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# USE OF EXHALED CO2 FOR CROP GROWTH IN URBAN ENVIRONMENTS

Ruiz de Alegría Sala, Alba (1); Ruana-Jornet, Fermín (1); Canals Casals, Lluc (1); Macarulla, Marcel (1)

(1) UPC

Aiming for synergies between indoor air quality in high-occupancy buildings and urban agriculture, this research investigates the capacity to enhance crop growth based on the generation of CO2 from occupants' exhalation in university classrooms. Accordingly, the CO2 concentrations of eight campuses classrooms of the Polytechnic University of Catalonia have been analyzed over a period of one year. The data have been obtained from sensors installed through the climate action strategy designed by the university and are available through SIRENA platform. Results show great potential in the utilization of exhaled CO2 thanks to the generation during school periods. However, the profiles obtained show discontinuous CO2 availability throughout the year and during the hours of maximum photosynthetic activity of plants. Moreover, the measured CO2 levels exceed, on many occasions, the recommended limit for crop growth.

*Keywords:* IAQ; urban agriculture; HVAC

# APROVECHAMIENTO DEL CO2 EXHALADO PARA EL CRECIMIENTO DE CULTIVOS EN ENTORNOS URBANOS

Este trabajo se enfoca en la búsqueda de sinergias entre la calidad del aire interior en edificios de alta ocupación y la agricultura urbana. En particular, se investiga la disponibilidad de CO2 generado a partir de la exhalación de los ocupantes en aulas universitarias para potenciar el crecimiento de cultivos. Con este objetivo, se han analizado las concentraciones de CO2 de las aulas de 8 campus de la Universidad Politécnica de Cataluña durante un periodo de un año. Los datos han sido obtenidos de los sensores instalados a través de la estrategia de acción climática diseñada por la universidad, cuyos datos se encuentran disponibles a través de la plataforma SIRENA. Se observa un potencial de reutilización del CO2 exhalado durante los periodos lectivos. Sin embargo, los perfiles obtenidos muestran una disponibilidad de CO2 discontinua tanto a lo largo del año como durante las horas de máxima actividad fotosintética de las plantas. Remarcar que, en ocasiones, los niveles de CO2 monitorizados superan el límite recomendado para el crecimiento de los cultivos.

*Palabras clave*: CAI; agricultura urbana; HVAC

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## 1. Introduction

Indoor air quality (IAQ) is a crucial aspect of creating safe and comfortable environments, especially in spaces with high occupancy rates (Seppänen et al., 1999). According to a literature review (Sundell et al., 2011), low ventilation rates lead to an increased risk of allergies and respiratory infections such as colds, flu, or bronchitis. Another possible health effect is the Sick Building Syndrome (SBS), which can cause respiratory problems, skin irritation and fatigue among other symptoms (Stenberg et al., 1994). Additionally, several studies have revealed that poor ventilation, or high $CO_2$ concentration levels, can also lead to a drop in human performance, as measured through tests of response time, accuracy and decision-making skills (Cedeño Laurent et al., 2021; Satish et al., 2012). A higher rate of school absenteeism has also been linked to an increased level in $CO_2$ concentrations (Gaihre et al., 2014).

Even if the academia was aware of the importance of maintaining proper ventilation strategies, the awareness about the importance of IAQ and ventilation efficiency increased after the COVID-19 outbreak. Up to that date airborne pathogens and respiratory infections were poorly addressed by the regulations (Morawska et al., 2021). As a result, it has been underlined the need of developing control measures and preventive sustainable solutions to avoid this kind of disease from spreading (Agarwal et al., 2021).

