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Real-Time Monitoring of Particulate Matter in Indoor Sports Facilities Using Low-Cost Sensors: A Case Study in a Municipal Small-to-Medium-Sized Indoor Sport Facility

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Abstract

Indoor sports facilities present unique challenges for air quality management due to high crowd densities and limited ventilation. This study investigated air quality in a municipal athletic facility in Komotini, Greece, focusing on concentrations of airborne particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}), humidity, and temperature across spectator zones, under varying mask scenarios. Sensing devices were installed in the stands to collect high-frequency environmental data. The system, based on optical particle counters and cloud-enabled analytics, enabled real-time data capture and retrospective analysis. The main experiment investigated the impact of spectators wearing medical masks during two basketball games. The results show consistently elevated PM levels during games, often exceeding recommended international thresholds in the spectator area. Notably, the use of masks by spectators led to measurable reductions in $PM_{1.0}$ and $PM_{2.5}$ concentrations, because they seem to have limited the release of human-generated aerosols as well as the amount of movement among spectators, supporting their effectiveness in limiting fine particulate exposure in inadequately ventilated environments. Humidity emerged as a reliable indicator of occupancy and potential high-risk periods, making it a valuable parameter for real-time monitoring. The findings underscore the urgent need for improved ventilation strategies in small to medium-sized indoor sports facilities and support the deployment of low-cost sensor networks for actionable environmental health management.

Keywords: indoor air quality; face masks; ventilation efficiency

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1. Introduction

Indoor air quality (IAQ) in sports facilities has emerged as a critical concern in environmental and public health research. Among the key airborne pollutants present in these environments is particulate matter (PM), which spans a range of sizes—from ultrafine particles ($PM_{1.0}$) to coarse particles (PM_{10}). These particles pose varying degrees of health risk depending on their size and ability to penetrate the respiratory system. In particular, $PM_{2.5}$ and smaller fractions can reach the alveolar regions of the lungs, contributing to both acute and chronic health effects [1,2].

Studies have shown that fine and ultrafine particles constitute a substantial portion of total suspended particles (TSP) in athletic environments, with concentrations heavily influenced by human activity, inadequate ventilation, resuspension of dust, and the use of cleaning agents [3,4]. This is especially problematic in large indoor sports facilities where high occupancy loads, the simultaneous demand for heating or cooling, and poorly functioning air circulation systems can create localized pollutant hotspots. For instance, measurements taken in an ice arena without mechanical ventilation revealed sustained PM_{10} concentrations of around 80 $\mu g/m^3$, exceeding both WHO and Norwegian public health recommendations [4]. Similarly, CO_2 levels—an indicator of poor ventilation—rose from 870 ppm to nearly 1400 ppm within three hours of activity, far surpassing the recommended limit of 1000 ppm.

Personal protective measures such as surgical masks and FFP-standard respirators have been shown to offer some degree of filtration efficiency, particularly against fine particles. Mask use is widely recognized as a layered protective measure that can reduce the release of respiratory droplets [5]. In addition, masks may influence indoor air quality by retaining some of the inhaled particulate matter, which in the context of our study could partly explain the observed reduction in PM levels in poorly ventilated sports facilities [5]. However, due to limitations in mask fit and air leakage, these protections are insufficient in environments where pollutant levels are significantly elevated [6]. Moreover, the literature on $PM_{2.5}$ and health underscores that no safe threshold for long-term exposure has been identified. Epidemiological studies and cohort analyses have demonstrated a linear relationship between $PM_{2.5}$ concentrations and increased mortality risk, even at low exposure levels, emphasizing the importance of reducing PM levels wherever possible [7].

Little attention has been given to the role that ventilation systems may play in determining indoor air quality in sports facilities. Several studies [8–10] on naturally ventilated houses undergoing envelope renovations provide evidence that the integration of energy-efficient mechanical ventilation systems is critical for balancing indoor air quality, thermal comfort, and energy conservation. In cold climates, however, achieving sufficient ventilation often poses a financial challenge due to the additional thermal load required for preheating supply air [11]. Nevertheless, studies show that by applying ventilation rate reductions based on more realistic occupancy schedules [12], energy demand can be reduced by up to 30%, while annual CO_2 emissions decrease by as much as 12.5%.

