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REVIEW ARTICLE

Human exposure to air contaminants in sports environments

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Abstract

The aim of this review was to investigate human exposure to relevant indoor air contaminants, predictors affecting the levels, and the means to reduce the harmful exposure in indoor sports facilities. Our study revealed that the contaminants of primary concern are the following: particulate matter in indoor climbing, golf, and horse riding facilities; carbon dioxide and particulate matter in fitness centers, gymnasiums, and sports halls; *Staphylococci* on gymnasium surfaces; nitrogen dioxide and carbon monoxide in ice hockey arenas; carbon monoxide, nitrogen oxide(s), and particulate matter in motor sports arenas; and disinfection by-products in indoor chlorinated swimming pools. Means to reduce human exposure to indoor contaminants include the following: adequate mechanical ventilation with filters, suitable cleaning practices, a limited number of occupants in fitness centers and gymnasiums, the use of electric resurfacers instead of the engine powered resurfacers in ice hockey arenas, carefully regulated chlorine and temperature levels in indoor swimming pools, properly ventilated pools, and good personal hygiene. Because of the large number of susceptible people in these facilities, as well as all active people having an increased respiratory rate and airflow velocity, strict air quality requirements in indoor sports facilities should be maintained.

KEYWORDS
air pollution, exercise, exposure, indoor air, indoor sports environment, indoor sports facilities

1 | INTRODUCTION

Physical activity is one of the most basic human functions and a significant basis of health. The World Health Organization (WHO)[1] recommends that adults, including older adults, undertake at least 2.5 hours of moderately intense aerobic activity per week. With an increasing number of sports enthusiasts worldwide, the number of indoor sports facilities and the number of workers in those facilities have also increased dramatically in the past decades. However, unlike residential areas and other types of public spaces, such as schools and offices, there is relatively little published research about air quality and exposure to different pollutants in various indoor sports facilities,[2,3] where a growing number of people exercise, work full or part time, or attend athletic events.[4,5]

Although many studies of athletes' exposure to ambient air contaminants have been published,[6-10] little work is known about the exposure to air pollutants in different indoor sports facilities. Available publications have been focused on ice arenas, with the most investigated pollutants being carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter (PM_{10} and $PM_{2.5}$, referring to

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particulate matter with an aerodynamic diameter of <10 µm and <2.5 µm, respectively) emitted by the ice resurfacers,[3,11,12] and indoor swimming pools, with a focus on high concentrations of disinfection by-products (DBPs) (eg, trihalomethanes (THMs)).[13,14] In addition to these pollutants, also for example, ultrafine particles (UFPs), volatile organic compounds (VOCs), aldehydes (eg, formaldehyde (HCHO)), ozone (O_3), and bioparticles (fungi and bacteria)) could be cause for health effects in some sports facilities. Besides, important comfort parameters—temperature (T) and relative humidity (RH)—may affect for example material emissions[15-17] and occupant's perception of the indoor air quality (IAQ)[18] and should be taken into account when evaluating exposure issues in sports facilities.

The general outdoor and indoor sources as well as parameters affecting the concentrations of all those contaminants are already well known (see eg, references for: CO,[19,20] NO_2,[20-23] PM,[24-28] UFP,[29-35] VOC,[36-41] HCHO,[20] O_3,[21,42] bioparticles [43]). There are also many international reports by WHO[20,21,44] as well as epidemiological and other studies summarizing and showing a scientific evidence of several possible health effects of those contaminants (see eg, references for CO,[20,44] NO_2,[20,45-49] PM,[28,50,51] UFP,[52,53] DBP,[35,54-57] VOC,[36-40,58] HCHO,[20,35,59] O_3,[42,60,61] bioparticles[43,44,62-64]). However, the knowledge of the exposure to these pollutants in different sports facilities is very scattered and limited.

Like other indoor places, IAQ in indoor sports facilities is affected by the type of ventilation, building materials, and building maintenance,[65-68] but what makes indoor sports facilities different is the higher human occupancy and the type of activity taking place inside.[68] In addition, unlike other indoor areas, many different plastic and rubber materials (mats, exercise equipment, cushions, etc) are used in indoor sports facilities, and there is a lack of knowledge about their effects on IAQ and human health. Besides, cleaning products used in sports facilities and personal hygiene products can increase exposure to chemicals and influence the microbiome of the space (eg, favoring the presence of pathogenic microbes).[69-71] Indoor exercise facilities may be located in buildings not originally designed as sports facilities; thus, the dimensioning of ventilation relative to the activity in the facility may be insufficient. Chemical emissions from materials used in indoor sports facilities as well as the amount and quality of chemicals used will be further emphasized in the future through the Energy Performance of Building Directive 2010/31/EU (EPBD).[72] The directive requires energy savings for ventilation, which can increase the level of indoor air pollution (eg, chemical and particulate contaminants).

In contrast to working environments and ambient air, legally binding regulations as well as other guidelines are only partially established for indoor pollutants[20,21,73,74] (see Table S1 in the Supporting Information (SI)), and those proposed regulations and guidelines do not take into account specific actual exposure and risk during sport activities. Professional athletes and amateurs can be at special risk when they are exercising in polluted environments because 1) their respiratory rate increases proportionally to the quantity of inhaled pollutants; 2) the increased airflow velocity carries gaseous pollutants deeper into the respiratory tract; and 3) most of the air is inhaled through the mouth, bypassing the normal nasal filtration of large particles.[3,6,68,75]

Practical Implications

- Elevated levels of CO_2, PM_{10}, and $PM_{2.5}$ cause problems in fitness centers, gymnasiums, and sports halls.
- Exposure to CO and NO_2 is the main problem in ice skating arenas.
- Exposure to disinfection by–products (DBPs) such as $CHCl_3$ and NCl_3 is the main concern for indoor swimming pools.
- Air temperature and humidity should be in the thermal comfort range.
- Air quality guidelines are required for DBPs.

Due to that the most important international comfort standards, ASHRAE 55 (given by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE))[76] and ISO 7730 (given by the International Standards Organization (ISO))[77] are mainly applicable to sedentary activity, such as office work. Own comfort recommendations for T and RH in sport facilities are needed and recently proposed by the American College of Sports Medicine (ACSM) and the International Fitness Association (IFA) (see Table S1 in the SI).

The aim of this study is to collect and summarize information on the exposure to relevant indoor air contaminants in different types of sports facilities, predictors affecting the occurrence and concentrations of those contaminants, and the means to reduce harmful exposure to air contaminants in sports facilities.

To make the results more comparable, we converted all carbon monoxide (CO) and carbon dioxide (CO_2) values reported in mg/m^3 to ppm (part per million) by using the conversion calculator (available at https://www.cdc.gov/niosh/docs/2004-101/calc.html). The conversion equation is based on 25°C and 101,325 Pa: X ppm = (Y mg/m^3)·(24.45)/(molecular weight) or Y mg/m^3 = (X ppm)·(molecular weight)/24.45.[78]

2 | MATERIAL AND METHODS

2.1 | Search strategy and eligibility criteria

Web of Science, SCOPUS, Google Scholar, and PubMed were primarily used to search for literature published between 1999 and 2020. Other electronic databases available from Aalto University and Queensland University of Technology were also consulted. The literature search was conducted from October 2019 to May 2020. Altogether, different combinations of 76 search terms were used (see Table S2 in the Supporting Information (SI)). The search strategy included combinations of at least four terms simultaneously, and each combination included at least two of the following terms each time: indoor air, sports facilities, environment, exposure, physical exercise, and concentration. Quotation marks were used between search terms. Original peer-reviewed scientific journal articles, literature reviews, and conference articles (full papers) were included. The search was then extended to the reference lists of relevant articles, based on their abstract and/or full text. The decision to examine certain articles in more detail was based on the article titles. From the more than 400 publications identified in the initial search, 288 were selected for inclusion in the analysis. All publications reporting indoor air quality (IAQ) in different indoor sports facilities, the measured IAQ parameters, and information on the location of the studied facility (city and country) are listed in Table S3 in the SI.

2.2 | Definition of the different type of facilities

We classified the publications about different indoor sports facilities into nine categories: fitness centers, gymnasiums, ice hockey/ice skating arenas, indoor climbing facilities, indoor golf courses, indoor horse riding arenas, indoor motorsport arenas, indoor swimming pools, and sports halls.

