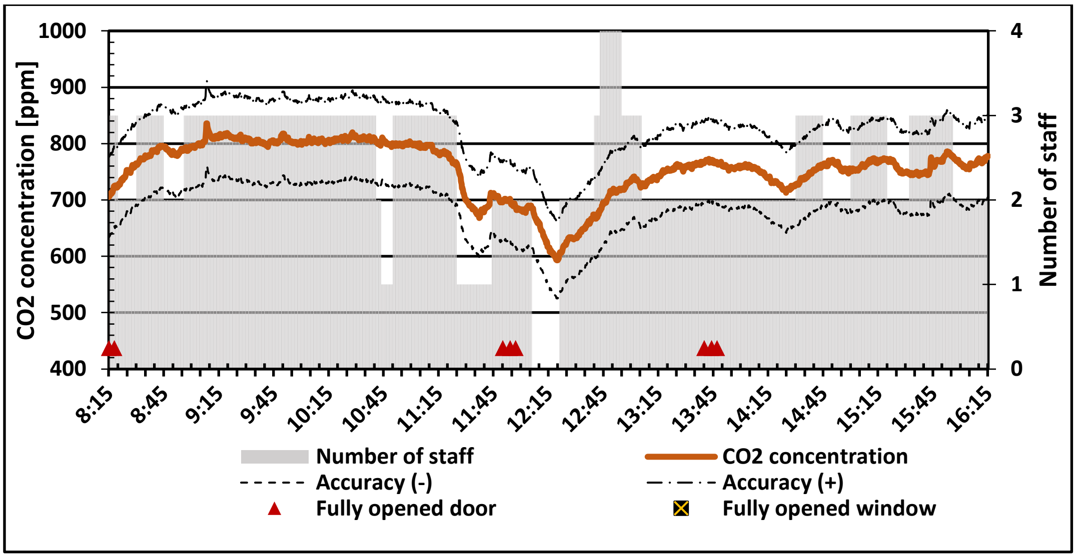


Figure 5-28 Evolution of CO_2 concentration in the measured environment on Thursday 25.3.2021

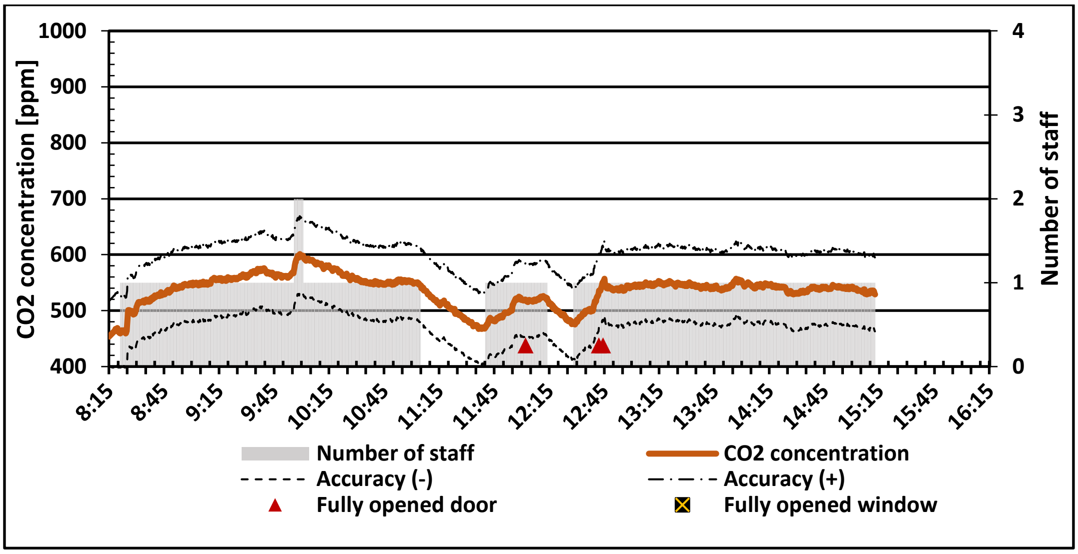


Figure 5-29 Evolution of CO_2 concentration in the measured environment on Friday 26.3.2021

