Acta Polytechnica **61**(5):617–623, 2021
https://doi.org/10.14311/AP.2021.61.0617

ON REDUCING CO_2 CONCENTRATION IN BUILDINGS BY USING PLANTS

Ondřej Franek*, Čeněk Jarský

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Construction Technology, Thákurova 7, 160 00 Prague, Czech Republic

* corresponding author: ondrej.franek@fsv.cvut.cz

Abstract. The article deals with the implementation of plants in the indoor environment of buildings to reduce the concentration of CO_2. Based on a specified model representing the internal environment of an office space, it was studied whether the requirement for the total amount of ventilated air could be reduced by using plants, thereby achieving savings of operating costs in the building ventilation sector. The present research describes the effect of plant implementation according to different levels of CO_2 concentration of the supply air, specifically with values of 410 ppm corresponding to the year 2020, 550 ppm to the year 2050 and 670 ppm to the year 2100, as well as according to different levels of CO_2 concentration in the indoor environment, namely 1000 ppm and 1500 ppm, the illumination of plants in the indoor environment is constant in the model, PPFD equals to 200 µmol m^{-2} s^{-1}. Based on the computational model, it was found that the implemented plants can positively influence the requirement for the total amount of ventilated air, the most significant effect is in the case of a low indoor environment quality, with the CO_2 concentration of 1500 ppm, and a high supply air quality 410ṗpm. The simulation also showed that compared to 2020, by the year 2100, it will be necessary to increase the ventilation of the indoor environment by 25.1 % to ensure the same quality of the indoor environment.

Keywords: Carbon dioxide, climate change, indoor greening, indoor air quality, building ventilation.

1. Introduction

Building's ventilation is essential for maintaining the quality of the indoor environment, especially with regard to the current concentration of CO_2. It is known that with an increased amount of CO_2 concentrations, there is a significant deterioration of work efficiency [1, 2]. The most significant impact of the high concentration of CO_2 is on the work performance that is directly associated with the worker's brain concentration, such as initiative and strategic decision-making. For these activities, it is absolutely essential to keep the CO_2 concentration ideally between 600–1000 ppm [3, 4], whereas at significantly higher concentrations, around 2500 ppm, the concentration of workers is significantly reduced and their ability to work in these areas can be described as insufficient and non-functional [1].

For these reasons, it is necessary to keep the CO_2 concentration in the workplace within the acceptable limits, which is ensured by the supply of outside air with a low concentration of CO_2 to the indoor environment of buildings. However, the outdoor concentration of CO_2 has increased significantly during the last century. In the years 1900–2000, the concentration ranged from 280 to 400 ppm, since 2000, values exceeding 400 ppm are common [5] and today, the outdoor concentration of CO_2 is typically around 410 ppm [6]. Based on the performed studies, it is expected that the outdoor concentration of CO_2 will continue to rise, it is estimated to reach 550 ppm in the year 2050, and 670 ppm in 2100 [7, 8]. Based on the performed studies, it is assumed that this finding raises a potential problem in the future with maintaining the required quality of the indoor environment in terms of CO_2 concentration with an economic sustainability of operation, especially in situations with a requirement for a high quality indoor environment. Of the total energy consumption for the operation of office buildings today, approximately 40 % is spent on the treatment of ventilated air [9].

An interesting solution may be the implementation of green plants in the indoor environment of buildings, in order to passively improve the air quality and thus reduce the total amount of air supplied to the indoor environment of the building, and ideally, for the maximum degree of optimization and prevention of shortcomings of the design itself [10]. It has previously been shown that the implementation of greenery can have a positive effect on indoor humidity, while it can also have a positive effect on the reduction of CO_2 concentration in naturally ventilated buildings [11]. The implementation of plants in the indoor environment is fundamentally affected by the degree of illumination, namely sufficient photosynthetic photon flux density (PPFD). In an indoor environment, PPFDs less than 10 µmol m^{-2} s^{-1} can be considered as low light levels, PPFD values around 50 µmol m^{-2} s^{-1} can be considered as high light levels [11].