In Mediterranean climates, a life-cycle analysis comparing different mechanical ventilation systems demonstrated the economic viability of Double-Glazed Façade Ventilation Systems [13]. Despite such findings, most current standards on indoor environmental quality (IEQ) in sports facilities primarily focus on dose-related indicators (e.g., ventilation rate), while building-related indicators (e.g., ventilation regime) and occupant-related indicators (e.g., IEQ preferences) are rarely considered. Further research is therefore needed to explore both occupant- and building-related indicators, as well as cross-modal effects between various IEQ factors, to inform future standards for sports facilities and enhance their attractiveness to visitors.

In addition to respiratory risks, indoor sports settings are increasingly recognized as potential hubs for the transmission of infectious diseases, especially during high-intensity group activities. Smaller, enclosed athletic spaces, particularly locker rooms, accumulate heat and moisture rapidly, creating ideal conditions for microbial growth and airborne transmission of pathogens. Previous studies have found high concentrations of bacterial and fungal bioaerosols in sports halls and locker rooms, particularly during peak occupancy and post-activity periods in small spaces just a few square meters in size ([14–16]. This is especially concerning given that athletes in these confined areas inhale significantly larger volumes of air during intense physical exertion, increasing their exposure risk.

Recent advances in environmental sensing technology have enabled real-time, high-frequency monitoring of IAQ using low-cost sensor networks. These devices offer reliable tracking of $PM_{1.0}$, $PM_{2.5}$, PM_{10}, CO_2, temperature, and humidity, and can be deployed at scale to identify pollution trends and assess the effectiveness of ventilation systems [17,18]. Although the deployment and calibration of such systems require interdisciplinary knowledge, including data science, electronics, and environmental engineering, their accessibility has made them valuable tools in athletic and public health research. Additionally, the use of platforms like Kaggle allows for efficient data analysis, visualization, and collaboration, particularly in projects involving large volumes of sensor data.

Despite growing interest in IAQ in sports settings, most studies have focused on general conditions during typical facility use. These microenvironments may play a disproportionate role in short-term respiratory burden and infection risk, yet remain understudied [19,20]. Furthermore, comparisons between large and small facilities have emphasized differences in ventilation efficiency but have seldom linked those findings to athlete-specific exposure profiles or time-resolved activity patterns.

This study seeks to address these gaps by investigating the concentration and distribution of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in relation to TSP in key indoor environments such as the spectators' area. Using a network of reliable, wall-mounted, low-cost sensors, the research captures high-resolution measurements across space and time to quantify athlete exposure during competitive basketball games. A unique feature of the study is the comparison of air quality before and after the application of protective face masks by spectators, allowing for an evaluation of both personal protection and ventilation effectiveness. By focusing on the temporal dynamics of air quality within performance-critical zones, this work contributes to a more nuanced understanding of IAQ in sports facilities. Leveraging real-time monitoring enables in situ interventions during matches to protect spectators, which is vital for safeguarding the health of athletes.

In conclusion, this study investigated the real-time status of indoor air quality and its fluctuations during a typical basketball game. The analysis focused on identifying patterns that may contribute to strategies for improving air quality in such environments. Furthermore, the research assessed the effectiveness of spectator face mask use during basketball games, highlighting its role not only in containing the spread of airborne diseases but also in contributing to improved air quality conditions.

2. Materials and Methods

2.1. Participants

A total of 26 university students participated in this study, comprising 11 male and 15 female basketball players, as well as 388 university students who served as spectators in a stadium with a capacity of 450 people. The first monitored match featured the top two women's university teams, while the second involved the top men's teams. All participants were first-year university students and competed under official FIBA regulations. Prior to participation, written informed consent was obtained from all players,

following full disclosure of the study's objectives, procedures, and potential risks. The study protocol regarding the study's athletes was approved by the Ethics Committee of the Department of Physical Education and Sport Science, Democritus University of Thrace (Protocol No: DUTH/EHDE/29660/206-21/01/2022), in compliance with the 2024 Declaration of Helsinki (eighth revision, approved at the 75th Meeting in Helsinki). The audience attending the basketball matches was informed verbally and in writing about the purpose of the study, the conditions under which the games would be conducted, and the role of mask use. Those who did not consent had the right to leave the sports facility without any repercussions.

