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INDOOR AIR QUALITY EVALUATION IN A HIGH-INTENSITY PHYSICAL ATHLETIC FACILITY: CO_2 AND PM ANALYSIS

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ABSTRACT

Assessing indoor air quality (IAQ) in athletic facilities has become crucial to ensure a healthy environment for their occupants, a need that has increased significantly in correspondence with the active lifestyle of current society. In this study, we investigated IAQ in a cross-training facility in San Antonio, Texas, USA, across six ventilation scenarios involving open/closed doors, and the use of ceiling fans and an air filtration unit. The monitoring campaign lasted six days, during which data on carbon dioxide (CO_2) and particulate matter (PM) were recorded every 5 minutes during high-intensity physical training sessions. Furthermore, scenarios with closed doors were used to determine the air infiltration rate of the building using the tracer gas decay method with monitored CO_2 data. Additionally, the deposition rates of PM potentially harmful to humans (PM2.5, PM5, and PM10) were determined based on monitored data. The deposition rates were found to be proportional to the particle diameter. Overall, this study demonstrated the effectiveness of natural ventilation in reducing indoor CO_2 and PM concentrations, as scenarios with open doors showed lower values compared to those with closed doors.

KEYWORDS

Indoor air quality; athletic facilities; CO_2 generation; particulate matter; natural ventilation

1. INTRODUCTION

Regular physical activity can prevent and reduce several causes of mortality, such as certain cancers, cardiovascular disease, and obesity, thereby improving human well-being. In light of this, there has been an increase in the number of athletic facilities and their occupants in recent years, necessitating a detailed evaluation of indoor air quality (IAQ) to ensure a healthy environment in these buildings. Various studies on exercise and ambient air pollution have stated that the concentrations of certain gaseous pollutants, such as carbon monoxide, volatile organic compounds (VOCs), and particulate matter (PM), need to be controlled (Carlisle and Sharp 2001; Strak et al. 2010). Additionally, other investigations on IAQ in sports environments have concluded that the main parameters of unhealthy conditions for humans are values of carbon dioxide (CO_2) that exceed a given threshold, as well as elevated levels of PM2.5 and PM10 (Salonen, Salthammer, and Morawska 2020).

Indoor CO_2 concentrations above 1000 ppm are associated with sick building syndrome (SBS) and a decrease in office work performance ("ASHRAE Position Document on Indoor Carbon Dioxide" 2025). Other regulations set by the United States Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) specify higher CO_2 healthy limits, namely 5,000 ppm averaged in time for airborne exposure in 8-hour work shift during a 40-hour work week, and a short-term exposure limit of 30,000 ppm averaged in 15-minute intervals during a workday. However, in this study we use the upper limit based on SBS symptoms of 1000 ppm as a benchmark. Regarding PM concentrations, the National Ambient Air Quality Standards (NAAQS) specifies a 24-hour average limit to ensure healthy environmental conditions in buildings. Specifically, the upper limits for PM2.5 and PM10 are 35 μg/m^3 and 150 μg/m3, respectively ("National Ambient Air Quality Standards (NAAQS)," n.d.).

As stated by Salonen et al. (Salonen, Salthammer, and Morawska 2020), high levels of CO_2, PM2.5, and PM10 can pose health risks in sports environments. Therefore, assessing IAQ in athletic facilities is essential, especially in those where high-intensity physical activities are undertaken. In such cases, higher levels of CO_2 can be produced by athletes, as its generation is proportional to the intensity of physical activity, among other factors. Therefore, the aim of this study is to analyze IAQ in a cross-training facility in San Antonio, Texas, USA, under six different ventilation scenarios by monitoring indoor CO2 and PM concentrations. Additionally, this study seeks to assess and quantify the effectiveness of natural ventilation in reducing indoor CO_2 and PM concentrations during cross-training sessions. Finally, this investigation aims to provide new insights into IAQ in high-intensity physical athletic facilities, a topic that has not been extensively studied in the current literature. In particular, the rate of CO_2 generation during highly demanding physical activities, such as cross-training sessions, requires detailed study (Kapalo et al. 2021). In this regard, the present investigation provides values for CO_2 generation rates as well as PM deposition rates during cross-training sessions in different ventilation scenarios.