With the help of light sources, even very high levels of illumination can be achieved in the indoor envi-

Cultivar	LCP [μmol m^{-2} s^{-1}]	Cultivar metabolism	Net CO_2 assimilation [g h^{-1} m^{-2}]
Hedera helix	30.9	C3	0.998
Spathiphyllum wallissii Verdi	20.1	C3	0.325

Table 1. Net CO_2 assimilation per m^2 of plant's leaf with PPFD 200 μmol m^{-2} s^{-1} [12].

ronment, even higher than 200 μmol m^{-2} s^{-1}. The design of the light source should consider the area that it should reliably illuminate. The basic possibilities of lighting sources include LED, PAR Source or Cycloptics technologies [12].

LED lamps are distinguished by their ability to illuminate a smaller area intensely, however, they are not suitable for illuminating larger areas with only one source and must comprise several smaller sources so as to cover the entire area addressed. Cycloptics sources can illuminate a much larger area from a single luminaire with a similar power to approximately same extent, their disadvantage is that their local intensity is lower. A certain compromise are PAR sources, which, at a similar power, have approximately half the local intensity as compared to LED sources, but at the same time, slightly better coverage in the area [13]. In the stage of designing luminaires, it must also be ensured that the leaves are not overburdened, especially by the heat radiated from the light reflector, and in the case of designing LED lighting, also take into account local overexposure, which could result in the gradual death of the plant [14].

When selecting the appropriate plants for the indoor environment, it is necessary to monitor the light compensation point (LCP), plants with a very low LCP are typically Hedera helix with LCP 30.9 μmol m^{-2} s^{-1} and Spathiphyllum wallissii Verdi with LCP 20.1 μmol m^{-2} s^{-1} [12]. It can clearly be seen from Table 1 that at PPFD values of 200 μmol m^{-2} s^{-1}, Hedera helix is able to assimilate 0.998 g h^{-1} m^{-2} of CO_2 and Spathiphyllum wallissii Verdi assimilates 0.325 g h^{-1} m^{-2} of CO_2 [12]. The above ability of plants to assimilate CO_2 from the indoor environment applies to an ambient temperature of 25°C, a relative humidity of 35–45 % and a CO_2 concentration of 400–450 ppm. It can be assumed that with increasing CO_2 concentration in the indoor environment, the ability of plants to assimilate CO_2 also increases, but it is fundamentally increasing with the rate of PPFD. For this reason, the effect of a high concentration of CO_2 on the ability to assimilate CO_2 by a plant can be neglected in the indoor environment [12]. The most important producers of CO_2 in the indoor environment are the users themselves (i. e., people), who produce approximately 31.5 g h^{-1} person of CO_2 during administrative activities [15].

2. Materials and methods

2.1. Method description

To determine the theoretical influence of green plants implemented in the indoor environment on the total amount of supply air from the outdoor environment, a basic model of an office room was defined. Before starting the simulation, all internal parameters of the indoor environment that are necessary for determining the ability to reduce CO_2 by the plant are defined. The methodology specifically examines the amount of the total air supplied for different combinations of situations depending on the presence of plants and the quality of the supply air. Subsequently, based on the simulation, it determines the differences in the total requirement for the amount of air supplied to the indoor environment depending on the presence of a defined number of plants and a defined quality of indoor and outdoor environment in terms of a mass concentration of CO_2. The simulation clearly shows the differences between the individual situations and based on this, evaluations can be made from the point of view of plant implementation efficiency.