Fitness centers have specific characteristics, such as types of occupants and activities, layout, equipment, daily patterns of use, and even frequent operation compared to other types of sports environments, like school or university gymnasiums and competitive sports arenas.[79,80] The term “fitness” identifies a range of activities conducted every day in fitness centers or gymnasiums, and these activities can be grouped into resistance training activities, group fitness activities, and functional fitness activities.[81] Typical spaces in a fitness center are classrooms (eg, for indoor cycling), studios (eg, for yoga and pilates), and gymnasiums (eg, for strength training).[82] *A gymnasium* is a large room with equipment for exercising the body and increasing strength.[83] A “gymnasium” is the same as a “gym” and it is equipped with bars, weights, ropes, climbing walls, etc, for physical training.[84] Gymnasiums in our study are mainly school or university gymnasiums. *An ice hockey/ice skating arena* is a hall with an ice rink. An ice rink (or ice skating rink) is a frozen body of water and/or hardened chemicals where people can ice skate or play winter sports. Arena's uses include ice skating, ice hockey, bandy, rink bandy, ringette, broomball, speed skating, figure skating, ice stock sport, and curling as well as exhibitions, contests, and ice shows. The rinks are mechanically frozen or artificial, where a coolant produces cold temperatures in the surface below the water, causing the water to freeze.[85] *Indoor climbing facilities* are for sport climbers who train and compete on an artificial climbing wall with safety points for hanging ropes or on a boulder wall. *Indoor golf courses* provide a virtual golf experience. *Indoor horse riding arenas* are buildings that are specially designed for equestrian sport with or without spectators. The floor of the arena usually consists of mixtures of different particulate materials. *Indoor motorsport arenas*, also known as kart facilities, are small racetracks with asphalt surfaces for the amateur and leisure sector. Motorsport events, like monster truck competitions, tractor pulls, motorcycle stunt shows, and races, are often presented in multipurpose arenas with capacities of 10,000-25,000 people. Usually, the engines of the vehicles are modified to achieve high power. Monster trucks, for example, run on methanol. They must pass a technical inspection before each show, but there is almost no public information about the composition of the exhaust gas.[86] A *swimming pool* is an artificial area of water for swimming[87] and indoor swimming pools are located inside, under a roof and insulated by at least three walls.[88] Indoor pools are built for the purpose of year-round swimming or training, and they are common in all climate types. A *sports hall* is a building or part of a building in which sports are played.[89] It offers spaces for example for basketball, badminton, volleyball running, long-jumping, and high-jumping. Different competition events are often organized in sports halls.

3 | RESULTS AND DISCUSSION

This section begins with a general treatise on the performance-dependent formation of carbon dioxide in exhaled human breath (Subsection 3.1). Exhaled CO_2 potentially affects all sports facilities and may result in elevated indoor levels of the gas. In Subsection 3.2, the different sports facilities are discussed separately with regard to the respective pollutants and possible exposure. All relevant references are summarized in Table S3 in the SI.

3.1 | Carbon dioxide in exhaled human breath

Depending on their physical condition and their level of activity, humans exhale more or less carbon dioxide. The problem of high levels of carbon dioxide indoors is well known in school classrooms[90] where respective guidelines[73] are often exceeded within a short period of time. A similar situation arises in workout rooms, where a large number of people exercise. In exercise physiology, the metabolic equivalent rate M (unit MET) corresponds to the consumption of 3.5 ml of oxygen per kg of body mass per minute. McArdle et al[91] provide a five-level classification of physical activity ranging from 1.6 to 3.9 MET (light) to >10 MET (unduly heavy) for men and from 1.2 to 2.7 MET (light) to >7.6 MET (unduly heavy) for women. Another important parameter is the basal metabolic rate (BMR), which defines the required energy to keep a body functioning at rest. According to Schofield,[92] the BMR is 7.25 MJ/day for a 75 kg 30- to 60-year-old male and 5.58 MJ/day for a 60 kg 30- to 60-year-old female. For calculating the carbon dioxide exhalation rate $\dot{V}_{CO_2}$ (l/s) from M and BMR, Persily and de Jonge[93] derived Equation (1).

$$\dot{V}_{CO_2} = RQ \cdot BMR \cdot M \cdot \frac{T}{p} \cdot 0.000211 \quad (1)$$

The respiratory quotient (RQ), which often equals 0.85, defines the ratio of the volumetric rate at which carbon dioxide is produced to the rate at which oxygen is consumed. T is the temperature (K) and p is the air pressure (kPa). For a 75-kg male (RQ = 0.85, M = 6 MET, BMR

= 7.25 MJ/day, T = 293 K, p = 101.3 kPa) a value of $\dot{V}_{CO_2}$ = 0.0225 l/s (81 l/hour) is obtained (see Persily and de Jonge[93] for more BMRs of males and females). Alternatively, $\dot{V}_{CO_2}$ can be calculated from the alveolar minute ventilation (AMV) and the carbon dioxide concentration in the exhaled breath, which is 3-4%.[91] In the range between 0 Watt (W) and 200 W, Hollmann[94] found a linear relationship between the exercising power and AMV.

3.2 | Exposure to indoor air contaminants in different sports facilities

Reported indoor air parameters in different sports environments from published studies are summarized in Table 1. More detailed information about the studies is available in Table S3 in SI. In the following subsections, each type of facility is discussed in detail.

3.2.1 | Fitness centers

We found sixteen studies reporting the indoor air quality parameters in fitness centers. The most often studied parameters were particles (62% of the studies), CO_2 (31% of the studies), and temperature (31% of the studies). Concentrations of PM_{10} and respirable dust in fitness centers as well as other sports environments are presented in Figure 1.

In fitness centers, the levels of particles were highly influenced by the level of occupancy, the type (intense) of indoor activity, and the type of ventilation.[68,95] The highest particulate matter concentrations exceeding mean target values for the 24 hours (50 μg/m^3 for PM_{10} and 25 μg/m^3 for $PM_{2.5}$)[74] and for the annual mean (40 μg/m^3 for PM_{10} and 25 μg/m^3 for $PM_{2.5}$)[28] were found especially during classes with elevated numbers of occupants, revealing a relation between PM concentration and the resuspension of dust caused by the physical activity practitioners.[68]

Concentrations of PM_{10} and $PM_{2.5}$ were much lower in the centers with mechanical ventilation, including filtration of outdoor air, than those with natural ventilation via open windows.[79,96] For example, Slezakova et al[79] found that fitness centers with natural ventilation exhibited two times higher PM, with PM_1 accounting for 93-96% of PM_4, and twice to three times higher than the median concentration of ultrafine particles (UFPs) at fitness centers without controlled ventilation systems. Those facilities with natural ventilation (windows open often) that were also situated directly on the street with windows facing busy roads had indoor PM levels that may have resulted from infiltrations of ambient emissions. Almeida et al[95] reported a PM_{10} average concentration of 15 ± 15 μg/m^3 in fitness centers having mechanical ventilation and filtration of air before supplied in the building.

Slezakova et al[79] reported that maxima of PM temporal variations were typically higher in rooms or studios for group classes than in large workout areas (a joint space with free weights, bodybuilding machines, and cardiovascular equipment) and occurred during

TABLE 1 Reported indoor air parameters in different sports environments

Sports environment/facility	Reported indoor air parameters
Fitness centers	Particulate matter (TSP, $PM_{0.3}$-PM_{10})
	Ultrafine particles (UFPs)
	Chemical composition of particles
	TVOC, VVOCs, and VOCs
	CO, CO_2, NO_2, O_3
	Microbial contaminations
	Climatic parameters (T, RH, AER)
Gymnasiums	Particulate matter (PM_1-PM_{10})
	Ultrafine particles
	Elemental concentrations
	Black carbon
	TVOC, VOCs
	Microbial contaminations
	Climatic parameters (T, RH, AER)
Ice hockey/ice skating arenas	Particulate matter (PM_1-PM_{10})
	Microbial contaminations
	CO, CO_2, NO, NO_2, SO_2
	Climatic parameters (T, RH, AER)
Indoor climbing facilities	Particulate matter (PM_1-PM_{10})
	Particle number concentration
	$MgCO_3$ from chalk dust
	NO
Indoor golf courses	Particulate matter (PM_{10})
	Asbestos
	CO, CO_2, NO_2, O_3, Rn
	TVOC
	Microbial contaminations
Indoor horse riding arenas	Particulate matter (PM_1-PM_{20})
	Endotoxins
Indoor motorsport arenas	Particulate matter (TSP, $PM_{2.5}$, PM_{10})
	VOCs
	CO, CO_2, NO_x
Indoor swimming pools	VVOCs and VOCs (especially halogenated compounds)
	Elemental halogens
	Endotoxins
	Microbial contaminations
	Climatic parameters (T, RH)

(Continues)

TABLE 1 (Continued)

Sports environment/facility	Reported indoor air parameters
Sports halls	Particulate matter ($PM_{2.5}$, PM_{10}) Black carbon CO, CO_2, NO, NO_2, SO_2, O_3 Microbial contaminations Climatic parameters (T, RH, AER)

Abbreviations: AER, air exchange rate; CO, carbon monoxide; CO_2, carbon dioxide; $MgCO_3$, magnesium carbonate; NO, nitrogen oxide; NO_2, nitrogen dioxide; O_3, ozone; $PM_{1.0}$, particulate matter (PM) with diameters that are 1.0 micrometers and smaller; $PM_{2.5}$, particulate matter (PM) with diameters that are 2.5 micrometers and smaller; PM_{10}, particulate matter (PM) with diameters that are 10 micrometers and smaller; PM_{20}, particulate matter (PM) with diameters that are 20 micrometers and smaller; $PM_{0.1}$-PM_{10}, particulate matter (PM) with diameters between 0.1 and 10 micrometers; $PM_{0.3}$-PM_{10}, particulate matter (PM) with diameters between 0.3 and 10 micrometers; PM_1-PM_{20}, particulate matter (PM) with diameters between 1 and 20 micrometers; RH, relative humidity; Rn, radon; SO_2, sulfur dioxide; T, temperature; TSP, total suspended particles; TVOC, total volatile organic compounds; UFP, ultrafine particulate matter, particulate matter of nanoscale size (<0.1 µm or 100 nm in diameter); VOC, volatile organic compounds; VVOCs, very volatile organic compounds.

