Air quality IN HOUSING THROUGH CO_2

AS A HEALTH RISK INDICATOR

Calidad del aire en vivienda a través del CO2 como indicador de riesgo para la salud

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RESUMEN. La calidad del aire se puede evaluar en función de la concentración de CO2. El límite de referencia teórico es de ~350 ppm en aire, pero debido a los efectos de las fuentes antropogénicas, ha llegado a ~410 ppm en aire. En tiempos de la pandemia de COVID-19, los dormitorios son un ambiente interior típico para el aislamiento, donde la tasa de ventilación tiene un efecto significativo en la transmisión del virus SARS-CoV-2. El aire exhalado tiene el potencial de emitir virus a través de las gotitas de Flügge/Wells, que afectan la salud de las personas que viven en una casa. El límite informado de CO2 en interiores es de 1,000 ppm en aire. En este estudio, las concentraciones de CO2 se midieron al aire libre, en interiores (casas), en la exhalación humana con/sin mascarilla. Las medidas se obtuvieron con una sonda Testo 535. La concentración de CO2 exterior alcanzó hasta 640 ppm indicando una calidad inaceptable y la interior osciló entre 902-1,101 ppm para casa habitación, superando el valor estándar para una buena calidad del aire. La concentración media de CO2 exhalado osciló entre 23,780 y 30,093 ppm. Se redujo la concentración de CO2 al exhalar con una mascarilla KN-95 o mascarillas quirúrgicas estándar de 3 capas. Por lo tanto, éstas pueden detener el paso de gotitas de Flügge/Wells que potencialmente contienen SARS-CoV-2 cuando una persona está enferma y disminuir el riesgo de transmisión de la enfermedad por coronavirus. Por lo tanto, el objetivo de este trabajo fue determinar la calidad del aire mediante la medición de la concentración de CO2 al aire libre; dentro de casas y durante la respiración sin máscara, con cubrebocas KN-95 o cubrebocas quirúrgico estándar de 3 capas como un indicador de riesgo en la transmisión del virus SARS-CoV-2.

Palabras clave: CO2, calidad del aire interior, calidad del aire exterior, SARS-CoV-2.

ABSTRACT. *Air quality can be evaluated based on the CO2 concentration. The theoretical reference limit is ~350 ppm in air, but due to the effects of anthropogenic sources, it has reached 410 ppm. In times of the COVID-19 pandemic, bedrooms are a typical indoor environment for isolation, where the ventilation rate has a significant effect on the transmission of the SARS-CoV-2 virus. Exhaled air has the potential to emit viruses through Flügge/Wells droplets, which affect the health of people living in a house. The reported limit for CO2 indoors is 1,000 ppm in air. In this study, CO2 concentrations were measured outdoors, indoors (houses), in human exhalation with/without a mask. The measurements were obtained with a Testo 535 probe. The outdoor CO2 concentration reached up to 640 ppm indicating unacceptable quality, and the indoor ranged between 902-1,101 ppm for home, exceeding the standard value for good air quality. The average concentration of exhaled CO2 ranged from 23,780 to 30,093 ppm. CO2 concentration was reduced when exhaling with a KN-95 or standard 3-layer surgical masks. Therefore, they can stop the passage of Flügge/Wells droplets that potentially contain SARS-CoV-2 when a person is sick and decrease the risk of coronavirus disease transmission.*
Therefore, the objective of this work was to determine the air quality by measuring the CO2 concentration outdoors; inside houses and during breathing without a mask, with a KN-95 mask or a standard 3-layer surgical mask as an indicator of risk in the transmission of the SARS-CoV-2 virus.

Key words: *CO2, indoor air quality, outdoor air quality, SARS-CoV-2.*

CO_2 or carbon dioxide is a colourless and odourless gas that can originate from natural or anthropogenic sources. Its presence has important consequences in the quality of outdoor air, indoor air, and the air that is exhaled due to the effects of air pollution and greenhouse gas emissions (Wark and Warner, 2020; Gert-Jan and Wim, 2021), although the CO_2 concentration has high temporal and spatial variability both indoor and outdoor environment. According to Romero *et al.* (2021) - exposure to air pollution is a significant environmental risk for many diseases, including respiratory infections, lung cancer, chronic respiratory and cardiovascular diseases. Outdoor ambient air quality is considered normal background concentration if the CO_2 concentration is under 410 ppm.

