

Review

Toward Health-Oriented Indoor Air Quality in Sports Facilities: A Narrative Review of Pollutant Dynamics, Smart Control Strategies, and Energy-Efficient Solutions

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Abstract

Indoor sports facilities face distinctive indoor air quality (IAQ) challenges due to high occupant density, elevated metabolic emissions, and diverse pollutant sources associated with physical activity. This review presents a narrative synthesis of multidisciplinary evidence concerning IAQ in sports environments. It explores major pollutant categories, including carbon dioxide (CO₂), particulate matter (PM), volatile organic compounds (VOCs), and airborne microbial agents, highlighting their sources, behavior during exercise, and associated health risks. Research shows that physical activity can increase PM concentrations by up to 300%, and CO₂ levels frequently exceed 1000 ppm in inadequately ventilated spaces. The presence of semi-volatile organics and bioaerosols further complicates pollutant dynamics, especially in humid and densely occupied areas. Measurement technologies such as optical sensors, chromatographic methods, and molecular techniques are reviewed and compared for their applicability to dynamic indoor settings. Existing IAQ standards across China, the USA, the EU, the UK, and WHO are examined, revealing a lack of activity-specific thresholds and insufficient responsiveness to real-time conditions. Mitigation strategies (e.g., including demand-controlled ventilation, use of low-emission materials, liquid chalk substitutes, and integrated HEPA-UVGI purification systems) are evaluated, many demonstrating pollutant removal efficiencies over 80%. The integration of intelligent building management systems is emphasized for enabling real-time monitoring and adaptive control. This review concludes by identifying research priorities, including the development of activity-sensitive IAQ control frameworks and long-term health impact assessments for athletes and vulnerable users.

Keywords: indoor air quality (IAQ); indoor sports facilities; particulate matter and VOCs; ventilation and purification technologies; exposure-dose assessment and health risk



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1. Introduction

1.1. General Background

In recent years, with the continuous advancement of urbanization and the in-depth implementation of the national fitness policy, urban residents' pursuit of a healthy lifestyle has been increasingly enhanced, driving the rapid development of various indoor sports facilities [1]. These buildings not only encompass traditional sports facilities such as gyms, swimming pools, and fitness centers but are also evolving towards multifunctional, intelligent, and composite designs, which become an indispensable part of modern urban

spaces [2]. Especially in high-latitude, high-density, or hot-humid urban areas, where climate constraints or land-use limitations significantly affect outdoor activity, residents increasingly rely on indoor environments to complete daily exercise and rehabilitation activities [3]. At the same time, these spaces are gradually required to provide multiple functions, including school education, professional training, public health interventions, and social cultural activities. Their service population has expanded from the public to include elderly individuals, children, professional athletes, and rehabilitation patients, which contributes to more diverse and sensitive demands for indoor environmental quality [4,5].

Under this circumstance, the environmental health issues in indoor sports facilities are no longer just architectural design or operational management topics but have gradually risen to a key node in public health and urban sustainable development [6]. Air quality is one of the most fundamental and crucial dimensions of the indoor environment, which directly affects users' exercise experience, health levels, and behavior sustainability [7]. At the city level, the construction and operation of sports facilities have become an essential part of public investment [8]. Their environmental performance not only concerns building energy consumption, operational costs, and carbon emission control, but also to some extent reflects a city's governance capability and technological level to green and healthy infrastructure [4,9]. Therefore, how to ensure users' physical health while achieving sustainability (e.g., operational efficiency, economic viability, and environmental friendliness) in building operations has become an urgent problem in the intersection of architecture and urban environment [10]. Beyond specific pollutant-related health risks, poor indoor air quality (IAQ) in sports facilities may also contribute to a range of nonspecific symptoms commonly referred to as Sick Building Syndrome (SBS) [11]. These symptoms (e.g., headache, eye or throat irritation, fatigue, and difficulty concentrating) often occur in indoor environments without a clear medical diagnosis [12]. Given the high occupancy and metabolic activity in sports facilities, the likelihood of SBS-like complaints may increase, especially in areas with inadequate ventilation or pollutant buildup. While typically studied in office or school settings, SBS remains an underexplored yet relevant issue for physically active indoor environments [11,12].

Compared to conventional residential or office buildings, indoor sports facilities exhibit distinct characteristics in terms of spatial use, occupant density, and activity intensity, all of which contribute to more complex and dynamic indoor air pollution profiles [13]. They frequently accommodate a large number of users engaged in high-intensity physical activities, leading to significantly increased respiration rates, enhanced resuspension of particulate matter, and rapid accumulation of carbon dioxide (CO₂) [14,15]. In many cases, ventilation systems are difficult to respond effectively in real time [13]. Moreover, sport-specific materials (e.g., magnesium carbonate powders, rubber mats, and synthetic equipment) can emit volatile organic compounds (VOCs) or fine particles during use, further burdening IAQ [11]. Adding to this complexity is the highly variable nature of usage patterns across different types of facilities and times of day [16]. Indoor sports facilities serve diverse functions, ranging from routine exercise and physical education to competitions and public events, each with different pollutant loads and ventilation demands [1,17]. In many cases, these facilities are repurposed or retrofitted from older buildings, where outdated layouts and poorly designed airflow systems increase the risk of pollutant accumulation and uneven distribution [18]. As a result, conventional IAQ management strategies used in static environments often prove inadequate. Addressing the unique IAQ challenges of indoor sports facilities requires tailored strategies integrating real-time monitoring, adaptive ventilation, and pollutant-source control to safeguard occupant health and comfort effectively.

1.2. Literature Gaps and Research Objectives

Numerous studies have explored various aspects of indoor air pollution in indoor sports facilities, which focus on specific pollutants such as particulate matter (PM₁, PM_{2.5}, PM₁₀, ultrafine particles), chemical contaminants (e.g., formaldehyde, benzene, aldehydes), CO₂ as an indicator of ventilation efficiency, and biological pollutants (e.g., bacteria and fungi) [11,19]. Health-related impacts (e.g., asthma, allergic responses, respiratory tract infections, and long-term cardiovascular risks) have also been highlighted, particularly for sensitive groups like children, the elderly, or individuals with pre-existing conditions [20,21]. In addition, the COVID-19 pandemic has significantly heightened public awareness of airborne transmission risks, further emphasizing the importance of air quality control in indoor sports settings [22].

For instance, Grande and Cao [23] investigated IAQ in ice halls through literature reviews and field measurements at Dalgård ice hall. They found that inadequate fresh air supply led to increased PM₁₀ (80 µg/m³) and CO₂ concentrations (up to 1400 ppm), which exceeded WHO recommendations. Results highlight the necessity for stricter ventilation requirements, especially considering health impacts on regular users. They mentioned that future research should develop tailored ventilation solutions addressing moisture, temperature, and pollutant control to improve air quality and user health in ice sports facilities. Then, Bralewska et al. [11] studied gaseous pollutants (CO₂, VOCs, NO₂, SO₂), ventilation efficiency, and factors affecting air quality in a Polish sports center. Indoor CO₂ (761–815 ppm) was higher than outdoors (521–525 ppm), linked to physical activity. Indoor VOCs, NO₂, and SO₂ were lower, mainly influenced by external pollution sources, and specific indoor pollutants (e.g., propanol) originated from cleaning and cosmetics. They suggested that future research should develop ventilation strategies and real-time monitoring to reduce pollutant exposure and improve user safety. In addition, Liu et al. [24] assessed IAQ in naturally ventilated badminton courts in Hubei Province, China, measuring CO₂ and PM_{2.5} concentrations in spring and autumn. Average indoor CO₂ (526.78–527.63 ppm) and PM_{2.5} (0.024–0.035 mg/m³) levels met GB/T 18883-2022 standards [25]. IAQ declined gradually with prolonged exercise due to pollutant accumulation, potentially impacting human health. They suggested that future studies should consider continuous monitoring and strategies to maintain acceptable IAQ during high-occupancy periods.

Although interest in this topic is increasing, existing research is still not well integrated and mostly comes from isolated disciplines, making it difficult to form a comprehensive understanding. Research tends to focus on isolated pollutant types, specific building typologies, or short-term monitoring campaigns, without systematically integrating findings across pollutant categories, building systems, or health and energy perspectives [26]. For instance, while some studies quantify particle concentrations during high-intensity workouts, they may not address the underlying ventilation design flaws, the energy implications of air purification strategies, or the long-term health exposure modeling needed to guide policies and retrofitting decisions [27]. Moreover, standards and guidelines for IAQ in sports facilities vary significantly between countries, and often fail to capture peak exposure events or synergistic effects of multiple pollutants under real-use conditions [7].

To address these knowledge gaps, this review offers a comprehensive and interdisciplinary synthesis of existing research related to indoor air pollutants and air quality management in sports facilities. Specifically, we (1) categorize and analyze the main types of indoor pollutants, including particulate matter, chemical contaminants, and microbiological agents, highlighting their sources, distribution patterns, and health implications in the context of physical activity; (2) evaluate assessment methods and standard frameworks, comparing international and regional guidelines and discussing the strengths and limitations of existing monitoring techniques; and (3) review practical strategies and emerging technolo-

gies for IAQ improvement, (e.g., ventilation optimization, source control, and advanced purification systems) with attention to energy performance and operational feasibility.

1.3. Literature Selection Methodology

This review adopts a narrative approach to synthesize multidisciplinary evidence on IAQ in sports facilities, with a structured literature selection process to enhance transparency and thematic coherence. Given the cross-disciplinary nature of the topic, which spans building science, environmental health, human physiology, and ventilation engineering, a structured, theme-based approach was adopted to guide the selection and synthesis of relevant literature across disciplines.

The search covered peer-reviewed publications between 1999 and 2025, focusing on both research and review studies. We retrieved literature from multiple academic databases, including Web of Science, Scopus, PubMed, and ScienceDirect. In addition, search engines such as Google Scholar were used to identify citation chains and access gray literature or technical reports. To ensure relevance across domains, the search strategy employed multiple keyword clusters, including “indoor air quality” AND “sports facilities” OR “gyms” OR “fitness centers” OR “indoor exercise”.

The search process was adapted across databases to reflect platform-specific features, with iterative adjustments made to maintain alignment with the review’s thematic scope. The inclusion criteria were as follows: (1) studies published in English; (2) peer-reviewed articles or official technical reports; and (3) clear relevance to IAQ issues in indoor physical activity environments. Studies were excluded if they focused solely on outdoor pollution, industrial settings, or sedentary indoor environments (e.g., offices or residential buildings).

A total of 1661 records were initially identified. After removing duplicates and screening titles and abstracts, 187 articles were selected for full-text assessment. Ultimately, 117 studies met the inclusion criteria and were retained for qualitative synthesis. The selection process is illustrated in Figure 1.