From the Figure 5-25, Figure 5-26, Figure 5-27, Figure 5-28 and Figure 5-29 the presence of workers during the working hours 8:15 - 16:15 is captured, with the presence of workers being highly variable both within days of the week and within hours within a working day. It can be conveniently observed that while when 3 workers are present, the concentration is steady around 800 ppm (see Figure 5-28), when they are present most of the time, the CO_2 concentration is steady around 700 ppm (see Figure 5-27). The measurement also captured a situation where only 1 worker was present at the workplace most of the time, with the CO_2 concentration steady around 550 ppm (see Figure 5-29). With frequent changes in worker presence, the CO_2 concentration cannot be steady and significant differences within working hours are evident (see Figure 5-25, Figure 5-26). From the above measurement, it is also worth noting the effect of the open door to the office and the effect of temporary natural ventilation by opening a window. While a full opening of the door to the office from the corridor has no obvious significant impact on the change of the CO_2 concentration in the office (see Figure 5-25, Figure 5-28, Figure 5-29), a full opening of the window even for a few minutes has an absolutely major impact on the CO_2 concentration in the office (see Figure 5-26, Figure 5-27), where the CO_2 concentration drops by leaps and bounds to the concentration of the outside air. From the above measurements it is also possible to trace the tendency of the workers in the office to ventilate in the afternoon (see Figure 5-25, Figure 5-26, Figure 5-27), with the window being opened mainly at concentrations higher than 700 ppm, except for one case where the window was also opened at a concentration of around 550 ppm, but here it should be mentioned that this opening of the window was also preceded by a significant ventilation through the window, which started at a concentration of around 700 ppm (see Figure 5-25). Taking into account the actual development of the CO_2 concentration in a real office environment, the design of the implementation of plants in the indoor environment can be optimised appropriately. While regulations often consider a constant supply of fresh air throughout the operation, it turns out that even the ventilation itself can be suitably optimized. Ventilation control according to the instantaneous value of the CO_2 concentration in the indoor environment is offered, but this option is still considered as a slight overkill and, if applied, also requires a proper design of the control system and sizing of the corresponding air handling units, which must meet the requirements of variable operation.

It can also be seen from this measurement that individual users may have different working habits, e.g. time slots for lunch breaks, refreshment breaks. These can also influence the actual requirement for the amount of air currently supplied.

6. Discussion

Based on measurements, this thesis has confirmed the author's theoretical assumptions that the implementation of plants in the indoor environment can contribute positively to savings in building ventilation. The savings in building ventilation depend on the amount of green leaves, the type of applied cultivar, the intensity and type of lighting and other aspects such as temperature and humidity of the environment.

The individual objectives of the dissertation were fully achieved when the computational model for the theoretical comparison of the equivalent efficiency of individual elimination methods was established (see Chapter 5.1), followed by the theoretical comparison of the equivalent efficiency of individual elimination methods and the evaluation of the efficiency of experimental methods based on the theoretical calculation (see Chapter 5.2). Next, the procedures for the practical measurement of the elimination methods were established (see Chapter 5.3 and Chapter 5.4) and the efficiency of the experimental method was evaluated based on the practical measurement (see Chapter 5.5), and finally a comparison of the theoretical calculated results with the practical measurement was performed (see Chapter 5.6). Based on the results from provided measurements and calculations, there are set recommendations and conclusions for building operational measures.

In general, it can be said that the practical measurement of the effectiveness of selected cultivars of Ficus Benjamina and Aloe Vera generally surpassed previous foreign measurements. The increased efficiency of assimilation of these cultivars is attributed to the good adaptation of the plants to the given environment, because before the start of the measurements the plants had been in the same environment for a long time and were not exposed to any stress associated with e.g. transplanting and changing the substrate, a significant change in the habitat, drying or, conversely, overwetting the substrate. In conclusion, it can therefore be stated that the constant placement of suitable cultivars in the internal environment of buildings can be appropriate in ensuring proper lighting, natural lighting is recommended. The application of cultivars to the indoor environment of buildings, where the plants would not be able to reach the light compensation point under local lighting and would thus suffer in the long term, appears to be inappropriate. Such spaces are especially long corridors without access to natural light. Artificial lighting alone may also not be a sufficient light source for plants if it is not adequately designed for it.

However, for a better and deeper understanding of the issue, it is necessary to carry out further research, calculations and work, which can again significantly contribute to the understanding of the behavior of plants in the internal environment of buildings. Research in this area must be seen as essential for the comfortable living of people in buildings for the next century and decades to come, and any contribution in research in this area must be seen as extraordinarily beneficial, as it will have an impact on every inhabitant of planet Earth.

7. Conclussions

Based on the theoretical calculations and practical measurements made, it can be concluded that plants can positively influence the quality of the indoor environment of buildings and lead to savings in the field of building ventilation, and the research has achieved favourable results confirming that the implementation of plants in the indoor environment of buildings can be favourable in terms of operating costs.