Indoor air quality (IAQ) in bedrooms and offices can significantly affect health, work efficiency and learning. The indoor ventilation ratio is one of the most important factors affecting indoor air quality. Thus, there is scientific significance in the study of ventilation rates in bedrooms and offices (Zhang *et al.*, 2015; Zucker *et al.*, 2017). Recirculated indoor air and shared air have long been recognized as a transmission mechanism for infectious diseases (Deng and Gong, 2021; Richardson *et al.*, 2014). The potential host-virus transmission mechanism of SARS-CoV-2 of person-to-person transmission of infectious agents has been reported to be through recirculated air from buildings and is a potential source of significant morbidity (Wang *et al.,* 2021; Chirizzi *et al.*, 2021). A key assumption is that airborne infectious particles are droplet nuclei that remain suspended in the air (Flügge droplets and Wells droplets) and body fluids (Tang *et al.*, 2020) for long periods of time, and their concentration is at a stable level throughout exposure. The transmission route of SARS-CoV-2 bioaerosol is through the air from animals to humans and from person to person (Ching and Kanijo, 2020). A person with COVID-19 is mainly infected externally from others breathing, sneezing, coughing, talking, or singing (Chirizzi *et al.*, 2021; Tang *et al.*, 2020). An infected person expels Flügge respiratory droplets (saliva or mucus from the mouth or nose) or Wells droplets that can easily reach the alveolar ducts. The speed of sneezing has been reported to range from 60-150 km h^{-1} and can reach a distance as little as 1 m (Tang *et al.*, 2020) or up to 7 to 8 m, depending on environmental conditions. In this period, depending on the size of the aerosol and the dispersion of solid or liquid microscopic particles in gaseous media (Wark and Warner, 2020; Wang *et al.*, 2021; Court and Lane, 2020), it can be deposited on surfaces (Chirizzi *et al.*, 2021) or suspended in the air depending on the sedimentation rate.

In Flügge respiratory droplets (Tang *et al.*, 2020; Bayarri *et al.*, 2021; Rodríguez *et al.,* 2021) or Wells droplets, moisture can evaporate when in contact with solar radiation. They then release solid particles of SARS-CoV-2 virus that are covered by mucus or saliva, and the active virus can be suspended freely in the air for a long time (Chirizzi *et al.*, 2021) with speed close to 0 m s^{-1}. The virus can then penetrate an organism and spread COVID-19, which mainly depends on the frequency of coughing (Escome *et al.*, 2019).

In the organism the SARS-CoV-2 virus has a protein envelope and spines of protein molecules called H and N spines (Horby and Landray, 2021). The virus infects living cells to reproduce. It reaches the cells of the nose, throat, and lungs, where a spine of the virus is inserted into a receptor molecule on the healthy cell membrane, and it enters the healthy cell. The virus accesses the ribosomes to generate viral proteins and new viruses (Nakagawa *et al.*, 2016). The ribosome is responsible for assembling all the parts of the new virus, which emerges from the cell to spread throughout the body. Therefore, the signs and symptoms of the disease appear, and the virus is transported through the nose, larynx, pharynx, bronchi, and bronchioles.

The virus eventually reaches the alveolar sacs, which are flexible and elastic airways. These sacs inflate like a balloon when people inhale and deflate when they exhale. On average, each alveolus is surrounded by approximately 1,000 capillaries, and the respiration process is carried out by passive diffusion (Rivero, 1991) when inhaling oxygen and exhaling carbon dioxide (Tang *et al.*, 2020). Lobar pneumonia occurs if only one lobe is affected, while bronchopneumonia occurs if both lobes are affected. It can generate respiratory failure that requires intubation to help improve the patient's condition. Depending on whether the patient's state of health is moderate or severe, death can occur.

COVID-19's complications include respiratory failure, acute respiratory distress syndrome, sepsis, septic shock, thromboembolism, and multi-organ failure, including acute kidney injury and heart injury (Rodríguez *et al.*, 2021; Salvat-Davila *et al.*, 2020). When the system deteriorates at the alveolar sac level, the exchange of O2-CO2 gases is affected. Therefore, the exhalation of CO2 can potentially vary as the exchange of gases in respiration is severely obstructed.

Belmonte *et al.* (2019) reported that the interrelationships between indoor environments with inadequate IAQ and associated health problems (such as allergies, respiratory tract infections, etc.) have been explored from different perspectives. They concluded that IAQ plays an important role in public health (Belmonte *et al.*, 2019; Madureira *et al.*, 2016; Ma'bdeh *et al.*, 2020; Zhang *et al.*, 2016).

