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An overview of CO_2 level as an infection risk proxy for different indoor environments in Istanbul

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Abstract
Indoor CO_2 concentration is widely recognized as an effective proxy for infection risk and ventilation efficiency. In addition to improving indoor air quality, the necessity of performing indoor ventilation correctly, effectively, and efficiently to prevent or minimize the spread of SARS-CoV-2 has gained even more importance during the COVID-19 pandemic. In this study, carbon dioxide (CO_2), fine particulate matter ($PM_{2.5}$,) temperature, and humidity were monitored in sixteen different indoor environments belonging to four categories: markets, restaurants, public transportation (Metrobus), and shopping centers in Istanbul, Türkiye, during March and April 2021. Measurements were conducted using calibrated low-cost sensors (±30 ppm accuracy for CO_2) that recorded data every 20 s for 15 min on four different days. The lowest variation in CO_2 measurements was observed in shopping centers (533–663 ppm), while the highest was in restaurants (532–974 ppm). Humidity, temperature, and $PM_{2.5}$ values were also recorded and discussed. Results indicate that restaurants exhibited the highest CO_2 based infection risk due to limited or natural ventilation, whereas shopping centers with central mechanical ventilation maintained CO_2 concentrations below 650 ppm, indicating low risk. Ventilation management through continuous CO_2 monitoring is emphasized as a crucial strategy for controlling epidemic risks indoors. Recommendations include improving ventilation efficiency, using portable air cleaners with HEPA/UV filters, and visually displaying CO_2 levels via a "traffic-light" system to inform occupants about indoor safety. This study provides the first quantitative comparison of CO_2-based infection risk across multiple indoor environments in Istanbul, providing baseline data for future research and public health policies.

Keywords CO_2 · Indoor air quality · Ventilation

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Introduction

Nowadays, people spend more than 90% of their time indoors in urban living spaces in the world (TurkStat 2020). Previous studies on indoor air pollution have mainly focused on the detection of particulate matter (PM). Several studies conducted in Istanbul revealed that indoor pollutant levels are generally 2–5 times higher than outdoor levels (Yurtseven et al. 2012; Şahin et al. 2012; Onat and Stakeeva 2013, 2014; Onat et al. 2017, 2019a, 2019b). In studies conducted on public transportation vehicles in Istanbul, it was determined that the $PM_{2.5}$ exposure in naturally ventilated buses is much higher than in the Metrobus and the rail systems with mechanical ventilation systems (Onat et al. 2019b). In public transportation vehicles, $PM_{2.5}$ exposure in naturally ventilated buses was found to be considerably higher than in rail systems equipped with mechanical (Onat et al. 2019b). Similarly, higher PM concentrations have been observed in underground metro systems compared to outdoor, and aerosols condensation in the air as the depth of the station increases and depending on the ventilation efficiency (Şahin et al. 2012; Onat et al. 2017).

Data from several studies suggest the highest risk of transmission in the COVID-19 by air and aerosols (Hadei et al. 2020; Morawska and Cao 2020; Morawska and Milton 2020).Numerous studies have shown that poorly ventilated indoor spaces significantly increase transmission risk. For instance, Onat et al. 2017 reported a strong correlation ($r=0.61$) between *Staphylococcus aureus* bacteria and $PM_{2.5}$ levels in Istanbul's public transport. Comparable patterns have been documented for various airborne microorganisms present in indoor environments, underscoring the coupled influence of particulate burden and ventilation dynamics on microbial persistence and dispersion. (Metiner et al. 2021; Sivri et al. 2020). Respiratory activities such as talking, coughing, and breathing release thousands of aerosols into the indoor atmosphere (Buonanno et al. 2020).

Studies have demonstrated that both aerosols and CO_2 are exhaled simultaneously and accumulate in closed environments, making CO_2 a reliable proxy for occupancy and ventilation (Rudnick and Milton 2003; Du et al. 2019; Peng and Jimenez 2021).While direct real-time monitoring of virus-laden aerosols is difficult and costly, CO_2 monitoring offers a simple and practical method to assess airborne infection risk (ASHRAE, 2024). The typical outdoor CO_2 level is around 420 ppm (NOAA 2021) and indoor concentrations increase with human activity and poor ventilation. Previous studies have shown that reducing indoor CO_2 below 600 ppm can substantially decrease the risk of airborne disease transmission (María et al. 2020) and classified below 700 ppm CO_2 as the low risk of transmission of COVID-19 (Di Gilio et al. 2021).

Recent studies have further emphasized CO_2 monitoring as an effective tool for managing indoor air quality and minimizing infection risk. For example, Di Gilio et al. (2021) and Sofuoğlu et al. (2025) highlighted its use in classrooms, while Malki-Epshtein et al. (2023) evaluated ventilation performance during mass indoor events. In addition, low-cost NDIR sensors have proven suitable for continuous CO_2 measurement with acceptable uncertainty (<3%) (Pastor-Fernández et al. 2022; Wiryasaputra et al. 2023).

Although there are studies in Türkiye focusing on indoor particulate levels and microbial contamination (Onat et al. 2017; Sivri et al. 2016, 2020), existing research aiming to evaluate CO_2-driven infection risk across multiple indoor environments remains limited in scope. Most investigations have focused on single locations or selected pollutants without assessing ventilation effectiveness or exploring meaningful interactions among key environmental parameters. Therefore, the objectives of this study are: (i) to monitor CO_2, $PM_{2.5}$, temperature, and humidity in representative indoor environments of Istanbul, including markets, restaurants, public transportation, and shopping centers; (ii) to evaluate indoor air quality and infection-risk levels using CO_2 thresholds from recent literature; and (iii) to provide recommendations for effective ventilation management and public awareness.By addressing these objectives, this study presents the first comparative CO_2-based infection-risk analysis covering multiple indoor environment types in Istanbul, contributing to healthier and better-ventilated indoor spaces in future public health strategies.

Material and method

Within the scope of this study, CO_2, $PM_{2.5}$, humidity, and temperature monitoring were carried out in sixteen different indoor environments belonging to four main categories: markets (M), restaurants (R), public transportation (Metrobus), and shopping centres' (SC) with high occupancy density. Measurements were performed in March and April 2021, a period during which the average daily COVID-19 case and death numbers in Türkiye were 34,738 and 190, respectively (MoH 2022). During these dates, schools were closed, but there were no restrictions on the selected indoor spaces, and regular daily activities continued. Site selection was made considering both occupant density and representativeness of typical urban indoor environments in Istanbul. In the public transportation category, the metrobus was chosen as the most preferred road transport in Istanbul, with a daily passenger count of up to 300,000 (IETT 2019). For the shopping mall category, the food court areas were selected as they represent the highest occupant turnover. In the market category, measurements were performed in the

central aisles, while for the restaurant category, lower floors with higher occupancy were chosen. These sites represent common indoor scenarios where people spend extended time with variable ventilation systems.Detailed information about the selected areas, sampling times, human densities, and air ventilation systems of places are provided in Table 1.

Monitoring was conducted for each of the four location categories by recording one data point every 20 s over a 15-min period on separate days. Also, outdoor data for $PM_{2.5}$, temperature, and humidity were obtained from the nearest air quality monitoring station in Avcılar operated by the Istanbul Metropolitan Municipality. 15 min averages corresponding to each indoor sampling period were used to compare indoor–outdoor differences.

