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CALIDAD DEL AIRE EN VIVIENDA A TRAVÉS DEL CO₂ COMO INDICADOR DE RIESGO PARA LA SALUD

AIR QUALITY IN HOUSING THROUGH CO₂ AS A HEALTH RISK INDICATOR

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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, pero debido a los efectos de las fuentes antropogénicas, ha llegado a ~410 ppm. 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 Flüggé/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 este estudio, las concentraciones de CO₂ se midieron al aire libre, en interiores, 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 Flüggé/Wells que potencialmente contienen SARS-CoV-2 cuando una persona está enferma y disminuir el riesgo de transmisión de la enfermedad por coronavirus.

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, 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 Flüggé/Wells droplets, which affect the health of people living in a house. The reported indoor CO₂ limit is 1,000 ppm. In this study, CO₂ concentrations were measured outdoors, indoors, in human exhalation with/without 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; decreasing the risk of coronavirus disease transmission.

Keywords: CO₂, indoor air quality, outdoor air quality, SARS-CoV-2.

INTRODUCCIÓN

CO₂ 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 CO₂ 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 CO₂ 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). 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 in the middle of the sampling 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 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 are ill with COVID-19. Therefore, they

should be the most representative areas to evaluate the emission of CO₂ from the occupants or patients in quarantine. Both bedrooms were occupied by only one person during measurements, and none the occupants were smokers.

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. 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.

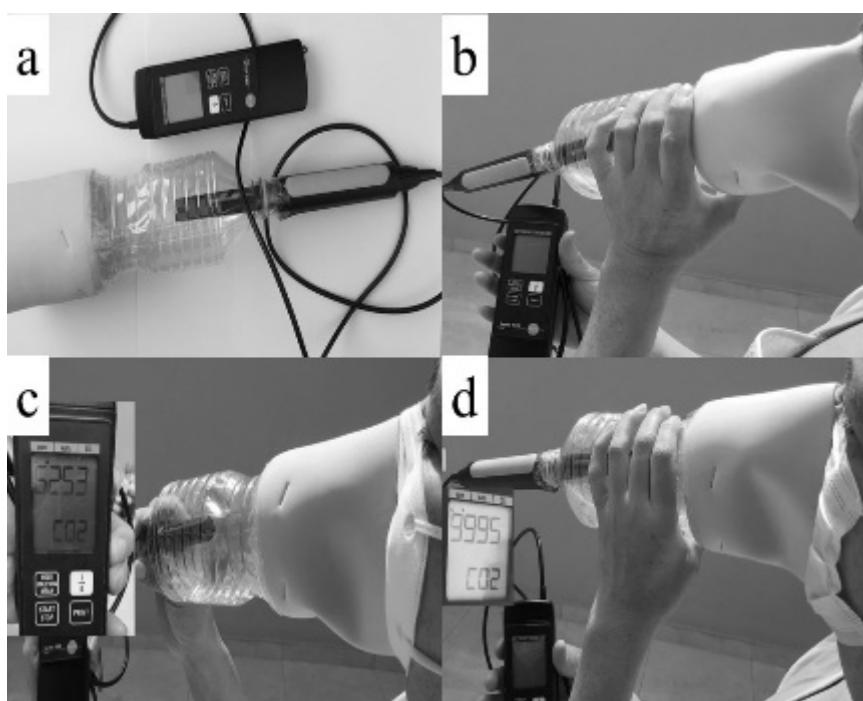


Figure 1. Measurement of carbon dioxide (CO₂) levels, during breathing without and with KN-95 and standard 3-layer surgical facemasks.

Source: 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 m³, and that of bedroom 2 (Inside 2) was 47 m³. 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. 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 330-410 ppm reported for outdoor environments (Wark and Warner, 2020; Zhang et al., 2016). CO₂ concentration levels during the data collection period were as high as 640 ppm.