2.2. Model description

An office room with a total area of 24.1 m^2, with a height of 3.1 m and a volume of 74.7 m^3 was chosen as a model environment for simulating the development of CO_2 concentration. For the purposes of the simulation, it is assumed that this room has a forced ventilation by a central ventilation system, while the amount of supply air is controlled according to the current CO_2 concentration in the room, based on the CO_2 concentration sensor. The room has 3 permanent posts, occupied by an administrative staff from 8:00 to 16:00. For the purposes of the model, 2 investigated conditions are considered from the point of view of the maximum permissible concentration. The first limit state specifies the maximum concentration of CO_2 in the indoor environment to be 1000 ppm, which is generally considered as acceptable for an administrative work. The second limit state specifies the maximum concentration of CO_2 in the indoor environment to be 1500 ppm, this concentration is considered as the maximum permissible from the point of view of the ability to perform administrative activities. At the beginning of the working hours, an initial concentration corresponding to the set modelling limit is considered.

The temperature of the indoor environment in office buildings can generally be considered stable, for the

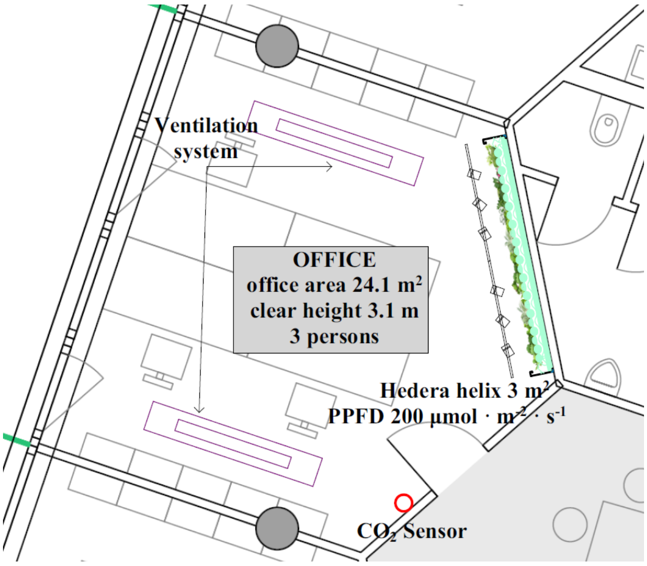

FIGURE 1. Scheme of model environment.

purposes of the model environment, the temperature is considered in the range of 19–25°C, the relative humidity of the indoor environment is considered to be 35 % to 55 %.

Atmospheric pressure is set at 101.3 kPa. The illumination of the implemented plants is considered at the PPFD value of 200 µmol m^{-2} s^{-1}, the simulation assumes the location of the Hedera helix plant, which under these conditions is able to reduce CO_2 value by approximately 0.998 g h^{-1} m^{-2}, the location of the 3 m^2 of green leaves of this plant is considered, which corresponds to a 1 m^2 sheet per 1 administrative worker. A schematic representation of the model environment can be seen in Fig. 1.

The supply of air to the indoor environment is considered by means of air distribution, while for the purposes of modelling, the variable values of the quality of the supply air from the outdoor environment are considered according to the expected development of CO_2 concentration in the Earth's atmosphere. A value of 410 ppm is considered for the year 2021, 550 ppm is considered for the year 2050 and 670 ppm is considered for the year 2100.

Local negative influences on the supply air are neglected for the purposes of the modelling, such influences, in the real environment, can occur especially in cases where the air intake from the outside environment is near traffic routes, or located in polluted industrial zones. Air penetration due to leaks in the building envelope or office operations is also neglected.

2.3. COMPUTATIONAL RELATIONS

Basic computational relations are used to simulate the development of the internal environment. To determine

$$Q_{sup} = \frac{V_{in}}{t} \times \left(\frac{C_{req} - C_{in}}{C_{out} - C_{in}}\right) \tag{1}$$

Where Q_{sup} [m^3 h^{-1}] is the requirement for the amount of air supplied to the office, V_{in} [m^3] is the volume of the air in the room area, t [h] is a defined period of time, C_{req} [g m^{-3}] is the desired pollutant concentration, where $C_{req} \in (C_{out}, C_{in})$, C_{in} [g m^{-3}] is the current pollutant concentration inside the room area, C_{out} [g m^{-3}] is the pollutant concentration of the supply air.