The conference paper is structured as follows. Section 2 describes the methodology, including the experimental setup and details about the determination of the air infiltration rate of the building, the CO_2 generation rates and PM deposition rates. Section 3 presents and discusses the results of this investigation. Finally, Section 4 summarizes our findings and draws our conclusions.

2. METHODOLOGY

This section outlines the methodology followed in this investigation. First, the experimental setup is presented, including a description of the cross-training facility, the different ventilation scenarios, and the monitoring campaign. Finally, details regarding the determination of the infiltration rate, CO_2 generation rate, and PM deposition rate from the in situ monitored data are provided.

2.1. Experimental setup

This study aimed to evaluate the IAQ in a cross-training facility in San Antonio, Texas, USA, under different ventilation strategies. The main structural frame of the building is constructed from metal, with its roof and internal walls insulated with batt insulation layers, each 15.2 cm thick and protected by vapor barriers on both interior and exterior sides. Figure 1 depicts an interior view of the building. It has dimensions of 25.5 m in length and 16.3 m in width, with ceiling heights ranging from 5 m to 6 m. These dimensions result in an effective volume of 2145 m^3 and a floor area of 390 m^2. Moreover, there are two garage-type doors (3 m wide and 3 m tall) on the north and the south facades, and an additional door (0.9 wide and 2.2 m tall) on the west facade. Finally, the cross-training facility, which has no HVAC system installed, relies on both natural ventilation and two ceiling fans to accommodate the athletes' thermal comfort needs during training sessions. Specifically, the Lucci Air® Viceroy ceiling fans have 1.3 m diameter and generate an airflow of 151 m^3/min.

Figure 1. Interior view of the cross-training facility

The cross-training facility offers 60-minute training sessions each weekday, specifically: i) from 05:00 to 09:30, except from 08:00 to 08:30 when no activities are scheduled; ii) from 12:00 to 13:00; and iii) from 16:30 to 19:30. The workouts combine cardio and weightlifting exercises using the gym's equipment, which includes stationary cardio machines and specific areas for calisthenics and weightlifting. Occupancy during the sessions was also recorded in this investigation to determine the CO_2 generation rate per person during the different training sessions.

Table 1 summarizes the various ventilation scenarios analyzed in this study. These scenarios were designed to investigate the influence of different variables, such as open/closed doors, the use of the ceiling fans, and the implementation of an air filtration (AF) unit, on the levels of CO_2 and PM monitored during the training sessions. The AF unit used in this study is the Medify Air® MA-112, with a total height of 71 cm. It features two air inlets on its sides and an air outlet for the filtered air at the top. The AF unit has a clean air delivery rate (CADR) output of 950 m^3/h and was positioned 50 cm away from any equipment in the cross-training facility to ensure adequate air circulation, following the manufacturer's guidelines. The filtration system of the unit consists of four layers, namely i) a pre-filter, ii) a High Efficiency Particulate Air (HEPA) H13 filter, iii) an activated carbon filter, and iv) an ozone-free ionizer. In particular, the HEPA H13 filter is specified to reduce up to 99.9 % of particles down to 0.1 μm, including $PM_{2.5}$, as stated by the manufacturer. Moreover, according to the United States Environmental Protection Agency (EPA), it can remove at least 99.97 % of particles with a diameter of 0.3 μm, which corresponds to the most penetrating particle size. Concentration levels of larger or smaller particles are reduced with even higher efficiency ("What Is a HEPA Filter? | US EPA," n.d.). Finally, the activated carbon filter is effective in absorbing VOCs.

It is worth noting that the definition of a ventilation scenario can differ slightly depending on whether the air exchange function is considered a proper feature of a ventilation scenario. In this regard, ceiling fans in the cross-training facility do not produce air exchange between indoor and outdoor spaces per se. They primarily move and mix the air within the building, providing an interesting scenario that can potentially affect CO_2 and PM concentrations during the training sessions.