Exhaled breath is a vehicle for releasing infectious airborne particles and contains ~40,000 ppm of CO2, normal breathing has been show to release up 7,200 aerosol particles per liter of exhaled air (Zhang *et al.*, 2016; Kim *et al.*, 2016; Rudnick and Milton, 2003; Simanic *et al.*, 2019). In comparison, there is approximately 350 ppm in outdoor air (Wark and Warner, 2020; Adali *et al.*, 2018), although it has currently increased to ~410 ppm due to global anthropogenic changes (Rudnick and Milton, 2003). The fraction of inhaled air that has been previously exhaled by someone in a building (the rebreathed fraction) is a transmission pathway for bioaerosols. Airborne communicable infections can only be acquired by inhaling air that has been previously exhaled, and CO2 is a marker of exhaled breath. Therefore, it would be useful to be able to relate the risk of infection directly to the fraction of re-inhaled air, particularly now that continuous monitoring of CO2 concentration is convenient. A method for calculating the infection risk based directly on continuous CO2 monitoring would also eliminate assumptions about steady state conditions, constant concentration levels in outside air, and the relationship between CO2 concentration and the supply rate of outside air. By reporting the levels of carbon dioxide in rooms, the probability of transmitting SARS-CoV-2 can be estimated (Kim *et al.*, 2013; Simanic *et al.*, 2019). It is necessary to highlight that there are many other sources in outdoor and indoor contributing to CO2 levels. Bioaerosols or particles of biological origin are among the infectious particles suspended in the air, which can include viruses (Deng and Gong, 2021; Adaji *et al.*, 2018; Argunhan and Avci, 2018) such as SARS-CoV-2 (Bayarri *et al.*, 2021; Rodríguez *et al.*, 2021). Submicron-sized viruses have been responsible for some of the worst human pandemics in history, such as influenza (1918), smallpox (1978), and COVID-19 (Chirizzi *et al.*, 2021; Bayarri *et al.*, 2021; Simanic *et al.*, 2019). COVID-19 is caused by the zoonotic virus SARS-CoV-2, and by November 23, 2022, it had caused 5-15 million deaths worldwide (Tang *et al.*, 2020; OMS, 2022). Therefore, the COVID-19 pandemic and global environmental changes have generated emerging multidisciplinary CO2 research needs (OMS, 2022; Barouki *et al.*, 2021; Jijo and Sajan, 2021). Thus, the objective of this work was to determine the air quality through to measure the levels of CO2 concentrations outdoors; indoors; breathing without mask, with a KN-95 facemask and standard 3-layer surgical facemasks, and in a car ventilation as a risk indicator in the transmission of the SARS-CoV-2 virus.

EXPERIMENTAL

Sampling sites: Two outdoor places were selected: Outside 1 (19° 15'58.10" N/99° 39'34.48" W) and Outside 2 (19° 15'45.44" N/99° 38'54.53" W). One bedroom was also selected in each of two houses: Inside 1 (19° 15'58.67" N/99° 39'34.56" W) and Inside 2 (19° 15'45.37" N/99° 38'55.16" W) in Mexico Center. The environment in both places is urban, which is why it is related to the quality of the outdoor air. The area and height of the rooms were recorded. A CO2-measuring instrument was placed in the middle of the room for the interior sites, the average height was 1.5 m, and for the exterior sites, it was placed at the center of the monitoring site. Both bedrooms had a door and a window, which were closed at the time of measurement. The rooms did not have an air ventilation system, and fresh air can only enter to the areas by opening the windows or by infiltration through air leaks under the door. Therefore, window-opening patterns in rooms can greatly affect IAQ. In the interior sites, the sensor was located in the bedrooms because it was assumed that sick occupants would spend most of their time in these places when they were ill with COVID-19. The orientation of both rooms was from West to East. Therefore, they should be the most representative areas to evaluate the emission of CO2 from the occupants or patients in quarantine. During the CO2 measurements in both houses, the occupant was the same person, 53 years old, in good health and the occupant was a non-smoker. It is necessary to point out that the rooms were not occupied before taking the measurements.

Carbon dioxide monitoring: Outdoor and indoor CO2 concentrations were measured with the same Testo 535 probe, which had been calibrated, such as Kim *et al.*, 2013 reported. The precision of the instrument was ± 75 ppm, and the measurement range of CO2 concentration was 0-9,999 ppm. The sampling time was one hour at each study place for 5 days from 10 to 11 am at internal sites. Sampling at outdoor sites was obtained at 12-13 pm from January 18 to 29, 2021. The measurements for indoor and outdoor were conducted the same days. 14 measurements were obtained per minute, and 840 continuous data points were measured per hour (16,800 data points in total).

The measurement of the CO2 concentration from individuals was obtained with and without KN-95 and standard 3-layer surgical facemasks (figure 1); it shows a) the device used, b) person breathing without a mask, c) person breathing with KN-95 mask, d) person breathing with standard 3-layer surgical mask. It should be noted that in all measurements the system was sealed to prevent CO2 leakage, ensuring reliable measurement.