2.2. Study Design

As part of a program agreement between the Democritus University of Thrace and the Municipality of Komotini, a study was conducted on airborne particles during basketball games held in small to medium-sized sports facilities. The primary goal was to propose solutions that enhance hygiene standards and reduce the risk of disease transmission through the respiratory system in such environments.

Specifically, on 27 May 2022, two basketball matches were conducted under controlled experimental conditions in a stadium with a capacity of 450 people to assess the impact of spectator mask usage on indoor air quality. Each match was attended by 388 university student spectators in a stadium with a capacity of 450 people. In the first match (women's teams), spectators entered the venue without masks and were instructed to begin wearing medical face masks at halftime. In the second match (men's teams), spectators wore masks from the beginning of the game and throughout its duration. To support air exchange, the stadium was fully emptied for a 45-min ventilation period prior to each match. For the second match, spectators re-entered the facility already wearing masks.

Both matches followed standard FIBA rules and consisted of four 10-min quarters (4×10 min). Prior to each game, players completed a standardized 25-min warm-up routine that included ball-handling drills, layups, shooting exercises, and dynamic stretching. A 10-min halftime break was followed by a 5-min re-warm-up period, during which players typically remained in the locker rooms.

Internal load and environmental data were continuously collected throughout both halves and during the halftime interval. For analysis, data were segmented into pre- and post-halftime periods. Sensor readings from the were timestamped and analyzed by game phase using descriptive statistics, line plots, and violin plots. Custom Python functions were developed to compute phase-specific summary statistics.

This experimental design enabled a direct, real-time comparison of pollutant trends under two spectator masking conditions—no mask during the first half, followed by mask use (intermittent), versus continuous full-game masking. It also assessed the impact of pre-event stadium ventilation by clearing the arena for 45 min prior to the event. The findings demonstrate that timely interventions—such as mask implementation and intentional ventilation—can significantly mitigate exposure risks in the audience area. The study offers actionable insights into how mask timing, spectator behavior, and facility-level ventilation strategies interact to influence indoor environmental quality in athletic facilities.

2.3. Internal Load Monitoring

Cardiovascular load was monitored using the Polar Team Pro system (Polar Electro Oy, Kempele, Finland). Each athlete wore a chest-strap heart rate monitor during both halves of the match and the halftime break. Heart rate data included average heart rate (HRavg), maximum heart rate (HRmax), time spent in five predefined intensity zones, and the Summated Heart Rate Zones (SHRZ) index. The intensity zones were calculated as

percentages of the age-predicted HRmax (220 − age): Zone 1 (50–59%), Zone 2 (60–69%), Zone 3 (70–79%), Zone 4 (80–89%), and Zone 5 (≥90%). Time (in minutes) spent in each zone was recorded for each athlete. The SHRZ was computed as a weighted score using the formula SHRZ = (Z1 × 1) + (Z2 × 2) + (Z3 × 3) + (Z4 × 4) + (Z5 × 5), where Z1–Z5 denote the duration in each HR zone. All data were collected and analyzed post-match using the proprietary Polar software (Team Pro app version 2.0).

2.4. System Architecture

The air quality monitoring system comprised three core components: hardware, back-end infrastructure, and a front-end data visualization platform. The hardware used was the Siba PM device, equipped with a pre-calibrated OPC-N3 optical particulate matter sensor capable of measuring $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in $\mu g/m^3$, as well as ambient temperature and humidity. The embedded system software, written in Python, collected data via a background daemon that accessed the device's file system and retrieved a rolling set of four recent measurements.

A Processing script captured live sensor data and updated a text file, which was transmitted to a cloud-based database using an embedded Telegraf service over HTTP. As the device operated on mains power, MQTT—typically reserved for low-power, battery-operated sensors—was not required. The system also included a delay-tolerant mechanism that stored data locally for up to 12 h in the event of network disruption.