Scenarios	Doors	Ceiling fans	Air filtration unit	Scenarios	Doors	Ceiling fans	Air filtration unit
S1	Closed	OFF	OFF	S4	Closed	ON	ON
S2	Closed	OFF	ON	S5	Open	ON	ON
S3	Closed	ON	OFF	S6	Open	OFF	OFF

Table 1. Description of the ventilation strategies analyzed in this study.

	Brand and Model	Range	Accuracy
Carbon dioxide	HOBO® MX1102A	[0, 5000] ppm	± 50 ppm
Particulate matter	WolfSense® PC3500	[0.3, 25] μm	50 % for PM = 0.3 μm 100 % for PM > 0.45 μm

Table 2. Specifications of the monitoring sensors.

Several indoor air parameters, including CO_2 and PM concentrations, were gathered during the monitoring campaign, which lasted for six different days in January 2022. Three HOBO® MX1102A sensors were equally distributed around the central area where the training sessions took place to gather CO2 concentration. They were situated at a height of 1.5 m, following the outcomes of Pei et al. (Pei et al. 2019). Similarly, the PM monitoring sensor, a WolfSense® PC3500, was located at the same height in the central area of the cross-training facility, at least 1.5 m away from all walls to reduce the effects of particle dispersion on the registered values (Holmberg and Li 1998; Jin et al. 2013). This sensor registered concentrations for different particle diameter sizes, including those potentially harmful to humans, namely PM2.5, PM5, and PM10. Finally, both CO_2 and PM concentrations were recorded at 5-minute intervals during the monitoring period. The specifications of the monitoring sensors are summarized in table 2. Additionally, the sensors were calibrated prior to the monitoring campaign following the guidelines provided by the manufacturers.

2.2. Determination of the infiltration rate, CO_2 generation rate, and PM deposition rate

The CO_2 concentration in the cross-training facility is given by the following first order differential equation based on the mass balance equation (Heidt and Werner 1986):

$$\frac{\partial(VC)}{\partial t} = q_i C_{out} - q_o C + S \,, \qquad (1)$$

where V is the air volume in the building, C and C_{out} are the CO_2 concentration indoors and outdoors, respectively, q_i and q_0 are the infiltration rates from the outside air into the facility and vice versa, and S is the CO_2 generation rate produced by the athletes during the cross-training sessions. Under several assumptions, namely $q_i = q_0 = q$, and V and S being constant in time, the concentration at time t can be obtained from Eq. (1) and expressed as:

$$C(t) = \left(C_{out} + \frac{S}{q}\right) - \left(C_{out} + \frac{S}{q} - C_0\right) e^{-K_1(t-t_0)} \,, \qquad (2)$$

where C_0 is the CO_2 concentration in the facility at the initial time t_0, and $K_1 = q/V$.

The infiltration rate q can be determined using the tracer gas decay method with the CO_2 monitored data. If there is no CO_2 source in the facility, i.e., when the building is unoccupied and closed, Eq. (2) yields an exponential decrease of the CO_2 concentration, and the infiltration rate can be obtained by fitting the monitored data using the equation:

$$ln(C(t) - C_{out}) = -K_1(t - t_{dec}) + ln(C_{dec} - C_{out}) \,, \qquad (3)$$

where C_{dec} is the concentration at the time t_{dec} when the CO_2 level begins to decrease.

Finally, the CO_2 generation rate during the cross-training sessions can be calculated once the infiltration rate is known, by fitting the monitored data in the form as $C(t) - C_{out}$ a function of $e^{-K_1(t-t_0)}$, derived from Eq. (2) (Faubel, Martinez-Molina, and Suk 2024).

Similarly, the PM concentration in the cross-training facility can also be determined using the mass balance equation. In this case, the indoor PM concentration at time is given:

$$C(t) = \alpha\left(C_{out} + \frac{S_{PM}}{q}\right) - \left[\alpha\left(C_{out} + \frac{S_{PM}}{q}\right) - C_o\right] e^{-K'_1(t-t_0)} \, . \quad (4)$$

where C_{out} is the outdoor PM concentration, S_{PM} is the PM generation rate produced by the athletes during the exercises, and K'_1 and α are defined by:

$$K_1' = K_1 + \frac{\kappa}{V} + \eta \frac{q_{AF}}{V},$$

and (5)

$$\alpha = \frac{1}{1 + \kappa/q + q_{AF}/q} \, .$$

In the last equation, κ stands for the PM deposition rate, is q_{AF} the CADR of the AF unit, and η corresponds to the total particle removal efficiency, which was set to one according to the AF unit specifications. It is worth noting that to derive Eq. (4), we assume: i) κ and S_{PM} are constant over time, and ii) a penetration efficiency of PM in the building equal to one for all the particle diameter sizes.