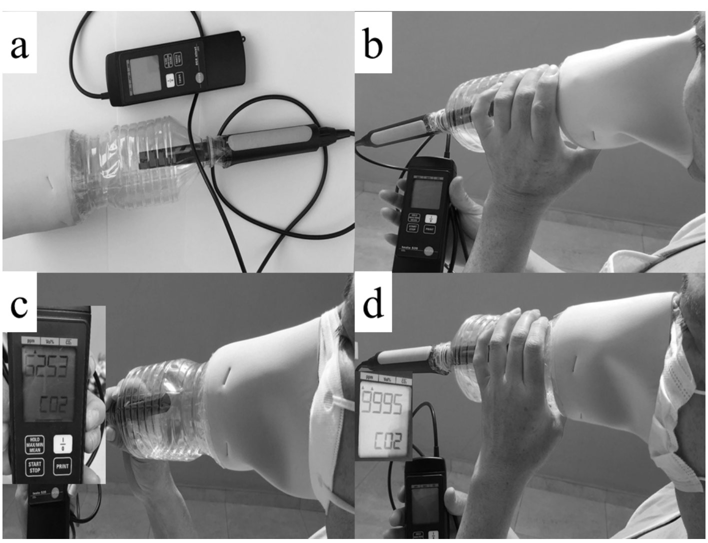

FIGURE 1. MEASUREMENT OF CARBON DIOXIDE (CO2) LEVELS, DURING BREATHING WITHOUT AND WITH KN-95 AND STANDARD 3-LAYER SURGICAL FACEMASKS.
FUENTE: PHOTOGRAPHY OF THE AUTHORS.

Person A was a male who had been externally infected with COVID-19, which was positively diagnosed using a polymerase chain reaction (PCR) test. His signs and symptoms were fever, dry cough, fatigue, and bronchitis. His condition was serious, and his sequelae were chronic dry cough as of three months after acquiring the disease. Person B was a female who had been infected by transmission of the virus in the indoor environment from person A. She had a positive COVID-19 diagnosis according to a PCR test with signs and symptoms of fatigue, anosmia (smell issues), and ageusia (taste issues). Her symptoms were acute, and no sequelae were observed. Lastly, person C was a female control with a negative PCR result for COVID-19.

CO2 concentration analysis and ethical aspects: The CO2 data were recorded in excel sheets for processing. All procedures involving human participants were performed in accordance with the ethical standards of the Declaration of Helsinki of 1964.

RESULTS AND DISCUSSION

Sampling sites: The doors and windows of both bedrooms were closed during the sampling period. The volume of bedroom 1 (Inside 1) was 29 m^3, and that of bedroom 2 (Inside 2) was 47 m^3. The average concentrations of CO2 in the rooms were 1,101 ppm and 902 ppm, which corresponded to 38 ppm m^{-3} and 19 ppm m^{-3}, respectively. These values indicate that the indoor air quality was unacceptable in bedroom 1, and the indoor air quality of bedroom 2 was 50% better than in the first room. Carbon dioxide concentration in the room may indicate air quality and ventilation system efficiency. In this case, the carbon dioxide concentration Inside 1 was of 0.0319 m^3/m^3 and for Inside 2 was of 0.0424 m^3/m^3. Thus, the volume of the room is an important variable for the concentration of CO2.

CO2 concentration development in outdoor places: Figure 2 shows the CO2 levels recorded in the outdoor sites (Outside 1 and 2). In both sites, the CO2 concentration exceeded the theoretical value of 350-416 ppm reported for outdoor environments (Wark and Warner, 2020; Zhang *et al.*, 2016; Organización Meteorológica Mundial, 2023). CO2 concentration levels during the data collection period were as high as 640 ppm.