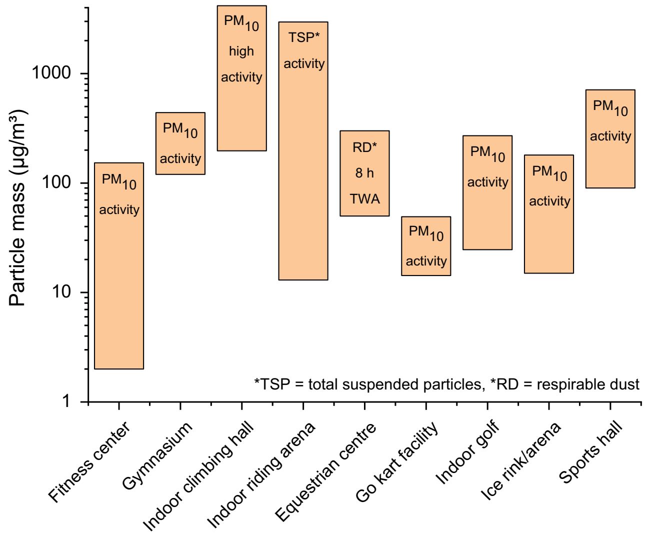

FIGURE 1 Concentrations of PM_{10} and respirable dust in different sports environments. Fitness center: eleven facilities, range of PM_{10} during the morning program[68]; gymnasium: one facility, different types of activity, range of PM_{10};[97] indoor climbing facility: nine facilities, range of PM_{10} during periods of high activity[143]; indoor riding arena: one facility, range of total suspended particles (TSP)[150]; equestrian center: one facility (sixteen measurements), eight-hour time-weighted average (TWA) of respirable dust[152]; go-kart facility: eight facilities (spectators area), range of PM_{10} maximum values during activity[158]; indoor golf: sixty-four facilities, range of PM_{10} during activity[148]; ice skating arena: four facilities, range of PM_{10} concentrations during activities, including resurfacing[129,136]; sports hall: three facilities, range of PM_{10} concentrations during activities[211]

high-intensity cardio activities. The highest maximum PM_1 was noted during a cycling class. Ramos et al[75] found that estimated inhaled doses of PM_{10} were higher in aerobics classes than in holistic classes (classes focusing on relaxation, reducing tension and breathing techniques, such pilates, yoga, and tai chi). PM_{10} concentrations in aerobics classes were, on average, two times higher than in holistic classes. Almeida et al[95] demonstrated that in aerobic classes, the alveolar minute ventilation increased and, consequently, levels of inhaled chemical elements were higher during this activity then in holistic classes. Slezakova et al[79] concluded that cardio activities (more demanding classes) caused ~2 higher inhalation doses, being 20% higher for females, than other types of activity.

Cleaning can also affect the PM_{10} concentrations.[68,97] For example, in a study by Ramos et al,[68] increased PM_{10} levels by six to eight times were monitored for floor cleaning activities. In some cases, increased median PM concentrations were found during non-occupied periods (during the night when empty).[96] That finding could be explained by the formation of new aerosols caused by oxidation of volatile organic compounds[98] emitted from late-afternoon cleaning or the effect of outdoor emissions accumulating due to the motionless conditions preventing mixing.[99]

Slezakova et al[96] monitored higher (by two times) indoor concentrations of ultrafine particles during occupied periods with larger temporal variations noted in general fitness areas than in classrooms and studios.[96] They also found that women exhibited 1.2 times higher UFPs intake than men, suggesting the need for gender-specific studies about UFP exposure in indoor sports environments. This finding was possible due to larger limitation of expiratory flow in female subjects and increased efforts to breath during intense physical exercise. Occupants in indoor sports facilities may be exposed to wet or dry aerosols (eg, metal and oxide nanoparticles) from nano-enhanced products, such as health and fitness products, which are likely to lead to inhalation exposure.[100] Those nanoparticles interact with other components, such as semi-volatile organic compounds (SVOCs), in indoor air,[33] possibly causing mixed aggregates exposure.[100]

Especially in fitness centers, elevated human occupancy promotes the increase of CO_2 concentrations. People are the dominant source of indoor CO_2, and its production rate depends primarily on the number of people in the room and on their metabolic level[68,75,101] (see Section 3.1). Ramos et al[75] found that in fitness centers, CO_2 was the gas most inhaled by physical exercise practitioners, and even high concentrations of CO_2 during physical exercise did not affect psychomotor performance. Ramos et al[68,75] also concluded that in a fitness center, the type of activity and physical intensity determined the CO_2 concentration; the CO_2 concentration was lower in a yoga class compared to a high-energy fitness class (body attack). The high levels of CO_2 concentrations indicated insufficient ventilation in those spaces. Slezakova et al[79] reported that CO_2 levels correlated well with relative humidity (r_s 0.534-0.625) and occupancy due to human exhalation and perspiration during exercising. They also found that the concentration of CO_2 was higher typically during periods of high frequent occupancy around midday (at ~12:00-13:00) and in early evening hours (at ~20:00-21:00). The lowest concentrations were monitored in the early morning and early afternoon (at ~08:00-09:00 and ~15:00-16:00). Temporal maximum values of CO_2 exceeded the recommended level of 1000 ppm (1800 mg/m^3) given by the American National Standard Institute (ANSI) and American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).[102]

Andrade et al[103] measured CO_2 concentrations in three fitness centers in Florianopolis, Brazil, and concluded that all three fitness centers recorded CO_2 concentrations significantly above (P <.01) the recommended maximum level of 750 ppm (350 ppm above the outdoor level of 400 ppm) given by the European Committee for Standardization.[104] The mean CO_2 concentration levels in their study varied between 1000 and 3752 ppm (median 914-3526 ppm). They noticed that the mean CO_2 concentrations were higher in the evening than in the morning or afternoon.

In the fitness center study, Ramos et al[75] revealed that except for CO, all other measured pollutants (TVOC (total volatile organic compounds), CO_2, PM_{10}, and $PM_{2.5}$) given limits[105] were sometimes exceeded. CO never exceeded the limit of 10 mg/m^3 (= 8.73 ppm).[20,105] TVOC exceeded the limit of 0.6 mg/m^3 (=600 μg/m^3)[105] both in aerobic and holistic classes.[75] High TVOC levels were also reported by Slezakova et al.[79] In their study of four health facilities, TVOCs highly exceeded the limit of 600 μg/m^3 in all spaces, even when unoccupied, indicating possible risks for the respective occupants. TVOC levels (both medians and range) were higher in the larger workout areas (a joint space with free weights, bodybuilding machines, and cardiovascular equipment) rather than in rooms or studios for group classes. In fitness centers, the high concentration of VOC may originate from alcohol-based hand disinfectant distributed throughout the facilities.[68] In addition, humans (exhaled breath, perspiration), personal-care products (perfumes, hair sprays, hand disinfectants),[68,79,106-108] and reactions between the ozone and human skin (secondary oxidation reactions)[109,110] can also be relevant sources of VOCs. In recently opened fitness centers, the high VOC and formaldehyde concentrations are probably associated with emissions from new building material, furniture, and equipment.[68,111] It is suggested to use a system composed by an activated carbon filter calcined with a copper oxide catalyst to remove VOCs from indoor environments controlled by a heating, ventilating, and air conditioning (HVAC) system.[112] Furthermore, care should be taken with the use of alcohol-based hand disinfectant or other types of cleaning products in environments used for physical exercise and sporting events because they are recognized as risk factors for respiratory health.[68]

Several studies have reported frequent or occasional daytime temperatures over the recommended values of 20-27°C[113-115] making the sport environment uncomfortable and fatiguing. For example, Onchang and Panyakapo[116] reported the temperature and humidity range of 20.9-36.6°C and 49.7%-99.8%, respectively, in three fitness centers. In two of those centers, the mean temperature value was over 30°C. Lower levels of RH in fitness centers were observed when non-occupied.[79] During exercise, breathing and perspiration generate a substantial amount of water vapor, which impacts RH.[117] The number of occupants is a predictor of room temperature; occupants generate heat,[117] as they are a source of internal heat, and body temperature is typically much higher than room temperature.[118]

All recommended T and RH values for sports facilities are summarized in Table S1 in the SI. The means to maintain comfort parameters within recommended levels include the proper use of air conditioning systems, room insulating, and sun or heat reduction.[79] It should also be noted that women generally prefer a warmer thermal environment.[119] Zhai et al[120] found a positive effect on the comfort of practitioners during exercise caused by the movement of air in the environment and suggested that fitness centers must operate with high air movement in the environment to improve comfort and efficiency. Inherently, localized air speed is able to be focused on the exercising clientele and, thus, solve the problem of cold discomfort among the non-exercising staff.

Ramos et al[121] studied indoor air microbiological contamination in three fitness centers in Lisbon, Portugal. They found that Gram-negative catalase-positive cocci were the dominant bacteria in indoor air samples of the studied centers. *Cladosporium* sp; *Penicillium* sp; *Chrysosporium* sp; *Acremonium* sp; and *Chrysonilia* sp were the most prevalent fungal species identified at night, while *Chrysosporium* sp; *Chrysonilia* sp; *Neoscytalidium hialinum*; *Sepedonium* sp; and *Penicillium* sp were more prevalent in the morning. They concluded that to ensure a healthier space for indoor physical activity, a well-designed sanitation and maintenance program for fitness centers is needed. Markley et al[122] reported that fitness centers' gymnasiums can serve as reservoirs for exposure to *Staphylococci*, leading to infection in the community. They also highlight the need for further research to better define the relationship of exposure to surface colonization with *Staphylococcus aureus* in fitness centers and subsequent development of clinical illness. However, there are also contradictory findings, for example, Ryan and others'[123] findings support the evidence indicating that community transmission is more likely to originate from skin-to-skin contact than from skin-to-surface contact, suggesting that aggressive surface disinfection programs may not be warranted in certain gymnasium environments.