Finally, the deposition rate is obtained from Eq. (4) when there is no PM source in the facility, i.e., when it is unoccupied and closed. In this case, the PM concentration is:

$$C(t) = \alpha C_{out} - (\alpha C_{out} - C_o) e^{-K_1'(t-t_0)} \, . \quad (6)$$

The deposition rate can be determined by fitting the monitored data in the form of the last equation using the *NonlinearModelFit* function in the software Mathematica (Wolfram Research 2023).

3. RESULTS AND DISCUSSION

This section delves into the outcomes of the analysis, first comparing the CO_2 concentration in the cross-training facility gathered during the monitoring campaign for the different ventilation scenarios listed in table 1. Specifically, figure 2 shows the CO_2 concentration as a function of time. It is worth noting that each scenario corresponded to different days in the monitoring campaign, although the results for the CO_2 concentrations are depicted in the same figure for better comparison. Moreover, the black dashed line represents the upper CO_2 concentration limit of 1000 ppm associated with SBS ("ASHRAE Position Document on Indoor Carbon Dioxide" 2025).

Some features in the CO_2 values were common to all the scenarios, such as the increase associated with the various 60-minute workout sessions each day, and the decrease observed when the facility was unoccupied and closed from 13:00 to 16:30, and at 19:30, respectively. The initial values at 00:00 remained approximately constant at 400 ppm until the beginning of the first cross-training session at 05:00. It is worth noting that the facility was closed the day before each scenario was monitored, so the initial CO2 concentration in all cases was similar to that outdoor, around 400 ppm. Conversely, S4 was monitored the day after S3, and some residual CO2 remained in the building. However, this remaining CO2 did not affect the calculations performed in this study. Additionally, all scenarios except those with open doors, namely S5 and S6, recorded CO2 levels above 1000 ppm at certain times during the training sessions. This underscores the importance of natural ventilation in maintaining healthy CO2 levels in the building during the exercises. Particularly, CO2 concentrations in S5 and S6 ranged from 400 ppm to 600 ppm throughout the day, well below the unhealthy limits.

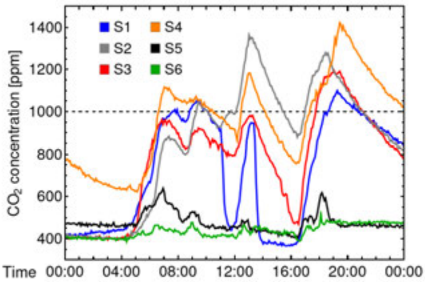


Figure 2. CO_2 concentration monitored for each ventilation scenario.

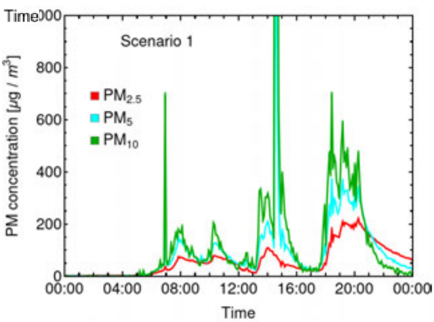
The infiltration rate of the building was determined using the monitored data from scenarios with closed doors, specifically from S1 to S4. In these cases, CO_2 levels exponentially decreased starting at 19:30, the time when the last training session finished and the facility was unoccupied. The data collected from 19:30 onwards were used to determine the air infiltration rate following the methodology explained in Section 2.2. The obtained values, ranging from 0.0554 to 0.0926 m^3/s, are summarized in table 3. The small variation among the infiltration rates calculated for the different scenarios can be understood by the fact that none of the ventilation scenarios included air exchange function by themselves. Based on the results, the AF unit had no measurable effects on the infiltration rate, suggesting that its specifications could be insufficient for this building.