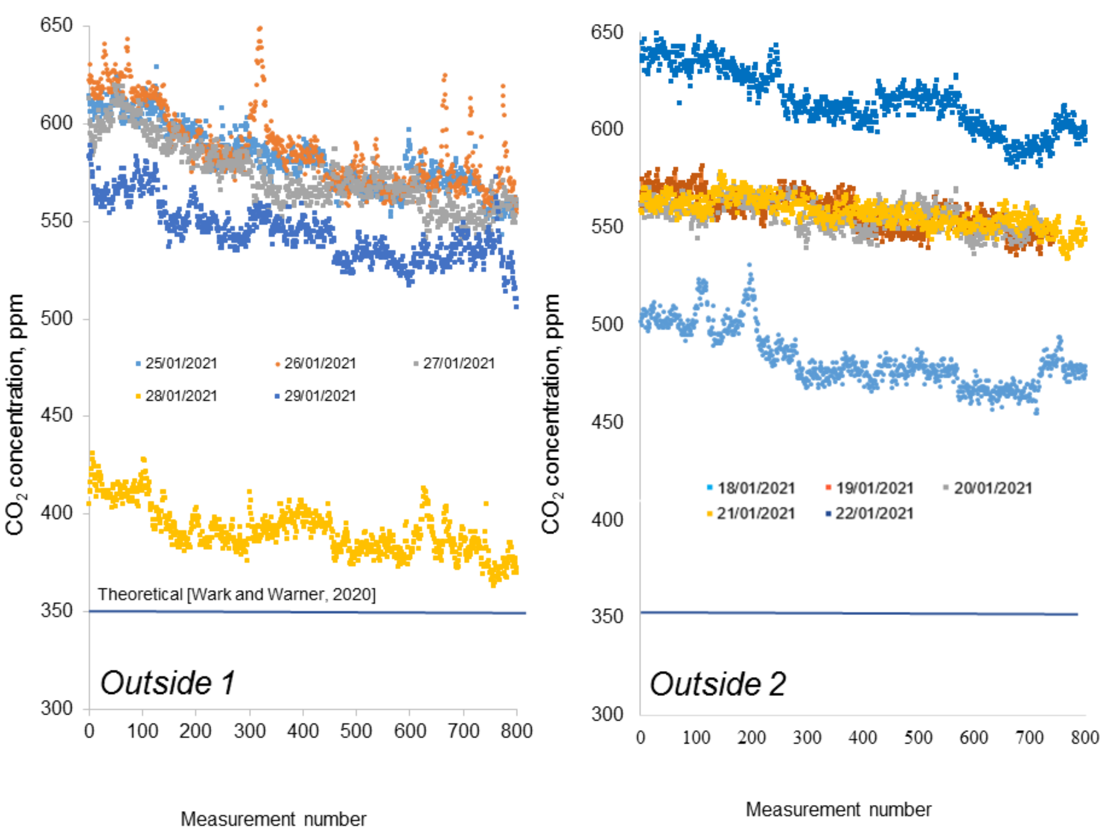

FIGURE 2. CO2 CONCENTRATION LEVELS OBTAINED FOR THE OUTDOOR ENVIRONMENT.
FUENTE: GRAPH OF THE AUTHORS.

The air quality reported in general according to the meteorological variables in both sites ranged from satisfactory to unacceptable. However, at Outside 1, the air quality was reported as normal on one day, correlating with values close to 350 ppm of CO2 (Wark and Warner, 2020). It can be seen that there is a great variation between the yellow line Outside 1 and the other lines, this is due to the fact that the air quality measured by the Toluca Monitoring Network on that specific day was reported as good. Otherwise in the other cases where the lines represent a bad quality of the outdoor air. Various studies have reported CO2 concentration levels from 400 to 2,230 ppm (Zhang *et al.*, 2016; Shibuola *et al.*, 2016). The CO2 concentration is a relevant and valid parameter that is included in national and international regulations to study air quality, but it fluctuates depending on the location.

CO2 concentration development in internal places: During approximately 100% of the monitored time, the CO2 concentration levels were very different with natural ventilation for both indoor sites (Inside 1 and 2). This was also reported by Yang and Jiang, 2017. Particularly unacceptable IAQ was recorded in the bedrooms. In some cases, CO2 concentration levels exceeded the recommended limits of 1,000 ppm established by Mexican regulations (Moreno-Rangel et al., 2021) and other countries for approximately 100% of the monitored time (Shibuola *et al.*, 2016; Chang and Fang, 2022; Du *et al.*, 2020). With this value SARS-CoV-2 could easily spread to the population during the pandemic.

Figure 3 shows that at Inside 1, the threshold of 1,000 ppm was exceeded the whole time, reaching up to 1,450 ppm of CO2. This indicates that the IAQ is unacceptable. However, at Inside 2, approximately 80% of the measurements did not exceed this threshold. One difference between the sites is their volume. The second is larger, which gives the opportunity to dilute the CO2 at this site. Therefore, Inside 1 had unacceptable IAQ.