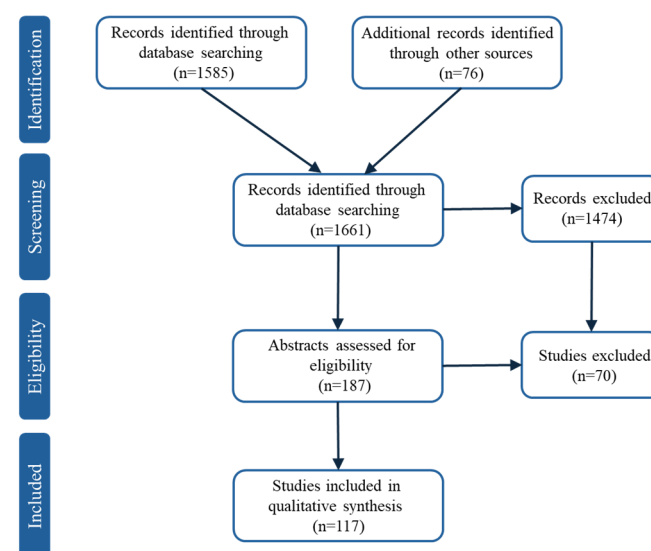


Figure 1. PRISMA flow diagram of the literature selection process for studies on indoor air quality in sports and exercise facilities [28].

After completing the initial screening and quality assessment, this study adopted a theme-oriented narrative approach to organize and synthesize the included literature. Specifically, the extracted information was categorized into three core domains according to research focus: (1) pollutant dynamics (e.g., particulate matter, VOCs, CO₂, and microbial factors); (2) assessment methods and standards (e.g., monitoring technologies, evaluation

frameworks, and health risk models); and (3) mitigation strategies and energy-efficient solutions (e.g., ventilation optimization, source control, and advanced purification technologies). Within each domain, the studies were further classified based on pollutant type, facility characteristics, and research methodology, ensuring that findings could be compared horizontally across similar contexts and examined vertically over different approaches. This process not only enabled the identification of common conclusions across studies but also revealed divergences and research gaps, thereby providing a foundation for deriving insights with stronger practical implications. Ultimately, the outcomes of this literature organization and synthesis are presented in a narrative review format and structured into Sections 2–4 of this paper, corresponding to pollutant characteristics, assessment and standards, and mitigation strategies, respectively. Such a structural arrangement ensures logical coherence and progressive development, allowing readers to clearly follow the reasoning from literature collection and thematic categorization to integrative analysis, and to grasp the overall contributions of the study step by step.

In addition to the initial structured search using core keywords (“indoor air quality” AND “sports facilities” OR gyms OR “fitness centers” OR “indoor exercise”), a supplementary set of approximately 40 studies was incorporated during the later stages of manuscript development. These additional references were identified through targeted searches using IAQ-related terms (e.g., “ventilation”, “airborne pollutants”, “thermal comfort”, “carbon dioxide”, “particulate matter”, “volatile organic compounds”) and health-related impacts (e.g., “respiratory symptoms”, “cognitive performance”, “Sick Building Syndrome”, “occupant health”, “physical activity and exposure”). These studies were selectively incorporated to address thematic gaps identified during the development of the review framework.

A comprehensive search combining all keyword clusters from the outset was intentionally avoided, as it would have returned tens of thousands of records due to the broad applicability of terms like “ventilation”, “PM”, and “VOCs” across various indoor environments unrelated to sports or physical activity. Such an extensive pool would have made systematic screening unmanageable in terms of scope and labor. Therefore, a two-step strategy was adopted: the initial core search was conducted using a structured and transparent selection process (see Figure 1), while the supplemental phase relied on iterative, theme-guided searches. As the latter was not part of the initial screening flow, those studies were not included in the selection diagram but were critically appraised for thematic relevance and scientific quality before being incorporated into the review.

For each included study, relevant data were extracted using a standardized template in Microsoft Excel. Key variables included study type, pollutant types, facility characteristics, assessment methods, measurement results, and mitigation strategies. This structured extraction enabled consistent cross-comparison and thematic coding across studies with diverse designs. Articles were managed and annotated using Mendeley reference management software (web version) to ensure consistency in documentation and citation formatting [29].

To supplement peer-reviewed evidence and facilitate cross-national comparisons, authoritative IAQ guidelines and standards were also reviewed, including the WHO IAQ Guidelines, ASHRAE Standard 62.1, EN indoor environmental quality standards, China’s national IAQ standard, and the UK’s CIBSE TM40, among others. A limited number of additional online sources (e.g., Wikipedia, agency websites) were consulted strictly for definitional clarification and were not used as primary evidence.

1.4. Novelty and Structure of the Paper

A key novelty of this review lies in its multidisciplinary synthesis of pollutant dynamics, occupant health risks, building operational practices, and energy efficiency considerations in sports environments, which is an intersection that remains underexplored in

the current literature. By identifying critical research gaps and practical challenges, this paper aims to inform future studies, guide evidence-based design and policy making, and ultimately contribute to the creation of safer, healthier, and more energy-efficient indoor sports facilities. The structure of the rest of this paper is as follows. Section 2 presents an overview of the primary pollutant types and their characteristics in indoor sports buildings. Section 3 discusses the methods and standards used to assess IAQ, including sensor technologies, microbial sampling, and health risk modeling. Section 4 reviews current mitigation strategies and technical solutions, and the final sections provide discussion and conclusions, with reflections on cost-effectiveness, post-pandemic considerations, and future research directions.

2. Major Indoor Pollutants in Sports Facilities

2.1. Particulate Matter (PM)

Particulate matter (PM) is typically classified based on its aerodynamic diameter into several categories: PM_{10} (particles with a diameter of 10 μm or less), $PM_{2.5}$ ($\leq 2.5 \mu m$), PM_1 ($\leq 1 \mu m$), and ultrafine particles (UFPs, $\leq 0.1 \mu m$) [30]. This size-based classification is critical, as it directly influences particles' deposition in the human respiratory tract and their potential to trigger physiological responses [31]. Coarser particles ($PM_{2.5-10}$) are more likely to deposit in the upper airways, while finer particles (e.g., $PM_{2.5}$ and UFPs) can penetrate deep into the lungs and even enter the bloodstream [32].

In indoor sports environments, PM arises from a wide range of primary and secondary sources, both internal and external. Figure 2 shows the key indoor PM sources, which originate from several key sources. Intense foot traffic, jumping, and the use of equipment can resuspend settled dust and skin flakes [33]. In addition, the use of chalk powder (magnesium carbonate) in activities (e.g., gymnastics, climbing, and weightlifting) contributes significantly to airborne particles [34]. In addition, abrasive wear of flooring materials, especially rubber or PVC sports mats and synthetic turf, also releases fine particulates into the air. Also, textile fiber shedding from sportswear, upholstery, and wall padding further adds to the indoor PM load. Additionally, cleaning activities, particularly dry sweeping or vacuuming without high-efficiency particulate air (HEPA) filters, can lead to the resuspension of settled particles [34]. Moreover, human metabolic emissions may act as precursors for secondary particle formation through chemical reactions with indoor oxidants, thereby exacerbating indoor air pollution [33,34]. Several studies have identified secondary particle formation indoors, resulting from the interaction of ozone (O_3) with VOCs emitted from building materials or human skin lipids. Such complex chemical interactions can contribute to ultrafine particle concentrations even in the absence of obvious dust-generating activities [35,36].

In addition to indoor sources, outdoor sources, especially in urban areas, can significantly affect IAQ [4], which include road dust, vehicle exhaust, industrial emissions, and pollen. Road dust, made up of fine particles from vehicles and roads, can enter through open windows or vents [37]. Vehicle exhaust, containing harmful chemicals like carbon monoxide and nitrogen oxides, can infiltrate through doors, windows, or ventilation systems [32]. Industrial emissions, including VOCs and PM, can also seep indoors, particularly when ventilation is poor [38]. Pollen, especially during certain seasons, can enter through open windows or ventilation systems, affecting those with allergies or respiratory issues [39]. Proper sealing and air filtration can help reduce these outdoor pollutants indoors [4].

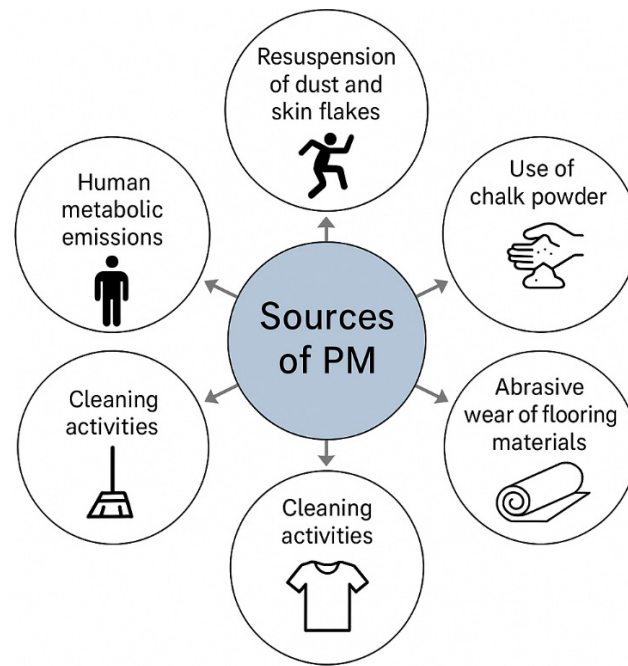


Figure 2. The main sources of PM [33,34].

The composition of PM in sports facilities can thus vary widely depending on the type of activity, building materials, user density, and ventilation performance, highlighting the importance of tailored monitoring and mitigation strategies [34].

Physical activity plays a pivotal role in influencing PM levels in indoor sports facilities. Vigorous movement (e.g., running, jumping, stretching, and rapid directional changes) not only increases airflow turbulence but also mechanically agitates settled dust and particles, leading to significant resuspension of PM [40,41]. These effects are particularly pronounced on surfaces (e.g., rubber flooring, synthetic mats, and unsealed concrete), which tend to accumulate fine particles over time [35]. Moreover, specific athletic practices (e.g., the application of chalk powder in gymnastics, climbing, or powerlifting) can generate acute spikes in PM₁₀ concentrations within localized areas [42,43]. These emissions are often highly episodic, which can result in short-term peaks that may be overlooked by long-interval average monitoring [43]. Without proper ventilation or source control, such concentrations can linger in the breathing zone, especially near floor level where many exercises occur [42].

In addition to affecting pollutant levels in the air, physical activity increases human respiration rate and tidal volume, leading to a greater inhalation dose of airborne particles [44]. This physiological factor amplifies the health impact of a given PM concentration compared to sedentary environments. The combination of increased pollutant levels and breathing effort highlights the increased vulnerability of sports facility users to PM exposure during exercise [45].

The health impacts of PM are closely associated with particle size, composition, and exposure duration [46]. Larger particles (PM₁₀) typically deposit in the upper respiratory tract, where they may cause irritation, coughing, and exacerbate symptoms in individuals with asthma or allergic rhinitis [46]. However, PM_{2.5}, PM₁, and UFPs can penetrate deep into the bronchioles and alveolar regions of the lungs, leading to more severe and systemic health problems. Prolonged or repeated exposure to fine and ultrafine particles (UFPs) has been linked to a range of adverse health effects, as shown in Figure 3 [46]. UFPs, in particular, pose a unique threat due to their ability to translocate across the alveolar-capillary barrier, potentially entering the bloodstream and reaching distant organs such as

the heart and brain. This systemic distribution has been associated with neuroinflammatory responses, cognitive impairment, and developmental effects in children [47].