To determine the actual concentration of C_{in} in the indoor environment, it is necessary to proceed from the relation 2:

$$C_{in} = m_{ori} + m_{per} - m_{pl} - m_{vent} \tag{2}$$

Where C_{in} [g m^{-3}] is the current pollutant concentration inside the room area, m_{ori} [g m^{-3}] is the initial indoor pollutant mass, m_{per} [g m^{-3}] is the indoor pollutant mass excess due to a workers' activity, m_{pl} [g m^{-3}] is the indoor pollutant mass loss due to the plant reduction, m_{pl} [g m^{-3}] is the indoor pollutant mass loss due to the air ventilation.

To express the photosynthetic reaction in grams, the relation 3 is used:

$$A_{Ph_g} = A_{Ph_{mol}} \times M_{CO_2} \times 3600 \tag{3}$$

Where A_{Ph_g} [g m^{-2} h^{-1}] and $A_{Ph_{mol}}$ [µmol m^{-2} s^{-1}] express the level of pure CO_2 assimilation by 1 m^2 of green leaves, M_{CO_2} [g µmol^{-1}] is the molar mass of CO_2.

3. RESULTS

3.1. SIMULATION RESULTS

Based on the performed computational simulation, it was proved that to ensure the same level of CO_2 concentration in the indoor environment, the concentration of CO_2 of the supply air from the outdoor environment has a very significant effect.

C_{req} [ppm]	C_{out} [ppm]	Rate of ventilation air flow for office [$m^3\,h^{-1}$] without plants	with plants and PPFD 200 [$\mu mol\,m^{-2}\,s^{-1}$]	Difference [%]
1000	670	50.627	50.462	0.33
1000	550	45.315	45.135	0.40
1000	410	40.373	40.186	0.46
1500	670	34.014	33.828	0.55
1500	550	31.531	31.347	0.58
1500	410	29.056	28.877	0.62

Table 2. The resulting simulation values according to the CO_2 concentration in the supply air, the CO_2 concentration required and the presence of plants..

The effect of the implementation of 1 m^2 of plants per 1 person in the simulation area has an interesting effect. A total of 3 m^2 of green leaves slightly favourably affects the values of the CO_2 concentration in the room and is able to achieve the effect of reducing the required amount of supply air, although only in tenths of a percent. The specific results of the performed simulation with various required CO_2 concentrations in the room, specific levels of CO_2 outdoor concentration and the implementation of plants are shown in Tab. 2.

From Tab. 2 it is evident that in order to maintain a concentration of 1000 ppm in the indoor environment, it should be supplied with 40.3 $m^3\,h^{-1}$ to the simulation area without any plant implementation for a CO_2 concentration of 410 ppm in the supply air, 45.3 $m^3\,h^{-1}$ in the case of a supply air with a concentration of 550 ppm and 50.6 $m^3\,h^{-1}$ in the case of a supply air with a concentration of 670 ppm.

To maintain a concentration of 1500 ppm in the indoor environment, a supply of 29.1 $m^3\,h^{-1}$ for a CO_2 concentration of 410 ppm in the supply air is needed, 31.5 $m^3\,h^{-1}$ for a CO_2 concentration of 550 ppm and 34.0 $m^3\,h^{-1}$ for a CO_2 concentration of 670 ppm . The implementation of plants in the indoor environment with a total amount of 3 m^2 of green leaves (this corresponds to 1 m^2 of green leaves per person) has, from the point of view of the total requirement for the amount of supplied air, only a minimal effect in the order of tenths of a percent.

The most significant effect of plants is observable when the simulation area is less ventilated (i. e. at higher CO_2 concentrations in the indoor environment). In the environment with the specified CO_2 concentration limit of 1000 ppm, the most significant effect of plants is observable in the case of air supplied from the outside environment with a CO_2 concentration of 410 ppm, the implementation of plants can reduce the demand for air supply by 0.46 %. Similarly, the effect of plants is observable in an environment with a CO_2 concentration limit of 1500 ppm, where the implementation of plants in the case of supply air from the outside environment with a CO_2 concentration of 410 ppm can reduce the demand for air supply by 0.62 %. As the concentration of CO_2 in the supply air increases, more air must be supplied to the model environment, and the effect of a constant amount of green leaves capable of a photosynthetic reaction decreases proportionally.