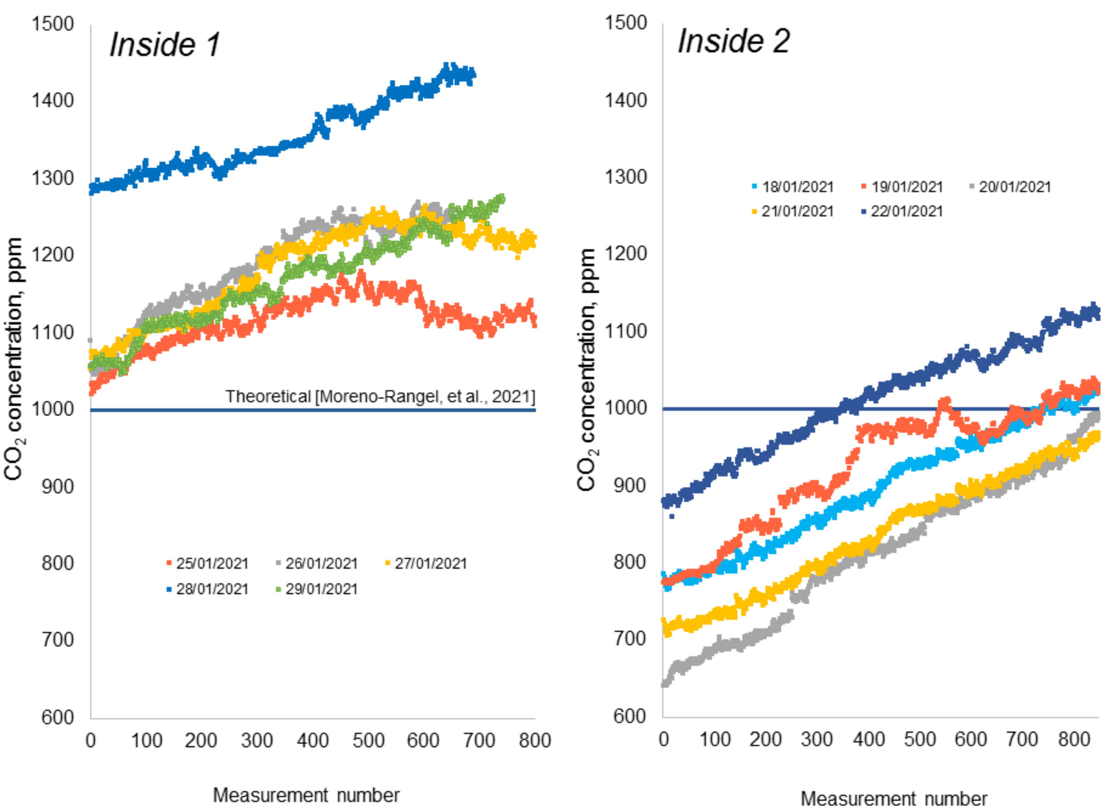

FIGURE 3. CO2 CONCENTRATION LEVELS IN AN INDOOR ENVIRONMENT WITH A SINGLE HOST INSIDE IT.

FUENTE: GRAPH OF THE AUTHORS.

IAQ is a key factor in indoor environmental health. According to the Environmental Protection Agency, 2021, inhabitants spend 93% of their lives indoors on average, but indoor air is probably 2 to 5 times more polluted than outdoor air. At Inside 1, the air quality was 2.1 times higher than that of the outdoor air, and at Inside 2, it was 1.6 times higher. IAQ applies to non-industrial indoor environments, such as office buildings, public buildings (schools, places of entertainment, restaurants, etc.), and private homes. In recent years, it has gained special relevance in association with "sick building syndrome," which comprises a wide range of symptoms or illnesses that are attributed to a building in which people work or live in this case the indoor air quality (Zucker *et al.*, 2017).

Thus, by taking care of the quality of the air or indoor environment, the health of the people who live or work there for a considerable time is taken care of.

Therefore, the risk of transmission of indoor airborne infections from person to person is currently estimated through the concentration of carbon dioxide (Kim *et al.*, 2013; Barouki *et al.*, 2021). The concentrations of CO2 indoors will increase accordingly and are dependent on atmospheric CO2 levels (Kumar *et al.*, 2021).

CO2 concentration development through exhalation: The breathing process consists of two stages: inhaling and exhaling. Three people were monitored during exhalation, as shown in the figure 4. First, an average value of 20 to 21 breaths per minute was obtained. The first average concentration of CO2 exhaled by person A was 1,672 ppm, that for person B was 1,189 ppm, and that for person C was 1,433 ppm. The number of breaths per minute was multiplied by each exhalation, which showed that the first person emitted 33,440 ppm of CO2, the second emitted 23,780 ppm of CO2, and the third emitted 30,093 ppm of CO2 during the study period. A value of 40,000 ppm of CO2 was reported in the literature (Richardson *et al.*, 2014; Kim *et al.*, 2013; Rudnick and Milton, 2003), although the time over which it was obtained was not indicated.

The values obtained here were 84, 60, and 75% of the literature value.