The main parameter in order to answer those needs is the ventilation that can be achieved through openings such as windows and doors (natural ventilation) or by the use of mechanical systems that control the airflow (force ventilation) (Liddament, 1996). In Spain, 90% of schools were built before 2007 (MITMA, 2020), when the regulations established mandatory mechanical ventilation in educational buildings for the first time (Gobierno de España, 2007). Most high educational facilities were also built before this date and, consequently, it can be inferred that natural ventilation is the predominant mode in educational buildings in Spain (Poza-Casado et al., 2021). It is important to note that, with this ventilation option, the IAQ is strongly influenced by the outdoor climate (REHVA, 2020) and the behaviour of the occupants (Franceschini & Neves, 2022), being their actions driven by their perception and pursuit of thermal comfort. In fact, various investigations have proven that natural ventilation often fails to provide save indoor environments, resulting in $CO_2$ concentrations over 900 ppm, which exceeds the regulated thresholds (Alegría-Sala, Clèries Tardío, et al., 2022; Gaihre et al., 2014; Gil-Baez et al., 2021). Furthermore, the recommendation to keep doors and windows open to reduce the risk of coronavirus transmission when heating systems were activated led to an increase in energy consumption (Gaspar et al., 2022). The limitations of natural ventilation could be overcome by the implementation of mechanical installations, as these systems provide a consistent flow of fresh air at the same time that maintain thermal comfort. However, HVAC systems constitute nearly half the energy consumed in buildings (Pérez-Lombard et al., 2008), reason why researches have been working on finding more sustainable and energy-efficient ventilation strategies (Chenari et al., 2016).

These ventilation systems usually exhaust indoor air directly to the outside of the building, while other agricultural production processes require the addition of $CO_2$. Therefore, one way to promote the sustainability of such systems is to explore synergies with greenhouses (Muñoz-Liesa et al., 2022). A greenhouse is a structure with a transparent enclosure, such as glass or plastic, that integrates the production of fruits or vegetables in controlled thermal environments. This environment facilitates the attainment of optimal conditions for plant growth, the prolongation of the duration of the production, the acceleration of the maturation process, and the enhancement of the quantity and quality of the yields (Gruda & Tanny, 2015). Further benefits can be achieved for the crops growth through an increase of the $CO_2$

concentration levels (Kimball et al., 2002). A study performed by Leiv M. Mortensen (1994) conclude that lettuce, carrot, and parsley yields exposed to high levels of $CO_2$, up to 900 ppm, resulted in an increase of the production of 18%, 19%, and 17%, respectively. Even if the optimal $CO_2$ concentration should be determined by specific production requirements (Dong et al., 2018), an adequate level of $CO_2$ enrichment can be set between 800 and 1000 ppm (Wang et al., 2022), which is what easily can be found in closed educational environments (Alegría-Sala, Marin-López, et al., 2022). Several methods are employed for the enrichment period, such as during the day and night, just during the day, or simply in the morning or at night. Nevertheless, carbon assimilation is more intense during the morning hours (Xu et al., 2014) and it has been proven that increasing the concentration of $CO_2$ only during the morning enhanced the accumulation of biomass in plants as much as when the same treatment is applied throughout the entire day (Ricardo et al., n.d.; Xu et al., 2014).

The direct delivery of compressed $CO_2$ is the primary $CO_2$ enrichment technique because it ensures a consistent and clean airflow. However, this method implies high costs related to the price of the product and the transportation (Wang et al., 2022) and requires specific equipment for the gas storage and pressure control that reduces the available space of the greenhouse (Li et al., 2018). The utilization of the gas produced from the combustion boilers as a source for supplying the crops has been also researched, but the filtration from harmful gases is essential and the time of dosage frequently mismatch with the heat needs (Li et al., 2018). Compost fermentation could also be an interesting $CO_2$ source but the risks of ammonia poisoning (Li et al., 2018) and the unsteady rate of $CO_2$ generation (Karim et al., 2020) should be addressed.

Given this background and with the aim of promoting the circular economy, this study aims to assess the potential increase of crop growth by using $CO_2$ produced by human exhalation in educational buildings with high occupancy, in the framework of the BINAFET and MOVE4EDU projects. To this end, $CO_2$ concentrations recorded at university classrooms of 8 different campuses during a period of 1 year are studied.

## 2. Methodology

The data for this study was obtained from the SIRENA platform (*Sirena 4.3.69*, n.d.), which is a tool that was developed and is maintained by the Universitat Politècnica De Catalunya (UPC). The SIRENA platform is a web-based application that enables users to monitor and evaluate the evolution of the consumption of various supplies (electricity, gas, water) at the UPC facilities, as well as the photovoltaic production that is generated by the solar panels installed on some of the buildings. Additionally, in response to the COVID-19 pandemic, since 2020 the platform also provides real-time assessment of the IAQ of the spaces of the UPC buildings, owing to the installation of IAQ self-calibrating sensors. The IAQ parameters that are available for consultation on the platform include the temperature, the relative humidity and the $CO_2$ concentrations. Table 1 shows the technical characteristics of the sensors that are installed across the campuses.