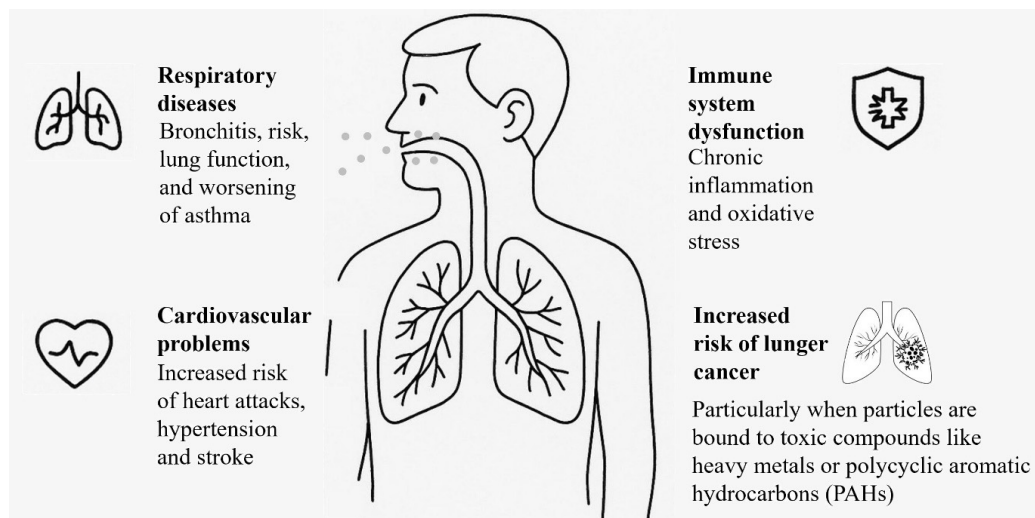


Figure 3. Health effects of fine and ultrafine particles.

In indoor sports facilities, the risks in Figure 3 are further amplified. Exercise increases both the respiratory rate and the depth of inhalation, allowing more pollutants to bypass nasal filtration and deposit deeper into the lungs [48]. Children, adolescents, and individuals with pre-existing respiratory conditions are especially vulnerable, as their respiratory systems are either still developing or more sensitive to environmental stressors [49]. Moreover, intermittent peak exposures, even if brief, may trigger acute respiratory responses in sensitive individuals [48]. While short-term exposure may lead to transient symptoms (e.g., eye or throat irritation), the long-term health burden, especially for frequent users or employees of sports facilities, should not be underestimated [49]. Therefore, minimizing PM exposure during physical activity is essential for safeguarding occupant health and maintaining the integrity of indoor sports environments. Table 1 summarizes the particle type and their effects on the occupants' health.

Table 1. Summary of particle types [30,32].

Particle Type	Aerodynamic Diameter, μm	Typical Sources in Sports Facilities	Deposition Region in Respiratory Tract	Health Risks
PM ₁₀	≤ 10	Dust resuspension, chalk powder, skin	Nasal cavity, upper respiratory tract	Irritation, coughing, asthma
PM _{2.5}	≤ 2.5	Floor abrasion, fine chalk, indoor-outdoor	Bronchi, bronchioles	Lung inflammation, reduced respiratory
PM ₁	≤ 1	Deep chalk particles, material wear, ambient fine dust	Alveolar region	Long-term pulmonary stress, cardiovascular effects
UFPs	≤ 0.1	Equipment friction, HVAC byproducts, secondary reactions	May enter bloodstream and organs	Oxidative stress, neurological risks, systemic inflammation

Notations: PM = particulate matter; UFPs = ultrafine particles; HVAC = heating ventilating and air-conditioning.

2.2. Chemical Agents

2.2.1. Volatile Organic Compounds (VOCs)

VOCs are a diverse group of carbon-based chemicals that readily evaporate at room temperature and can contribute significantly to indoor air pollution [50]. In indoor sports facilities, VOCs are critically important due to their widespread sources, chemical reactivity,

and potential health risks, especially under conditions of increased respiration during exercise [11,34].

The indoor environment of sports facilities typically contains a wide variety of VOC sources, many of which are either continuously emitting or periodically introduced during cleaning, maintenance, or occupant activities [11]. Figure 4 shows the key sources of indoor VOCs, which include building and finishing materials (e.g., paints, adhesives, synthetic flooring, and particleboard furniture), cleaning and disinfecting products containing alcohols and aldehydes, personal care products (e.g., deodorants and perfumes used by occupants), metabolic emissions from users (e.g., isoprene and acetone), which react with ozone to form secondary pollutants, and equipment or supplies stored in poorly ventilated areas, contributing to VOC buildup [11,51,52]. These compounds often accumulate indoors due to limited dilution with outdoor air and insufficient removal by heating ventilating and air-conditioning (HVAC) systems, especially in high-use areas with intermittent ventilation or inadequate air exchange rates.

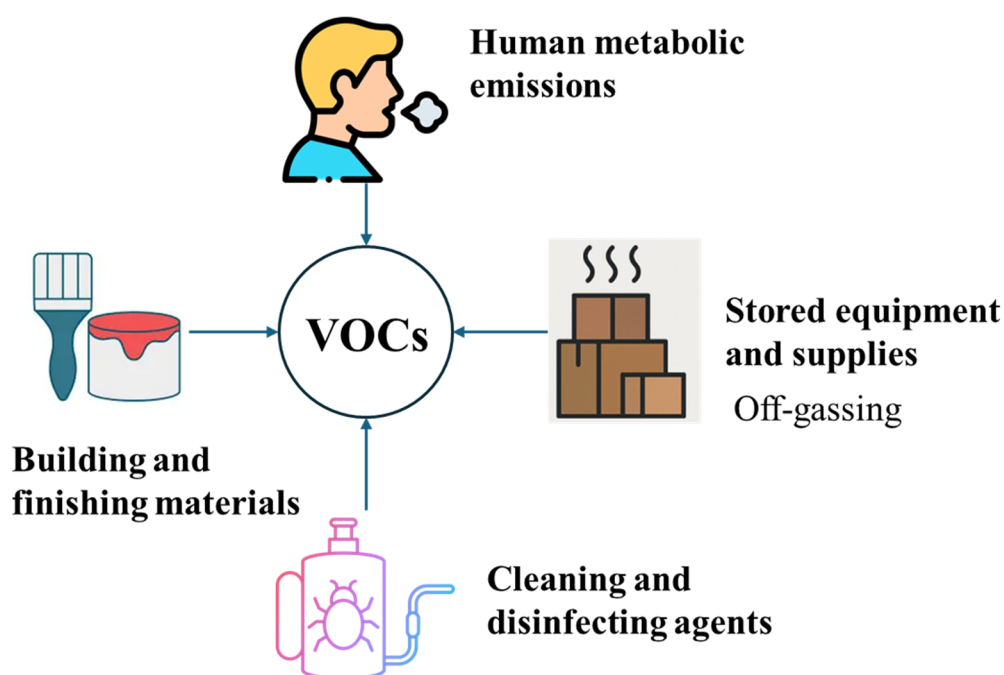


Figure 4. Key sources of indoor VOCs [11,51,52].

VOCs found in indoor sports facilities span multiple chemical families, including aromatic hydrocarbons, terpenes, aldehydes, alcohols and esters, and siloxanes, as illustrated in Figure 5 [11,53]. Measured concentrations of VOCs in sports facilities can vary significantly depending on building type, material age, cleaning frequency, and ventilation efficiency. Studies have reported TVOC (Total VOC) concentrations in gyms and sports halls ranging from a few $\mu\text{g}/\text{m}^3$ to over $500 \mu\text{g}/\text{m}^3$, occasionally exceeding recommended indoor air thresholds during or shortly after cleaning activities or high-occupancy events [11,54].

The health effects of VOCs depend on their toxicity and exposure level. Short-term exposure can cause irritation, headaches, nausea, and reduced cognitive performance [54]. Long-term or repeated exposure, especially to harmful compounds like formaldehyde and benzene, may lead to chronic respiratory issues, organ damage, and increased cancer risk [55]. In indoor sports facilities, higher breathing rates and poor ventilation can increase VOCs intake, making children, adolescents, and staff more vulnerable. Some measures (e.g., monitoring both TVOC levels and specific compounds, limiting high-emission materials,

and improving ventilation) are essential to reducing health risks (see Figure 6) [11,54]. Table 2 compares typical VOCs in indoor sports facilities.

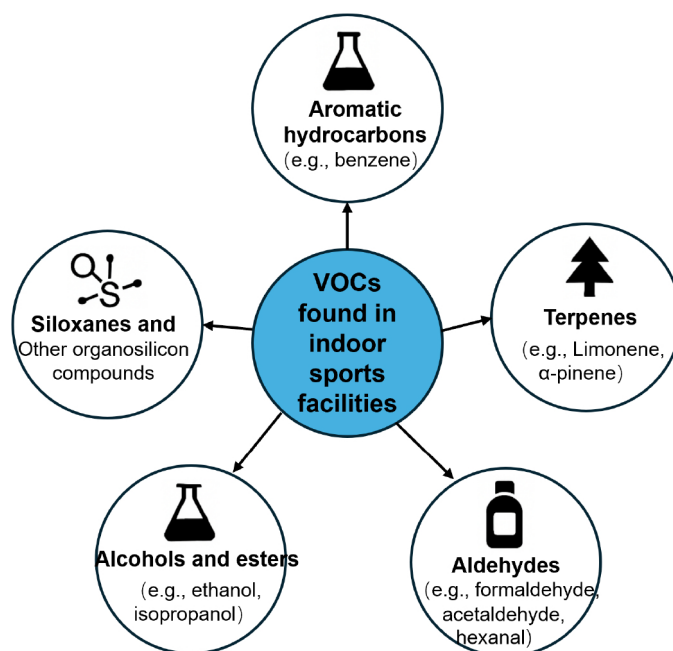


Figure 5. Common VOC Species in indoor sports facilities [11,53].

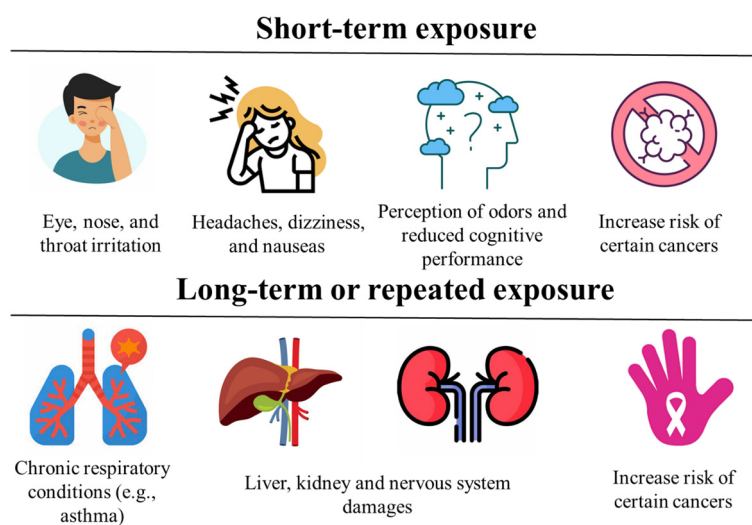


Figure 6. Health effects of VOC exposure: short-term symptoms and long-term risks [11,54].