Airqoon IAQ sensor device produced and serviced by Airqoon was used to measure the parameters. The general view of the device, its use at measurement sites, and the data tracking screen are shown in Fig. 1. Measurements

Table 1 Measurement places, location codes, date, time, and descriptions

Location categories	Location codes	Date	Time interval	Human density level (from low −1 to high level-5)*	Air ventilation system
Metrobus (PT)	PT 1	17.03.2021	13:29–13:44	2	Natural with door and Central/Work on
	PT 2	06.04.2021	13:45–14:00	3	Natural with door and Central/Work on
	PT 3	06.04.2021	14:26–14:41	5	Natural with door and window and Central/Work on
	PT 4	06.04.2021	14:55–15:10	2	Natural with door and window and Central/Work on
Market (M)	M 1	17.03.2021	14:30–14:46	1	Central/Work on
	M 2	31.03.2021	15:22–15:36	2	Central/Work off
	M 3	31.03.2021	15:52–16:07	2	Central/Work on
	M 4	05.04.2021	15:52–16:07	2	Central/Work on
Shopping Center (SC)	SC 1	17.03.2021	15:09–15:28	4	Central/Work on
	SC 2	05.04.2021	16:58–17:15	2	Central/Work on
	SC 3	05.04.2021	18:42–18:57	2	Central/Work on
	SC 4	06.04.2021	15:55–16:13	1	Central/Work on
Restaurant (R)	R 1	17.03.2021	16:20–16:40	3	Central/Work off
	R 2	19.03.2021	13:58–14:13	4	Central/Work on
	R 3	19.03.2021	15:57–16:12	2	Natural with door
	R 4	06.04.2021	13:04–13:19	3	Natural with door

*Human density levels; PT(persons for each Metrobus): 1:0–40, 2:40–80, 3:80–120, 4:120–160, 5:160–200. Market(persons for each 100m^2 area): 1:0–5, 2:5–10, 3:10–15, 4:15–20, 5:20–25. SC(persons for each 1000m^2 area): 1:0–20, 2:20–40, 3:40–60, 4:60–80, 5:80–100. Restaurant(occupancy %percentages of tables): 1:0–20, 2:20–40, 3:40–60, 4:60–80, 5:80–100

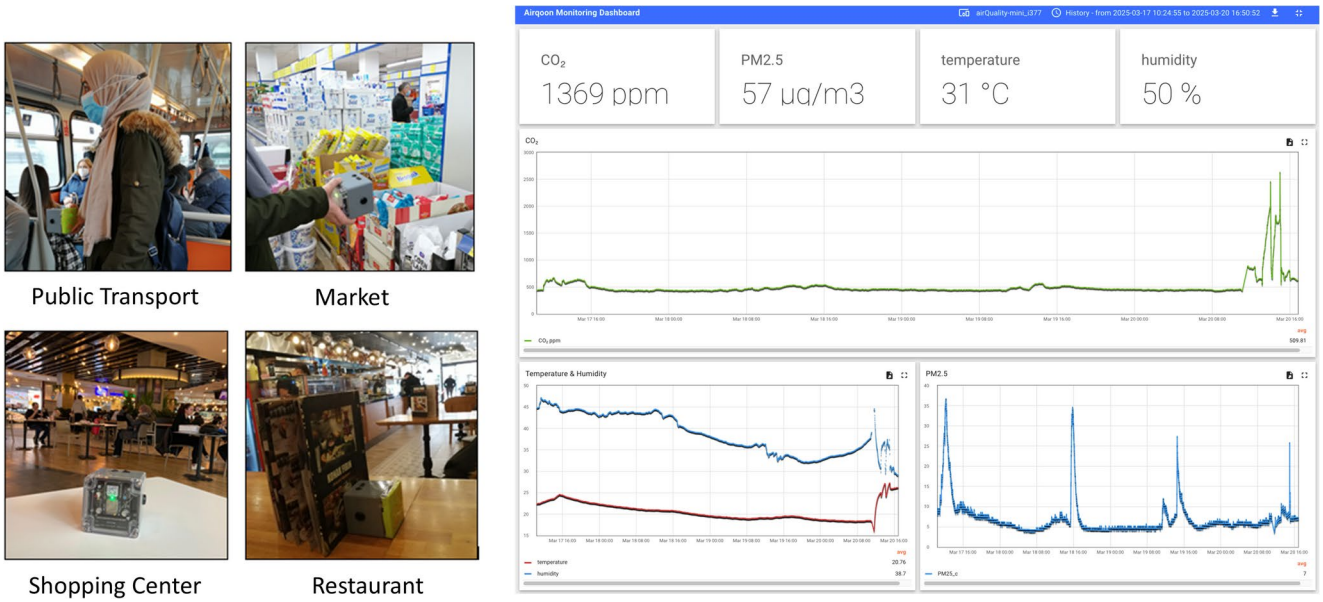


Fig. 1 Photos of the usage areas of the airqoon indoor air quality (IAQ) measurement equipment and data tracking screen

were conducted using Airqoon IAQ devices, which contain three sensor modules: Sensirion SCD30 (CO_2), Honeywell HPMA115S0 ($PM_{2.5}$), and SI7021 (temperature and humidity). The device is portable, rechargeable (up to 8 h operation), and transmit data in real time through the Airqoon cloud platform. CO_2, relative humidity, and temperature sensors were calibrated with Testo 480 (Testo 2021). $PM_{2.5}$ sensor was calibrated with Envea SA MP101M (Envea 2021). Instrumental uncertainties were estimated as follows: ±30 ppm for CO_2, ±5 µg m^{-3} for $PM_{2.5}$, ±0.5 °C for temperature, and ±3% for relative humidity. Data quality assurance was ensured through pre- and post-deployment zero checks and inter-comparisons.

All data and functional management of the device is carried out remotely by the Airqoon cloud platform. The device's internet access can be followed via GSM and by

Table 2 Measurement areas, date, time and descriptions. (Out: outdoor level, In: indoor level)

Areas	Codes	CO_2 (ppm)	$PM_{2.5}$ (µg/m^3)		Temperature (°C)		Humidity (%)		Risk class* of indoor
		In	Out	In	Out	In	Out	In	
Public Transport (PT)	PT 1	740±59	13.3	4.9±0.8	9	22.2±0.1	76.6	32.9±0.8	moderate
	PT 2	618±20	21.0	8.1±2.1	14	21.9±0.7	78.3	43.5±1.6	low
	PT 3	804±122	23.4	10.6±2.8	14	22.9±0.5	71.6	44.0±1.4	high
	PT 4	700±62	25.4	11.0±2.4	14	23.0±0.1	70.5	43.5±1.7	moderate
Market (M)	M 1	523±29	13.3	9.4±4.2	9	21.0±0.2	73.6	33.0±0.6	low
	M 2	904±146	9.5	7.7±0.8	10	14.0±1.4	69.8	52.0±1.4	high
	M 3	601±21	7.3	5.0±0.9	10	17.0±0.8	71.4	45.0±1.1	low
	M4	561±23	13.4	7.2±1.8	9	18.0±0.5	89.3	39.0±0.4	low
Shopping Center (SC)	SC 1	632±21	13.0	10.9±2.1	9	21.8±1.0	73.7	32.4±1.1	low
	SC 2	663±5	9.4	17.6±1.1	9	19.3±1.0	85.8	44.8±2.0	low
	SC 3	533±5	8.8	14.0±1.0	9	20.1±0.5	86.0	40.8±1.2	low
	SC 4	585±4	21.7	30.1±2.2	9	22.6±0.7	65.9	42.5±1.4	low
Restaurant (R)	R 1	974±117	10.7	91.5±6.5	9	21.0±0.8	75.7	37.3±0.4	high
	R 2	638±8	17.5	40.0±30.1	10	17.2±0.8	71.7	42.9±1.0	low
	R 3	827±160	15.0	15.6±3.1	10	16.6±1.3	86.0	47.3±2.3	high
	R 4	532±9	23.4	37.2±8.4	14	19.5±0.6	60.6	49.8±0.8	low

*CO_2 concentrations for risk classes: CO_2 < 700 ppm = low risk, 700 < CO_2 < 800 ppm = moderate risk, 800 < CO_2 < 1000 ppm = high risk, CO_2 > 1000 ppm = very high risk