**Table 1. Technical characteristics of SIRENA IAQ sensors**

| | Measuring range | Resolution | Accuracy |
|---|---|---|---|
| Temperature [°C] | 0 – 50 | 0.1 | ± 0.2 if T < 25<br>± 0.03T if T ≥ 25 |
| $CO_2$ concentrations[ppm] | 0 – 5000 | 1 | ± 50 |
| Relative Humidity [%] | 0 – 95 | 1 | ± 2 |

The option to consult the air quality in the SIRENA platform was implemented by the UPC in November 2020. However, the installation of the sensors was carried out gradually, and therefore the data availability vary across different campuses, as presented in Table 2. In order to have an equivalent sample for all campuses while maintaining a one-year period, the study is based on data recorded between November 30, 2021 and November 30, 2022. Note that campus 7 presents a lower amount of readings since it only counts with data since December 14, 2021. Table 2 also shows the quantity of sensors installed at each campus. A single sensor is installed in each room, regardless of its volume.

**Table 2. Monitoring dates and quantity of spaces**

| Campus | Qty sensors | Downloaded data | |
|---|---|---|---|
| | | Start | End |
| Campus Nord | 118 | 28/05/2021 | 30/11/2022 |
| Campus Terrassa | 109 | 30/11/2021 | 30/11/2022 |
| Campus Sud | 203 | 31/05/2021 | 30/11/2022 |
| Campus Baix Llobregat | 60 | 31/05/2021 | 30/11/2022 |
| Campus Nautica | 25 | 17/11/2021 | 30/11/2022 |
| Campus Manresa | 23 | 31/05/2021 | 30/11/2022 |
| Campus Sant Cugat | 27 | 14/12/2021 | 30/11/2022 |
| Campus Vilanova | 38 | 28/05/2021 | 30/11/2022 |

The main ventilation mode in all campuses is through natural ventilation and the few classrooms that provide mechanical ventilation have the set point at 900 ppm, as demanded by the Spanish Regulation of Thermal Installations in Buildings (RITE) (Gobierno de España, 2007).

The SIRENA platform displays the information related to the classrooms temperature, relative humidity and $CO_2$ concentrations in separate sections. Thus, after downloading the different data sets from the platform, they have been merged into a single file for further analysis in this study. Furthermore, the platform offers the option of downloading the data with different frequencies, ranging from 1 month to 15 min. The 15 min frequency option was selected for this study in order to obtain a more detailed and accurate data set. However, it was observed that the data did not always provide information for every 15 min interval, and some rows were missing information for some or all parameters. Therefore, all the rows without information were filtered out from the data set, and only the complete rows were used for the analysis.

As for the analysis, the monthly $CO_2$ profile is analysed by comparing the mean levels of $CO_2$ with temperature mean values. This comparison reveals the influence of the occupants' thermal comfort on their ventilation preferences. Moreover, this analysis allows to determine the periods with low occupancy, as the $CO_2$ concentrations will not surpass the outdoor concentrations, always considering the sensors accuracy. The outdoor $CO_2$ concentration is assumed to be 418.56 ppm, which is the annual mean value for 2022 reported by the ESRL's Global Monitoring Laboratory (GML) of the National Oceanic and Atmospheric Administration (NOAA) in Mauna Loa (Lan et al., 2023). To facilitate the analysis of the potential availability of $CO_2$ based on the occupation of the spaces, the daily profile of $CO_2$ is computed. This calculation is performed after excluding the data from the weekends and the holidays periods, which are assumed to have no or minimal occupancy. The only exception to this exclusion criterion is the data from June and July, which are considered as low occupancy periods by the UPC and are therefore included in the analysis.