Table 2. Comparison of typical VOCs in indoor sports facilities.

VOC Compound	Typical Indoor Sources	Guideline Limit (mg/m ³)	Reference	Short-Term Health Effects	Long-Term Health Risk
Formaldehyde	Plywood, foam mats, adhesives	0.1 (WHO, GB/T 18883)	[25,56,57]	Eye/nose irritation, coughing, throat discomfort	Carcinogenicity (Group 1, IARC), asthma development
Benzene	Paints, rubber products, cleaning agents	ALARA (WHO); 0.11 (China)	[25,56,57]	Dizziness, headaches, respiratory irritation	Carcinogenicity (Group 1, IARC), blood disorders

Table 2. *Cont.*

VOC Compound	Typical Indoor Sources	Guideline Limit (mg/m ³)	Reference	Short-Term Health Effects	Long-Term Health Risk
Toluene	Solvents, disinfectants, sports equipment	0.2 (China)	[25]	Fatigue, nausea, mucous membrane irritation	Potential liver/kidney damage, neurological effects
Xylene	Synthetic flooring, resins, lacquers	0.2 (China)	[25]	Skin/eye irritation, drowsiness	Chronic respiratory symptoms, neurotoxicity
TVOCs (Total)	Combined emissions from materials and activities	0.6 (China); varies internationally	[25,26,57]	General discomfort, reduced cognitive performance	Chronic exposure risks not fully defined

2.2.2. Carbon Dioxide (CO₂) as an Indicator of Ventilation Efficiency

Carbon dioxide (CO₂) is a naturally occurring, colorless, and odorless gas produced primarily through human respiration [58]. While CO₂ itself is not classified as toxic at the concentrations typically found in indoor environments, it is widely used as a proxy indicator for ventilation efficiency and IAQ [59]. This is particularly relevant in indoor sports facilities, where high occupant density and increased metabolic activity can result in the rapid accumulation of CO₂, especially during peak usage periods [11,60].

The primary source of indoor CO₂ in sports facilities is human respiration, which is directly linked to the number of occupants and the intensity of physical activity [11]. During moderate to vigorous exercise, the metabolic rate, and consequently CO₂ exhalation, increases significantly. For example, a person at rest may exhale approximately 0.3–0.4 L/min of CO₂, while this rate can increase up to 4–8 L/min during intense exercise [61]. In sports facilities with insufficient or uneven ventilation, this leads to a fast and localized rise in CO₂ concentrations.

CO₂ levels tend to accumulate in areas with poor airflow or suboptimal HVAC design [62]. In sports halls and gyms with high ceilings, CO₂ may stratify and escape detection by sensors placed above the breathing zone, giving a false sense of acceptable ventilation. This may result in underestimating the actual exposure experienced by occupants, particularly during high-intensity activities where breathing rates are elevated [63]. Moreover, ventilation systems that operate intermittently or rely heavily on natural air exchange may not respond promptly to sudden increases in occupancy, allowing CO₂ to temporarily exceed recommended thresholds [26]. Several international and national organizations have established guidelines for indoor CO₂ concentrations to assess ventilation adequacy. Table 3 compares CO₂ concentration limits in IAQ standards.

Table 3. Comparison of CO₂ concentration limits in IAQ standards.

Region/Organization	Standard/Guideline	References	CO ₂ Limit Value	Averaging Time	Notes
China	GB/T 18883-2022	[25]	≤1000 ppm	1-h average	Applies to general indoor environments including sports facilities

Table 3. *Cont.*

Region/ Organization	Standard/ Guideline	References	CO ₂ Limit Value	Averaging Time	Notes
USA	ASHRAE Standard 62.1-2022	[64]	≤1000 ppm (design target)	Not strictly defined	sed as an indicator for acceptable ventilation rate (approx. 7.5 L/s-person)
EU	EN 16798-1:2019 (formerly EN 15251)	[27]	Category I: +350 ppm above outdoor Category II: +500 ppm Category III: +800 ppm	Instantaneous or short-term	Based on perceived air quality and comfort levels
WHO	WHO Guidelines for IAQ (2010)	[57]	No strict numerical limit	N/A	Recommends sufficient ventilation to maintain comfort and limit bioeffluents

Notation: These CO₂ limits reflect acceptable indoor air quality based on ventilation rate assumptions and perceived air freshness, rather than direct health-based exposure limits. The WHO IAQ Guidelines (2010) do not define a strict numerical limit or averaging time for CO₂. Instead, they recommend maintaining sufficient ventilation to ensure thermal comfort and to limit bioeffluents, emphasizing general principles rather than quantitative thresholds.

While these levels do not represent health-based limits, they are strongly associated with perceived air freshness, cognitive performance, and comfort. Studies have shown that CO₂ concentrations above 1000 ppm can result in feelings of stuffiness, fatigue, and reduced task performance, factors that could impact the exercise experience and safety of facility users [59]. In indoor sports environments, monitoring CO₂ provides a cost-effective and real-time method for assessing whether the ventilation system is sufficient to handle the dynamic occupancy loads. High CO₂ levels are often indicative of inadequate air exchange rates (AER), potentially signaling the concurrent buildup of other pollutants (e.g., VOCs, humidity, and bio effluents) [58].

Given that athletes and recreational users inhale greater volumes of air during exercise, prolonged exposure to increased CO₂ may not only cause discomfort but may also reflect poor overall air quality, increasing susceptibility to pollutants that co-occur with low ventilation [48]. CO₂ trends can thus serve as an early warning tool, prompting operational adjustments (e.g., increasing mechanical ventilation rates during peak hours, adjusting HVAC zoning strategies to match occupancy distribution, and scheduling maintenance and filter replacement in ventilation systems) [65].

Overall, CO₂ monitoring, when integrated with other air quality parameters, offers an essential metric for ensuring healthy and responsive ventilation in sports facilities, aligning environmental performance with the physiological needs of physically active occupants.

2.3. Microbial Pollutants

Microbial pollutants, particularly airborne bacteria and fungi are important yet often overlooked contributors to IAQ degradation in both homes and sports facilities [66]. Unlike chemical or particulate pollutants, biological contaminants are living organisms or biological fragments that can grow, reproduce, and interact with their environment, making their behavior more complex and variable [67]. In indoor sports facilities characterized by high occupancy, increased humidity, and intensive physical activity, the conditions are often conducive to microbial survival, dispersal, and proliferation [68].

Microbial contamination in indoor air primarily originates from three major sources, including human occupants, infiltration of outdoor air and humid and poorly ventilated environments [69–71]. Figure 7 shows the sources of indoor microbial emissions. To be specified, human occupants are a major source of indoor microbial emissions, especially during physical activity, which increases the shedding of skin cells, hair, and respiratory bioaerosols [71]. Outdoor air can also introduce microbial particles like pollen and fungal spores through ventilation or leakage, particularly in urban or vegetated areas [70]. Inadequate filtration or airflow can lead to their accumulation indoors. Moreover, high humidity in spaces, such as locker rooms and swimming pools, supports microbial growth, while moisture from leaks or condensation creates favorable conditions for colonization [69]. Poorly maintained HVAC systems may further contribute to microbial buildup and distribution [69].

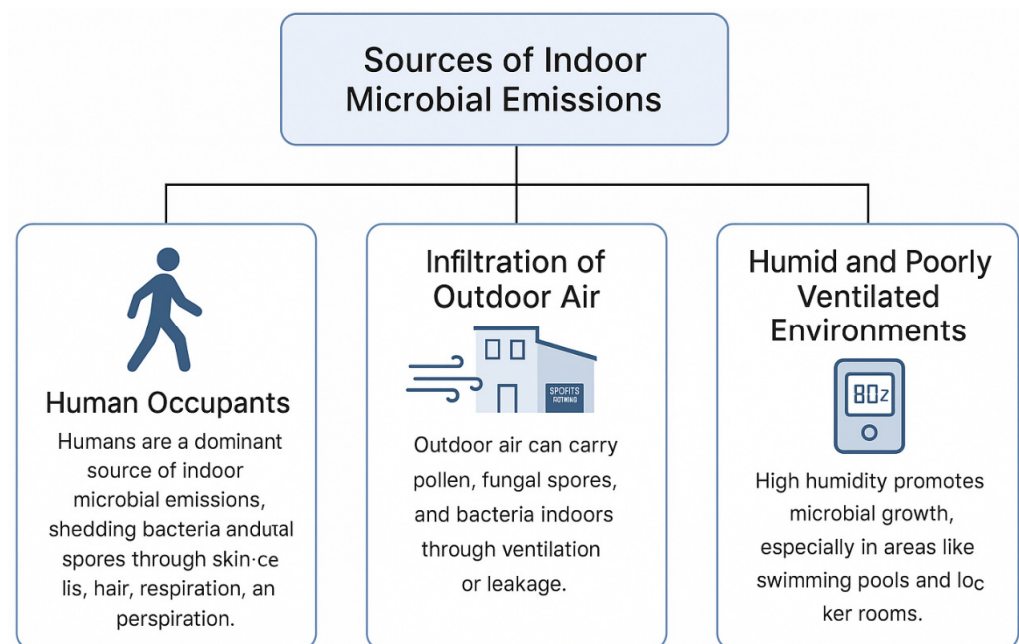


Figure 7. Sources of indoor microbial emissions [69–71].

The microbial communities present in indoor sports facilities are typically dominated by skin-associated bacteria (e.g., *Staphylococcus*, *Corynebacterium*), environmental fungi (e.g., *Aspergillus*, *Cladosporium*, *Penicillium*), and moisture-loving molds (e.g., *Alternaria*, *Trichoderma*) [72,73]. These organisms can be detected in both airborne samples and surface swabs, with concentrations varying by location, occupancy patterns, and environmental conditions [74].

Although not all microbes pose health risks, certain species have been linked to a range of adverse effects, particularly in sensitive populations [75]. Figure 8 shows an overview of possible health impacts caused by microbes. Exposure to indoor fungal spores and fragments can lead to allergic responses (e.g., rhinitis, conjunctivitis, dermatitis, and asthma-like symptoms), especially among children and individuals with atopic predispositions [76]. The upward arrow (↑) indicates an increased risk associated with physical activity under microbial exposure conditions. Opportunistic bacteria and fungi may cause respiratory infections such as bronchitis and sinusitis when contaminated aerosols are inhaled, notably during periods of intense physical activity [67]. Furthermore, microbial components (e.g., endotoxins, mycotoxins, and glucans) can induce non-allergic inflammatory responses, resulting in fatigue, coughing, throat irritation, or symptoms resembling sick building syndrome [77].

The dynamic activity levels and fluctuating occupancy of sports facilities can result in highly variable microbial exposure, both temporally and spatially [70]. Moreover, enhanced breathing rates during exercise increase the risk of deep lung deposition, making users more susceptible to microbial hazards than in sedentary indoor environments [48].