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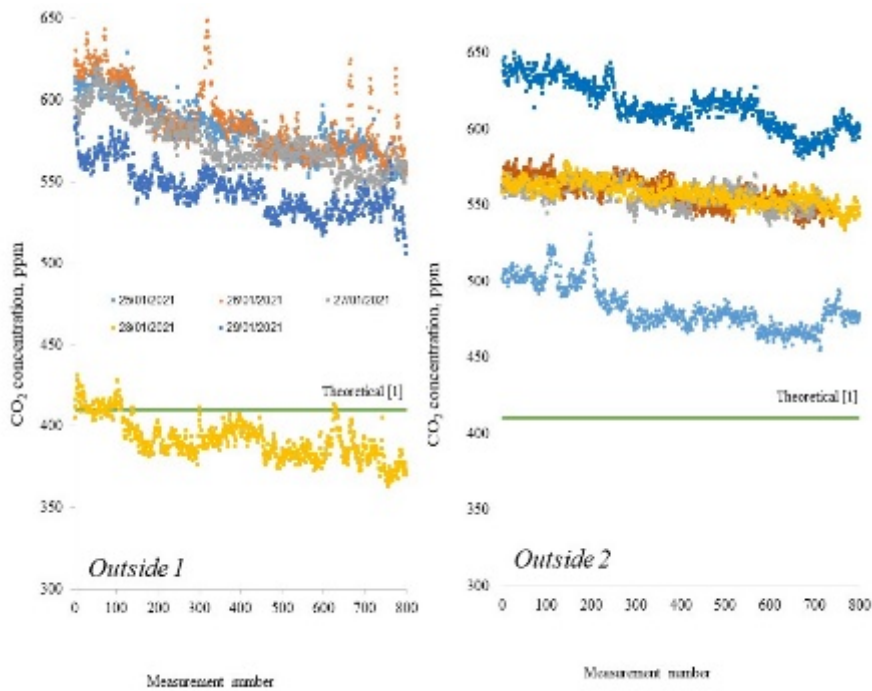


Figure 2. CO₂ concentration levels obtained for the outdoor environment.

Source: 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). 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 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.

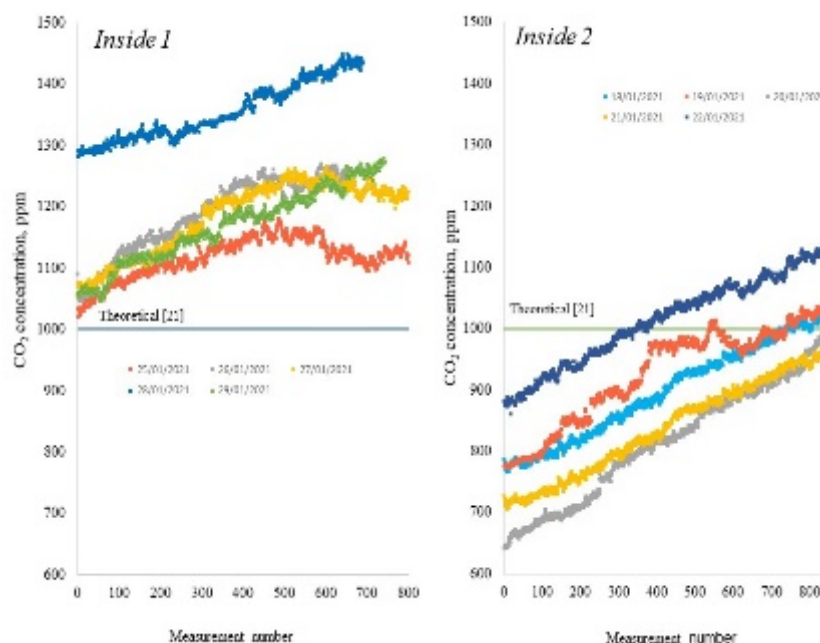


Figure 3. CO₂ concentration levels in an indoor environment with a single host inside it.

Source: 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, people’s health was taken care who live or work there for a considerable amount of time. 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.