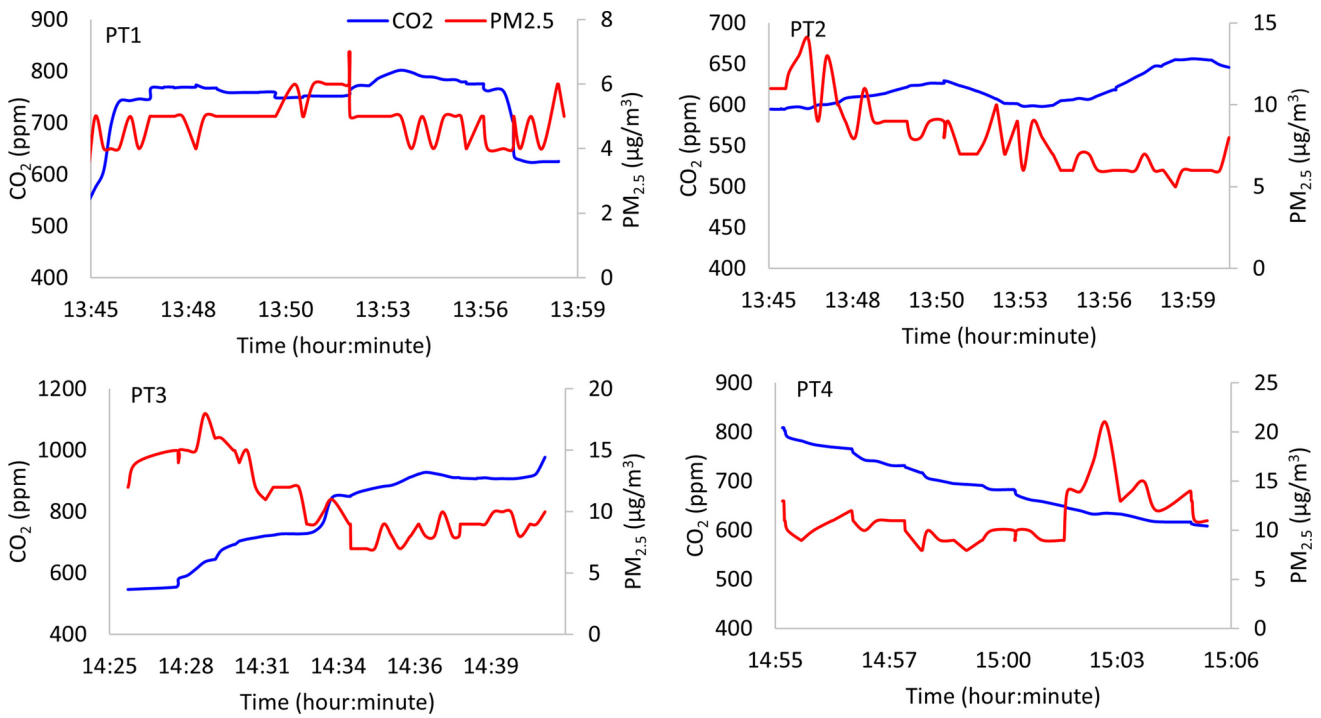


Fig. 2 CO_2 and $PM_{2.5}$ concentration changes in the indoor air of the PT

entering user information, both from mobile and computer, as real-time data, and graphical visuals. An example page view is given in Fig. 1. The relationships among parameters (CO_2, $PM_{2.5}$, temperature, and humidity) were analyzed using the coefficient of determination (R^2), and statistical significance was tested at the 95% confidence level ($p < 0.05$). All statistical analyses were performed in Microsoft Excel and verified with SPSS software for consistency.

Results and discussion

Average values of all measurements made in indoor environments are given in Table 2. It was not possible to make simultaneous outdoor measurements times indoor measurements. There are 39 outdoor air quality measurement stations in Istanbul and only 18 of them measure $PM_{2.5}$. Detailed information about measurement methods and data acquisition are given in the study by Şahin et al. (2020 and 2024). The closest outdoor air quality measurement station to the area where indoor measurements were made is Avcılar, and hourly average $PM_{2.5}$, temperature, and humidity values of the measurements made at the same time were used and the results are given in Table 2. While the highest $PM_{2.5}$ change was observed on March 19 and April 6 when indoor measurements were made, the average hourly $PM_{2.5}$ concentration in all stations generally varied between 5 and 40 µg/m^3. There is no statistically significant correlation between the mean $PM_{2.5}$ measured indoors and the $PM_{2.5}$ measured at outdoor air quality measurement

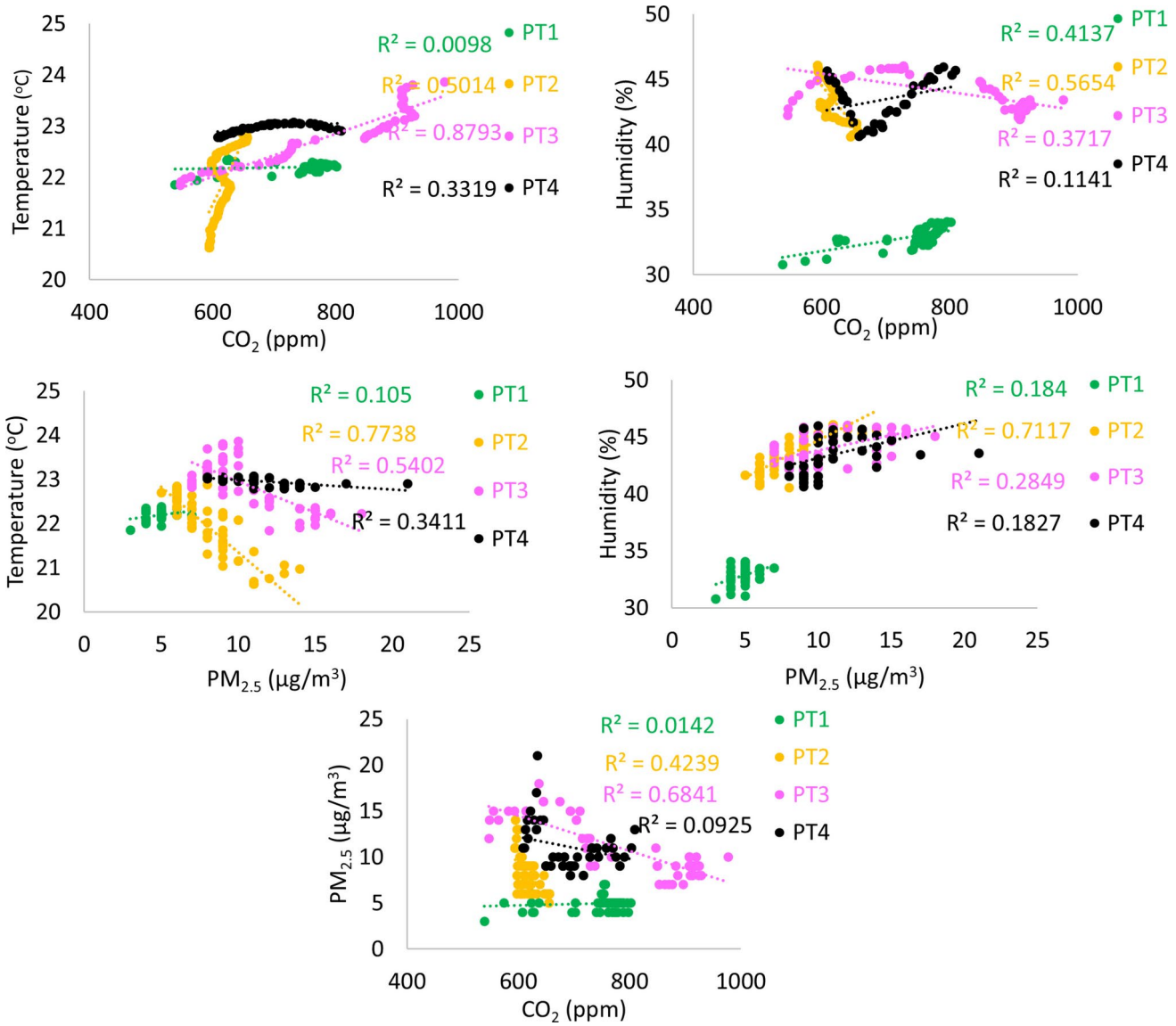


Fig. 3 The correlation among the parameters: CO_2, $PM_{2.5}$, temperature, and humidity measured in the PT

stations ($p > 0.05$). However, in previous studies on $PM_{2.5}$ levels in public transportation vehicles, it has been stated that the outdoor air quality in micro-environments such as vehicle routes and stations significantly affect the interior environment of public transportation vehicles (Onat et al. 2019a). While studies during the pandemic have focused on the relationship between outdoor $PM_{2.5}$ concentrations and COVID-19, indoor studies have primarily measured air quality. However, achieving indoor $PM_{2.5}$ concentration targets can be challenging. A study conducted in Spain found that, after schools reopened during the pandemic, indoor $PM_{2.5}$ concentrations exceeded the WHO's recommended limits by 63% (Villanueva et al. 2021). Additionally, another study in a hospital environment found that the number of patients and their symptoms affect both $PM_{2.5}$ levels and the amount of SARS-CoV-2 RNA present in the air (Nor et al. 2021). In this study, it was not possible to take simultaneous outdoor measurements for each indoor environment, and therefore a direct relationship could not be established; however, previous research provides evidence of consistent associations between outdoor conditions and corresponding indoor parameters.