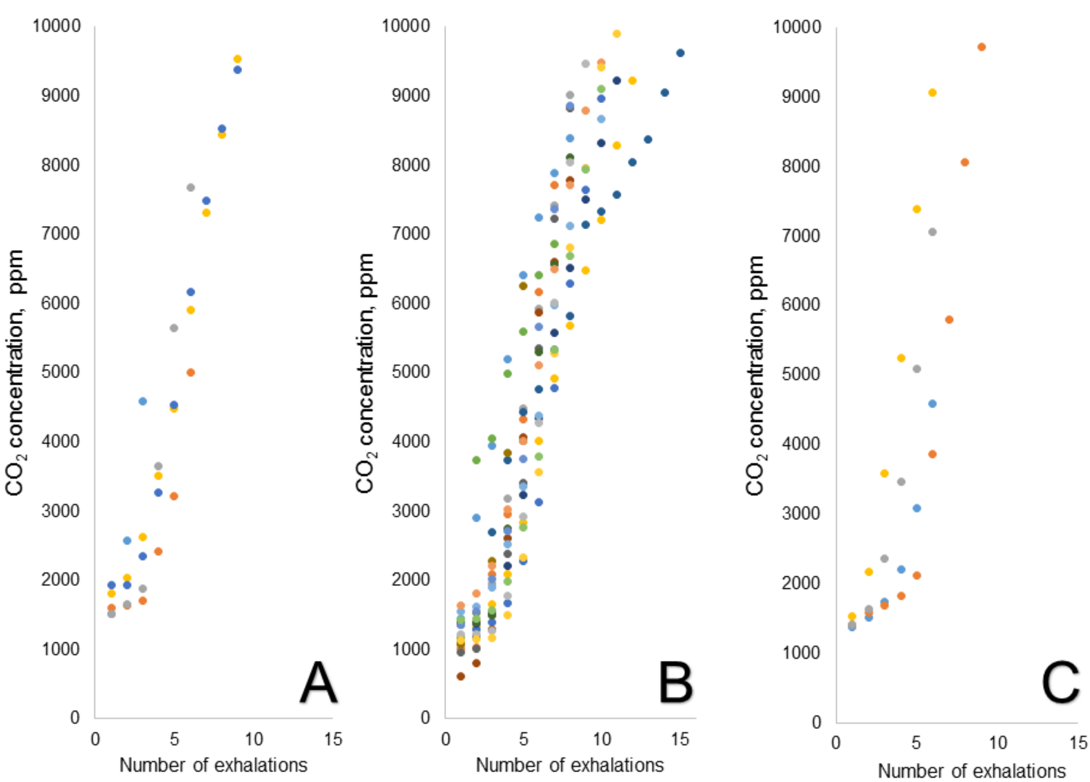

FIGURE 4. CO2 CONCENTRATION LEVELS DURING EXHALATION OF PEOPLE.
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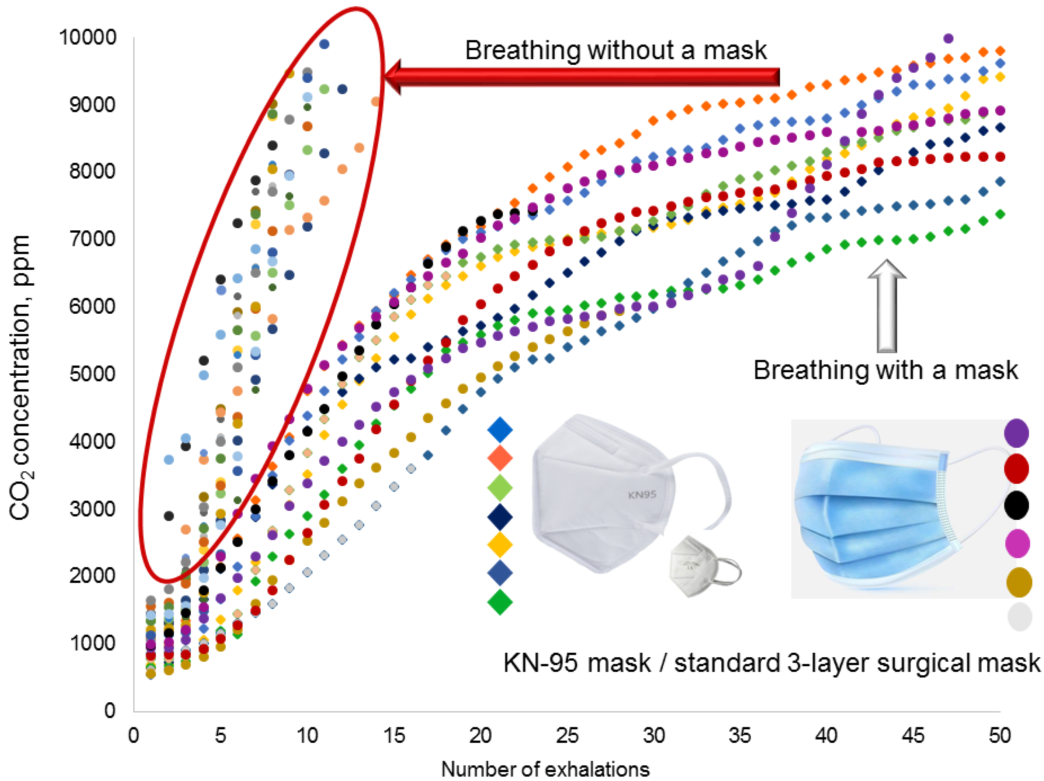

Figure 5. CO_2 concentration levels when exhaling without and with a KN-95 and standard 3-layer surgical facemasks.
Fuente: Graph of the authors.