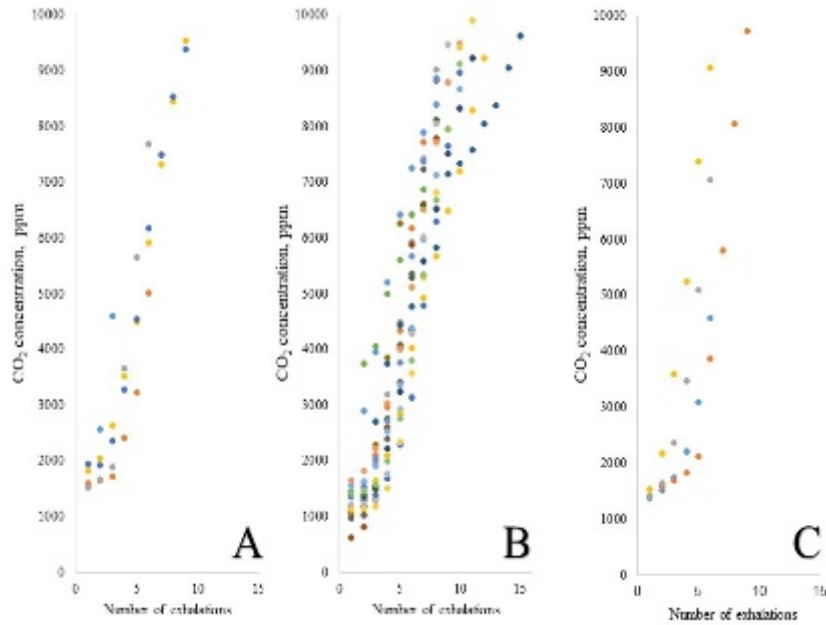


Figure 4. CO₂ concentration levels during exhalation of people.

Source: 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.

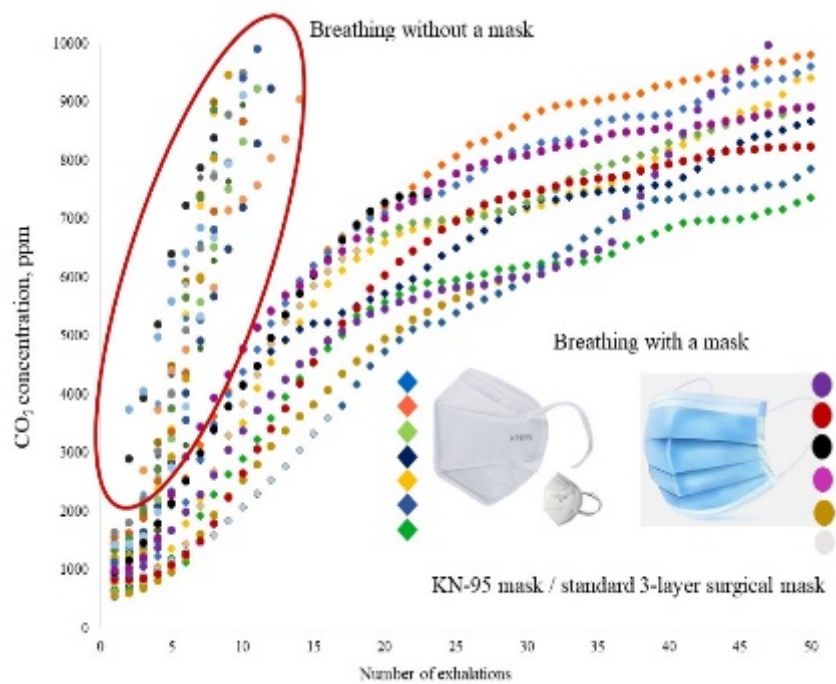


Figure 5. CO₂ concentration levels when exhaling without and with a KN-95 and standard 3-layer surgical facemasks.

Source: Graph of the authors.

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 CO₂ 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 (HCO₃⁻) and a hydrogen ion (H⁺). The majority, 89.5%, is in the bicarbonate ion form. In this case, 40% of the CO₂ 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 CO₂ is above the concentration of the atmosphere of ~410 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 CO₂ 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 CO₂ concentrations varied compared to the control, reaching values higher than 23,780 ppm of CO₂. 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 measurement of CO₂ 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.