The device was portable and lightweight, featuring connectivity via Wi-Fi, Bluetooth 4.0, and Ethernet. It ran the Raspbian OS and could be remotely accessed via an embedded TeamViewer micro-server. The back-end infrastructure consisted of a network server with four vCores, 16 GB of RAM, a 200 GB SSD, a 1 Gbps port, Ubuntu 22 OS, and 46 Tbit of monthly bandwidth. Data were stored in an InfluxDB time-series database and accessed via REST APIs. Real-time visualization was provided via Grafana dashboards. Data transmission frequency was customizable through editable scripts.

In particular, two Siba PM devices were installed in April 2022 at key indoor locations (Figure 1) within the municipal athletic facility: (1) above the spectator stands in the central basketball court and (2) near the referees' entrance. Each unit was mounted approximately 2 m above the ground in zones free of interference from court activity. Power and Ethernet connections supported uninterrupted data transmission. Due to a hardware malfunction, the sensor at the referee entrance was initially excluded from analysis until it had been repaired and replaced. As a result, only a subset of its data have been included in the analysis.

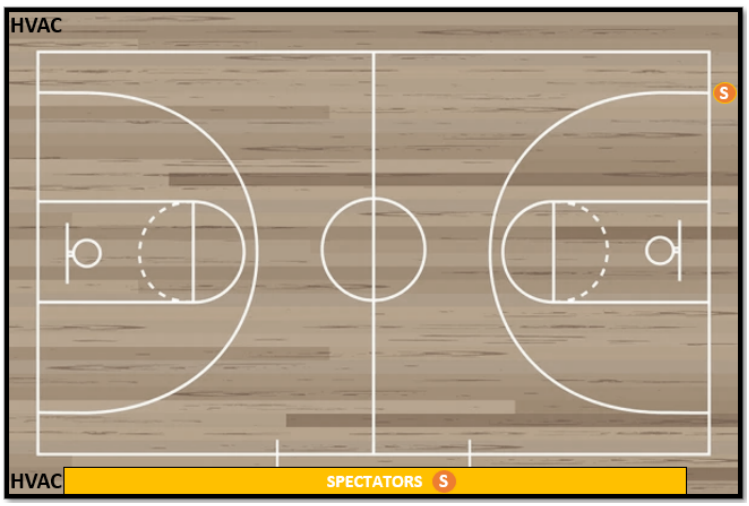


Figure 1. A diagram of the sensors' placement in the room.

The remaining two devices collected continuous data on $PM_{1.0}$, $PM_{2.5}$, PM_{10}, relative humidity, and ambient temperature. These measurements were stored in InfluxDB and exported as structured CSV datasets. The datasets were imported into Kaggle and analyzed using Python 3.11 and Jupyter notebooks for data cleaning, statistical summarization, time-series visualization, and segmentation by game phase. Data from 27 May 2022—when the experimental matches occurred—were isolated for focused analysis.

2.5. Sensor Calibration

The particle sensor used in this study is an optical particle counter, factory pre-calibrated by the manufacturer and therefore not requiring additional calibration before or during measurements [21]. It operates by measuring the scattering of light from individual airborne particles illuminated by a laser beam, from which particle size and concentration are determined.

The instrument classifies particles into 24 diameter bins ranging from 0.35 to 40 µm. From the resulting particle size distribution histogram, concentrations in $\mu g/m^3$ are calculated using an assumed particle density of 1.65 g/mL and a refractive index of 1.5. Particle loads are reported for three characteristic fractions—PM_{10}, $PM_{2.5}$, and $PM_{1.0}$—representing typical sizes of inhaled particles in adults. International regulations define limit values for PM_{10} and $PM_{2.5}$, and the sensor is capable of measuring concentrations up to 2000 $\mu g/m^3$.

The sampling interval for histogram calculation can be set between 1 and 30 s. The device operates with a total flow rate of 5.5 L/min and can register a maximum particle count rate of 10,000 particles per second. At high concentrations, coincidence errors remain low, with a maximum probability of 0.84% at 10^6 particles/L and 0.24% at 500 particles/L.

In terms of power use, the sensor functions either in measurement mode, with a typical consumption of 180 mA, or in a reduced-power standby mode below 45 mA. Additional onboard features include a temperature and humidity sensor (operating ranges –10 to 50 °C and 0–95% RH), a real-time SPI communication interface, a micro-USB port for firmware updates, and a micro-SD card for data storage.

2.6. Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy and ethical restrictions.