Practical measurements have shown that the major factor for plant efficiency in terms of CO_2 elimination in the indoor environment is lighting, where the ability of the plant to bind CO_2 decreases significantly with decreasing PPFD intensity. Therefore, it is suggested that cultivars should be placed in well-lit areas of the indoor environment if possible, with proximity to windows with sunlight or supplemented with artificial lighting as a suitable operational measure. It has been shown by research and measurements that conventional indoor lighting, which is sufficient for office work purposes and meets the national regulations for minimum illuminance in lm (lumens) in the plane of work (500 lm), is not sufficient to overcome the breakpoint of the plants and therefore, at such a level, the plants are not significantly able to assimilate CO_2. In the indoor environment, artificial lighting for plants shall be specifically designed for the plants to provide the required illuminance in PPFD units at leaf level. It is advisable to select lighting with a spectral rendering approaching that of sunlight, and at the same time lighting that has the correct efficiency for the purpose of the building operation, e.g. LED sources (light-emitting diode) commonly exceed 100 [$\mathrm{lm} \cdot \mathrm{W}^{-1}$] already and LED applications exceeding 300 [$\mathrm{lm} \cdot \mathrm{W}^{-1}$] are expected in the near future.

The theoretical benefits and facts in field of study

Research has also shown the necessity to take into account the degree of adaptation of the plant to the environment. While other research has worked with plants freshly transplanted or newly brought into a new test environment, this research worked with plants fully adapted and long established in their habitats. Fully adapted and thriving plants were shown to be able to assimilate CO_2 and recruit more efficiently. This fact is one possible explanation for the more favorable results of CO_2 assimilation ability of the selected cultivars measured in this research compared to foreign research. Furthermore, when selecting cultivars for indoor environments, it is suggested that cultivars with a lower light breakpoint for CO_2 assimilation should be selected to ensure that the cultivars thrive appropriately. Cultivars from the CAM group may be suitable, but CO_2 assimilation is significantly lower in the indoor environment. It is also important for the building operator to take a closer look and understand user habits.

The benefits for practice

The main benefit for practice is the verification of the functionality of the experimental method consisting in the implementation of plants in the indoor environment, which can achieve savings in the field of operating costs of building operations. Although the expected savings are minimal from the point of view of building operation management, in the long term and considering the total volume of ventilated air in buildings, the savings can be significant. The real potential of this research can be expected in the future, in the horizon of several decades, due to climate change and a significant increase in the concentration of CO_2 in the supply air. The issue is directly related to the field of operation and building management in innovation implementation.

If the building management decides to try this experimental method, it is necessary to install a CO_2 sensor in the indoor environment to regulate the amount of supply and extract air. Together with the potential variability of the system, where, compared to conventional systems operating with a steady supply of a constant amount of air to the indoor environment or to individual rooms, the air supply will only be required based on the currently measured CO_2 concentration, the HVAC (Heating, ventilation and air conditioning) unit must also be adapted and properly designed to cover operational peaks, but at the same time have sufficient efficiency even at part loads in the lower tens of percentages. Such partial utilization of HVAC units can be expected, for example, during nighttime hours when office buildings are unoccupied or during daytime hours when residential buildings are unoccupied. It is essential that the overall ventilation concept is appropriately configured and coordinated.

Together with the installed CO_2 sensors in the indoor environment, it is necessary to check the accuracy of the measurements and to calibrate the sensors regularly in order to achieve the desired indoor environmental quality. Without properly calibrated sensors and without properly adjusted control systems, satisfactory indoor environmental results cannot be expected. The advantage of systems working on the basis of an instantaneous evaluation of the current CO_2 concentration in the indoor environment is in their greater variability or the possibility to work with an instantaneous present indicator. As an example, the frequent complication of office buildings in the summer period is precisely on those days when the outside temperatures approach the maximum and are at the limit of the design conditions of the air handling units and cooling systems. When conventional systems are used with a constant air supply, HVAC and refrigeration unit failures and subsequent shutdowns often occur because the units are not able to meet the required amount of cool fresh air in an instantaneous time. When systems operating with instantaneous CO_2 concentration are used together with plant implementation, smaller start-up peaks can be expected and therefore greater system stability can be expected.

It can be assumed that the current ventilation method based on supply air from the outside will no longer be sufficient to ensure sufficient indoor air quality, especially when considering occupations with high indoor air quality requirements at indoor CO_2 concentrations below 600 ppm. This is a major problem that will affect every building user and it is very likely that fresh clean air will no longer be the standard for everyone in developed countries, as it was and still is today. The implementation of plants in the indoor environment of buildings, or the creation of entire greenhouse systems to support building ventilation, may be a partial solution and may contribute to solving this issue from a global perspective. A completely non-negligible aspect is also the prediction of the evolution of the operating costs for heating and cooling of buildings, which has been mentioned in this research. Due to a certain global warming trend, it is expected that buildings within all world capitals will be forced to spend more energy on cooling buildings. This will be partly compensated by savings on heating of buildings, as according to international studies the global warming trend will be directly affected by milder winters.