3.2.2 | Gymnasiums

We found 21 studies reporting indoor air quality in 65 gymnasiums. The majority of the gymnasiums (74%) located in the context of the school or university. The most commonly studied contaminant was particulate matter, reported in the 67% of the studies. High particulate matter concentrations in school gymnasiums were found during classes with elevated numbers of occupants and particle resuspension.[2,97,124] For example, Alves et al[2] found that during human occupation, PM_{10} concentrations in a gymnasium ranged from 154 μg/m^3 to 198 μg/m^3, and on the weekend (without occupation) the PM_{10} concentration was 17 μg/m^3. Gymnasiums are often equipped with climbing walls (se also Section 3.2.4) and the high particle levels were mainly due to the use of climbing chalk and constant resuspension. Castro et al[97] reported that the air quality in the gymnasium in their study was strongly influenced by the number of gymnasts training and the use of magnesia alba ($MgCO_3$). Average PM_{10} concentrations of over 440 μg/m^3 were reached due to the use of climbing chalk and the constant resuspension. The type of activity also affects the level of inhaled pollutants. Žitnik et al[117] concluded that an exercising person in the gymnasium would receive about six times higher levels of PM_{10} inside than she/he would have received at rest outside. This conclusion was based on their finding that the intensity of breathing in the observed exercise was about three times faster than that in a resting condition, and the exercise-induced PM_{10} concentration was about two times greater indoors than outdoors.

Although there are some studies reporting low CO_2 concentrations in gymnasium, even at times of elevated human occupation,[2] a recent study by Andrade et al[125] concluded that inefficient ventilation in gymnasiums is a significant problem, with high concentrations of CO_2 leading to impaired indoor air quality and high health risks to occupants, including increased risk of infections (eg, influenza and tuberculosis).

Viegas et al[126] studied the prevalence of fungi in gymnasium, specifically containing swimming pools, and found the most commonly isolated fungi as follows: *Cladosporium* sp (37%); *Penicillium* sp (19%); *Aspergillus* sp (10%); *Mucor* sp (7%); *Phoma* sp; and *Chrysonilia* sp (3%). For yeasts, three different genera were identified, namely *Rhodotorula* sp (70%), *Trichosporon mucoides*, and *Cryptococcus uniguttulattus* (10%). Montgomery et al[127] found that significant exposure to *Staphylococcus aureus* (MRSA) exists in gymnasiums.

Elevated temperature in a gymnasium makes the sports environment uncomfortable and fatiguing and can led to occupants, especially children, suffering serious illness.[2] For example, in the study by Alves et al,[2] the relative humidity values in the gymnasium during the occupancy periods were within the comfort limits, but frequent daytime temperatures, over 30°C, exceeded the recommended values of 18-27°C[113-115,128] (see Table S1 in the SI).

Considering the cleaning done in the different sports facilities used for physical exercise and athletic events, it is recommended the use of powerful vacuum cleaners with multi-stage HEPA filtration systems and graduated filters. Other measures to prevent likely health outcomes are a regular renewal of tatami (a type of mat used as a flooring material) and foam cubes (in gymnastics foam pits), the use of liquid chalk instead of the common magnesia alba, and the installation of indoor multi-stage filtration systems.[97]

3.2.3 | Ice rinks/ice arenas used for skating or hockey

Indoor air quality in enclosed ice skating arenas became a public concern in the 1990s and 2000s due to the use of propane- or gasoline-powered ice resurfacers and edgers.[129] According to the United States Environmental Protection Agency,[48] a primary source of indoor air concerns is the release of combustion pollutants, such as carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter (PM), into the indoor air from the exhaust of fuel-fired ice resurfacers. In several studies, the highest CO levels were recorded in the ice rink with gasoline-fueled resurfacers, and the highest NO_2 levels in the ice rink were recorded where propane-fueled ice resurfacers were used.[129] Later, it was tested and suggested that an electric resurfacer is the best solution to abate indoor air pollution in ice arenas,[12] and during the last few years, new ice resurfacers that meet the most stringent US EPA standards (given by the United States Environmental Protection Agency (US EPA)) has been reported to reduce hydrocarbon, nitrous oxide, and carbon monoxide emissions by about 70%, 80%, and 60%, respectively.[48] Concentrations of CO, NO, and NO_2 in ice skating rinks as well as other sports environments are presented in Figure 2.

We found 31 studies reporting air contaminants in ice skating rink or arenas (see Table S3 in the SI), and in 48% of those studies, the CO concentrations were measured. For example, Guo et al[129] reported the average CO concentration ranged from 2.78 ppm to 5.89 ppm (3190 μg/m^3 to 6749 μg/m^3) in Hong Kong ice arenas. Cox et al[130] measured average concentrations of CO for all activities ranging from 0 ppm to 60 ppm and reported that elevated CO exposure measured while using the resurfacer may have residual CO from prior edging activities (activities using the ice resurfacer). Minimal CO exposure was recorded when resurfacing occurred without edging. The maximum CO concentrations observed were during edging (202 ppm) and exceeded recommended levels for short-term exposure (ie, TLV Excursion = 125 ppm and NIOSH Ceiling = 200 ppm)[130,131] (see Figure 2). Macnow et al[132] found that electric resurfacers decreased the risk of CO exposure, while internal combustion engine resurfacers caused high levels of CO and were responsible for an increase in carboxyhemoglobin (COHb) blood levels. They concluded that youth hockey players in ice arenas with internal combustion engine resurfacers have an increase in carboxyhemoglobin (COHb) during games and have elevated baseline COHb levels compared with players at arenas with electric resurfacers. Carboxyhemoglobin (COHb) prevents O_2 from binding to hemoglobin. It follows that less O_2 is released from the hemoglobin to the muscular myoglobin. This in turn causes serious health risks because the heart must work harder and beat faster.[6] Salonen et al[12] examined four cases of CO poisoning among 325 hockey players and skaters, both children and adults. The symptoms observed were headache, dizziness, fatigue, and nausea. In order to avoid harmful exposure, it is suggested to monitor indoor CO levels, ensure that resurfacing equipment is properly maintained, and institute procedures that minimize worker`s exposure (eg, replacing gasoline-powered edgers with electric edgers).[130]

The concentration of NO_2 was reported in 39% of the ice arena studies. In Finland, Salonen et al[12] studied thirty-one enclosed ice arenas, with propane (65%), gasoline (29%), and electric (6%) resurfacers and reported 228 μg/m^3 average concentrations of NO_2, ranging from 21 μg/m^3 to 1176 μg/m^3 (see Figure 2). In Sweden, Thunqvist et al[133] studied fifteen ice arenas with either propane- or electric-powered resurfacing machines and reported the following indoor mean concentration of NO_2: 276 μg/m^3 (propane) and 11 μg/m^3 (electric). In Hong Kong, Guo et al[129] studied three

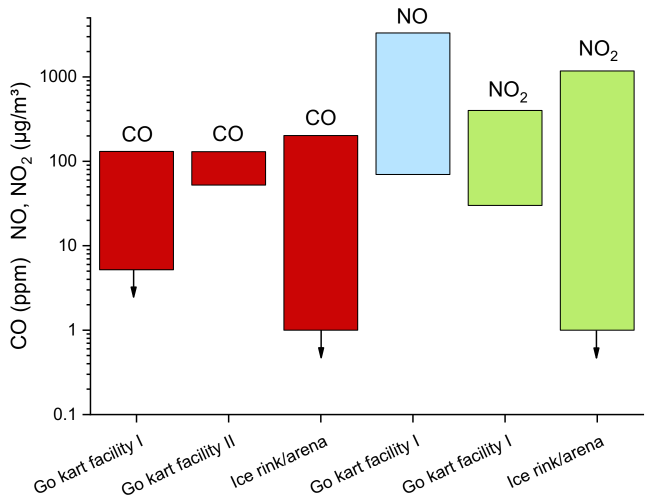

FIGURE 2 Concentrations of CO, NO, and NO_2 in different sports environments. Go-kart facility I: eight facilities, range of CO, NO, and NO_2 maximum concentrations in the track areas[159]; go-kart facility II: one facility, maximum of one minute average CO concentrations during driving[157]; ice rink: multiple facilities, range of CO and NO_2 concentrations.[12,130] The arrows indicate that the minimum concentration is below the limit of quantitation

large indoor skating rinks and reported that the average NO_2 concentrations ranged from 58 to 242 μg/m^3. In Utah, United States, Cox et al[130] reported that the NO_2 concentrations were negligible for all rinks and all activities in their study. However, they concluded that the peak concentration level (0.4 ppm = 750 μg/m^3) was nearly one-half the short-term recommended exposure limit (REL), indicating that exposures to NO_2 are still possible in these rinks despite the use of gasoline-powered equipment. In a study by Salonen et al,[12] the exposure to NO_2 (mean 228 μg/m^3) in ice rinks was associated with rhinitis (18.3%) and a cough (13.7%) prevalent in hockey players during or after training or a game, and those symptoms were reported to possibly decrease performance. There is also evidence that exposure to high levels of NO_2 in an indoor ice arena may be associated with an increased occurrence of airway symptoms several years later.[134]