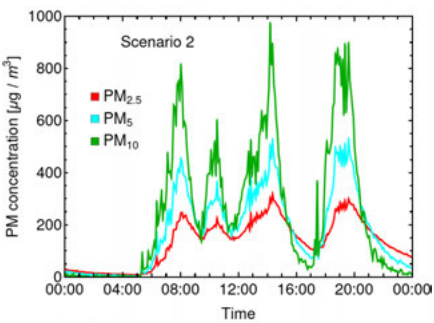
The CO_2 generation rate was determined following the methodology discussed in Section 2.2, using the data from one of the 60-minute training sessions held each monitored day, specifically the session conducted from 05:00 to 06:00. The values for the CO2 generation rate and occupancy during the workout are summarized in table 3. Comparing the measured CO2 generation rates with those from other studies in the literature is complex, as various factors associated with human metabolism (gender, age, body composition and size) and the level of physical activity affect its determination. However, the values obtained in this investigation, which were proportional to the occupancy during the workouts, can be used as benchmarks for CO2 generation rates in high-intensity physical activities such as cross-training, which has been scarcely investigated in the literature. The metabolic equivalent of task (MET) associated with cross-training can be considered to range from 8 to 10 (or even higher), as these values correspond to circuit training and calisthenics, and team practice, respectively (Ainsworth et al. 2011).

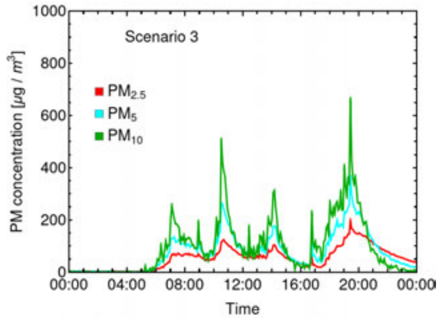
Figure 3 depicts the PM2.5, PM5, and PM10 concentrations monitored for each ventilation scenario. Some features in the PM values were common to all the scenarios, such as the increase associated with the various 60-minute workout sessions each day, and the decrease observed when the facility was unoccupied and closed from 13:00 to 16:30, and at 19:30, respectively. Scenarios with open doors registered lower concentrations than those with the doors closed, highlighting the effectiveness of natural ventilation in reducing PM concentration levels during the exercises. The NAAQS determines upper limits for indoor PM concentrations to ensure healthy environmental conditions in buildings. Specifically, it sets the daily average limit for PM2.5 at 35 $\mu g/m^3$ and for PM_{10} at 150 $\mu g/m^3$ ("National Ambient Air Quality Standards (NAAQS)," n.d.). In the scenarios with closed doors, the $PM_{2.5}$ limit was exceeded only in S2, with a daily average of 36.5 $\mu g/m^3$. Conversely, S1, S3, and S4 yielded values below the unhealthy limit, approximately around 15 µg/m3. Scenarios with open doors, namely S5 and S6, registered similar results around 9 µg/m3, well below the unhealthy limit. This underscores the impact of natural ventilation on reducing indoor PM concentrations. In the case of PM_{10}, the daily average limit was exceeded in all scenarios with closed doors except for S3, which recorded 148 µg/m³. The PM_{10} concentration in S1, S2, and S4 were 171.2 µg/m³, 355 µg/m³, and 164 µg/m³, respectively. Scenarios with open doors, specifically S5 and S6, registered similar results around 91 µg/m³, well below the unhealthy limit. This highlights the effectiveness of natural ventilation in reducing indoor PM concentrations.

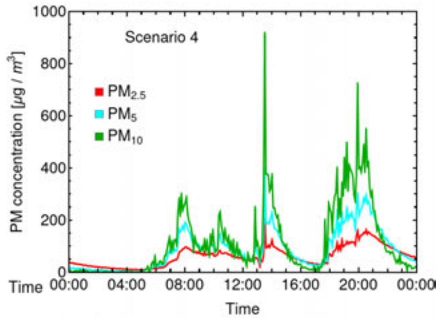
Finally, scenarios with closed doors were used to determine the PM deposition rates as explained in Section 2.2. The results are summarized in table 3. It was shown that the deposition rate increases with the particle diameter size, consistent with similar findings in the relevant literature (Hussein et al. 2009).