The humidity variation in the outdoor atmosphere of Istanbul during the measurement period is between 60 and 90% (Table 2). On the other hand, it is seen that there is a variation between 32 and 52% in indoor environments. During the pandemic, indoor humidity is an important criterion in the spread of the virus and the recommendation to keep it in the range of 40–60% is stated in many studies (Ahlawat et al. 2020; Guo et al. 2021). Particularly, indoor humidity modulates the spread and severity of COVID-19 outbreaks (Verheyen and Bourouiba 2022). Low humidity increases the formation of aerosols exhaled from infected individuals, and raising indoor air humidity from dry air improves respiratory health while reducing the viability of infectious viruses (Wolkoff 2024). Temperature does not have a significant impact on the spread of COVID-19 indoors (Park et al. 2022). However, this is applicable for warm seasons, and increasing temperatures in cold environments significantly reduces the transmission of COVID-19. Additionally, areas with low temperatures and high humidity should be carefully examined (Mao et al. 2023). While outdoor temperatures vary between 9–14 °C, indoor temperatures vary between 14–23 ^{0}C in this study.

It is known that the CO_2 values in the outdoor environment are generally between 420–480 ppm (Pacitto et al. 2020), and not very large changes are expected in the outdoor atmosphere and are considered constant. Although the measurement did not done simultaneously in this study, the CO_2 concentration was determined in the range of 400–450 ppm in the outdoor measurement made after all measurement campaign. In this study, all indoor CO_2 levels were determined higher than 500 ppm. Di Gilio et al. (2021) determined the risks of transmission of COVID-19 according to the indoor CO_2 concentration. They described four risk classes depending on the CO_2 concentration: < 700 ppm

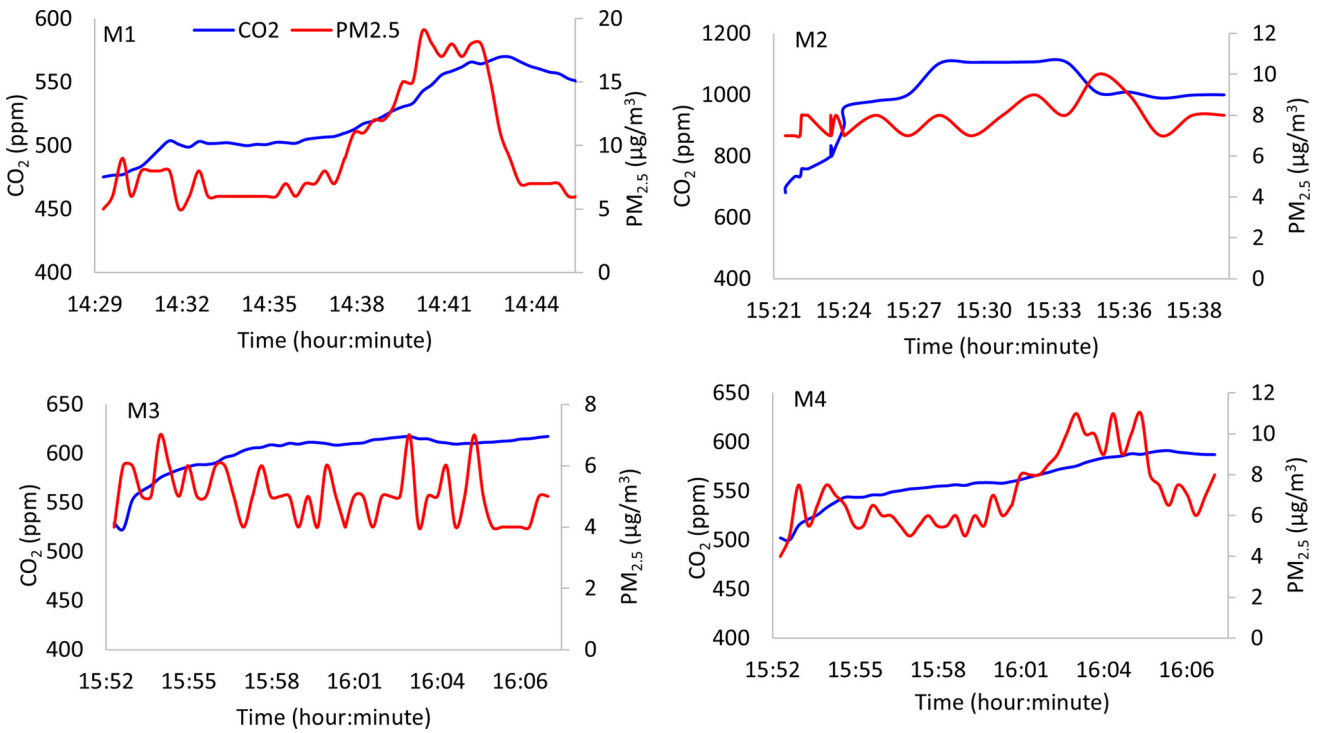


Fig. 4 CO_2 and $PM_{2.5}$ concentration changes in the indoor air of markets (M)