The concentration of SO_2 was reported in 6% of the studies reviewed. Game and Bell[135] reported surprisingly high concentrations of SO_2 in ice arenas, ranging from 0.3 to 4.5 ppm throughout the season. In Hong Kong, Guo et al[129] measured much lower values. The average concentrations of SO_2 ranged between 10 ppb and 13 ppb (0.01-0.013 ppm) and corresponded to the SO_2 concentration in outdoor air. The cold, dry air, the presence of molds inside and outside the ice arena, the presence of SO_2 in the arena air, combined with intense exercise during practices or competition, as well as living in a cold environment may trigger pulmonary impairment and possibly negatively affect athletic performance.[135]

Concentrations of PM or UFP were reported in 24% of the studies on ice arenas. For example, in Norway reported PM_{10} values were between 20 μg/m^3 and 180 μg/m^3 and $PM_{2.5}$ values up to 30 μg/m^3.[136] In Hong Kong, the average $PM_{2.5}$ (28 μg/m^3 to 62 μg/m^3) and PM_{10} (50 μg/m^3 to 79 μg/m^3) concentrations inside the arenas were lower than those measured outdoors ($PM_{2.5}$:97 μg/m^3 to 134 μg/m^3; PM_{10}: 138 μg/m^3 to 157 μg/m^3).[129]

Measured PM_{10} values and some measured $PM_{2.5}$ values were above the 24-hour recommended mean values, 50 μg/m^3 for the PM_{10} and 20 μg/m^3 for the $PM_{2.5,}$ given by the WHO.[60] It has been concluded that the PM values were not affected by the electrical resurfacer but were caused by an inadequate ventilation system and accumulation of PM[136] and that the increased concentrations of both $PM_{2.5}$ and PM_{10} were probably related to the location of the nearby heavily traveled roads. Based on those reported PM values and the general use of filtering systems in ice arenas, it can be concluded that the resurfacers had little effects on the levels of PM in the ice rinks. However, in studies with low ventilation rates, high FP (fine particles, diameter <2.5 μm), UFP,[137,138] and CO concentrations were associated with the resurfacing process.[137] Rundell[138] concluded that acute exposure to PM_1 generated by ice resurfacing may aggravate an asthmatic reaction, while the precise effect of years of chronic exposure at high ventilation rates during ice sport activity from an early age may modify the morphology of the peripheral airways.

Microbiological contaminants were studied in only one ice arena in a Canadian study conducted by Game and Bell.[135] In their study, *Eurotium amstelodami* was the only species to show an increase over the entire hockey season inside the ice arena, but these levels were lower than in the outdoor sample. Additionally, the only species recorded at a concentration of 50 CFU/m^3 (colony forming units per cubic meter) or higher in the arena were *Eurotium amstelodami* and *Alternia alternata*, the concentrations being at the same level as the levels in outdoor air.

In addition to chemical and microbiological indoor air pollutants, comfort parameters for CO_2 and temperature affect the indoor air quality and well-being of occupants, as reported in several studies. For example, Toomla et al,[139] Grande and Cao,[136] and Guo et al[129] reported CO_2 values exceeding the upper limit guideline value of 1200 ppm.[140] In Finland, Toomla et al[139] demonstrated that although the measured concentration levels of CO_2 were below 1200 ppm for the majority of the time, some measurements exceeded that value briefly, especially during the weekend when more people occupied the space. In Norway, Grande and Cao[136] found that the CO_2 concentration increased from 870 ppm to almost 1400 ppm in just under three hours with stabile high activity (during the training on the ice rink). In Hong Kong, Guo et al[129] found that the average CO_2 concentration ranged from 851 ppm to 1329 ppm and concluded that the high CO_2 levels recorded in the ice arenas were attributed to overcrowding and an insufficient supply of fresh air.[141]

In Finland, the reported average temperature and humidity inside the arenas were 3.5°C–8.8°C and 64.5%–82%, respectively.[139,142] Salonen et al[12] listed the following means to reduce exposure in ice arenas: 1) the use of electric resurfacers instead of combustion engine powered resurfacers; 2) retrofitting emission control technology in propane-fueled resurfacers as an efficient temporary option to reduce engine emissions; 3) mechanical ventilation at a reasonable air exchange rate (0.25-0.5 h^{-1}) during opening hours; 4) personnel training to understand the risks associated with poor maintenance practices if combustion engine resurfacers are used; 5) if the CO concentration is >20 mg/m^3 (17.46 ppm) or the NO_2 concentration is >150 µg/m^3, ventilation should be increased; 6) at CO concentration >60 mg/m^3 (52.37 ppm) or NO_2 concentration >2000 µg/m^3, ice arena users and spectators should be evacuated if the elevated pollutant level cannot be effectively reduced within 15-30 minutes.

3.2.4 | Indoor climbing facilities

The fact that climbing and bouldering are Olympic disciplines demonstrates the increasing popularity of this sport. Climbing and bouldering can now be practiced in countless facilities, and the number of facilities is still increasing. In the beginning, standard gyms were equipped with climbing walls. Later, special halls became necessary in order to be able to practice the different climbing techniques. We found 5 studies (see Table S3 in the SI) reporting the indoor air quality parameters in indoor climbing facilities, and all of those include measurements of particulate matter. For the athlete, it is essential to keep the hands dry, and $MgCO_3$ (magnesia or magnesia alba) is the material of choice. However, magnesia is a strong source of particulate matter. Weinbruch et al[143] studied the particle mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} in nine indoor climbing facilities and in five sports facilities. For periods of high activity, PM_{10} values between 1000 µg/m^3 and 4000 µg/m^3 were monitored (see Figure 1). $PM_{2.5}$ reached concentrations up to 500 µg/m^3. The size distribution and the total particle number concentration (3.7 nm–10 µm electrical mobility diameter) were determined in one climbing facility. The highest number of concentrations were approximately 12,000/cm^3, and the authors concluded that the use of magnesia alba was not a strong source for ultrafine particles. Weinbruch et al[144] also studied different application techniques of magnesia and found that suspensions in ethanol led to similar low-mass concentrations as the prohibition of magnesia alba. Today, the use of liquid chalk is common in indoor climbing facilities. However, air ventilation was considered as the most effective way of reducing dust concentrations in indoor climbing gyms. Other studies produced analogous results. Almand-Hunter et al[145] measured up to 597 µg/m^3 PM_{10} (6 hours on average) in a gym. Alves et al[146] measured PM_{10} concentrations in the indoor environment of climbing venues and found distinct differences in the chemical composition of indoor and outdoor particles. The use of magnesia alba caused a significant increase in the mass and number of coarse mode particles. Moreover, $MgCO_3$ was the dominant component of indoor particles. Moshammer et al[147] examined 109 climbers before and after a climbing activity and found acute and subacute adverse effects in lung function.

3.2.5 | Indoor golf courses

Little is known about the indoor air quality of indoor golf courses. Most popular is screen golf in which a computer, connected to sensors and cameras, provides a virtual golf experience in a projected landscape. Moreover, most indoor arenas offer training facilities for tee-off and putting. Goung et al[148] published the only comprehensive study on indoor air quality in sixty-four Korean screen golf courses. Concentrations of PM_{10}, carbon monoxide, carbon dioxide, nitrogen dioxide, ozone, formaldehyde, TVOC, bacteria, asbestos, and radon were measured. The average concentrations of the target pollutants did not exceed the respective pollutant standard set by the Korean law. However, some of the facilities showed increased concentrations of PM_{10}, formaldehyde, and bacteria.

3.2.6 | Indoor horse riding arenas

The riding surface is an important component in the equestrian discipline. The surface should support the performance of the horse but should also help prevent injuries. Materials like sand, sawdust, and synthetic fiber are commonly used in riding arenas.[149] The constant walking, trotting, and cantering of heavy horses on such grit causes the resuspension of particulate matter and, consequently, exposure to different types of airborne pollutants. We found six studies (see Table S3 in the SI) reporting the indoor air quality parameters in indoor horse riding arenas. Particles (83% of the studies) and dust (67% of the studies) were the most commonly studied contaminants. Lühe et al[150] investigated the distribution of grain sizes in four German riding arenas: 80-90% were between 125 µm and 500 µm and 3-7% were smaller than 63 µm. The mean particle mass in the air of indoor riding arenas, averaged over one year, was between 0.022 mg/m^3 and 0.233 mg/m^3, but extreme peak concentrations up to 3 mg/m^3 were observed (see Figure 1). Venable et al[151] showed that recycled rubber material can reduce particulate matter in the air during an indoor riding event when applied over the layer of sand. The personal exposure of an equestrian worker to crystalline silica and respirable dust was studied over 16 days by Bulfin et al[152] The concentrations measured over 8 hours per day resulted in time-weighted averages of <0.01-0.34 mg/m^3 for respirable dust (see Figure 1) and <0.01-0.09 mg/m^3 for crystalline silica. The concentrations were lower on days when the arena was watered. Claußen et al[153] studied the release of PM_{10} from footing materials, including pure sand, sand-wood chips, and sand-fiber in dependence of their moisture content, density, and particle size distribution. It was found that the density of the sand-fiber footings had a significant influence on the release of PM_{10}. The authors considered regular watering a suitable measure to lower emissions of particulate matter. In horse stables, Samadi et al[154] measured high concentrations of airborne particulate matter. The maximum value was 9.6 mg/m^3. Moreover, increased concentrations of endotoxins and ß (1 → 3) glucan were found. The problem of extreme particle concentrations in horse stables were also investigated by Hessel et al,[155] who measured the generation of PM_{20}, PM_{10}, $PM_{2.5,}$ and PM_1 from horse feed. The maximum concentrations were 35.31 mg/m^3 (PM_{20}), 9.58 mg/m^3 (PM_{20}), 0.34 mg/m^3 ($PM_{2.5}$), and 0.13 mg/m^3 (PM_1).