3.2. Influence of environmental concentration

The present simulation describes basic theoretical assumption that a building operation with increasing CO_2 concentration in the outdoor environment requires larger amount of ventilated air to the indoor environment to ensure the required concentrations of CO_2 in the indoor environment. Such a trend is evident from Fig. 2. From Fig. 2 it can be seen that while in the year 2021, it is sufficient to supply 40.4 $m^3\,h^{-1}$ from the outdoor environment to maintain the concentration of the indoor environment 1000 ppm CO_2, by the year 2050, it will increase to 45.3 $m^3\,h^{-1}$, which represents an increase by 12.1 %, by the year 2100, it will increase to 50.6 $m^3\,h^{-1}$, which represents an increase, when compared to the year 2021, by 25.2 %. Similarly, the trend applies to maintaining the CO_2 concentration of the indoor environment of 1500 ppm. In the year 2021, it is necessary to supply 29.1 $m^3\,h^{-1}$, 31.5 $m^3\,h^{-1}$ in the year 2050, which represents an 8.2 % increase, and 34.0 $m^3\,h^{-1}$ in the year 2100, which represents a 16.8 % increase, when compared to the year 2021.

3.3. Influence of plant implementation into the indoor environment

The results of the simulation showed that the implementation of living plants in the indoor environment can favourably affect the concentration of CO_2 in the indoor environment, although the amount of green leaf area and lighting level defined in the simulation are only in the order of tenths of percent. The potential for reducing the supply air demand is shown in Fig. 3 and Fig. 4.

It is clear from Fig. 3 that at the given parameters of the model environment, which is the implementation of 1 m^2 of plant per 1 worker and with the lighting values of this plant being PPFD 200 $\mu mol\,m^{-2}\,s^{-1}$,

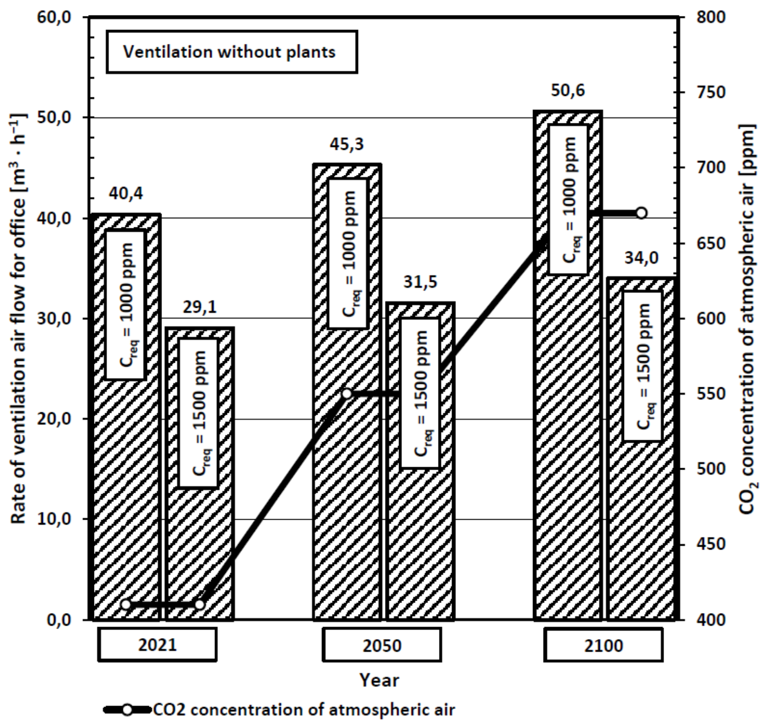

FIGURE 2. Development of the amount of ventilated air depending on the concentration of CO_2 in the supply air and according to the required concentration of CO_2 in the indoor environment.