Finally, four ranges of $CO_2$ concentrations have been defined based on their potential use for crop enrichment. The percentage of measurements falling within these four categories on an hourly basis is analysed each month to determine the current availability of $CO_2$ in the UPC spaces. The ranges are as follows:

- Concentration levels lower than 468.56 ppm, which correspond to unoccupied spaces or areas with natural cross-ventilation, where $CO_2$ enrichment is not feasible.
- Concentrations ranging between 418.56 and 800 ppm, indicating occupied rooms where $CO_2$ levels are below the optimal concentration.
- Concentrations ranging from 800 to 1000 ppm, representing occupied rooms where optimal $CO_2$ is delivered based on previous research that indicates that this range is the ideal one for enhancing plant growth and productivity (Wang et al., 2022).
- Concentrations exceeding 1000 ppm, where $CO_2$ levels surpass the desired range.

The data collected for the analysis has been processed using the software Python 3.9.0 (Van Rossum & Drak, 2009) and its built-in libraries for data manipulation and analysis. The evaluation has been conducted by means of graphical representations of the data, which have been generated with the Python data visualization libraries Seaborn (Waskom, 2021) and Matplotlib (Hunter, 2007).

## 3. Results

The analysis of data gathered from the SIRENA platform reveals a significant variability in the generation of exhaled $CO_2$ throughout the year. Figure 1 illustrates this variability and highlights the periods of low occupancy, which include weekends, holidays, and low occupancy periods defined by the UPC.

For instance, during the Christmas holidays that start on December 23 and end on January 6, there is a substantial decrease in $CO_2$ concentrations. It should be noted that in 2022 the exam period did not start until the 10th and therefore, although the university opened on the 7$^{th}$, that day the $CO_2$ concentrations remained lower than the ones recorded in the following weeks. Similarly, the first two weeks of February correspond to holidays that are held between the end of the January examination period and the beginning of the second semester, resulting in low levels of $CO_2$ emissions. However, it should be noted that, during this period, $CO_2$ concentrations were not as low as in the abovementioned holiday periods since the university staff does not have holidays, and events and parallel courses are being held. Another significant reduction in occupancy occurs during the Easter holidays, which ran from April 9 to April 18. Additionally, the end of the spring semester on June 24 and the gradual start of the autumn semester, with Degree courses starting on September 7 and Masters courses commencing on September 12, are also periods of reduced occupancy. Finally, there are isolated holidays on June 6, October 12, December 6, and December 8, during which a decrease in occupancy is also observed. As stated in section 2, these dates are excluded from the data set for the subsequent analysis. Since the beginning of the autumn semester is gradual, the data until September 12 is disregarded as the previous week contains more unoccupied rooms and can disrupt the results.

Apart from the low occupancy periods, Figure 1 also highlights a notable correlation between the $CO_2$ concentrations and the temperature within the classrooms. Specifically, during the cold months, the $CO_2$ concentrations rise as the occupants seem to prioritize thermal comfort. Conversely, as the temperature increases, the tendency to have cross ventilation becomes higher, resulting in lower $CO_2$ concentrations. It is noteworthy to mention the change in the behaviour of the occupants from the cold months at the beginning of 2022

(February to April) to those at the end of the year, specially November as December corresponds to 2021. This change can be attributed to a greater awareness of the COVID-19 disease during the beginning of the year, as it was the first academic year after the pandemic. This is further reflected in the indoor temperature fluctuations, which are more pronounced during the initial months of the year.

A significant difference in $CO_2$ concentrations can also be detected between the teaching and evaluation periods. During the final exams in January and June, a noticeable decrease in $CO_2$ generation was observed. This reduction can be attributed to the fact that, during these periods, most students only come to the university on exam days, occupying only the classrooms designated for the exams while leaving the rest of the spaces mostly empty. Consequently, the $CO_2$ concentrations in these areas remains at the same level as the outdoor concentrations due to a lower occupancy rate. On the other hand, during mid-term exams, which take place over a shorter period of time, spanning the weeks of April 19-22 and the first week of November, the difference in $CO_2$ concentrations is not as pronounced. While exams for all subjects and courses take place during these periods, the spaces are more occupied than during final exams, resulting in less significant changes in $CO_2$ concentrations.