3. Results

3.1. Subjects' Characteristics

A total of 26 university student-athletes participated in the study, comprising 11 men and 15 women. Additionally, 348 university students attended the matches as spectators. Table 1 presents the descriptive characteristics of the athletes.

Table 1. Participants' Descriptive Characteristics.

Variable	Men (*n* = 11)	Women (*n* = 15)
Age (years)	20.07 ± 1.90	19.14 ± 0.64
Height (m)	1.88 ± 0.11	1.65 ± 0.04
Body Mass (kg)	82.91 ± 7.16	58.87 ± 5.22
BMI (kg/m^2)	23.52 ± 2.19	21.52 ± 1.82

Table 2 details the physiological responses of participants during the match, including average and maximum heart rate (HR), time spent in different HR zones, and the Session Heart Rate Zone (SHRZ) score, a cumulative workload indicator.

Table 2. Physiological Demands during Basketball Matches.

Category	Match Phase	HR Avg (bpm)	HR Max (bpm)	Time in HR Zone 1 (50–59%) [min]	Time in HR Zone 2 (60–69%) [min]	Time in HR Zone 3 (70–79%) [min]	Time in HR Zone 4 (80–89%) [min]	Time in HR Zone 5 (90–100%) [min]	SHRZ (AU)
Men	1st Half	162.36 ± 15.54	190.68 ± 13.37	2.28 ± 4.59	5.22 ± 4.76	5.90 ± 2.83	8.11 ± 4.41	9.51 ± 5.44	110.42 ± 16.41
	2nd Half	160.23 ± 18.18	192.27 ± 16.19	3.44 ± 6.34	6.48 ± 5.79	5.79 ± 4.25	10.12 ± 6.89	9.14 ± 8.13	119.97 ± 27.75
	Half-Time Break	145.36 ± 11.13	183.91 ± 12.91	0.48 ± 0.64	3.36 ± 2.11	2.79 ± 1.29	1.54 ± 1.15	0.53 ± 0.58	24.39 ± 4.68
Women	1st Half	156.73 ± 17.69	195.90 ± 13.93	4.74 ± 6.95	7.81 ± 5.55	6.02 ± 1.70	10.25 ± 5.09	7.87 ± 4.83	118.79 ± 25.62
	2nd Half	160.90 ± 14.73	196.43 ± 12.16	2.85 ± 6.12	9.16 ± 5.78	4.34 ± 4.46	5.48 ± 3.84	6.72 ± 3.95	89.72 ± 21.02
	Half-Time Break	137.60 ± 13.71	163.47 ± 15.32	0.78 ± 2.12	2.81 ± 2.05	2.44 ± 0.98	4.52 ± 2.89	3.88 ± 2.70	51.21 ± 9.98

Men's HR data show that the average HR during match play remained relatively stable between halves (162.36 ± 15.54 bpm in the first half vs. 160.23 ± 18.18 bpm in the second half), with slight increases in time spent in higher intensity HR zones (zone 4 and zone 5) during the second half, indicating sustained or increased cardiovascular demand. The SHRZ also increased in the second half (119.97 ± 27.75 AU vs. 110.42 ± 16.41 AU). During the half-time break, HR values dropped considerably (HR_avg: 145.36 ± 11.13 bpm), and time spent in higher zones (zone 4 and 5) was minimal, as expected.

Women displayed a different pattern. Average HR increased slightly from the first to the second half (156.73 ± 17.69 bpm to 160.90 ± 14.73 bpm), and although the time in zone 5 decreased slightly, there was a notable drop in SHRZ from 118.79 ± 25.62 AU in the first half to 89.72 ± 21.02 AU in the second half. This suggests a reduced cumulative cardiovascular load during the latter part of the match. Interestingly, during the halftime break, women maintained higher HR values and spent more time in higher HR zones compared to men, possibly reflecting greater residual physiological activation or use of changing room facilities during the break.