The benefits for education and training

The measurements and calculations that are presented in the present paper enable the transfer scientific knowledges to the teaching of student subjects dealing with the quality of the internal environment of buildings and the application of plants to the internal environment. It was confirmed that the application of plants in an indoor environment requires a quality source of lighting. This can be solved either by placing the plants directly near the opening fillings, ideally with incident sunlight, or by adding additional lighting intended for the plants. An important role of the science is also the correct choice of cultivars, where in some places CAM type of plants can be appropriately used, which have the potential to survive even in worse conditions with less maintenance. The present paper is also shows that plants in the indoor environment of buildings can positively influence the quality of the indoor environment from the point of view of CO_2 and VOC concentration. The increasing trend of the construction of all-glass facades of buildings directly affects the placement of plants in the interior environment of buildings. Therefore, the solved problem is expected to be further elaborated and researched more closely in study subjects, when the facts obtained from applied research will be able to be taught later. In the near future, the issue has the potential to create its own field, which will have a significant contribution to the practical environment. This is a cross-cutting issue across several fields, especially the technical, natural science and health fields.

The potential of other research activities

In this research, the effect and difference in plant efficiency in CO_2 fixation capacity based on light source was not considered. Due to the fact that plants respond differently to different parts of the light spectrum, it is suggested that further research be done on the dependence of CO_2 assimilation by the plant on the basis of source, where it is expected that while the natural spectrum from sunlight is optimal for the plant, the spectrum from artificial lighting may only approximate the solar spectrum, decreasing or potentially increasing the actual plant efficiency based on the selected cultivar. This fact may play an important role in assessing the energy efficiency of artificial lighting fixtures. Nowadays, there are already LED technologies available that approximate the real spectrum and at the same time already offer efficiencies in excess of 100 $[\mathrm{lm} \cdot \mathrm{W}^{-1}]$ of delivered energy. If the right spectrum is chosen for a particular cultivar, further optimisation can again take place.

This research captured the evolution of CO_2 concentration in a selected office, in a real office building environment, by means of practical measurements. From the measurements it was clear that user habits cannot be ignored and, on the contrary, further savings in building ventilation can be achieved by respecting them. Basic user habits include in particular lunch breaks, coffee breaks, but also regular arrivals of users to the buildings – for example, regular arrival of employees to the offices or departure and arrival of people to or from the residential buildings. These breaks can be observed to have a certain regularity and can also be adapted to the ventilation concept of the building, whereby it is not necessary to maintain a very high indoor environmental quality during periods of absence. It should be mentioned here that methods such as free-cooling carried out overnight during the summer months can in turn contribute to operational savings, so again everything must be properly aligned in terms of economic efficiency.

The research shows that the issue of implementing plants in the indoor environment of buildings has not been fully explored yet, despite the fact that it can contribute to operational savings in combination with operational measures. Therefore, it can be recommended that further advanced research should be performed to better understand the behaviour of implemented greenery in the indoor environment. In particular, it should be mentioned that the end of CO_2 in the Earth's atmosphere is currently on an increasing trend and new technologies will be necessary. In order to ensure the appropriate quality of the indoor environment, it will most likely be necessary to implement separate mechanisms that will also work with the implementation of greenery to improve the quality of the supply air. Furthermore, with the development of more advanced technologies and the desire to reach areas that are not easily ventilated, or places without ventilation, it will also be necessary to come up with new solutions. Such areas may include, for example, buildings below the water surface (e.g. at the bottom of the sea) or deep underground without ventilation. On the other hand, buildings without complete ventilation capability may include in particular facilities and buildings that may be located on foreign space bodies, in particular on the Moon and nearby planets, which can be expected to be progressively inhabited in the near future, and where it will be necessary to provide technologies that produce air quality at least comparable to the Earth's atmosphere. Working with plants in this area is absolutely essential for ambitious, large-scale projects, and space agencies such as NASA (The National Aeronautics and Space Administration) and ESA (The European Space Agency) have been working on research in similar areas for a long time, which only confirms and underlines the importance of the subject under study.

In further research, it is appropriate to focus on finding so-called supercultivars and combinations of supercultivars, where it can be expected that, due to the initial research, a sufficient number of plants found on planet Earth have not yet been explored, and therefore other plants can be found that can be surprising with their survival abilities and characteristics and provide even more suitable results. The properties of supercultivars may include, for example, their low breakpoint in terms of CO_2 assimilation, as well as their resistance to freezing or toxicity and others. Taking into account the unsatisfactory development of CO_2 in the Earth's atmosphere, where the CO_2 concentration in the supply air is expected to be around 670 ppm by the 2100 year, the issue of finding alternative and experimental ways of achieving good indoor air quality is very important.

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List of Figures

List of Tables

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