**Figure 1. Monthly average values of $CO_2$ concentrations and temperature**

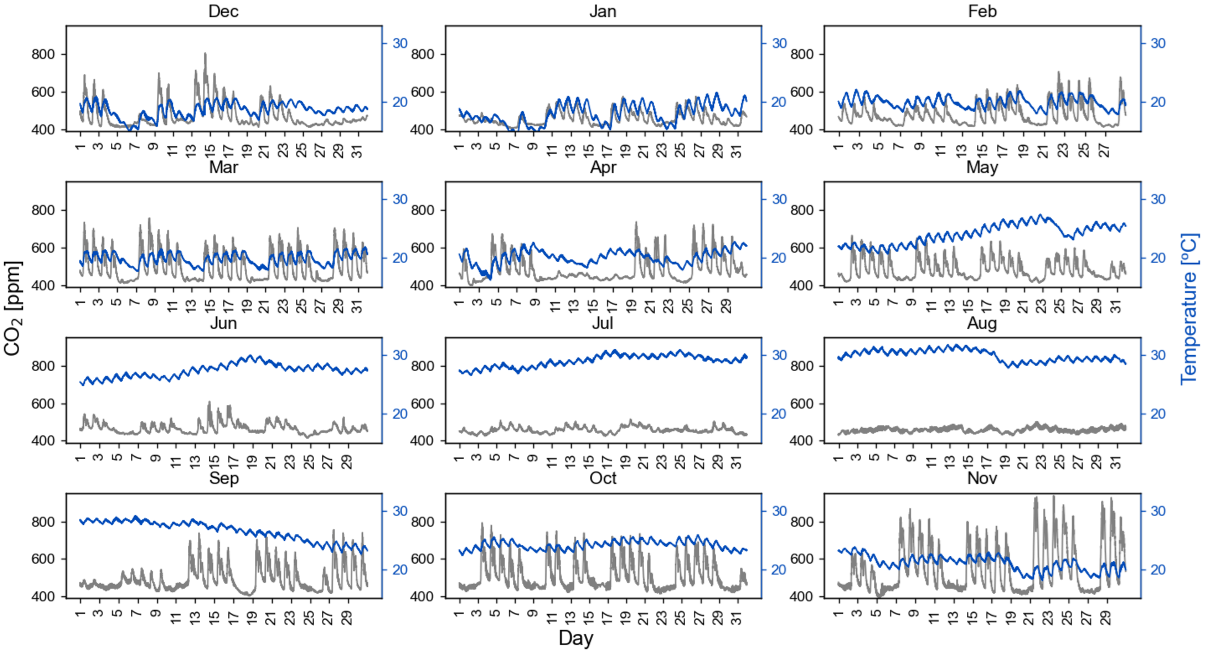
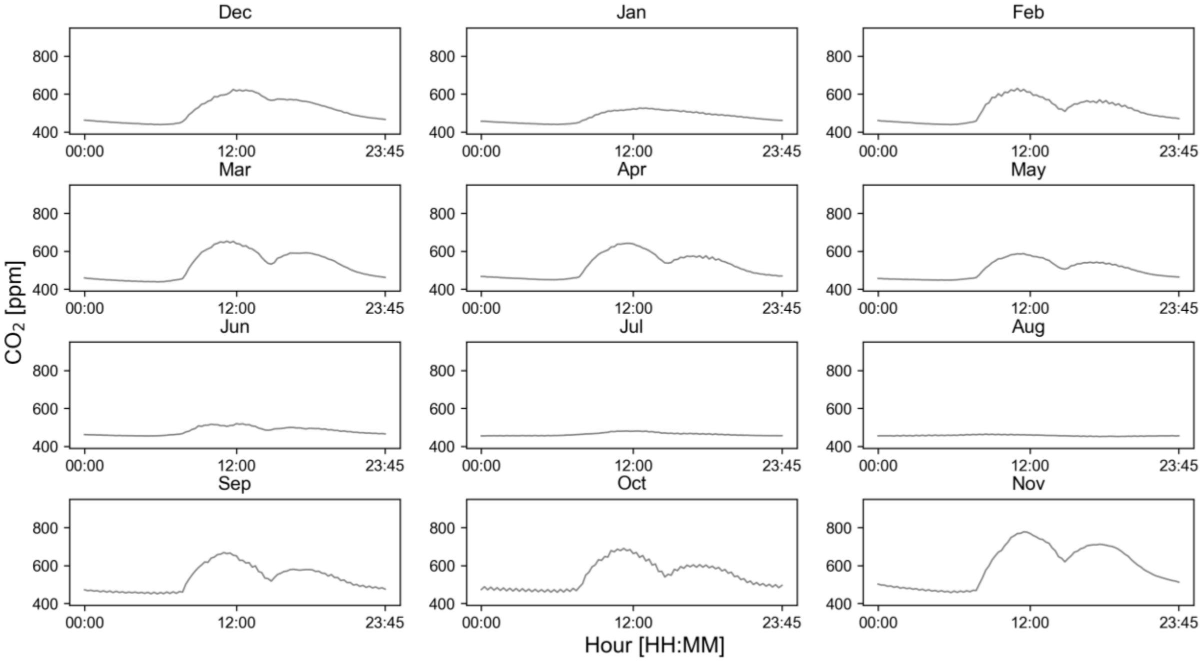