3.2. Indoor Air Quality During the Non-Mask/Mask Game

During the girls' basketball game, face masks were introduced at halftime. The facility-wide air quality showed moderate stability during the first half, followed by a notable improvement after the adoption of masks. Between Q1 and Q2, PM concentrations remained relatively stable, although PM10 increased by 20% (Table 3). Starting from Q2 to Q3, the introduction of masks resulted in a measurable decrease in all monitored particulate matter categories. PM1.0 dropped by 13.8%, followed by a further 0.7% reduction from Q3 to Q4. PM2.5 showed a 15% reduction post-halftime and an additional 5% decline in the final quarter. PM10 experienced a 7% decrease from Q2 to Q3 and dropped more sharply by 21% between Q3 and Q4. Humidity levels also decreased in a two-stage process: a 7.5% drop occurred following halftime, followed by a further 2.6% decline in Q4.

Table 3. Statistics by period in the Spectators area during the girls' game.

Period	PM1.0 (Mean ± std)	PM2.5 (Mean ± std)	PM10 (Mean ± std)	RH% (Mean ± std)
Girls Q1	4.210 ± 0.440	9.126 ± 2.860	22.369 ± 26.436	37.945 ± 0.710
Girls Q2	4.362 ± 0.565	9.319 ± 2.933	26.682 ± 31.405	39.664 ± 0.266
Girls HTB	4.365 ± 0.714	8.652 ± 2.135	24.872 ± 31.030	37.477 ± 1.030
Girls Q3	3.758 ± 0.502	7.907 ± 2.701	24.801 ± 35.741	36.656 ± 0.721
Girls Q4	3.731 ± 0.554	7.510 ± 2.604	19.556 ± 24.142	35.688 ± 0.708

The coefficients of variation (CV) for $PM_{1.0}$ and $PM_{2.5}$ remained low and stable at 0.1 and 0.3, respectively, suggesting consistent particulate behavior. PM_{10} displayed greater variability, increasing slightly from 1.2 to 1.4 in Q3 and stabilizing again in Q4. Humidity variability spiked during Q2 (cv = 149), possibly indicating the use of cleaning agents

or temporary ventilation disturbances. This trend is visible in the humidity violin plots (Figure A7) and corroborated by temporal spikes in Figure A3.

From a game flow perspective, pollutant concentrations remained relatively unchanged between Q1 and Q2. During halftime, a minor increase in pollutant levels was observed, possibly due to locker room activity or reduced airflow. However, following the adoption of masks in Q3, a consistent downward trend in all pollutant types was observed, which continued through Q4, confirming the effectiveness of personal protective equipment in reducing aerosol presence during indoor sporting events (Figures A4–A7).

3.3. Indoor Air Quality During the Mask Game

During the boys' basketball game, spectators wore masks throughout, providing a continuous intervention model. The facility-wide particulate concentrations were lower overall than in the girls' game, suggesting that early adoption of masks limited pollutant buildup. From Q2 to Q3, $PM_{1.0}$ decreased by 7.7%, $PM_{2.5}$ by 2.8%, and PM_{10} by 2.7%. Humidity declined more modestly by 2.1% (Table 4).

Table 4. Statistics by period at the Spectators' area during the boys' game.

Period	$PM_{1.0}$ (Mean ± std)	$PM_{2.5}$ (Mean ± std)	PM_{10} (Mean ± std)	RH% (Mean ± std)
Boys Q1	3.657 ± 0.571	7.691 ± 2.514	29.581 ± 45.275	32.291 ± 0.336
Boys Q2	3.384 ± 0.448	7.263 ± 3.216	22.833 ± 41.710	31.964 ± 0.225
Boys HTB	3.443 ± 0.467	6.666 ± 1.867	22.959 ± 27.057	31.572 ± 0.408
Boys Q3	3.645 ± 0.553	7.060 ± 2.151	17.157 ± 21.075	31.304 ± 0.289
Boys Q4	3.171 ± 0.378	5.968 ± 1.939	15.365 ± 22.536	30.946 ± 0.235

The coefficients of variation for $PM_{1.0}$ and $PM_{2.5}$ remained stable (cv = 0.2 and 0.3), while PM10 variability increased to 1.8 during Q3, possibly indicating heightened spectator movement or behavioral responses to match events. Figure A14 illustrates these trends across periods, while violin plots in Figures A6 and A7 confirm the gradual reduction in particulate load.

Analyzing match progression, a steady decline in PM levels was evident from Q1 to Q2. This trend persisted through halftime and into Q4, although reductions were less pronounced than in the mask-intervention game. This indicates that continuous mask usage maintained a consistently low pollutant profile rather than producing a sharp post-halftime drop.