In figure 4, the development of the CO2 concentration exhaled for persons A, B, and C are presented. It can be seen that the concentration of CO2 emitted varies depending on the metabolism. For person A, the values vary. For person B, there were minor variations, and for person C (the control) there was homogeneous behaviour in the emission of CO2 at the moment of exhaling.

The use of a facemasks and keeping a healthy distance are among the measures to protect against the spread of the SARS-CoV-2 virus (Morawska and Cao, 2020). Thus, the exhaled CO2 concentration was also evaluated using a KN-95 facemask made of polypropylene fiber (non-woven) and it is recommended by health authorities around the world. In figure 5, the CO2 concentration is shown for exhaling with and without KN-95 and standard 3-layer surgical facemasks. It can be seen that without a facemask, the CO2 concentration shows a high increase. When a facemask is used, however, the concentration decreases because the facemasks act as a barrier against the passage of CO2 gas. Therefore, it should also stop the passage of Flügge or Wells droplets that could potentially contain SARS-CoV-2.
The use of face masks is among the measures taken to prevent person-to-person transmission of the virus (SARS-CoV-2) responsible for the coronavirus disease (COVID-19). The masks act as a protective agent, their use reduces the concentration of CO2 from exhalation to the outside environment. That in the event that the person was sick with COVID-19, the mask reduces the risk of transmission of the virus to the outside environment, because it is appreciated that CO2 decreases, which indicates that it is a risk indicator for COVID-19; the lower the CO2 concentration, the lower the risk of contagion if a person has SARS-CoV-2. In addition, from another point of view, the mask protects from the outside environment towards the individual's breathing, also reducing the risk of being infected if a close person has coronavirus disease.

In each exhalation, a water vapour concentration was released in which the CO2 gas can be dissolved (normal products of the exhalation process) and when it comes into contact with the material of the mouthpiece, the CO_2 together with the vapour were sorbed on the surface of the KN-95 facemask. Carbon dioxide gas dissolves in water. Therefore, dissolved carbon dioxide reacts with water and dissociates into a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+). The majority, 89.5%, is in the bicarbonate ion form. In this case, 40% of the CO_2 released was retained in the KN-95 facemask with a pH~6.5 where, according to the distribution diagram, both species are almost in equilibrium.

CONCLUSIONS

The quality of the outdoor air regarding CO_2 is above the concentration of the atmosphere of ~416 ppm, and the reported air quality ranges from satisfactory to unacceptable.

The concentration levels of the indoor sites evaluated exceeded the IAQ limit of 1,000 ppm reported as unacceptable in closed conditions, but once ventilated, it regained its optimal IAQ. The presence of a CO_2 concentration in a closed room higher than 1,000 ppm is a sign that ventilation is unacceptable, and there is a latent probability of SARS-CoV-2 bioaerosol spreading when there is a COVID-19 patient.

The exhalation of CO_2 concentrations varied compared to the control, reaching values higher than 23,780 ppm of CO_2. This allows us to deduce that during the emission of gas, bioaerosol is suspended in air, putting the other inhabitants of the house at risk of being infected through coughing or sneezing an infected person. A KN-95 and standard 3-layer surgical mask facemask can reduce the concentration of the exhaled gas (8,000-10,000 ppm) in time and prevent the release or dispersion of SARS-CoV-2 if there is a COVID-19 sick person. The masks are useful as barriers against the virus that is in the air in the form of aerosol, although the protection is not total, a reduction in the contagion rate is appreciated.

The measurement of CO_2 is useful because it is exhaled when you breathe together with Flügge and Wells drops. These particles can be loaded with SARS-CoV-2 viruses and remain suspended in the air, putting the population at risk. It is therefore important to highlight the role that indoor air quality plays in environmental pollution and viral spread, the latter of which requires greater research focus. From an architectural point of view, it is recommended that to improve the quality of indoor air in homes, frequent ventilation should preferably be carried out with cross ventilation. It is important to indicate that there is no optimal room volume to improve indoor air quality, but that it must be ventilated until concentrations of up to 1,000 ppm are obtained, as established by the regulations. Since there are large volume rooms that do not reach the IAQ of 1,000 ppm and there will be small volume rooms where the IAQ of 1,000 ppm will potentially be exceeded, so it is suggested to ventilate to reduce these concentrations. Without and with the presence of one or more people, the IAQ value must not exceed 1,000 ppm on site.

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