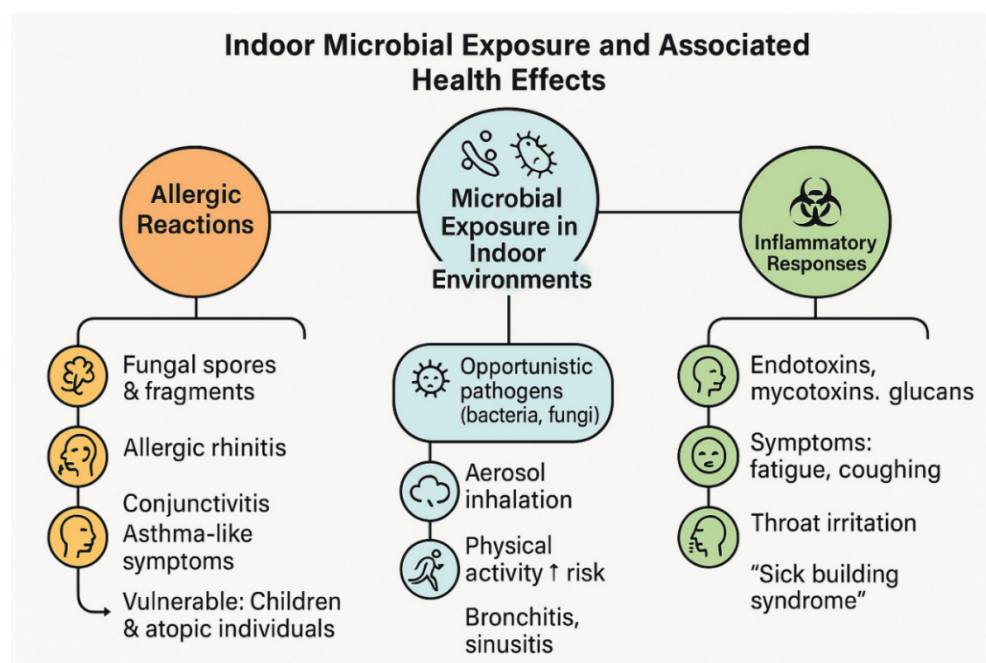


Figure 8. Indoor microbial exposure and associated health effects [67,75,77].

To mitigate these risks, it is essential to control indoor humidity, maintain good ventilation, regularly clean and disinfect high-contact surfaces, and monitor microbial load through targeted sampling methods (e.g., culture-based analysis, qPCR, or next-generation sequencing) [78]. Understanding the microbial landscape of sports facilities is crucial for safeguarding health and ensuring a hygienic indoor environment for physical activity. Table 4 shows the common indoor microbes, risk factors, and control strategies.

Table 4. Common indoor microbes, risk factors, and control strategies [70,71,79].

Microbial Genus/Group	Common Sources	At-Risk Populations	Potential Health Effects	Environmental Conditions Favoring Growth	Recommended Control Measures
Staphylococcus	Human skin, nasal cavity, equipment surfaces	All users (esp. with cuts/abrasions)	Skin infections, MRSA, wound complications	High humidity, warm temperatures, skin contact surfaces	Surface disinfection, hand hygiene, proper wound care
Corynebacterium	Skin microbiota, sweat, shared	Athletes with sensitive skin or dermatitis	Body odor, minor infections, irritation	Sweaty, poorly ventilated areas	Regular cleaning, humidity control, fabric sanitization
Aspergillus	Damp materials, ventilation ducts, indoor air	Asthmatics, immunocompromised individuals	Allergic asthma, invasive aspergillosis	Damp surfaces, warm air, insufficient air exchange	Dehumidification, HEPA filtration, duct maintenance

Table 4. Cont.

Microbial Genus/Group	Common Sources	At-Risk Populations	Potential Health Effects	Environmental Conditions Favoring Growth	Recommended Control Measures
Penicillium	Dust, flooring, locker room surfaces	Allergic individuals, children	Allergic rhinitis, asthma exacerbation	Moist dust, moderate humidity	Dust control, cleaning protocols, humidity balance
Cladosporium	Outdoor air infiltration, ventilation filters	Allergic individuals, elderly	Seasonal allergies, eye/throat irritation	Outdoor-origin spores + inadequate filtration	Improved filtration, sealing of external air leaks
Alternaria	Showers, wet walls, poorly ventilated spaces	Asthmatics, allergy-prone children	Severe allergic reactions, respiratory inflammation	High moisture, wet areas, poor drainage	Mold remediation, shower area ventilation, moisture control

2.4. Physical Environmental Parameters

In indoor sports facilities, the physical parameters of the environment, particularly temperature, relative humidity, air velocity, and radiant heat, play a critical role in shaping both IAQ and thermal comfort [80]. Unlike sedentary indoor settings, sports environments are characterized by high metabolic activity, large spatial volumes, and heterogeneous occupancy patterns, which introduce complex interactions between physical conditions, pollutant dynamics, and human perception [81,82].

Temperature and relative humidity directly affect the behavior, persistence, and transformation of indoor pollutants. Higher temperatures can increase the emission rates of VOCs from materials and equipment, while also enhancing the evaporation of sweat and moisture, contributing to increased indoor humidity [83]. Conversely, cooler temperatures may reduce chemical emissions but can lead to thermal discomfort, hinder air mixing in stratified spaces, and when coupled with low relative humidity, increase occupants' susceptibility to respiratory infections [83,84].

Relative humidity (RH) also influences several critical processes, as shown in Figure 9 [83]. The upward arrow (↑) indicates an increase in the associated risk or phenomenon (e.g., enhanced PM resuspension at low RH, increased mold growth at high RH).

- At low RH (<30%), resuspension of PM increases due to reduced adhesion to surfaces and drier dust conditions. This can worsen exposure to PM, especially during intense movement.
- At high RH (>60%), biological pollutants such as mold and bacteria may proliferate, especially on porous surfaces. High humidity also facilitates the aggregation and settling of fine particles, altering their dispersion and inhalation risks.
- RH outside the comfort range (typically 40–60%) may also lead to respiratory tract irritation, eye discomfort, and decreased perceived air quality.

From a thermal comfort perspective, sports facility users are more sensitive to microclimatic variations due to increased body heat production during exercise. Excessive temperatures or humidity can cause heat stress, fatigue, and performance decline, while overly cool or dry conditions may lead to muscular stiffness or increased respiratory discomfort [80,85].

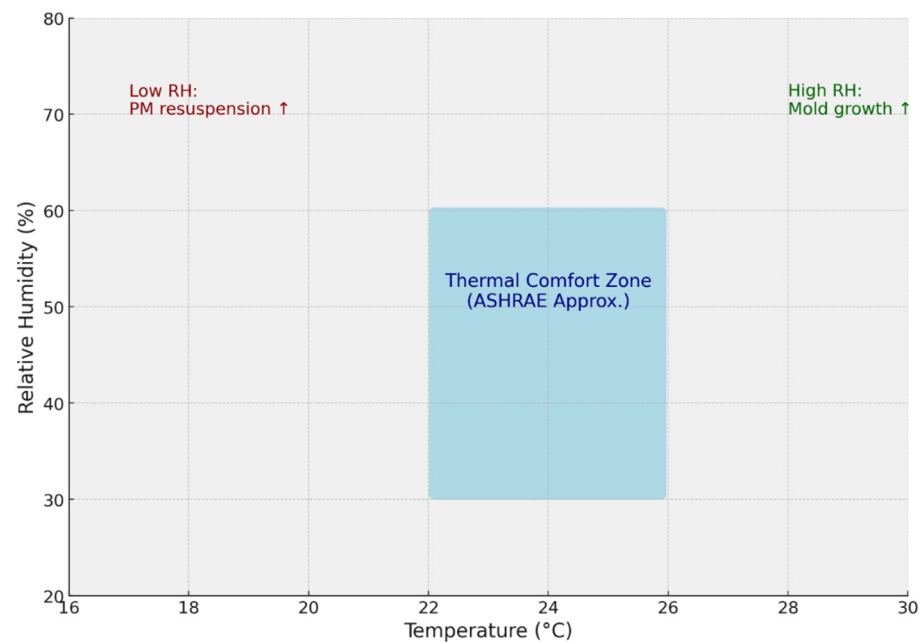


Figure 9. Thermal comfort and relative humidity effects on IAQ [83].

In addition, air velocity is another crucial factor in both thermal comfort and pollutant transport [86]. In high-ceiling spaces (e.g., gymnasiums or sports halls), air stratification is common, and poor air distribution can lead to stagnant zones with localized buildup of CO₂, VOCs, and PM [83]. Controlled air movement is essential for diluting and removing pollutants from the breathing zone, preventing hot/cold spots that reduce user comfort, and enhancing sweat evaporation and heat dissipation during physical exertion. However, excessive air velocity (>0.3 m/s in occupied zones) may result in draft discomfort, particularly during low-intensity activities or recovery phases. Therefore, balancing airflow distribution through ceiling-mounted diffusers, displacement ventilation, or personalized airflow strategies is key to maintaining optimal conditions [83].

Radiant heat exchange, especially from large wall and ceiling surfaces, also significantly affects perceived comfort [86,87]. In poorly insulated facilities or those with large glass façades, uneven radiant temperatures can lead to discomfort even when air temperature is within acceptable limits [87,88]. This is particularly relevant in multipurpose arenas where thermal zoning is challenging.

In summary, maintaining an optimal combination of temperature, humidity, air velocity, and radiant conditions is essential not only for thermal comfort and athletic performance, but also for controlling the dispersion, transformation, and inhalation of indoor pollutants. Integrated environmental control strategies (e.g., smart HVAC systems, localized climate control, and adaptive ventilation) are vital to creating healthy and comfortable indoor sports environments.

3. Evaluation Methods and Standard Systems for IAQ

3.1. Pollutant Monitoring Techniques

Accurate and timely monitoring of indoor air pollutants is essential for maintaining healthy and comfortable environments in sports facilities, where occupancy patterns, pollutant sources, and ventilation conditions fluctuate frequently [26]. A comprehensive monitoring strategy typically involves the integration of microbial sampling, chemical pollutant detection, and continuous real-time monitoring systems, each offering unique insights into indoor air dynamics [78,89].

To effectively manage IAQ in sports facilities, a comprehensive monitoring approach should integrate microbial, chemical, and real-time sensing methods (see Figure 10). Microbial sampling combines culture-based techniques for quantifying viable organisms with high-throughput sequencing to capture broader microbial diversity [78]. Chemical pollutants (e.g., VOCs, aldehydes, and ozone) can be detected through high-precision methods (e.g., gas chromatography or real-time sensor technologies) [90]. Continuous monitoring systems, including PM, CO₂, and TVOC sensors, help track rapid fluctuations caused by occupant activity and environmental changes, supporting responsive ventilation and exposure control across different facility zones [89]. Data from continuous systems can be integrated into building management systems (BMS) or mobile platforms to provide alerts, analytics, and real-time control signals, enhancing responsiveness and occupant safety [91].

In summary, the selection of pollutant monitoring techniques should consider not only accuracy and sensitivity, but also deployment feasibility, response time, and integration with building operation systems. A hybrid approach, combining advanced microbial profiling, targeted chemical detection, and real-time sensing, is recommended for effective IAQ management in high-performance sports environments. Table 5 compares monitoring techniques for indoor air pollutants in sports facilities.