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REFERENCES

- Adaji, E.E., Ekezie, W., Clifford, M., Phalkey, R. (2018), “Understanding the effect of indoor air pollution on pneumonia in children under 5 in low- and middle-income countries: a systematic review of evidence”, *Environmental Science and Pollution Research*, pp. 1-18.
- Argunhan, Z., Avci, A.S. (2018), “Statistical Evaluation of Indoor Air Quality Parameters in Classrooms of a University”, *Advances in Meteorology*, pp. 4391579.
- Barouki, R., Kogevinas, M., Audouze, K., Belesova, K., Bergman, A., Birnbau, L., Boekhold, S., Denys, S., Deseille, C., Drakvik, E., Frumkin, H., Garric, J., Destoumieux-Garzon, D., Haines, A., Huss, A., Jensen, G., Karakitsios, S., Klanova, H., Koskela, I.M., Laden, F., Marano, F., Matthies-Wiesler, E., Morris, G., Nowacki, J., Paloniemi, R., Pearce, N., Peters, A., Rekola, A., Sarigiannis, D., Sebková, K., Slama, R., Staatsen, B., Tonne, C., Vermeulen, R., Vineis, P. (2021), “The HERA-COVID-19 working group. The COVID-19 pandemic and global environmental change: Emerging research needs”, *Environmental International*, (146), pp. 106272.
- Bayarri, B., Cruz-Alcalde, A., Lopez-Vinent, N., Mico, M.M., Sans, C. (2021), “Can ozone inactivate SARS-CoV-2? A review of mechanisms and performance on viruses”, *Journal of Hazardous Materials*, 415(5), pp. 125658.
- Belmonte, J.F., Barbosa, R., Almeida, .G. (2019), “CO₂ concentrations in a multifamily building in Porto, Portugal: Occupants' exposure and differential performance of mechanical ventilation control strategies”, *Journal of Building Engineering*, 23, pp. 114-126.
- Chan, P.C., Fang, C.T. (2020), “The role of ventilation in tuberculosis control”, *Journal of the Formosan Medical Association*, 120(3).
- Chirizzi, D., Conte, M., Feltracco, M., Dinoi, A., Gregoris, E., Barbaro, E., La Bella, G., Ciccicarese, G., La Salandra, G., Gambaro, A., Contini, D. (2021), “SARS-CoV-2 concentrations and virus-laden aerosol size distributions in outdoor air in north and south of Italy”, *Environment International*, 146, pp. 106255.
- Ching, J., Kajino, M. (2020), “Rethinking Air Quality and Climate Change after COVID-19”, *Int. J. Environ. Res. Public Health*, 17, pp. 5167.
- Court, G., Lane, G. (2020), “Evidence summary for airborne transmission of SARS-CoV-2 via aerosols”, *Health Information and Quality Authority*, pp. 2-37.
- Deng, X., Gong, G. (2021), “Investigation of exhaled pollutant distribution in the breathing microenvironment in a displacement ventilated room with indoor air stability conditions”, *Journal of Environmental Sciences*, 99, pp. 336-345.

- Du, C.R., Wang, S.C., Yu, M.C., Chiu, T.F., Wang, J.Y., Chuang, P.C., Jou, R., Chan, P.C., Fang, C.T. (2020), "Effect of ventilation improvement during a tuberculosis outbreak in under ventilated university buildings", *Indoor Air*, 30, pp. 422-432.
- Escombe, A., Ticona, E., Chávez-Pérez, V., Espinoza, M., Moore, D.A. (2019), "Improving natural ventilation in hospital waiting and consulting rooms to reduce nosocomial tuberculosis transmission risk in a low resource setting", *BMC Infect Dis*, 19, pp. 88.
- Gert-Jan, Braun & Wim, Zeiler. (2021), "CO₂-concentration of the surrounding air of sleeping infants inside a crib", *International Journal of Ventilation*, 20, pp. 161-171.
- Horby, P.W., Landray, M.J. (2021), "Convalescent plasma in patients admitted to hospital with COVID-19 (RECOVERY): a randomised controlled, open-label, platform trial", *Lancet*, 397, pp. 2049–59.
- Jijo, L., Santhosh, C., Sajan, D.G. (2021), "Optical technologies for the detection of viruses like COVID-19: Progress and prospects", *Biosensors and Bioelectronics*, 178, pp. 113004.
- Kim, C.H., Kim, M.H., Choi, E.G., Jin, B.O., Baek, G.Y., Yoon, Y.C., Kim, H.T. (2013), "CO₂ Distribution Due to Thermal Buoyancy in the Greenhouse", *IFAC Proceedings*, 46(4), pp. 53-57.
- Kumar, M.A., Schiavon, S., Wargocki, P., Wai, T.K. (2021), "Respiratory performance of humans exposed to moderate levels of carbon dioxide", *International Journal of Indoor Environment and Health*.
- Ma'bdeh, N., Al-Zghoul, A., Alradaideh, T., Bataineh, A., Ahmad, S. (2020), "Simulation study for natural ventilation retrofitting techniques in educational classrooms – A case study", *Heliyon*, 6(10), pp. e05171.
- Madureira, J., Paciência, I., Pereira, C., Teixeira, J.P., Fernandes, E. de O. (2016), "Indoor air quality in Portuguese schools: levels and sources of pollutants", *Indoor Air*, 26(4), pp. 526-537.
- Morawska, L., Cao, J. (2020), "Airborne transmission of SARS-CoV-2: The world should face the reality", *Environment International*, 139, pp. 105730.
- Nakagawa, K., Lokugamage, K.G., Makino, S. (2016), "Viral and Cellular mRNA Translation in Coronavirus Infected Cells", *Advances in Virus Research*, pp. 96.
- Organización Mundial de la Salud (oms), A dos años de la emergencia sanitaria internacional por COVID-19, se han reportado 370 millones de casos y 5.6 millones de muertes. Disponible en <https://coronavirus.onu.org.mx/a-dos-anos-de-la-emergencia-sanitaria-internacional-por-covid-19-se-han-reportado-370-millones-de-casos-y-5-6-millones-de-muertes-oms>, consultado el 7 de mayo de 2022.
- Richardson, E.T., Morrow, C.D., Kalil, D.B., Bekker, L.G., Wood, R. (2014), "Shared Air: A Renewed Focus on Ventilation for the Prevention of Tuberculosis Transmission", *Plos one*, 9(5), pp. e96334.