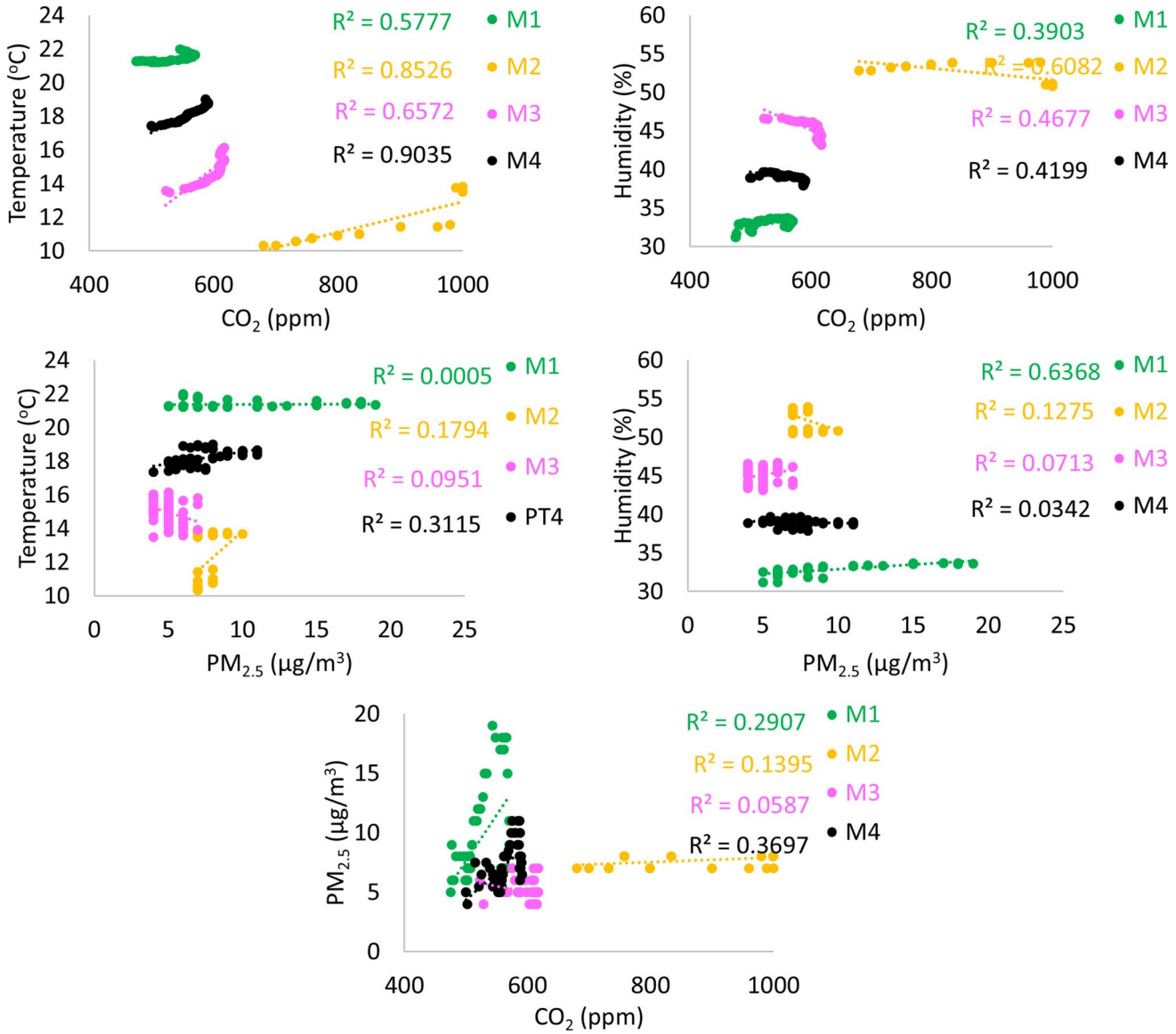


Fig. 5 The correlation among the parameters: CO_2, $PM_{2.5}$, temperature, and humidity measured in the markets

for low risk, from 700 to 800 ppm for moderate risk, from 800 to 1000 ppm for high risk, > 1000 ppm for very high risk. Based on this study, the risk class of indoor areas in this study was evaluated and reported in Table 2. Accordingly, it can be clearly seen that SCs have the lowest risk and R have the highest risk despite they are changing for each measurement campaign.

Public transport

The temporal variation of the CO_2 and $PM_{2.5}$ measurements conducted in the public transport vehicles are shown in Fig. 2.The lowest average CO_2 (618 ppm) was recorded in PT2, while the highest (804 ppm) occurred in PT3, coinciding with the highest passenger density (level 5). A short-term CO_2 peak of approximately 804 ppm was detected during the PT3 trip, coinciding with door closure and maximum passenger load. This transient rise indicates that even brief interruptions in air exchange can cause a rapid increase in indoor CO_2, demonstrating the sensitivity of public transport environments to occupancy dynamics and ventilation timing. The lowest mean $PM_{2.5}$ concentration was observed in PT1 at 4.9 µg/m^3, and the highest at 11.0 µg/m^3 in PT4 (Table 2). In the previous study conducted by Onat et al. (2019a) in Istanbul, $PM_{2.5}$ concentrations in the metrobus and the stations were observed at 17.1–26.5 µg/m^3 and 24.0–35.5 µg/m^3, respectively. Smaller $PM_{2.5}$ concentrations in this study may be related to the measurement conducted during the non-rush hours in the vehicle for only 15 min (Onat et al. 2019a).

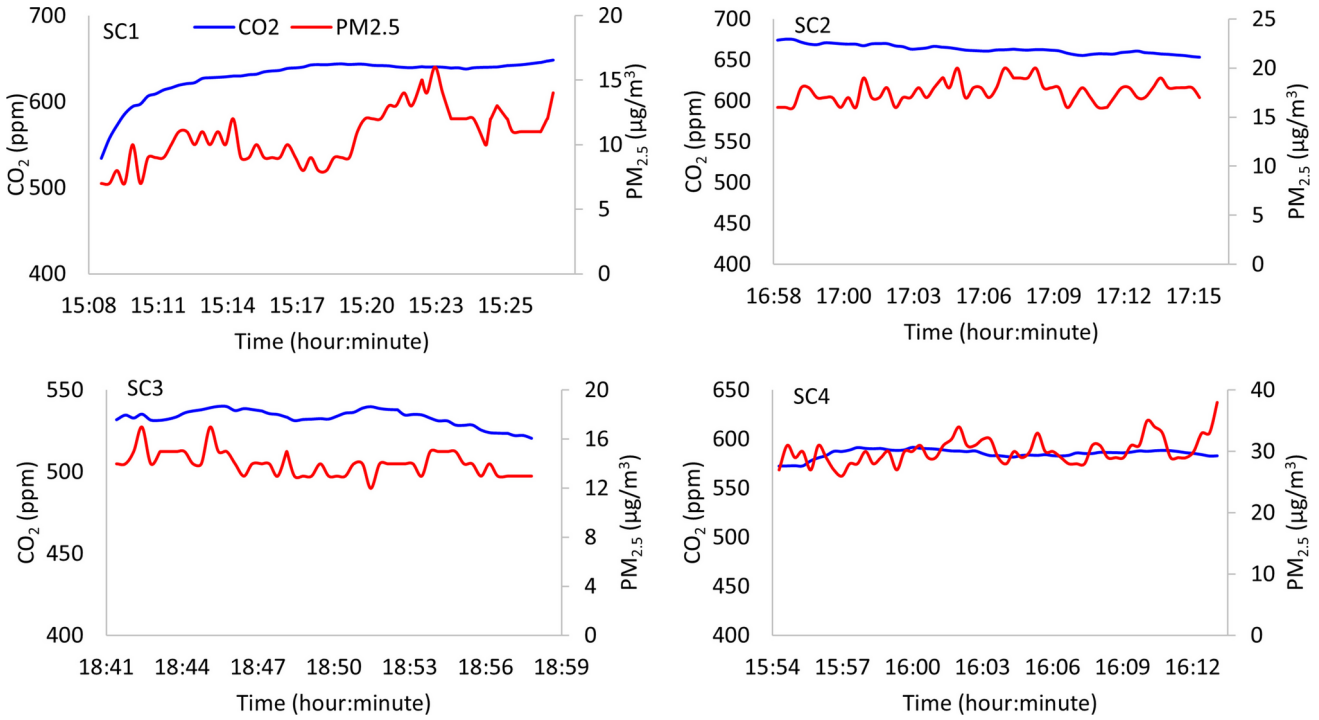


Fig. 6 CO_2 and $PM_{2.5}$ concentration changes in the indoor air of SCs

Due to the high number of occupants in PT3 compared to other trips, the highest CO_2 level was observed, and an increasing trend occurred during the trip (Fig. 2). CO_2 variation depends on the number of people in the indoor environment (Huang and Hsu 2009; Kim 2020). Differences in $PM_{2.5}$ are due to the difference in $PM_{2.5}$ concentrations in the external environment. Onat et al. (2019a) stated that factors such as opening and closing of doors at stops, characteristics of stations (closeness to the main road, route, etc.), and traffic density can affect in-vehicle pollutant concentrations.

The correlation between the changes of all parameters in of the public transport vehicle is given in Fig. 3. There was no significant correlation ($p > 0.05$) between the parameters in PT1 and PT4. However, a significant negative correlation (PT2-R = −0.65, PT3-R = −0.82) is observed between CO_2 and $PM_{2.5}$ during PT2 and PT3 measurements. In addition, while there is a positive correlation between CO_2 and temperature in PT2 and PT3, there is a negative significant correlation between $PM_{2.5}$ and temperature. Onat et al. (2019) showed that temperature was a significant factor in the variations of $PM_{2.5}$(Onat et al. 2019c). In PT2 and PT3, CO_2 values increased as the ambient temperature increased, whereas $PM_{2.5}$ decreased. As seen in Table 1, the density of people in the vehicle in PT2 and PT3 trips is relatively higher compared to other trips. In the study conducted by Onat et al. (2017), a significant correlation (0.61) was found between $PM_{2.5}$ and *Staphylococcus aureus* bacteria and the relationship between the CO_2 mixed with the air and the $PM_{2.5}$ increase in Istanbul Metrobus vehicles (Ding et al. 2016; Onat et al. 2017).

Market

The temporal concentrations in 4 different markets are given in Fig. 4. The highest average CO_2 (904 ppm), humidity (52%), and lowest temperature (14 °C) values were determined in M2 (Table 2). There is central ventilation in all markets, but it was observed that the ventilation system was working during the measurement in M1, M3, and M4, while the ventilation did not work in M2. Although the average people density in the markets is similar, the fact that the ventilation system is not operated and there are no open doors (automatic doors are available) and windows that are constantly not open for natural ventilation causes an increase in CO_2 in the environment. When $PM_{2.5}$ measurements are evaluated, it is seen that the average $PM_{2.5}$ varies in the range of 5–10 µg/m^3 in all measurements. It is not possible to reveal the effectiveness of ventilation with $PM_{2.5}$ change since there are different times and different places and a fixed background $PM_{2.5}$ cannot be defined.