3.2.7 | Indoor motorsport arenas

We found five studies (see Table S3 in the SI) reporting the indoor air quality parameters in indoor motorsport arenas, and carbon monoxide was the most commonly studied contaminant (80% of the studies). Particulate matter was reported in 40% of the studies. Morley et al[86] investigated the exposure of employees and spectators to carbon monoxide at a monster truck and motocross show. The peak concentrations were between 75 ppm and 340 ppm, and the time-weighted average during the show was between 42 ppm and 80 ppm. Levesque et al[156] investigated the air quality during an indoor monster truck and car demolition show in a Canadian arena. For carbon monoxide, extreme peak concentrations between 219 ppm and 1645 ppm were found. Time-weighted averages ranged between 33 ppm and 100 ppm. The nitrogen dioxide concentrations were below the detection limit of the measuring device (0.5 ppm).

For many people, go-kart driving is also a popular activity. Today, most go-kart arenas are organized as multi-event complexes and offer other facilities, like bowling, restaurants, and business centers. Reports about acute cardiovascular events among drivers at an indoor go-kart arena prompted a study by Kim and Wagner[157] on carbon monoxide and $PM_{2.5}$ inside an indoor go-kart facility. For drivers, the peak exposures to carbon monoxide ranged from 52 ppm to 130 ppm (see Figure 2). In the case of $PM_{2.5}$,peak concentration ranged from 39 μg/m^3 to 350 μg/m^3, and the maximum 5-minute average $PM_{2.5}$ concentrations was between 28 μg/m^3 and 42 μg/m^3. Sysoltseva et al[158] studied particulate matter in air at eight indoor go-kart facilities. The mean PM_{10} concentrations were 4.9 μg/m^3 to 34.9 μg/m^3 for workplaces and 5.6 μg/m^3 to 28.4 μg/m^3 for spectator areas (see Figure 1). The mean $PM_{2.5}$ concentrations were 2.3 μg/m^3 to 29.2 μg/m^3 for workplaces and 2.4 μg/m^3 to 27.4 μg/m^3 for spectator areas. The authors point out that not only motor emissions but also brake and tire debris contribute to air pollution in kart arenas. In parallel measurements, Wolf et al[159] found increased concentrations of carbon monoxide, NO_x, C1-C3-benzenes, naphthalene, and benzo[a]pyrene dependent on the fuel (regular, special, and liquid gas). The lowest pollutant concentrations were measured for electrically powered karts.

3.2.8 | Indoor swimming pools

We found 62 studies (see Table S3) reporting the indoor air quality of indoor swimming pools and aquatic centers. Since chlorine (Cl_2) and sodium hypochlorite (NaOCl) are the most common disinfectants used in swimming pools, air quality in light of disinfection by-products (DBPs) is unique in that kind of sport environment.[160] Chlorine and hypochlorite react with natural organic matter (eg, sweat, skin cells, cosmetics, and urine from swimmers) in the water of swimming pools.[161,162] Hypochlorite can also be produced from alternative disinfectants like trichloroisocyanuric acid and bromochlorodimethylhydantoin.[163] The DBPs, mainly consisting of halomethanes, especially trihalomethanes (THMs) and chloramines, can be found in pool water and in the air of indoor swimming pools.[4,164-166] Chloroform ($CHCl_3$) is the dominant THM by mass in swimming pools, and as chloroform is a highly volatile compound, in addition to absorption via dermal uptake, it can be also inhaled.[167]

In indoor chlorinated swimming pool facilities, both air and water qualities are relevant issues with respect to the health of the facility users.[168] Chiu et al[57] concluded that work-related eye and respiratory symptoms were about five times more common among employees working in the waterpark than employees working in the other parts of the resort (non-waterpark employees consisted of maintenance staff, an arcade attendant, a bartender, housekeeping staff, hotel front desk staff, office staff, and managers). These symptoms were consistent with exposure to chemicals formed when chlorine used to disinfect pool water reacts with materials from swimmers' bodies.

In Italy, Fernández-Luna et al[169] reported that the mean chlorine level in the air of twenty-one swimming pools was 4.3 ± 2.3 mg/m^3, and in 85% of the facilities, the concentration of 1.5 mg/m^3, the suggested limit for the risk of irritating effects, was exceeded. They also found that the concentration of chlorine in indoor swimming pool air had a direct effect on self-perceived health problems among swimming pool workers.

In Portugal,[14,170] the reported THM concentrations in the pool air varied between 28 μg/m^{3}and 906 μg/m^3. Gouveia et al[14] used the measured values to predict multi-pathway chronic daily intake (CDI), cancer risk (CR), and hazard index (HI), and they highlighted the need to develop comprehensive guidelines to safeguard the health of individuals involved in elite swimming. Sa et al[170] found that THM concentrations at 150 cm above water surface were about 30% lower than the corresponding values found at 5 cm. Their data confirmed that swimmers are exposed to higher concentrations of THMs by inhalation than lifeguards. In Italy,[56,165] the reported mean levels of THMs in ambient air at swimming pools in Modena and Emilia Romagna region were 58 μg/m^3 and 81 μg/m^3, respectively, being lower than the mean THMs values of 119 μg/m^3 (ranging from 58 μg/m^3 to 552 μg/m^3) measured in Canada[171] and the mean THMs values of 146 μg/m^3 (±117.8 μg/m^3) measured in France.[172]

The concentration of chloroform ($CHCl_3$) has been reported by several authors.[4,165,173-178] For example, in Europe, the reported mean chloroform concentrations in the air of indoor swimming pools ranged between 35 μg/m^3 and 55 μg/m^3.[4,165,179] It should be noted that the presence of chloroform indicates the formation and potential for exposure to additional chlorine disinfection by-products, such as chloramines (CAMs).[57] The possible factors affecting chloroform concentrations in the air in indoor swimming pool facilities include ventilation rate, bather load, and free chlorine concentration.[180]

Trichloramine (NCl_3), among the most commonly studied THM, is encountered as a by-product of chemical reactions between ammonia derivates and chlorine and has been associated with irritative ocular and upper airway symptoms, symptoms associated with the lower respiratory track, and an increased risk of asthma both in swimming pool workers and swimmers.[181-185] The formation of trichloramine in swimming pools from urea is presented in Figure 3. However, other nitrogen compounds (amines, amides, and amino acids) also act as precursors.[186] Due to the low Henry constant of $H = 9.9 \cdot 10^{-4}$ mol/($m^3 \cdot$Pa),[187] the compound is volatile in water. Chu et al[188] found both the concentration of free available chlorine in water and the number of swimmers to be significantly associated with the airborne concentration of NCl_3 ($P < .05$). Bessonneau et al[176] found that indoor trichloramine (geometric mean 190 μg/m^3) as well as THM (geometric mean of 74.9 μg/m^3) concentrations were associated with the number of swimmers. They also reported that trichloramine was linked to air temperature and pH value.

In Switzerland[189] and France,[190,191] the suggested exposure limit for trichloramine in indoor swimming pool air is 300 μg/m^3. However, frequent pool users who may be exposed to trichloramine for longer periods might be more sensitive to lower concentrations, and respiratory symptoms with concentrations as low as 17 μg/m^3 were reported.[188] In Switzerland, Parrat et al[189] measured a 114 μg/m^3 mean concentration of trichloramine and concluded that there is an increased risk of irritative symptoms up to a level of 200-300 μg/m^3 of trichloramine. Rundell et al[192] observed significant ocular and respiratory symptoms for lifeguards and trainers when they were exposed to 500-1300 μg/m^3 of trichloramine. Fantuzzi et al[193] recognized that irritative symptoms become significant at trichloramine concentrations over 500 μg/m^3. Those studies by Rundell et al[192] and Fantuzzi et al[193] confirmed that the recommended values given by the WHO can be considered protective in occupational exposure to airborne trichloramine in indoor swimming pools.