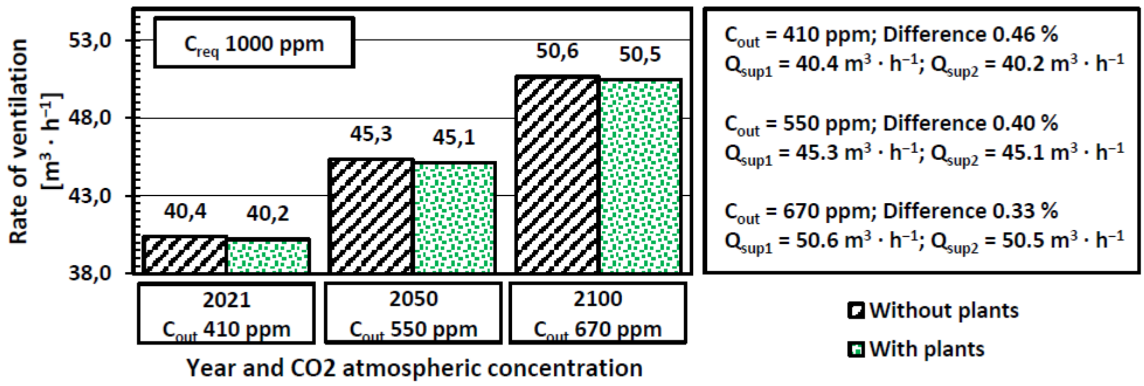

FIGURE 3. Influence of the implementation of plants into the indoor environment on the total amount of ventilated air with the maximum C_{req} concentration of 1000 ppm.

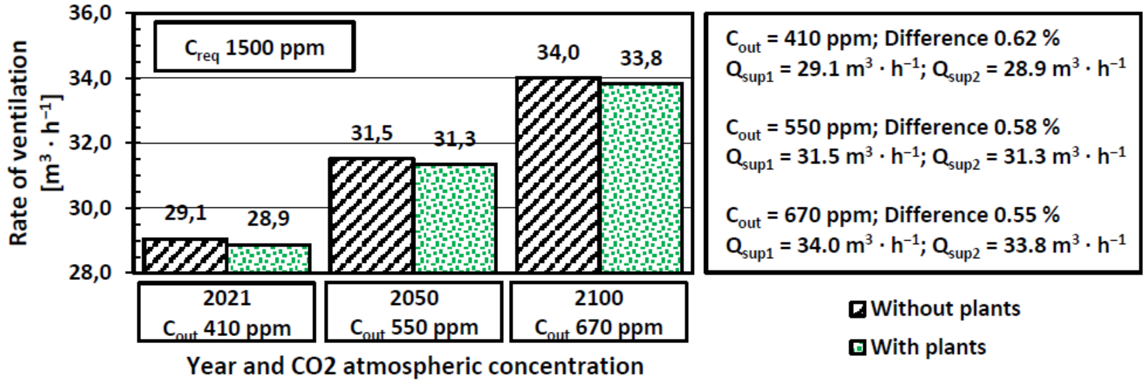

FIGURE 4. Influence of the implementation of plants into the indoor environment on the total amount of ventilated air with the maximum C_{req} concentration of 1500 ppm.

the amount of supplied air to the office environment slightly decreases. At the required limit concentration of 1000 ppm, in the case of an outdoor air with a CO_2 concentration of 410 ppm, the plant implementation is able to reduce the supply air requirement by 0.46 %, at an external CO_2 concentration of 550 ppm, the supply air requirement is reduced by 0.40 % and at an external CO_2 concentration of 670 ppm, the requirement is reduced by 0.33 %. It is obvious that in general, with the decreasing rate of indoor air exchange, the relative efficiency of the implemented plants increases. If the limit concentration of CO_2 in the indoor environment is set at 1500 ppm, it is generally sufficient to ventilate less to achieve the desired concentration and thus increase the efficiency of the implemented plants. From Fig. 4, it can be seen that to maintain a CO_2 concentration of 1500 ppm in the indoor environment, the plant implementation can reduce the supply air requirement by 0.62 % for 410 ppm of CO_2 in the supply air, by 0.58 % for 550 ppm of CO_2 in the supply air and by 0.55 % in the case of a concentration of 670 ppm of CO_2 in the supply air.