In Fig. 5, the correlation between the changes of all parameters in the markets is given. There is a significant correlation (R from 0.75 to 0.95-$p < 0.05$) between temperature and CO_2 in all market measurements. However, there is no relationship between $PM_{2.5}$ and temperature. Likewise, a moderate correlation was observed between CO_2 and

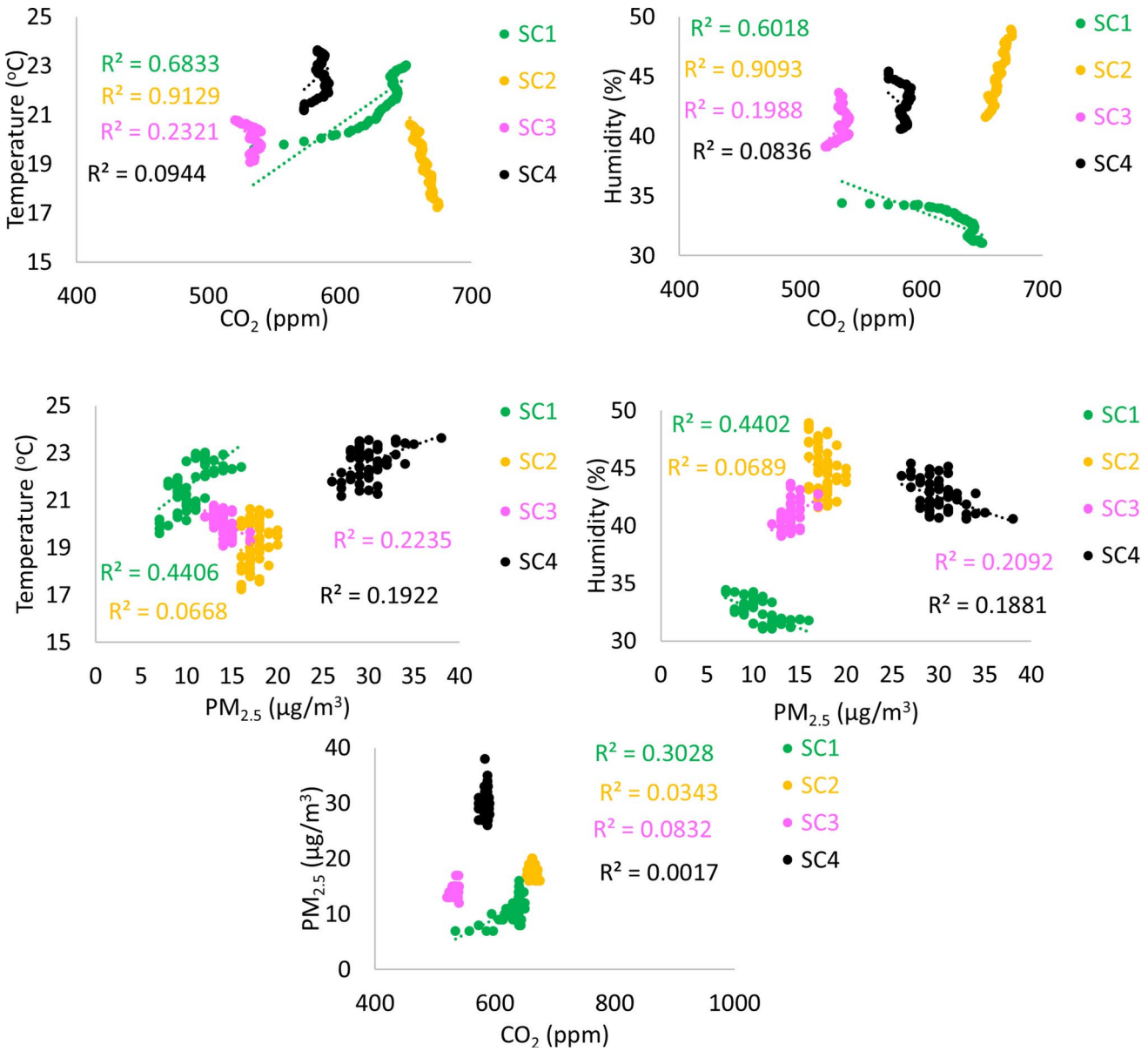


Fig. 7 The correlation among the parameters: CO_2, $PM_{2.5}$, temperature, and humidity measured in the SCs

humidity, but no significant correlation was observed with $PM_{2.5}$, except for M1. While a moderate correlation was observed between $PM_{2.5}$ and CO_2 in M1 and M4 measurements, no significant correlation was detected in M2 and M3.

Shopping center

In Fig. 6, the change in CO_2 and $PM_{2.5}$ measured in Shopping Centers is given. It is seen that the CO_2 level is 500–600 ppm and the general deviation during the measurement is at the level of 5 ppm. However, while $PM_{2.5}$ varies between 10–17 µg/m^3 in SC1, SC2, and SC3, 30 µg/m^3 was detected in SC4. While the concentration of $PM_{2.5}$ in the outdoor environment is approximately 10 µg/m^3 in SC1, it is seen to be 21 µg/m^3 at the time of SC4 measurement. In addition, $PM_{2.5}$ concentrations in SC indoor environments are generally about 1.5 times higher than outdoors. On the contrary, in the previous study in Istanbul, $PM_{2.5}$ concentrations in the SC were observed lower than the outdoor concentration (Onat et al 2011). However, the outdoor $PM_{2.5}$ concentration and the variation of ventilation mode can affect indoor $PM_{2.5}$ concentrations. Within the scope of pandemic measures, central ventilation in all SCs is operated with 100% outdoor air during the measurement process. Although this situation provides good ventilation despite the human density in the indoor environment, it causes the accumulation of polluted air from the outdoor environment

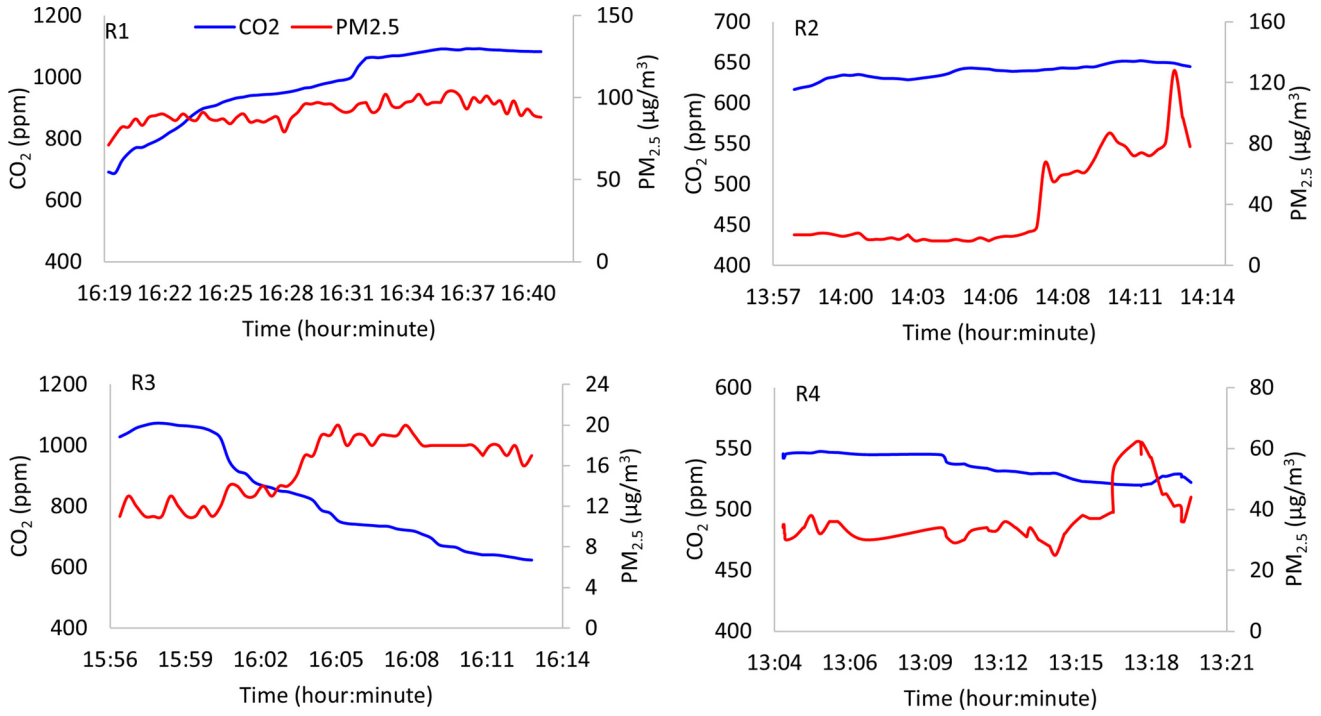


Fig. 8 CO_2 and $PM_{2.5}$ concentration changes in the indoor air of the restaurants (R)

in the indoor environment. For this reason, to the energy efficiency and healthy indoor air, ventilation filtration systems must be improved in SCs.