- Rivero, S.O. (1991), *Neumología*, Editorial Trillas S.A. de C. V. México, 1ª reimpresión. 348 pp.
- Rodríguez, M., Llanos, P.M., Seseña, S., Rodríguez, A. (2021), “¿Are the Portable Air Cleaners (PAC) really effective to terminate airborne SARS-CoV-2?”, *Science of The Total Environment*, 785, pp. 147300.
- Romero-Guzmán, E.T., Reyes-Gutiérrez, L.R., Romero-Guzmán, L., Hernández-Mendoza, H., Uría-Gómez, L.C., Gutiérrez-Reyes, J. (2021), “An overview of bioaerosols suspended in the atmosphere of Metropolitan Zone of Toluca Valley”, *Journal of the Mexican Chemical Society*, 65(2), pp. 214-224.
- Rudnick, S.N., Milton, D.K. (2003), “Risk of indoor airborne infection transmission estimated from carbon dioxide concentration”, *Indoor Air*, 13, pp. 237-245.
- Schibuola, L., Scarpa, M., Tambani, C. (2016), “Natural ventilation level assessment in a school building by CO₂ concentration measures”, *Energy Procedia*, 101, pp. 257-264.
- Salvat-Dávila, C., Suárez-Fernández, J.P., Domínguez-Grande, M.L., Vigil-Díaz, C., Fernández-Llana, B., Martín-Fernández, N., González-García, F.J. (2020), “SARS-CoV-2 (COVID-19) pneumonia: Incidental finding on 18F-FDG PET/CT study for vasculitis diagnosis”, *Rev Esp Med Nucl Imagen Mol*, In press.
- Simanic, B., Nordquist, B., Bagge, H., Johansson, D. (2019), “Indoor air temperatures, CO₂ concentrations and ventilation rates: Longterm measurements in newly built low-energy schools in Sweden”, *J. of Building Engineering*, 25, pp. 100827.
- Tang, S., Mao, Y., Jones, R.M., Tana, Q., Ji, J.S., Li, N., Shen, J., Lv, Y., Pan, L., Ding, P., Wang, X., Wang, Y., MacIntyre, C.R., Shi, X. (2020), “Aerosol transmission of SARS-CoV-2? Evidence, prevention and control”, *Environment International*, 144, pp. 106039.
- U.S. Environmental Protection Agency (USEPA). The Inside Story: A Guide to Indoor Air Quality. Building air quality. 2021. A guide for building owners and Facility Managers. Office of air and Radiation.
- Wang, C., Prather, K.A., Sznitman, J., Jimenez, J.L., Lakdawala, S.S., Tufekci, Z., Marr, L.C. (2021), “Airborne transmission of respiratory viruses”, *Science*, 373, pp.1-12.
- Wark K., Warner, CF. (2020), *Contaminación del aire: origen y control*, Editorial Limusa. México.
- Yang, D., Jiang, L. (2017), “Simulation study on the Natural Ventilation of College Student’ Dormitory”, *Procedia Engineering*, 205, pp. 1279-1285.
- Zhang, X., Wargocki, P., Lian, Z., Thyregod, C. (2016), “Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-

assessed acute health symptoms, and cognitive performance”, *Indoor Air*, pp. 1-18.

Zhang, W., Wang, L., Ji, Z., Ma, L., Hui, Y. (2015), “Test on Ventilation Rates of Dormitories and Offices in University by the CO₂ Tracer Gas Method”, *Procedia Engineering*, 121, pp. 662-666.

Zucker, G., Sporr, A., Garrido-Marijuan, A., Ferhatbegovic, T., Hofmann, R. (2017), “A ventilation system controller based on pressure-drop and CO₂ models”, *Energy and buildings*, vol. 155, núm. 15, pp. 378-389.