There are several studies in which the suggested exposure limits for trichloramine were frequently exceeded. For example, in Belgium, the reported mean value for trichloramine in air varied from 300 to 660 μg/m^3.[182,194,195] In Spain, the mean concentration of trichloramine ranged from 170 to 858 μg/m^3.[179,196] In Sweden, reported mean concentrations of trichloramine in the pool air varied between 23 μg/m^3 and 210 μg/m^3 (range 1-770 μg/m^3).[181,184,197,198] For personal exposure to trichloramine in indoor swimming pool facilities in Sweden, the reported mean values varied between 36 μg/m^3 and 71 μg/m^3 (range < 1 μg/m^3 to 240 μg/m^3).[198,199] A swimming school teacher and a lifeguard presented the highest exposures to trichloramine of 240 μg/m^3 and 220 μg/m^3, respectively.[199] In the United States[168] and in Canada,[200] the reported mean concentrations of trichloramine in the air were 150 μg/m^3 and 380 μg/m^3, respectively. In indoor chlorinated swimming pool facilities located in Southern Europe, the reported mean concentration of indoor bromoform ($CHBr_3$), dibromochloromethane ($CHClBr_2$), chloroform ($CHCl_3$), and bromodichloromethane ($CHBrCl_2$) was 0.4 μg/m^3-11.2 μg/m^3; 1.9 μg/m^3-13.2 μg/m^3; 35.0 μg/m^3-54.5 μg/m^3; and 4.2 μg/m^3-14.6 μg/m^3, respectively.[165,179] In indoor seawater swimming pools located in France, the reported mean concentration of indoor bromoform ($CHBr_3$) and dibromochloromethane ($CHClBr_2$) were 200 μg/m^3 (max 1600 μg/m^3) and 13 μg/m^3(max 150 μg/m^3), respectively.[164,172] Bromoform is the most abundant trihalomethane (THM) compound in seawater swimming pools, and measured levels of bromoform ($CHBr_3$) in those kinds of pools are particularly alarming. Consequently, it seems important to determine the occupants exposure to bromoform (and to the other THM), not only in water but also in air.[164] The measured values of bromoform exceeded frequently the recommended value of 350 μg/m^3.[201]

Studies concerning pollutants other than DBPs in swimming pool facilities are rare. Tolis et al[4] did a comprehensive air quality investigation at an aquatic center in Greece, measuring different indoor air parameters. They found that, in general, the mean concentrations of VOCs were very low, except in the morning. Chloroform was the most abundant compound found in the atmosphere of the aquatic center due to the disinfection of the water. In addition to chloroform, *m*-xylene, *p*-xylene, octane, and toluene were three compounds with the highest concentrations found indoors. Limonene, commonly contained in cleaning products and

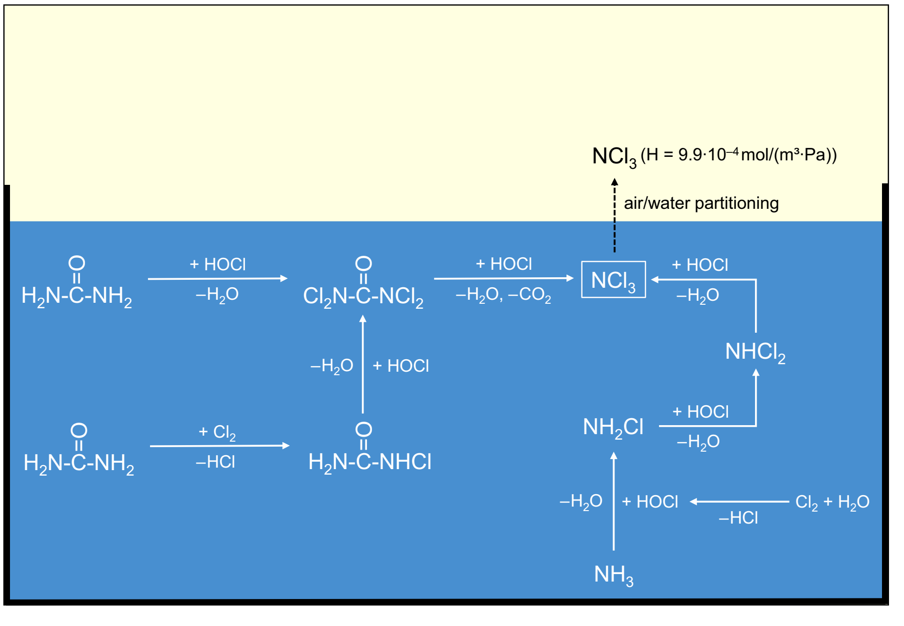

FIGURE 3 The formation of NCl_3 in swimming pools (see also Schmalz et al[186])

personal hygiene products, used inside the swimming pool was characterized by a high indoor/outdoor value. The concentrations of NO_2 indoors (mean 113.07 μg/m^3) was higher than outdoors (mean 63.31 μg/m^3), and the hourly concentrations of NO_2 for indoor areas sometimes exceeded the WHO guideline of 200 μg/m^3 (for one-hour exposure).[20] In their study, indoor concentrations of NO_2 showed an increased pattern when the swimming pool was fully occupied (around hours 16:00 to 21:00). The concentrations of ozone outdoors (mean 81.96 μg/m^3) was higher than ozone concentrations inside the facility (mean 59.90 μg/m^3). This indoor/outside ratio of 0.73 is high but not uncommon.[42] In a swimming pool, the surfaces are covered with a film of water, which slows down the surface reaction of ozone.[202] The Henry constant of ozone is small with H = 1.0.10^{-4} mol/(m^3·Pa).[187] Therefore, the pool water is not a significant sink. The diurnal variation of ozone indoors followed the diurnal variation of the ozone outdoor concentration (a clearly increasing trend, starting from 11:00 and ending by 21:30). The explanation for this may be that swimming pool areas started to be ventilated during these hours, while for the rest of the day, these areas remain unventilated or closed. One possible explanation for the lower concentrations of ozone indoors may be that if there are not indoor sources of ozone present, gas phase reactions, and deposition, which might result in lower indoor ozone.[42]

In Italy, Brandi et al[203] investigated the occurrence of mycotic species in 10 swimming pools, and they found moderate mycotic titers and high biodiversity. *Penicillium* spp.; *Aspergillus* spp.; *Cladosporium* spp.; and *Alternaria* spp. were continually detected in air and surface samples by the swimming area, while pathogenic yeast *Candida albicans* was never detected. *Fusarium* spp. was the most common taxon isolated from surfaces. In Iran, Mansoorian et al[204] found that *E coli*; *Actinobacteria*; *Pseudomonas alcaligenes*; *Pseudomonas aeruginosa*; and *Klebsiella pneumonia* were the most important isolated bacteria types in swimming pool environments, and bacterial contamination was observed in about 17% of the samples. In waterpark studies conducted in the United States, the reported mean endotoxin levels[22,57] in the pool area were 45 EU/m^3 (endotoxin units per cubic meter of air volume) (range: not detectable to 84 EU/m^3).

Indoor CO_2 concentrations in swimming pool facilities usually meet the recommendations. For example in Greece, the reported mean concentration of CO_2 was 502 ppm (range: 259-1322 ppm).[205]

The air temperature and RH levels measured in the swimming pool facilities and waterparks did not always meet the given guidelines[206,207] (see Table S1 in the SI). For example, in the Southern European swimming pool studies, the daily average air temperature and humidity were 26.5°C (range: 19.2-37.5°C) and 64.5% (range: 23.9%-95.7%), respectively.[165,172,205,208] In a US waterpark study by Dang et al,[22] daily average air temperature and relative humidity ranged from 27.8°C to 31.7°C, and 41% to 69%, respectively. ASHRAE[206] recommends that air temperatures be 2˚C to 4˚C above the water temperature to reduce evaporation and avoid chilling effects for waterpark users. For buildings containing swimming pools, ASHRAE[206] guidelines require an RH of 50-60%, exceeding of which (over 60%), can lead to mold growth.[57]

Efficient means to reduce indoor exposure in swimming facilities include carefully regulated chlorine levels and temperatures in swimming pools, properly ventilated pools, and information transmitted to bathers about the importance of personal hygiene to reduce irritants in swimming pool environments.[209] Using indoor pools treated with combined chemical treatments (eg, ozone) can reduce direct exposure to disinfection by-products and their negative effects on respiratory function compared to chlorinated pools.[210]

3.2.9 | Sports halls

We found nine studies reporting indoor air contaminants in sports halls (see Table S3 in the SI). The most often studied parameters were carbon dioxide (78% of the studies), temperature (78% of the studies), and relative humidity (67% of the studies). The measured mean indoor CO_2 concentrations varied between 420 ppm and 1287 ppm (ranging from 294.8 ppm to 1529 ppm).[211-215] This indicates that inside closed spaces, where physical activity is practiced,[215] recommended optimum levels and guidelines of CO_2 are very often exceeded.[102,104,105,140,216] (see Table S1 in the SI). For example, in Spain, Accili[213] found that CO_2 concentration increases significantly during the evening, and the recommended comfort levels of CO_2[217] (see Table S1 in SI) are not met starting from 19:00. The study establishes that the users of the sports hall experience periods of discomfort due to poor air quality when the occupation is maximum.

In Europe,[211,212,214] the reported mean values for T and RH in the sports halls varied between 15.9 and 22.1°C and 48.5 and 49.9%. In several cases, the temperature were under the recommended range of 20°C and 22°C[115] (see Table S1 in the SI), while the relative humidity in those facilities were in accordance with the recommendations (under 60%).[115] In Australia, Rajagopalan and Luther[218] investigated (by using the comfort cart designed according to the ASHRAE standard[219]) the thermal and ventilation performance of a naturally and hybrid ventilated sports hall within an aquatic center located in Victoria, Australia. They found a high level of thermal discomfort during warm weather, with high solar radiation.