Figure 1 shows another distinctive characteristic of the $CO_2$ concentrations, which is the clear separation that occurs between each day based on the rises and falls in the levels of this gas. However, Figure 2 offers a more comprehensive analysis of the daily profile of $CO_2$ concentrations for the different months of the year. In August, the profile is almost constant around the outdoor concentrations, while during July slight variations can be appreciated. This is due to the fact that during this month the Degree's and Master's Final Thesis presentations are carried out and university workers still work on-site. However, in comparison with the rest of the months, attendance is very low and only happens during the morning.

For the months when teaching activities are carried out in the university, the profile tendency of $CO_2$ concentrations is consistent throughout the days, even if the maximum values change slightly (Figure 2). It can be clearly observed that the day starts at 08:00 h when the morning lessons begin, and a peak concentration of $CO_2$ is reached around 11:30 h. From this point onwards, the concentrations start to decline gradually until 15:00 h when the afternoon lessons start. It can also be inferred from Figure 2 that the attendance to the university is lower in the afternoon than in the morning, since the maximum level of $CO_2$ reached in the afternoon is not as high as in the morning. Another interesting aspect of the profile of $CO_2$ concentrations is the gradual way in which the $CO_2$ decreases after the teaching periods of the afternoon. This could be explained by the fact that once the spaces are used for teaching purposes, they are not always ventilated adequately by opening doors and windows, which would facilitate cross ventilation and reduce $CO_2$ levels more rapidly.

Regarding the $CO_2$ profile corresponding to the months of exams, the trend changes with respect to that shown during the teaching months, and the maximum values are notably lower. During these months the profile seems to be more constant, even if during July the differentiation between the morning and the afternoon hours is clearer than in January.

**Figure 2. Daily average values of $CO_2$ concentrations and temperature for each month**



Although Figure 2 provides information about the time intervals when the $CO_2$ generation occurs, which correspond to the periods when enrichment treatments can be applied to the crops, it does not accurately represent the actual availability of the gas for this purpose. This happens because, the average daily value of $CO_2$ concentration is calculated based on the measurements obtained by every installed sensor in the UPC, regardless of the occupancy of the spaces. As the occupancy information is not available for the calculation, the average value is largely affected by the elevated number of empty rooms within the campuses.