In Fig. 7, the correlation between the changes of all parameters in the SCs is given. A high negative and positive correlation ($R = -0.95$ and 0.95) between CO_2 and temperature and humidity was observed in SC2 and a moderate positive and negative correlation ($R = 0.77$ and -0.82) was observed in SC1, respectively. Similar to CO_2 in SC1, a moderate positive and negative correlation ($R = 0.66$ and -0.66) was observed between $PM_{2.5}$ and temperature and humidity, respectively.

Restaurant

Figure 8 shows the results of CO_2 and $PM_{2.5}$ measurements conducted in restaurants. It represents 4 different measurements in terms of both CO_2 and $PM_{2.5}$.The highest CO_2 concentration (974 ppm) was recorded in R1, where central ventilation was inactive and windows were closed. This anomalously high CO_2 concentration in R1 reflects the combined effect of limited air exchange, high occupancy, and continuous human activity during peak dining hours. The CO_2 level approached the "very high risk" threshold (>900 ppm) defined by Di Gilio et al. (2021), emphasizing the critical role of ventilation mode and occupancy control in restaurants. The CO_2 measured in R2 and R4 is constant with a standard deviation of 8–9 ppm and below 650 ppm. R1 and R2 have central ventilation, while R1 is closed, R2 is open during the measurement. R3 and R4 have natural, open-door ventilation. Closed central ventilation and insufficient natural ventilation cause an increase in CO_2 concentration. While $PM_{2.5}$ is between 10–23 µg/m^3 in the outdoor environment, the average values are between 15–91 µg/m^3 in indoor measurements (Table 2) and there is no significant relationship between indoor and outdoor environment. Pacitto et al. (2020) stated that the particles between PM_1 and PM_{10} are more than in the external environment, especially in indoor environments with human density, and the particle number count (PNC) does not change.

In studies where aerosols emitted from breathing, speaking, and sneezing respiratory activities were directly measured, aerosol sizes were found to range from 10 nm to 145 µm (Holmgren et al. 2010; Johnson et al. 2011; Asadi et al. 2019). It was determined that 14600 particles/minute particle number (PN) was given to the air by speaking and 6210 particles/minute was by breathing. This high difference in PN (2.3 times) does not occur in CO_2, but it has been shown that 139 ppm/minute is given to the air in speaking and 143 ppm/minute in breathing (Kappelt et al. 2021). Sudden $PM_{2.5}$ increases, especially in R2, R3, and R4, are due to human mobility nearby in the measurement areas, eating without a mask, and talking loudly. CO_2 levels can be reduced with central ventilation and natural ventilation (Cheng et al. 2022). However, it will be possible to remove

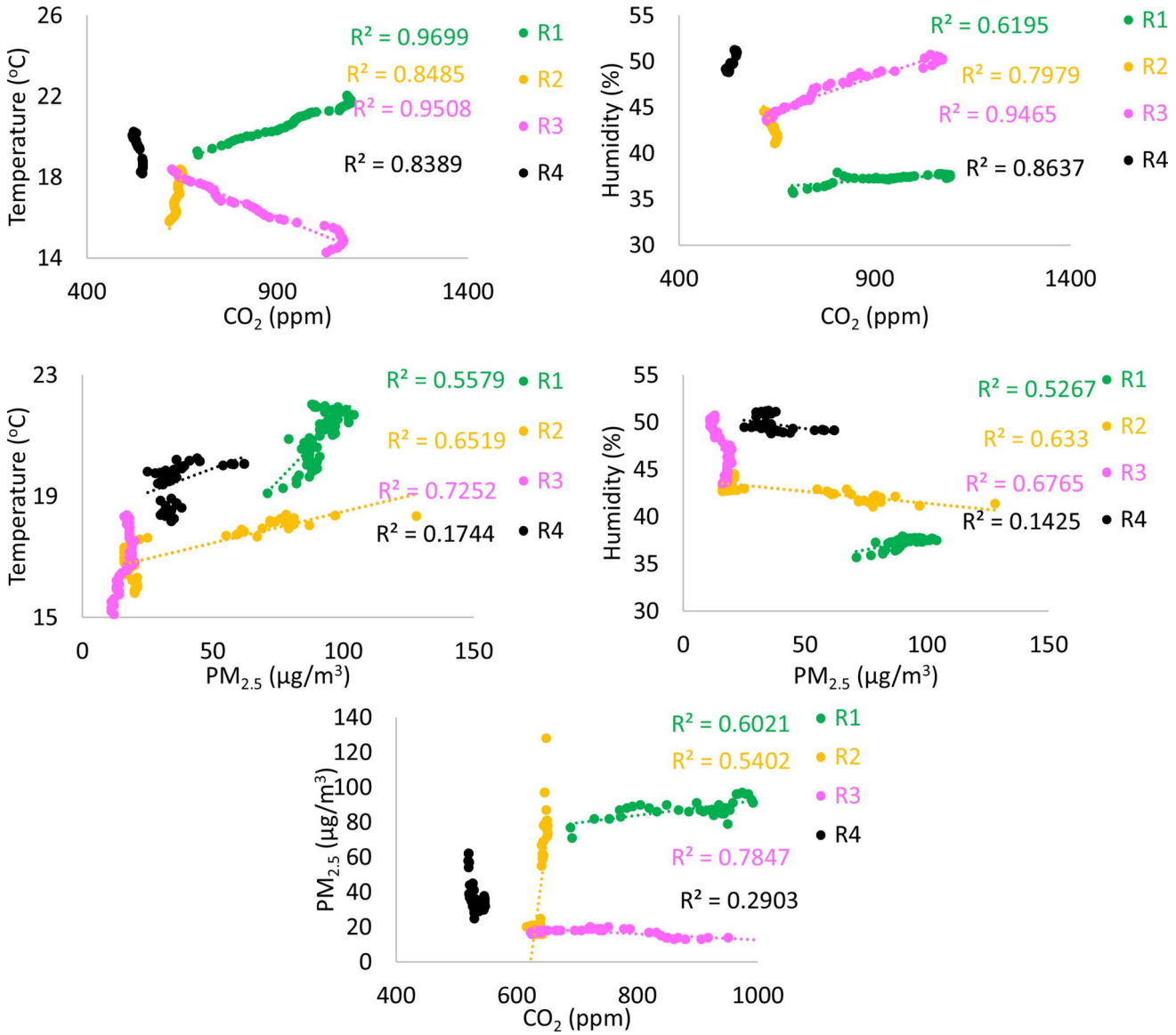


Fig. 9 The correlation among the parameters: CO_2, $PM_{2.5}$, temperature, and humidity measured in the Rs

very fine particles from the environment by filtering them. In addition, in restaurants that are ventilated with open doors, pollutants may enter from the outside environment together with mobility.

Figure 9 represents the correlations among the parameters measured in the restaurants. There is a significant high correlation (R=0.89–0.98) between CO_2 and temperature and humidity for all restaurants. Except for R4, there is a moderate correlation between $PM_{2.5}$ and temperature and humidity (R=0.72–0.86). The correlation between $PM_{2.5}$ and CO_2 measurements, excluding R4, varies between 0.77 and 0.88.