Particulate matter in sports halls were measured in 33% of the studies. The concentration of PM_{10} (mean 400 ± 310 μg/m^3) were measured only in three sports halls[211] and the range of concentration is presented in the Figure 1. In all those sports halls, the recommended values of 20-50 μg/m^3 [21,28,74,114] (see Table S1 in the SI) for PM_{10} were exceeded. The concentration of $PM_{2.5}$ were measured only in one sports hall in Greece by Tolis et al[212] In their study, the $PM_{2.5}$ concentration was a little higher outdoors (mean 13.98 μg/m^3) than indoors (mean 11.96 μg/m^3) and the I/O (indoor/outdoor) ratio was always under 1, indicating the influence of outdoor sources to indoor $PM_{2.5}$ concentrations. The recommended annual target value of 10 μg/m^3 [21] (see Table S1 in SI) for $PM_{2.5}$ was slightly exceeded.

The VOC in sports halls were found at very low levels, both at indoor and especially at outdoor air, and toluene was the compound with the highest concentrations both indoors and outdoors.[212] The I/O ratio was below 1 for most of the compounds, indicating the major source to be outdoor air. Styrene and d-limonene with the maximum observed I/O ratio value of 4.7 and 3.7, respectively, seems to have both indoor sources and an outdoor influence through the air exchange. Possible indoor sources of those compounds in sports halls are the cleaning process and the plastic substrate of the floor for the volley playing field. It was also found that athletic events influence the VOC concentrations in indoor and outdoor air.[212]

The sports hall results have revealed that outdoor sources of O_3 significantly affected indoor air quality inside the halls.[5,212] The measured O_3 indoor air concentrations (mean 12-36 μg/m^3) in sports halls has been lower than concentrations in outdoor air (50-64 μg/m^3) both in the "event period" as well as "no event period."[5,212] For example, in Greece, Stathopoulou et al[5] studied two large differently ventilated sports halls and found that both in the naturally ventilated as well as in the mechanically ventilated sports halls, the concentration of O_3 is much higher at the outdoor air than at indoor air (I/O ratio 0.3 in the naturally ventilated sports hall and 0.6 in the mechanically ventilated sports hall) during the event and at a period when there are no events.

For NO_2, the findings are contradictory. For example, in the study by Stathopoulou et al,[5] the NO_2 concentrations found at outdoor air (33-41 μg/m^3) were lower than that found at indoor air (mean 38-61 μg/m^3). This is opposite to that observed by Tolis et al[212] In their study, the mean NO_2 concentration at indoor and outdoor was 73 μg/m^3 and 95 μg/m^3, respectively. Microbial contamination was studied in three sports hall studies.[211,215,220] The measured concentrations of fungi and bacteria in those studies ranged between 0-1649 CFU/m^3 for fungi and 0-6872 CFU/m^3 for bacteria. After intense sporting activities, hemolytic bacteria were present in high concentration. The correlation between the microorganisms (fungi and bacteria) and the number of persons showed that intense athletic activities influenced the variation of microorganisms.[215]

In order to ensure comfort and energy efficiency as well as achieve and maintain sport performance in sports halls, many parameters must be considered in an integrated approach.[5,215] The studies have revealed that the outdoor pollution, the type of the ventilation, and the operating patterns of the HVAC system when ventilation is mechanical, the indoor materials, the location of the sports hall, and the location of its physical openings as well as the different indoor activities with the varied number of occupants are important factors affecting and controlling IAQ in sports halls as well as in other large enclosures where large number of spectators are present during athletic events.

4 | CONCLUSIONS AND RECOMMENDATIONS

This study provides a review on human exposure to indoor air contaminants in different types of indoor sport facilities, the contributing factors of various levels of those contaminants, and the means to reduce the exposure. The respective people can be active themselves or be a spectator.

Combustion engines are used in many sporting events with or without an audience. Here, for example, the available indoor guide values for CO, NO_x, and TVOC can be used as a criterion (see Table S1 in the SI). In ice hockey arenas, NO_2 and CO exposure are most concerning, and the means to abate these indoor air pollutions is an electric resurfacer instead of the combustion engine powered resurfacer and the use of mechanical ventilation at a reasonable air exchange rate during opening hours.

Assessments become more difficult in the case of exposure to coarse particles. During horse riding events, it has to be assumed that high concentrations of particles released from the grit can be measured directly in the arena. However, systematic studies on the size-dependent particle distribution in the entire riding hall and the possible exposure of spectators are not yet available.

The air quality in large closed arenas with spectator capacities of up to 25,000 people has rarely been examined (see Table S3 in the SI). In contrast, there is much work on outdoor air quality in open stadiums[221] and at major sporting events such as the Olympic Games[222,223] and World Championships.[10] The same applies to the health effects of air pollutants on athletes in the amateur and professional sectors. Brunekreef and colleagues[7,224] examined the effects of photochemical air pollutants and particles on cyclists. As early as 2001, Carlisle and Sharp[6] discussed adverse effects of ambient air pollutants in sporting activities. Various works deal with the influence of air pollution on marathon runners.[8,225] In 2018, the Clean Air Initiative of the International Association of Athletics Federation's (IAAF) has started a project for the regular measurement of air pollution at major sporting events.[226] On the other hand, there is a lack of risk assessments for indoor sport activities.

The evaluation of measured pollutant concentrations shows that trained and recreational athletes as well as children and all asthmatic individuals could also be at risk when they are practicing in indoor environments. The effect on athletes is apparent as metabolic demands of exercise increase the alveolar minute ventilation (AMV) and thus the rate of inhalation of pollutants. At moderate levels of activity (approx. 100 W), the AMV of a standard person is quadrupled with approx. 30 l/min compared to the resting volume. At maximum power of athletes, the AMV is even increased tenfold (see Figure 4). Therefore, the question arises, whether published indoor air guidelines[20,73] can also be used during physical activity. The results are contradictory. In various studies, no adverse response during exposure to ozone,[227] NO_2,[228] or VOCs[229] was found under light training conditions. On the other hand, the combination of terpenes and ozone caused irritation even at low concentrations.[230]

In addition, occupants working in the facilities may be at risk. The high CO_2 concentrations and the calculated ventilation rates in several studies demonstrated that, in general, fitness centers and gymnasiums have inefficient ventilation, considering the large number of people, and relatively small room sizes for the types of activities

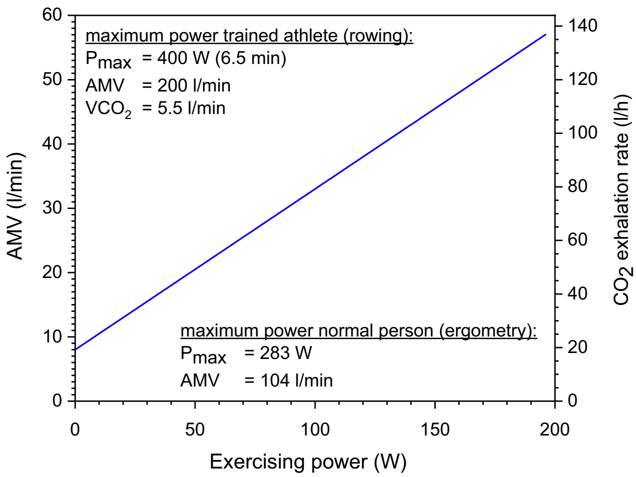

FIGURE 4 The blue line shows the carbon dioxide exhalation rate (l/hour) of a standard person in dependency on the exercising power (W) and alveolar minute ventilation AMV (l/minute). Maximum values for a trained athlete (rowing) and a normal person (ergometry) are provided for comparison. The data were taken from Hollmann[94]

conducted in those facilities. High CO_2 concentrations have also been found to be a problem in sports halls, especially during the evenings with elevated number of occupants. When exercising at 100 W, a standard person exhales approx. 80 l CO_2 per hour. In a 400 m^3 room, an occupancy of 25 people would require a minimum air change of 6 h^{-1} to keep the CO_2 concentration permanently in the range of 1000 ppm. The location of air intakes and air filtration is also essential for the maintenance of good IAQ. As cleaning practices affect chemical exposure and cleaning chemicals are recognized as risk factors for respiratory health, low emitting cleaning agents and cleaning practices should be used. In addition, attention should be paid to the number of people attending the facility as well as the occupant's behavior. Comfort parameters (T and RH) should be maintained within the recommended ranges (eg, by the proper use of an air conditioning system, room insulation, or sun and heat reduction). At indoor swimming pools, the most concerning pollutants are DBPs, such as $CHCl_3$ and NCl_3. Appropriate ventilation to minimize chloramine accumulation, control of water chlorination and temperature, and adequate hygiene of swimmers should be enforced to reduce irritants in swimming pool environments for the occupants.

In conclusion, better and more efficient ventilation concepts for sport facilities are required, especially for fitness centers and climbing halls due to the potentially high concentrations of CO_2 and particles. In general, there is a lack of knowledge regarding IAQ in sports facilities and additional studies representing different climatic areas are urgently needed. The respective measurement strategy should be based on the individual circumstances. In climbing halls, it can make sense to measure the personal concentration of particles instead of the air concentration. Air quality guidelines are already available for many types of pollutants.[33,129] However, for several important compounds like DBPs such guidelines are still missing. Moreover, a critical discussion on stringent air quality requirements for sport facilities is advisable, thus young people as well as vulnerable groups spend a lot of time in these facilities at high pulmonary ventilation rates. Benefits of physical activities can be strengthened by reducing the exposure to pollutants and by minimizing the risk of possible adverse health effects in different indoor sport environments.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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