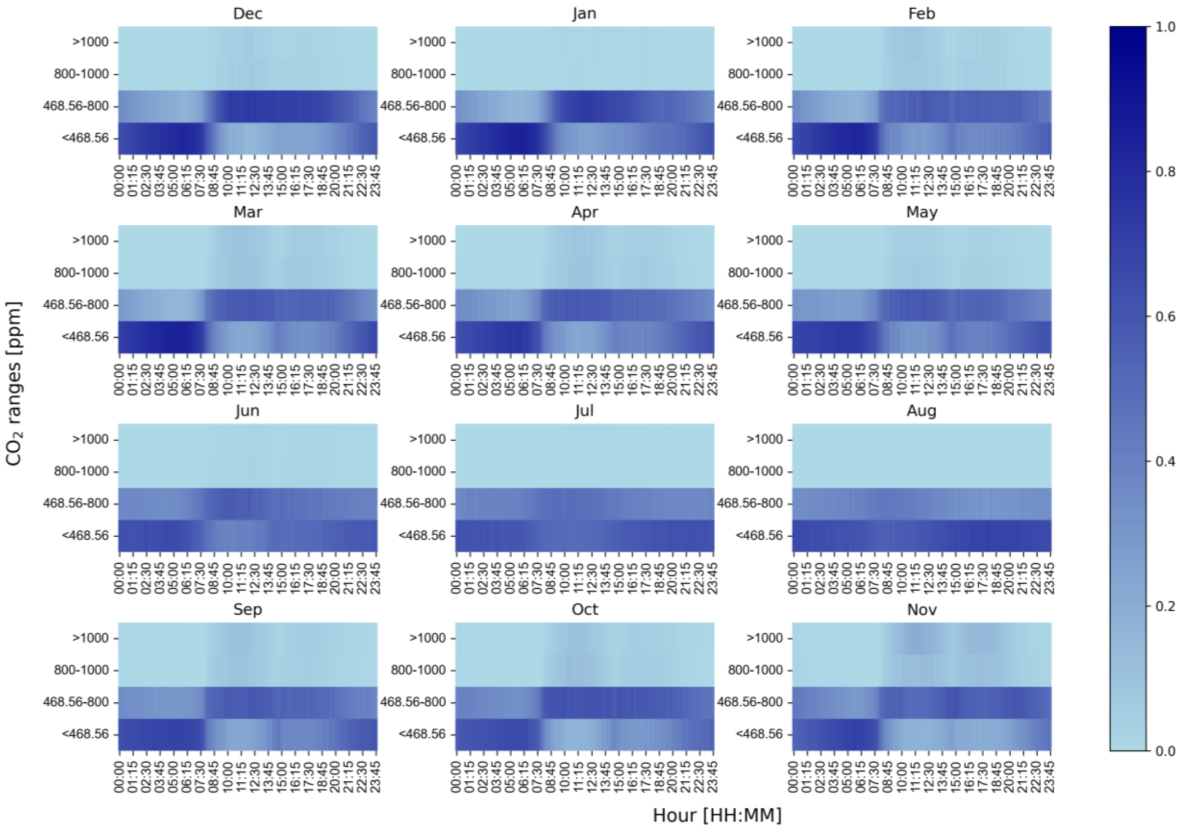
In order to address this issue, the proportion of spaces that have measurements within each of the $CO_2$ ranges that have been defined for this study has been calculated and presented in Figure 3. As expected, during the months of July and August no readings above 800 ppm are collected, staying mainly around the external $CO_2$ concentrations. In the case of seeking to maintain continuous enrichment treatment for the plants throughout the year, complementary methods should be sought. In January and June, the months corresponding to the examination season, $CO_2$ generation by exhalation of people should also be combined with alternative techniques as the measured values do not reach the optimal $CO_2$ concentrations for plants enrichment.

For the remaining months of the year, when classes are conducted, the obtained results are temperature-dependent, as concluded from Figure 1. However, if it were desired to take advantage of all the $CO_2$ generated in the classrooms, it would be necessary to use forced ventilation systems and the occupants would not have at their disposal the option of operating windows. Therefore, to analyse the generation potential, the most representative month is November, since it is assumed that the occupancy of the university remains similar during the different teaching periods of the year.

Based on the data of that month and putting the focus on the range of $CO_2$ concentrations that are optimal for plant growth (800-1000 ppm) the following results are obtained: between 08:00 h and 09:15 h, only a small proportion of spaces (less than 10%) have this range of $CO_2$ concentrations; from 09:30 h to 13:45 h, the proportion of spaces within this range increases up to 13%; then, the levels decrease again, and less than 10% of the spaces stay at this range until 15:30 h; after that, the proportion increases again until 19:30 h, attaining 12%; from then onwards, the proportion decreases until 4:00 h, when there are no spaces within this range.