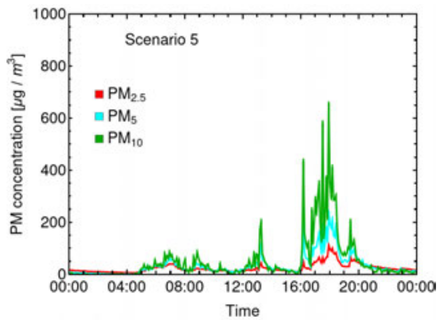
Figure 3. PM2.5, PM5, and PM10 concentrations monitored for each ventilation scenario.

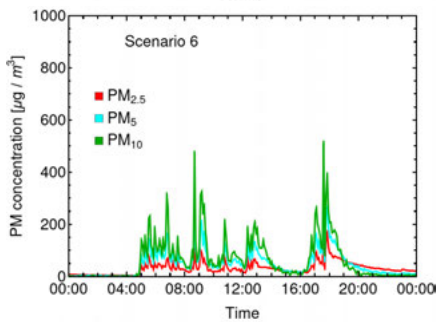












Scenarios	q [m^3/s]	Occ.	s [l/min]	$PM_{2.5}$ DR [h^{-1}]	PM_5 DR [h^{-1}]	PM_{10} DR [h^{-1}]
S1	0.0554(7)	2	6.3(3)	0.300(11)	0.80(3)	1.26(6)
S2	0.0803(7)	2	4.2(4)	0.241(14)	0.526(18)	0.80(9)
S3	0.0926(7)	11	14.4(8)	0.277(16)	0.85(3)	1.75(11)
S4	0.0676(7)	10	5.9(4)	0.208(19)	0.53(2)	1.51(7)

Table 3. Results for the air infiltration rate (q), occupancy (Occ.) and CO2 generation rate (S) during the cross-training sessions, and PM2.5, PM5, and PM10 deposition rate (DR) for each scenario with closed doors, namely S1, S2, S3, S4.

4. CONCLUSIONS

This study analyzed IAQ in a cross-training facility located in San Antonio, Texas, USA, under six different ventilation scenarios. Specifically, indoor CO_2, PM2.5, PM5, and PM10 concentrations were monitored at 5-minute intervals during six different days in January 2022. The authors acknowledge that analyzing IAQ during such a specific period might be a limitation of the study. Different results could be obtained during other times of the year with varying weather conditions. In this regard, as a continuation of the present study, the same experimental setup will be replicated on different days in the summer months to assess the influence of outdoor environmental conditions on IAQ in the cross-training facility.

CO2 data collected in scenarios with closed doors were used to determine the air infiltration rate of the building using the tracer gas decay method. The slight variation among the resulting infiltration rates, which ranged from 0.0554 to 0.0926 m^3/s, can be attributed to the fact that none of the ventilation scenarios included air exchange function by themselves. Additionally, the AF unit had no measurable effects on the infiltration rate, suggesting that its specifications could be insufficient for this building. Regarding the CO_2 generation rates, the values obtained in this study, which were proportional to the occupancy during the workouts, can serve as benchmarks for CO_2 generation rates in high-intensity physical activities such as cross-training, which has been scarcely investigated in the literature. Lastly, the deposition rates determined for PM2.5, PM5, and PM10, were proportional to the particle diameter, consistent with similar findings in the relevant literature.

Overall, the outcomes of this investigation demonstrate the impact of natural ventilation on improving IAQ in high-intensity physical athletic facilities. Scenarios with open doors, which ensured natural ventilation and fresh air circulation within the building, registered lower indoor CO_2 and PM concentrations compared to scenarios with closed doors. Moreover, the use of fans and/or AF unit had no discernible impact on reducing CO_2 and PM levels, unlike natural ventilation (open doors), which had a significant effect on improving IAQ during the cross-training sessions. The results of this investigation, which highlight the effectiveness of natural ventilation in reducing indoor CO_2 and PM concentrations, could have practical implications for other similar athletic facilities.

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