4. Discussion

The simulation theoretically showed a trend that with increasing concentration of CO_2 in the outdoor environment, it will be necessary to ventilate buildings with more air to ensure the required concentration of CO_2 in the indoor environment. The results show that these are very significant differences that may have a significant impact on the operating costs of buildings in the future. Almost alarming is the fact that in the year 2100, it will be necessary to increase the ventilation of the air in the indoor environment by 25 ppm to maintain a CO_2 concentrations of 1000 ppm as compared to the year 2021. It is necessary to assume that to ensure a higher quality of the indoor environment such as a lower concentration CO_2 (e. g. 800 ppm), it will be necessary to supply even more outside air, while the percentage difference will increase even further. The implementation of plants in the indoor environment of buildings has the potential to slightly reduce the concentration of CO_2 in the indoor environment, but it is affected by many paremeters. The most important parameters include the total possible area of greenery implemented in the indoor environment and ensuring a sufficient lighting, with the area of green leaves in the indoor environment increasing, the total amount of assimilated CO_2 in the indoor environment increases proportionally.

From the point of view of the development of CO_2 in the external environment, the question also arises as to how spaces with a requirement for a high quality of the indoor environment (i. e., with a requirement for a low CO_2 concentration such as 600 ppm) will be ventilated. It follows from the basic limiting conditions of the modelling that if the concentration of CO_2 in the air supplied to the indoor environment is higher than the required concentration, the required concentration cannot be achieved and the environment will not meet the quality requirements.

Another issue that needs to be addressed is how to solve plant lighting to ensure a maximum efficiency of the luminaire from the point of view of PPFD while minimizing the cost of operating such a lighting source.

5. Conclusion

Based on the simulation, it was theoretically demonstrated that plants in indoor conditions can contribute to CO_2 reduction and slightly reduce the requirement for the total amount of ventilated air, if the ventilation is controlled by a sensor based on the current CO_2 concentration in the room. The most significant share of plants in reducing the demand is evident at lower ventilation levels, i. e., in the case of a low CO_2 concentration in the supply air – C_{out} 410 ppm, or at a lower quality of the indoor environment – C_{req} 1500 ppm. The increasing concentration of CO_2 in the supply air, C_{out} 550 ppm and C_{out} 670 ppm, results in a deterioration of the overall efficiency of the implemented plants, their effect on the total amount of supply air is minimized with a deteriorating quality of the supplied air. The same applies to increasing the requirement for the quality of the indoor environment such as for a lower required C_{req} concentration of 1000 ppm, where the percentage efficiency of the plants in the simulated environment is considerably lesser than in the case of the required CO_2 concentration C_{req} 1500 ppm. For a higher level of CO_2 assimilation by plants in the indoor environment, it is necessary to adjust the input parameters, especially lighting conditions (PPFD $> 200\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) or increase the overall amount of greenery implemented in the indoor environment. Although the simulation theoretically shows the minimal impact of plants in the indoor environment of buildings from the point of view of ventilation, the ability to generally reduce the quantity requirement by tenths of percent in the long run is very important in terms of potential operational savings in ventilation. On a global scale, this is an important area that can be slightly offset by the ever-increasing amount of air supplied to the indoor environment of buildings to ensure the same quality of the indoor environment. It is appropriate to research the implementation of greenery in the indoor environment of buildings, to deal with their ability to assimilate CO_2, especially with regard to the potential for significant savings on a global scale and try to find optimal options for the implementation of plants in the indoor environment.