Temperature and humidity measurements showed little change throughout all measurements. The standard deviation in temperature measurements varies between 0.1 and 1.3 °C, and 0.4% and 2.3% in humidity measurements (Table 2). Although these are small changes and a short-term follow-up study, it is understood that there are important factors in the change in CO_2 and $PM_{2.5}$ concentration. In future studies, it is necessary to reveal the relationship between these parameters by monitoring these closed areas for much longer periods.

Generally, the indoor air exchange coefficient (ACH) is recommended to be at least 6 for infection control (WHO 2021). This means fresh air changes every 10 min, and the ambient air will be completely replaced with fresh air every half hour on average. The important factors in the risk of infection are the viral load in the infected environment and the duration of stay in the environment. Therefore, the risk will be minimal in frequent and well-ventilated areas. As

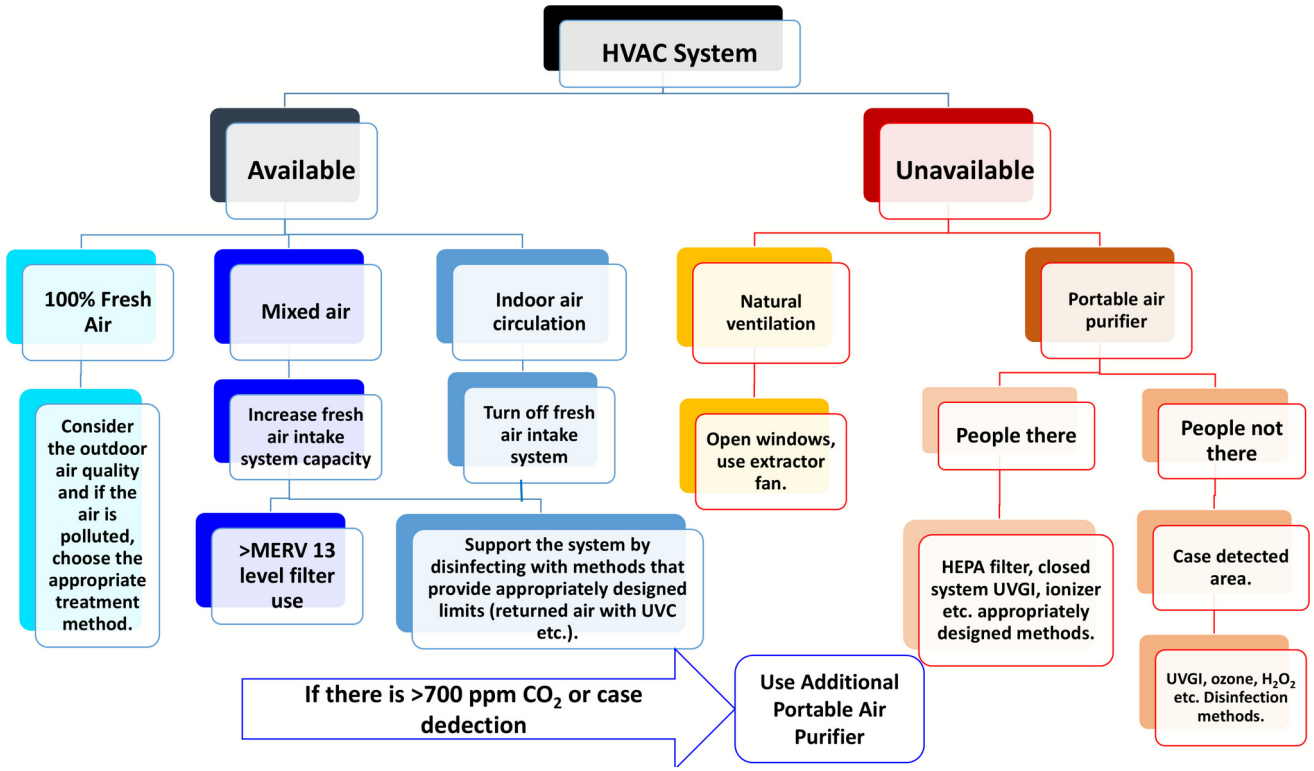


Fig. 10 Infection control plan for indoor areas

an indicator of good natural ventilation, CO_2 monitoring is important. A flowchart showing indoor air quality improvement management for outbreak control was created and shown in Fig. 10.

Portable air cleaners can be used in situations with poor ventilation (<6 ACH) to reduce the risk of virus transmission indoors. Air cleaners with HEPA filters are risk-free for human health and can capture particles < 1 µm with an efficiency of over 99% (EPA 2021). Beyond all these, "ozone-free" disinfection methods, which are not harmful to human health, should be preferred in areas where there is insufficient ventilation or where technically central ventilation filtration (>MERV 13 filter) cannot be increased. It is very important to evaluate and supervise the use of the methods described above and to encourage the development of new technologies since the use of 100% outdoor air in central ventilation will increase energy costs, especially in winter. In addition to these technical measures, establishing clear CO_2-based indoor air quality guidelines and regular inspection programs would help local authorities and building operators maintain safe ventilation performance. The implementation of real-time CO_2 monitoring and public display systems could increase occupant awareness and enable adaptive ventilation control. Moreover, the development of national IAQ certification or labeling schemes based on CO_2 and ventilation indicators would provide a practical framework for policymakers to ensure healthy indoor environments.

It should be noted that this study represents a short-term monitoring campaign conducted during the post-lockdown period. Although the measurement duration and number of sampling sites provide valuable baseline insights, they do not capture seasonal variations or long-term ventilation patterns. Future research including extended monitoring periods, additional cities, and continuous CO_2-based ventilation tracking is recommended to enhance the representativeness and general applicability of the findings.

Conclusion

This study provides the first quantitative assessment of CO_2 levels as an infection risk proxy across various indoor environments in Istanbul, including public transport, shopping centers, markets, and restaurants. In the selected areas, CO_2 concentrations were observed between 500 and 900 ppm. These values indicate that shopping malls with central ventilation systems generally maintain good indoor air quality (<700 ppm, low risk), while restaurants without mechanical ventilation frequently exceeded recommended thresholds (>800 ppm, high risk). In public transport, despite mechanical systems and open windows, local CO_2 peaks still occurred in crowded sections, confirming the need for dynamic ventilation management based on occupancy. In markets, the risk was typically low, except where the central system was inactive.

To keep the epidemic risk under control indoors CO_2 concentration should be maintained below 700 ppm (low-risk threshold), as supported by previous studies (Di Gilio et al. 2021; Meiss et al., 2021). Ventilation rates corresponding to ≥6 air changes per hour (ACH) are recommended (WHO 2021), with real-time CO_2 monitoring serving as a practical proxy for assessing air renewal efficiency.

Policy and practical implications:

- Integrate low-cost CO_2 monitoring in all crowded indoor spaces for continuous ventilation assessment.
- Define alert levels using a traffic-light display system (green < 700 ppm, yellow 700–1000 ppm, red > 1000 ppm) visible to occupants.
- Enforce regular ventilation performance testing and certification in facilities such as restaurants, schools, and public transport.
- Implement portable HEPA/UV air purifiers in poorly ventilated areas (< 6 ACH) to complement natural or central ventilation.
- Avoid exclusive operation with 100% outdoor air for long periods to minimize energy demand and greenhouse gas emissions; instead, adopt CO_2-based demand control ventilation for balance between air quality and sustainability.

This study represents a short-term, location-limited monitoring campaign during the pandemic. Overall, the findings emphasize that systematic CO_2 monitoring can serve as a practical and evidence-based tool to ensure adequate ventilation, reduce airborne infection risks, and support the development of resilient and energy-efficient indoor environments. Future research should extend measurements over longer periods, include more diverse building types and cities.

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Author contributions **CA:** Planning methodology, Writing-Reviewing and Editing. **UAS:** Data curation, Writing-Original draft preparation. **EY:** Field survey, Data collection. **SD:** Field survey, Data collection. **KO:** Field survey, Data collection. **BUA:** Formal analysis. **DAA:** Formal analysis. **BO:** Editing, Formal analysis. **NS:** Editing, Reviewing.

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Declarations

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Consent for publication Not applicable.

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