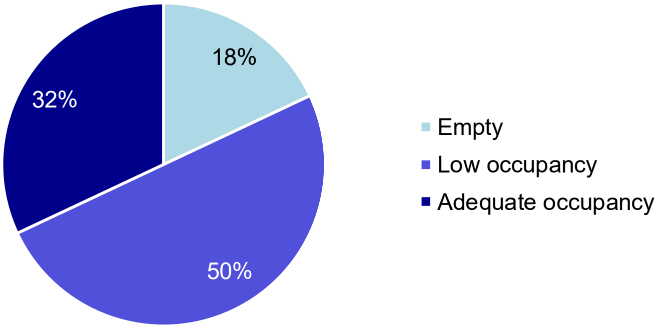
Outside from that range, there are several areas with concentrations greater than 1000 ppm. In this case, the following trends may be observed: from 08:00 h to 9:00 h, less than 10% of the spaces have excessive $CO_2$ concentrations; between 09:15 h and 14:00 h, the percentage reaches up to 20%; thereafter, the proportion of spaces decreases by 10%, but increases again to 14% between 15:30 h and 19:30 h. As in the preceding range, $CO_2$ concentrations fade until 04:00 h, when any rooms display $CO_2$ concentration levels above 1000 ppm.

**Figure 3. Ratio of rooms with $CO_2$ concentrations within the defined ranges**



Considering the data from November and based on the assumption that none of the classrooms were ventilated to maintain an acceptable thermal comfort, the percentage of classroom occupancy during the hours of highest $CO_2$ generation is calculated. As shown in Figure 4, just the 32% of the spaces have an occupancy rate adequate to deliver useful $CO_2$ levels, since the other used spaces (50%) remain under-occupied. Taking into account that low occupancy means that 800 ppm is not reached and assuming that lessons have a duration of 1.5 h, the volume per occupant is calculated to be 15.18 $m^3$/pers using equation 3 from a previous study (Alegría-Sala, Clèries Tardío, et al., 2022). Therefore, if greater quantities of $CO_2$ were to be generated, the spaces will have to be organized so that the volume per occupant is below this value. Finally, it is noteworthy the high percentage of spaces that remain unused during peak hours, suggesting that university buildings are currently underexploited.

**Figure 4. Percentage of use of university rooms during high occupancy hours**



## 4. Conclusions

This study analyses indoor air quality (IAQ) data from 603 rooms of 8 different UPC campuses gathered from the SIRENA platform to assess the feasibility of using occupants' exhalation as a source for greenhouse crops enrichment, while reducing the environmental impacts of mechanical ventilation.

The results suggest that relying solely on $CO_2$ generated by occupants of university classrooms may not be sufficient to maintain optimal $CO_2$ concentrations for plant growth (800 – 1000 ppm) throughout the year, due to low occupancy periods including weekends and holiday seasons. Additionally, during exam periods, the $CO_2$ concentrations are too low compared to the current treatments applied in greenhouses yields.

Furthermore, we observed a dependence of $CO_2$ concentrations on temperature, with occupants prioritizing thermal comfort, resulting in open windows and doors during hot seasons that reduce $CO_2$ concentrations. To address this issue, the study proposes to promote synergies to maintain adequate thermal comfort and ventilation conditions through the implementation of mechanical systems that recirculate the air extracted from the classrooms to the crops, eliminating the need for interactions of occupants over the ventilation.

For the analysis, the data from November is the most representative one, since during that period the concentrations were the highest, and similar occupancy rates are assumed during the rest of the scholar year. In this scenario, the hours with higher $CO_2$ generation are from

09:00 to 14:00 h and between 15:30 and 19:30 h, with the percentage of spaces with values over 800 ppm reaching 33%. Note that this also includes the rooms where the measured $CO_2$ values are over 1000 ppm, since through the mechanical ventilation the generation could be adapted to the need of the crops. It should be highlighted that the photosynthesis of the plants occurs mainly during the sunlight hours, and is most active in the morning, so the timings of $CO_2$ generation by occupants match with the daylight hours, with the exception of the first hours after sunrise when no $CO_2$ produced by occupants could be provided.

Additionally, the data underlines the urgent need of implementing mechanical or mix ventilation strategies in university classrooms since the thermal conditions cannot be maintained while assuring acceptable air quality conditions. Although the use of forced ventilation systems results in higher energy costs, the implementation of the proposed measures could contribute to mitigate climate change mitigation efforts by reducing energy and eliminating $CO_2$ transportation pollution. Therefore, future studies should be done in order to measure the potential energy savings that can be achieved by the implementation of the solution, while analysing the reduction in the costs of purchasing compressed $CO_2$ for the crops enrichments.

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**Communication aligned with the Sustainable Development Objectives**