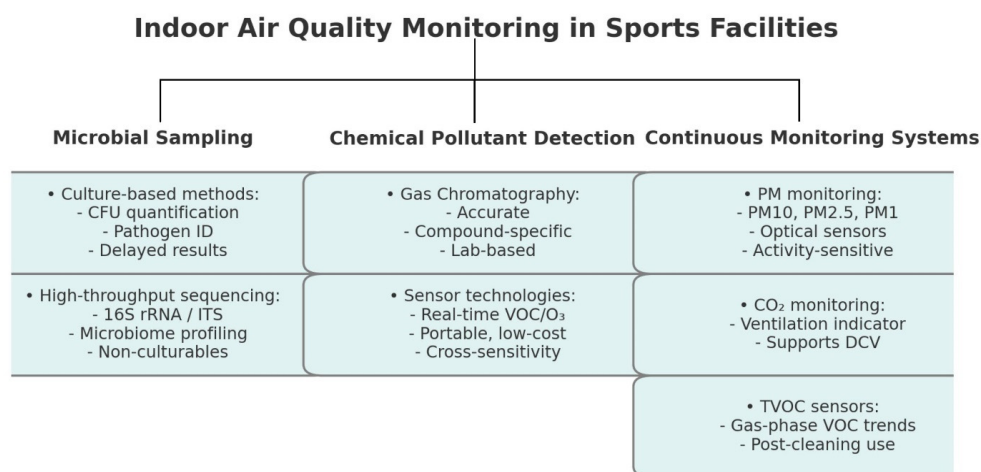


Figure 10. Integrated IAQ monitoring strategies in sports facilities [78,89,90].

Table 5. Comparison of monitoring techniques for indoor air pollutants in sports facilities.

Pollutant Type	Monitoring Technique	Detection Principle	Advantages	Limitations	Estimated Cost Level	Example Studies
PM	OPC	Light scattering from particles	Real-time, size-resolved data, compact and portable	Limited accuracy for UFPs, calibration required	Medium	[47,92]
PM	Gravimetric Filter Method	Mass of particles collected on filters	High accuracy, reference standard	Delayed results, manual processing, no size resolution	Low	[93]
VOCs	Gas Chromatography (GC/MS)	Separation and identification via retention time and mass	High specificity and compound identification	Costly, time-consuming, requires lab conditions	High	[11]

Table 5. Cont.

Pollutant Type	Monitoring Technique	Detection Principle	Advantages	Limitations	Estimated Cost Level	Example Studies
VOCs	PID	Ionization of VOCs by UV light	Fast, portable, detects total VOC load	Non-specific, prone to interference, needs frequent calibration	Medium	[94]
Microbes	Culture-based Sampling	Growth of colonies on selective media	Low cost, viable organism detection	Misses non-viable or low-abundance microbes	Low	[95]
Microbes	High-throughput Sequencing	DNA/RNA extraction and sequencing of microbial genomes	Comprehensive microbial profiling, detects non-culturable species	Expensive, complex data interpretation	High	[96]

Notations: OPC = optical particle counter; PID = photoionization detector; VOC = volatile organic compounds.

3.2. Comparison of International and Regional Standards

IAQ standards provide essential references for healthy indoor environments, but their direct applicability to sports facilities, characterized by high physical activity, fluctuating occupancy, and diverse emissions, is often limited. Table 6 summarizes key IAQ guidelines from WHO, EU, China, USA, and UK, focusing on parameters relevant to indoor sports settings, such as CO₂, PM_{2.5}, formaldehyde, ventilation, and monitoring [25,27,57,86,97].

Table 6. International and Regional IAQ Guidelines: overview.

Region/Organization	Reference	CO ₂ Limit (ppm)	PM _{2.5} Limit (µg/m ³)	Formaldehyde Limit (mg/m ³)	VOC Guidance	Ventilation Rate (L/s·Person)	Monitoring/BMS Integration	Applicability to Sports Facilities
WHO	[57]	Not specified	15 (annual), 25 (24 h)	0.1 (30-min avg)	Pollutant-specific	Recommends good ventilation	Not specified	General guidance only
EU (EN 16798-1:2019)	[27]	+500 above outdoor (Cat II)	Not specified	Not specified	Comfort/perception driven	7–10	Optional	Not specifically addressed
China (GB/T 18883-2022)	[25]	≤1000 (1 h avg)	75 (24 h)	0.1	Benzene ≤ 0.11 mg/m ³	~8–10 (based on building type)	Not emphasized	General public buildings, gyms included
USA (ASHRAE 62.1-2022)	[86]	Design target ~1000	Not directly defined	Not specified	Controlled through dilution rates	10–15 (gyms), varies by activity	CO ₂ sensors, DCV recommended	Yes (explicit occupancy/activity scaling)
UK (BB101, CIBSE TM40)	[97]	(CIBSE TM40) ≤ 1000–1500	≤10 (schools)	0.08–0.10 (schools)	Low-emission materials encouraged	8–10	CO ₂ monitoring recommended	Yes (focus on schools, gyms, halls)

While CO₂ is widely used as a ventilation indicator, only China enforces a strict limit. WHO and China provide clear PM_{2.5} thresholds, but other regions lack enforceable limits. Formaldehyde and VOC regulations are strictest in WHO and China, while EU and US approaches focus more on ventilation and material guidance. Ventilation requirements are most detailed in ASHRAE and Chinese standards, with the US and UK also recommending CO₂ monitoring and demand-controlled ventilation.

However, existing standards often overlook key features of sports environments. Most rely on long-term average pollutant levels, ignoring short-term peaks during intense activity or cleaning. Multi-pollutant interactions (e.g., VOC-ozone reactions) and bioaerosols in humid zones like locker rooms are rarely addressed. Assumptions of constant occupancy and ventilation do not reflect the dynamic use patterns of sports facilities.

Future IAQ standards should be more adaptive and sport-specific, factoring in exercise intensity, real-time monitoring, and facility types (e.g., gyms, pools, arenas). A shift toward health-based, multi-pollutant, and context-aware frameworks would better protect occupants in these dynamic environments.

3.3. Health Risk Assessment Models

Health risk assessment is a critical tool for evaluating the potential health impacts of indoor air pollutants in sports environments, where individuals are subject to increased inhalation rates and intermittent peak exposures [98]. Unlike conventional indoor settings, physical activity in gyms, sports halls, and arenas can significantly alter exposure dynamics, requiring tailored assessment models that incorporate exercise physiology, pollutant concentration variability, and population vulnerability [48].

The core of health risk assessment lies in estimating exposure dose, the actual amount of pollutant taken into the body over a defined period. Concerning IAQ, this is typically modeled as Equation (1) [98]. Equation (1) allows for quantification of both acute (short-term) and chronic (long-term) exposures. It can be further extended into hazard quotient or incremental lifetime cancer risk when toxicological reference values or cancer slope factor are known.

$$Dose(D) = C \times IR \times ET \times EF/BW \quad (1)$$

where C is pollutant concentration, mg/m^3 or $\mu\text{g}/\text{m}^3$; IR is inhalation rate, m^3/h ; ET is exposure time, h/day ; EF is exposure frequency, days/year ; BW is body weight, kg .

In sports facilities, certain vulnerable populations (e.g., children, the elderly, individuals with asthma, and professional athletes with high cumulative exposure) are at increased risk due to factors like higher pollutant uptake per kilogram of body weight, reduced detoxification capacity (e.g., in children), and the presence of pre-existing conditions that can be exacerbated by indoor pollutants [48,75]. Advanced models also integrate age-specific physiological data, behavioral patterns, and building microclimate variability, enabling more personalized and realistic exposure risk estimates [99].

Physical activity significantly increases the inhalation rate (IR), making it a crucial factor in assessing indoor pollutant exposure. For instance, the IR ranges from 0.5 to $0.6 \text{ m}^3/\text{h}$ at rest, increases to 1.0 to $1.5 \text{ m}^3/\text{h}$ during light activity such as walking, rises further to 2.0 to $3.5 \text{ m}^3/\text{h}$ during moderate exercise, and can exceed 4.0 to $6.0 \text{ m}^3/\text{h}$ during vigorous exercise [48,99]. This means that even if indoor pollutant concentrations are within regulatory limits, the actual internal dose during intense exercise can exceed health-based thresholds, especially for pollutants with short-term exposure risks (e.g., PM_{10} , VOCs, CO_2). Additionally, deeper breathing during exercise allows more particles to bypass nasal filtration and deposit in lower respiratory regions.

Studies have shown that during high-exertion workouts, the inhalation of fine $\text{PM}_{2.5}$ and VOCs can increase by four to eight times compared to resting conditions, significantly amplifying the risk of both acute effects (e.g., asthma attacks, fatigue, and cognitive slowing), and long-term health consequences (e.g., chronic inflammation, respiratory decline, and cardiovascular strain) [48,100]. To enhance accuracy in assessing these risks, some advanced models adopt dynamic dose estimation by linking real-time measurements of CO_2 and PM levels with wearable sensors that monitor physical activity and respiration rates [101]. This individualized exposure profiling offers a promising pathway for integration into smart building management systems, enabling adaptive ventilation strategies that respond to occupants' physiological needs in real time [102].

In conclusion, accurate health risk modeling in indoor sports facilities requires activity-aware exposure estimation, sensitive population consideration, and integration of environmental and physiological data. Future tools may increasingly rely on real-time data, sensor

integration, and machine learning-based dose-response prediction models to support healthy design and operation of high-performance athletic spaces.

4. Strategies and Technologies for IAQ Improvement

4.1. Ventilation System Design and Optimization

Effective ventilation plays a pivotal role in IAQ control in sports facilities, where high occupant density, increased respiration rates, and dynamic activity patterns pose continuous challenges to pollutant removal [26,103]. A well-designed ventilation system must balance the need for adequate pollutant dilution and removal, thermal comfort, and energy efficiency [64]. This section reviews the comparative performance of mechanical and natural ventilation, strategies to optimize air exchange rates, and airflow management techniques for high-ceiling spaces such as gymnasiums and arenas.

Mechanical ventilation systems (e.g., central air handling units, fan coil systems, or displacement ventilation setups) offer precise control over airflow, filtration, and temperature [26]. In sports facilities with high internal loads or limited access to outdoor air, mechanical ventilation is often preferred due to its consistent air supply regardless of weather or external pollutants, its filtration capability for particulates and bioaerosols, and its integration with HVAC systems for thermal regulation [104,105]. However, mechanical systems are energy-intensive, especially when designed conservatively to cover worst-case occupancy scenarios. Without intelligent control strategies (e.g., demand-controlled ventilation or CO₂ sensing), they may result in over-ventilation and unnecessary energy waste [106].

Compared to mechanical systems, natural ventilation uses windows, vents, or rising warm air to bring in fresh air. It needs little energy and can be controlled by users. This method works well in places with fewer people and mild weather, like yoga studios or seasonal training centers [107]. Nevertheless, it faces several limitations, including poor performance under unfavorable weather or wind conditions, inconsistent ventilation during peak occupancy, and limited ability to control PM, VOCs, or humidity, especially in urban or humid regions [108]. Hybrid systems, which combine natural and mechanical ventilation, have shown promise in maintaining IAQ while minimizing energy use when intelligently controlled [107].