Acknowledgements

The authors would like to express their gratitude to the Czech Technical University in Prague. This study was financially supported by the grant SGS21/007/OHK1/1T/11 of the Czech Technical University in Prague.

References

[1] U. Satish, M. J. Mendell, K. Shekhar, et al. Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives* **120**(12):1671–1677, 2012. https://doi.org/10.1289/ehp.1104789.

[2] J. G. Allen, P. MacNaughton, U. Satish, et al. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives* **124**(6):805–812, 2016. https://doi.org/10.1289/ehp.1510037.

[3] C.-Y. Lu, J.-M. Lin, Y.-Y. Chen, Y.-C. Chen. Building-related symptoms among office employees associated with indoor carbon dioxide and total volatile organic compounds. *International Journal of Environmental Research and Public Health* **12**(6):5833–5845, 2015. https://doi.org/10.3390/ijerph120605833.

[4] D.-H. Tsai, J.-S. Lin, C.-C. Chan. Office workers' sick building syndrome and indoor carbon dioxide concentrations. *Journal of Occupational and Environmental Hygiene* **9**(5):345–351, 2012. https://doi.org/10.1080/15459624.2012.675291.

[5] L.-G. Hersoug, A. Sjödin, A. Astrup. A proposed potential role for increasing atmospheric CO_2 as a promoter of weight gain and obesity. *Nutrition and Diabetes* **2**(3):e31, 2012. https://doi.org/10.1038/nutd.2012.2.

[6] NOAA: National Oceanic and Atmospheric Administration. Global Monitoring Laboratory: Earth system research laboratories. NOAA/GML and scripps institution of oceanography, 2021. [2021-04-07], https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html.

[7] B. I. McNeil, T. P. Sasse. Future ocean hypercapnia driven by anthropogenic amplification of the natural CO_2 cycle. *Nature* **529**(7586):383–386, 2016. https://doi.org/10.1038/nature16156.

[8] C. B. Field, V. R. Barros, D. J. Dokken, et al. *Climate Change 2014 Impacts, Adaptation, and Vulnerability*, chap. Human Health: Impacts, Adaptation, and Co-Benefits, pp. 709–754. Cambridge University Press, Cambridge, 2014. https://doi.org/10.1017/CBO9781107415379.016.

[9] D. Ürge-Vorsatz, L. F. Cabeza, S. Serrano, et al. Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews* **41**:85–98, 2015. https://doi.org/10.1016/j.rser.2014.08.039.

[10] M. Tuháček, O. Franek, P. Svoboda. Application of FMEA methodology for checking of construction's project documentation and determination of the most risk areas. *Acta Polytechnica* **60**(5):448–454, 2020. https://doi.org/10.14311/AP.2020.60.0448.

[11] D. Tudiwer, A. Korjenic. The effect of an indoor living wall system on humidity, mould spores and CO_2-concentration. *Energy and Buildings* **146**:73–86, 2017. https://doi.org/10.1016/j.enbuild.2017.04.048.

[12] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang. Can houseplants improve indoor air quality by removing CO_2 and increasing relative humidity? *Air Quality, Atmosphere & Health* **11**(10):1191–1201, 2018. https://doi.org/10.1007/s11869-018-0618-9.

[13] J. A. Nelson, B. Bugbee, D. A. Campbell. Economic analysis of greenhouse lighting: Light emitting diodes vs. high intensity discharge fixtures. *PLoS ONE* **9**(6):e99010, 2014. https://doi.org/10.1371/journal.pone.0099010.

[14] J. A. Nelson, B. Bugbee, Z.-H. Chen. Analysis of environmental effects on leaf temperature under sunlight, high pressure sodium and light emitting diodes. *PLoS ONE* **10**(10):e0138930, 2015. https://doi.org/10.1371/journal.pone.0138930.

[15] ANSI/ASHRAE 62.1-2013: Ventilation for acceptable indoor air quality. Informative appendix C — Rationale for minimum physiological requirements for respiration air based on CO_2 concenrtation. ASHRAE, Atlanta, 2013.