Air exchange rates (AER), defined as the number of times the indoor air is replaced per hour (ACH), is a key parameter in achieving IAQ targets while avoiding excessive energy consumption [64]. In sports facilities, the optimal AER depends on several factors, including the type of physical activity (e.g., weightlifting versus aerobics), the nature and intensity of pollutant sources (e.g., chalk dust, CO₂, and VOCs), the occupancy density and duration of use, as well as the local climate and energy costs. ASHRAE recommends a ventilation rate of 10–15 L/s·person for gym environments [64], while Chinese standards define per-area and per-person minimum requirements based on specific building uses [25].

To improve energy efficiency, AER can be optimized through multiple strategies. Demand-controlled ventilation adjusts airflow in response to real-time occupancy or CO₂ levels, ensuring that ventilation aligns with actual demand [65]. Heat recovery ventilation systems reclaim thermal energy from exhaust air to reduce the load on heating and cooling systems [109]. Zoned ventilation targets airflow where it is most needed, delivering higher rates to active zones while reducing ventilation in storage or low-use areas [110]. Simulation studies have demonstrated that integrating occupancy prediction with adaptive AER control can reduce energy consumption by 15–30% without compromising IAQ, highlighting the potential of intelligent ventilation strategies in high-performance sports environments [111,112].

Large-volume spaces (e.g., basketball courts, climbing halls, or multi-purpose arenas), typically 0.8–1.8 m above the floor, require specialized airflow design to ensure uniform pollutant dispersion and occupant comfort within the breathing zone [113]. Effective strategies include displacement ventilation, which introduces cooler air at floor level and removes warmer, contaminated air at ceiling level, an approach well-suited for stratified pollutant removal [114]. Ceiling-mounted fabric ducts or air diffusers can provide wide, low-velocity air distribution that avoids uncomfortable drafts, while destratification fans or air circulation units help prevent thermal layering and the accumulation of pollutants in upper zones [115]. Zonal control and microclimate design further enhance performance by tailoring airflow patterns to specific activity areas, such as differentiating between workout and rest zones [110].

Proper airflow design not only improves ventilation effectiveness, but also significantly enhances perceived air freshness, thermal comfort, and overall system energy performance [113]. For sports facilities, well-designed ventilation systems must be adaptive, responsive, and energy-conscious, especially in the post-pandemic era where health and sustainability are equally critical. Future-ready solutions will rely heavily on the integration of IAQ monitoring, smart control logic, and user-centered zoning to maintain optimal conditions across varying occupancy and activity levels [113]. Figure 11 shows different ventilation strategies for high-ceiling spaces. Arrows indicate airflow direction. Blue arrows represent supply or downward airflow, while red arrows represent upward or return airflow associated with heat sources or microclimate control.

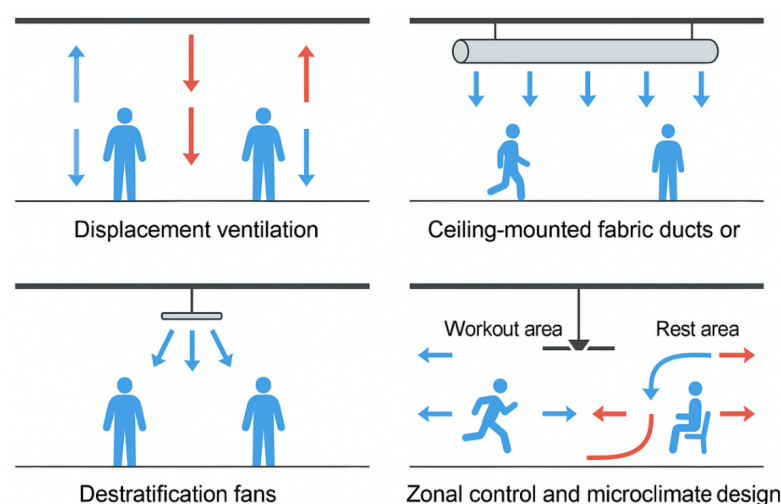


Figure 11. Ventilation strategies for high-ceiling spaces.

4.2. Source Control Technologies

Source control is the most effective and proactive strategy for maintaining healthy IAQ, as it targets the root causes of pollution rather than relying solely on removal or dilution [116]. In sports facilities, where materials, equipment, human activity, and moisture are key contributors to indoor pollutants, source control measures are essential to reduce emissions of VOCs, PM, and biological contaminants [90]. This section discusses practical and evidence-based approaches to limiting pollutant generation at the source.

Building materials, finishes, sports equipment, and maintenance products are significant sources of chemical pollutants in indoor sports environments, particularly VOCs and formaldehyde [11]. These emissions can be intensified by the unique conditions of sports settings, such as increased ventilation rates, higher thermal loads, and frequent contact with surfaces. Effective mitigation strategies begin with the use of certified low-emission materials, including rubber flooring, foam mats, and adhesives that comply with recog-

nized standards like GREENGUARD, or China's GB/T 35602-2017 for indoor decoration material VOC limits [117,118]. Avoiding solvent-based coatings and paints is especially important in enclosed training rooms or multipurpose halls, where air exchange may be limited, and exposure risks are higher.

The substitution of conventional cleaning products with green-certified, low-VOC alternatives further reduces the risk of secondary pollutant formation and respiratory irritation [119]. Proper storage management is also critical, high-emission substances should be kept in well-ventilated, sealed areas to prevent off-gassing into occupied spaces. Selecting appropriate materials during the design or renovation phase can reduce indoor VOC levels by 50–80%, thereby lessening the burden on mechanical ventilation and air purification systems and supporting both occupant health and energy efficiency [119].

Magnesium carbonate, commonly known as chalk powder, is widely used in gymnastics, weightlifting, climbing, and CrossFit-style training to enhance grip [43]. Despite its effectiveness, it is a notable source of both coarse and fine PM, especially PM₁₀, which can linger in the air long after application [43]. In enclosed or poorly ventilated environments, the use of chalk contributes to increased respiratory symptoms and throat irritation, reduced visibility, and dust accumulation on surfaces and HVAC filters, all of which raise maintenance costs and increase the filtration burden [120]. To mitigate these issues, the promotion of alternative grip-enhancing products offers a viable solution. Liquid chalk, a suspension of magnesium carbonate in alcohol, dries quickly on the skin and generates significantly less airborne dust. Rosin-based grip products, used in various sports, also serve as low-emission alternatives. Encouraging the adoption of these cleaner grip options through educational signage, facility policies, and coaching practices is particularly effective in shared or high-traffic training environments [120].

In parallel, managing indoor humidity is critical in controlling microbial proliferation, especially of fungi and bacteria [119,121]. This is especially relevant in sports environments that involve water use, such as swimming pools and showers, or those with high levels of perspiration, such as fitness gyms [119]. Maintaining the relative humidity (RH) within the optimal range of 40–60% is essential for minimizing mold growth while ensuring respiratory comfort [119]. Effective control strategies include the use of dehumidification systems in changing rooms, weight rooms, and enclosed studios, as well as ensuring adequate drainage and drying in wet areas to prevent the formation of microbial hotspots [122]. Regular inspection and cleaning of HVAC components like coils and condensate trays is also vital, as these areas can become breeding grounds for biofilms if left unmaintained. An integrated HVAC design that incorporates humidity sensors, real-time monitoring, and targeted dehumidification can play a pivotal role in minimizing microbial risks and mitigating related issues such as unpleasant odors, allergic reactions, and infection risks, thereby enhancing the overall health and comfort of sports facility users [66].

4.3. Application of Advanced Purification Technologies

IAQ has become a growing concern in post-pandemic, high-occupancy environments such as sports facilities. To address both health and performance demands, advanced purification technologies are increasingly integrated with ventilation and source control strategies [103]. These technologies specifically target airborne PM, VOCs, bioaerosols, and pathogens [102]. When combined with smart building management systems (BMS), they allow for real-time monitoring, automatic adjustments, and optimized energy use, making them highly effective for dynamic and high-use indoor sports environments [123]. Figure 12 shows the advanced purification technologies for sports facilities [123].

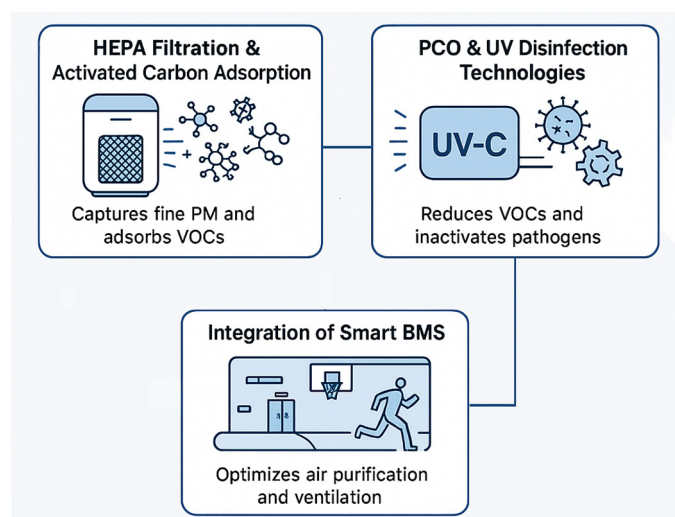


Figure 12. Overview of advanced purification technologies for sports facilities [123].

High-efficiency particulate air (HEPA) filters are among the most reliable solutions for removing airborne particles, including fine and ultrafine PM. Certified H13 or H14 filters under EN 1822 can remove at least 99.95% of particles as small as 0.3 microns [124,125], making them ideal for capturing chalk dust, resuspended particles, and biological contaminants common in gyms and sports halls [126]. Activated carbon filters are often used alongside HEPA to adsorb gaseous pollutants such as formaldehyde, benzene, and unpleasant odors emitted by building materials, cleaning agents, and human activity [127]. These systems can be deployed through central HVAC networks, portable purifiers in poorly ventilated or high-traffic zones, and return air plenums to prevent pollutant recirculation.

Photocatalytic oxidation (PCO) and ultraviolet (UV) disinfection provide complementary mechanisms for controlling airborne chemicals and pathogens [128,129]. PCO combines UV light and a catalyst are typically titanium dioxide (TiO_2), which oxidize VOCs and microbial matter into benign byproducts like CO_2 and water. However, its effectiveness varies with airflow, contaminant type, and exposure time, and poor design may lead to harmful byproducts such as ozone [130,131]. UV disinfection, especially using germicidal UV-C light (254 nm), is widely applied in HVAC ducts, upper-room systems in large spaces, and surface disinfection in changing rooms when unoccupied [131]. These systems have proven effective in reducing transmission risks in humid and high-contact environments [132]. Figure 13 shows the typical air purification process: HEPA filtration, activated carbon adsorption, and photocatalytic oxidation [133].

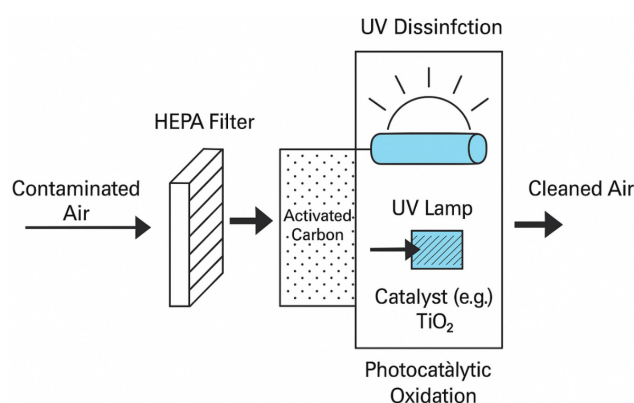


Figure 13. Typical air purification process: HEPA filtration, activated carbon adsorption, and photocatalytic oxidation [133].

The efficiency and coordination of purification technologies can be significantly improved by integrating them with smart building management systems [134,135]. These platforms continuously track key indoor air parameters such as CO₂, PM_{2.5}, total VOCs, and relative humidity [134]. Based on occupancy patterns or preset thresholds, BMS can automatically trigger ventilation, purification, or UV disinfection, ensuring both air quality and energy use are balanced [136]. Additionally, they enable long-term data logging for maintenance planning and performance analysis. Advanced systems may also incorporate wearable devices, mobile applications, or occupant feedback to personalize environmental control and support both comfort and athletic performance.

In summary, advanced purification technologies offer a robust line of defense against indoor air contaminants in sports facilities, when properly selected, installed, and maintained. A comparative summary of different purification and management technologies is presented in Table 7. Their effectiveness is maximized when paired with intelligent control systems and targeted deployment strategies, ensuring clean, healthy air while minimizing operational burden.

Table 7. Comparison of air purification and management technologies.

Technology	Target Pollutants	Advantages	Limitations	Estimated Cost Level	Reference
HEPA Filtration	PM ₁₀ , PM _{2.5} , bioaerosols	High efficiency for particulate removal; widely available	Does not remove gases or VOCs; filter replacement required	Medium	[124,125]
Activated Carbon Adsorption	VOCs, odors, some semi-volatile compounds	Effective for broad-spectrum VOCs and odors; low maintenance	Limited for PM or microbes; saturation over time	Low	[133]
UVGI	Airborne bacteria, viruses, mold spores	Strong microbial disinfection; good for humid zones	Requires safety shielding; effectiveness depends on dose and contact time	Medium-High	[131,137]
PCO	VOCs, some microbial degradation byproducts	Dual effect on chemicals and microbes; energy-efficient	May generate byproducts; variable effectiveness	Medium	[129]
Smart BMS	CO ₂ , PM, VOCs (indirect control via system response)	Real-time monitoring and control; data-driven IAQ optimization; integration with HVAC, purification, and user feedback	High initial setup cost; depends on sensor accuracy and system integration; requires skilled operation and maintenance	High	[135]

Notations: HEPA = high-efficiency particulate air; UVGI = UV germicidal irradiation; PCO = photocatalytic oxidation; BMS = building management systems.

5. Discussion

Managing IAQ in indoor sports facilities involves challenges that are both technically complex and insufficiently addressed in current research and practice. These environments differ substantially from typical indoor settings due to elevated occupant density, dynamic activity levels, and higher ventilation demand. Physical exertion increases respiratory rates and tidal volume, resulting in greater pollutant uptake. Consequently, even moderate pollutant concentrations can lead to disproportionately higher exposure doses, especially

during prolonged or intensive physical activity. Existing IAQ standards, which are largely derived from sedentary environments, seldom account for this critical physiological factor.

A growing body of literature has identified the presence of elevated levels of particulate matter, carbon dioxide, volatile organic compounds, and bioaerosols in sports facilities. Many studies have reported pollutant concentrations that either fluctuate dramatically with occupancy or accumulate in poorly ventilated areas, particularly near floor level. These conditions can impair both comfort and health, especially for children, individuals with asthma, and those with increased respiratory sensitivity. However, despite these findings, real-world IAQ management in athletic spaces remains reactive, and typically focuses on thermal comfort or energy use, rather than inhalation risk or pollutant-specific control.

The complexity of sports environments extends beyond pollutant sources. These facilities often serve multiple functions throughout the day, including exercise, instruction, rehabilitation, and events. This variability produces temporally and spatially uneven pollutant distributions, which are rarely captured by fixed-location monitoring systems or addressed by uniform ventilation schemes. Static HVAC designs based on average occupancy or worst-case assumptions often result in either over-ventilation with unnecessary energy use or under-ventilation during peak exposure periods. Addressing this mismatch requires a more nuanced approach that aligns ventilation and purification strategies with activity patterns and exposure profiles.

Technological advancements now allow for more responsive environmental control. Continuous monitoring of key parameters such as carbon dioxide and particulate matter can support real-time feedback for ventilation adjustment. Integration with intelligent control systems can improve operational efficiency and reduce exposure risk. However, such systems are still uncommon in most sports buildings. In many cases, monitoring devices are not installed, or their data are not linked to ventilation control or communicated to users. Without transparent IAQ information, it is difficult to support behavioral adaptations or build trust in shared environments.

The COVID-19 pandemic has highlighted the vulnerability of enclosed spaces and has accelerated interest in airborne exposure mitigation. In sports settings, this has led to increased use of ventilation, filtration, and disinfection technologies. Nonetheless, many of these interventions were implemented without long-term strategies for integration into building operation. For sustained improvements, IAQ management must be embedded into facility design, maintenance protocols, and user engagement processes. Visual indicators of air quality, adaptive control based on occupancy, and clear communication of IAQ status can improve both perceived and actual safety.

Another area of concern involves pollutants that are not yet comprehensively regulated or monitored. These include microplastics from synthetic sports flooring, semi-volatile organic compounds from personal care products and cleaning agents, and by-products from chemical reactions within indoor environments. For example, ozone–VOC interactions can generate secondary organic aerosols, especially in spaces with high levels of human activity and chemical product use. Although the acute toxicity of these compounds may be low, repeated exposure in confined settings may contribute to chronic health effects that remain poorly characterized. Most existing studies focus on short-term concentrations rather than cumulative exposure or long-term health outcomes.

To close these gaps, future research should prioritize longitudinal cohort studies and refined exposure modeling that incorporates both environmental and physiological variables. Activity-specific exposure dosimetry is essential for evaluating the true health risks of exercising indoors. Wearable technology and portable monitoring systems offer new opportunities to capture individualized exposure data in real time. Coupled with

environmental sensing and machine learning, such data can inform predictive control strategies and tailored ventilation responses.

There is also a pressing need to revisit the structure of IAQ standards. Few existing guidelines differentiate between facility types or account for intensity and duration of physical activity. International frameworks vary in pollutant coverage and do not consistently include biological contaminants or secondary pollutants. In most cases, regulations focus on steady-state exposure, neglecting short-term peaks and synergistic pollutant effects. A shift toward exposure-informed and context-aware guidelines would help align regulation with the actual risks encountered in athletic settings.

Ultimately, improving IAQ in sports facilities requires collaboration across disciplines. Engineers, environmental scientists, health researchers, data analysts, and facility operators must work together to develop solutions that are technically feasible, scientifically grounded, and operationally sustainable. Beyond pollutant removal, the goal is to support physical activity in environments that enhance well-being, minimize risk, and respond to evolving user needs. Creating healthier indoor sports environments is not only a technical endeavor, but also a public health imperative that requires a shift in how buildings are designed, evaluated, and managed.

Overall, the reviewed studies point to the need for integrated IAQ strategies in sports facilities that are pollutant-specific, activity-sensitive, and responsive to contextual factors such as occupancy patterns and ventilation design. Future efforts should prioritize improved exposure assessment frameworks and context-adapted mitigation techniques to ensure both health protection and performance support.

6. Conclusions

This review offers a comprehensive narrative synthesis of the key challenges, mitigation strategies, and emerging research priorities surrounding indoor air quality (IAQ) in sports facilities. Drawing from the reviewed literature, several overarching insights can be highlighted:

- Indoor sports facilities have distinct IAQ challenges. High occupant density, increased respiration rates, and active body movement significantly increase exposure risks compared to sedentary indoor environments. Common pollutant sources include resuspended particles, magnesium chalk, building material emissions, cleaning agents, and bioaerosols in humid areas.
- Key pollutant categories must be addressed in an integrated way. PM: Highly influenced by activity level; resuspension and chalk use are major sources. Chemical pollutants: VOCs and CO₂ levels reflect material selection, occupancy, and ventilation effectiveness. Microbial pollutants: thrive in high-humidity or high-contact zones; lack of regulation in most standards is a concern.
- Physical activity drastically alters exposure dynamics. Inhalation rates during exercise may increase pollutant intake by 4–8 times compared to rest. Risk assessments must incorporate dose-response models linked to activity intensity and duration, particularly for vulnerable groups (e.g., children, athletes, individuals with asthma).
- A multi-tiered strategy is essential for IAQ control. Ventilation: must be optimized for both airflow efficiency and pollutant removal, with zoning and demand-control. Source control: including low-emission materials, cleaner grip agents (e.g., liquid chalk), and humidity regulation, is the most cost-effective prevention method. Advanced purification: HEPA, activated carbon, UV, and photocatalytic systems can supplement ventilation, especially when integrated with real-time monitoring.
- International standards show significant variation and limitations. Most current guidelines do not fully address dynamic, high-exertion environments. China and the

US provide relatively sport-aware standards, however, few explicitly consider real-time adaptation or emerging pollutants. Cross-national harmonization and expansion of pollutant categories (e.g., SVOCs, microplastics, DBPs) are needed.

- Post-pandemic expectations are reshaping IAQ design. Users now expect visible air quality indicators, adaptive systems, and evidence of clean air. Hybridized facility usage and irregular occupancy require flexible, smart IAQ solutions. Public trust and operational resilience increasingly depend on how air safety is communicated and managed.
- Future research and development priorities. Develop exposure models accounting for physical activity, age, and environmental variability. Investigate long-term health effects from repeated pollutant exposure in athletic populations. Advance real-time IAQ monitoring and predictive control, integrating environmental sensing with wearable data and AI-based risk management.
- Multidisciplinary collaboration is essential. Effective IAQ solutions require input from building engineers, health experts, policy-makers, data scientists, and facility operators. Standards and regulations must shift from passive compliance to proactive health promotion, especially in spaces dedicated to movement and performance.

This structured summary provides a foundation for future research, design innovation, and policy development aimed at creating healthier, safer, and smarter indoor sports environments.

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Abbreviations

The following abbreviations are used in this manuscript:

AER	Air exchange rates
BMS	Building management systems
CO ₂	Carbon dioxide
DBPs	Disinfection by-products
HEPA	High-efficiency particulate air
HVAC	Heating ventilating and air-conditioning

IAQ	Indoor air quality
IR	Inhalation rate
LCC	Lifecycle cost
LD	Linear dichroism
OPC	Optical particle counter
O ₃	Ozone
PID	Photoionization detector
PM	Particulate matter
PCO	Photocatalytic oxidation
ROI	Return on investment
SOAs	secondary organic aerosols
SVOCs	Semi-volatile organic compounds
TiO ₂	Titanium dioxide
UFPs	Ultrafine particles
UV	Ultraviolet
UVGI	UV germicidal irradiation
VOCs	Volatile organic compounds

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