3.4. Summary of Non-Mask/Mask Vs. Mask Conditions

Qualitative analysis of the two basketball games reveals distinct environmental effects stemming from differences in spectator mask usage. In the girls' game, where masks were introduced only after halftime, a sharp and immediate decline in PM1.0 and PM2.5 concentrations was observed. This pattern supports the hypothesis that surgical masks are particularly effective in reducing ultrafine and fine particulate matter. PM10 levels also decreased after halftime, but with greater variability. These trends are visually confirmed in Figures A4–A7 and numerically detailed in Tables 3 and 4.

In contrast, the boys' game, during which masks were worn by spectators throughout the entire match, showed more stable and consistently lower levels of all particulate matter types. The decreases in PM levels across periods were more gradual and less pronounced after halftime, suggesting a sustained mitigation effect from continuous mask use. These trends are corroborated by violin plots (Figures A6 and A7) and time-series data (Figures A8–A11).

Together, these observations—supported by Tables 3 and 4 and Figures 1 and A1, Figures A2–A18—highlight the tangible impact of mask-wearing policies and usage patterns on indoor air quality. They also emphasize the need for tailored ventilation and occupancy management strategies in indoor sports settings to minimize exposure risks and enhance the safety of both athletes and spectators.

4. Discussion

This study investigated the dynamics of indoor air quality (IAQ) in a municipal facility during two basketball games, with a focus on how spectator masking policies influenced airborne particulate concentrations in a real-world setting. By combining real-time sensor data with event timing and match flow, the findings provide novel insights into the role of personal protective behaviors and environmental conditions in shaping exposure risks in small-to-medium-sized athletic environments.

These results also highlight why diseases continue to spread in enclosed sports facilities. Close contact between individuals facilitates transmission, as droplets released through heavy breathing, shouting, or sweating may circulate before being removed by ventilation. Moreover, air filtration systems only clean the air that passes through them, meaning that in the absence of adequate air renewal, contaminated air can persist within the facility.

Specifically, a decrease in $PM_{1.0}$ and $PM_{2.5}$ concentrations was observed, which may be partly attributable to the use of masks by spectators during the events. Although the precise mechanisms cannot be established with certainty, exhaled microdroplets containing biological material may remain airborne, behaving similarly to PM, or adhere to existing particles, thereby increasing their persistence and dissemination in indoor environments [22–24]. Among children, the average concentration of exhaled particles increased with activity intensity, being lowest during tidal breathing and highest during sneezing. High-intensity activities were associated with an increase primarily in the respirable size. Mask use, particularly surgical masks, was associated with lower average particle concentrations compared to no mask use [25]. Furthermore, particle emission was strongly influenced by speaking volume, with emissions decreasing as volume decreased. Surgical masks were found to reduce particle emission even for the smallest particle sizes [26].

4.1. Spectator Area: Effects of Mask Interventions

The most prominent and consistent pattern observed in the spectator area was the reduction in particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}) concentrations following mask usage. In the girls' game—where spectators began wearing surgical face masks only after halftime—sharp declines were recorded in the second half. Specifically, $PM_{1.0}$ decreased by 13.8% from Q2 to Q3, while $PM_{2.5}$ fell by 15%, followed by a further 5% reduction in Q4. These rapid declines suggest that even partial or delayed implementation of mask use can have an immediate mitigating effect on fine and ultrafine particulate concentrations in enclosed sports venues (Figures A4–A7; Table 3).

In the boys' game, where spectators wore masks continuously, overall PM levels were lower and more stable throughout the match (Tables 3 and 4). Though reductions in PM from quarter to quarter were less dramatic, the consistent downward trend and lower baseline suggest that early mask implementation is effective at preventing the buildup of pollutants in the first place. Violin plots and time-series visualizations (Figures A8–A11, A16 and A17) further reinforce this conclusion, showing narrower distributions and fewer high-concentration outliers.

The relationship between particulate matter (PM) and COVID-19 has been proven beyond doubt in the literature [27]. The above observations therefore support existing

literature on the effectiveness of surgical masks in reducing personal exposure to PM, as decreased mass concentrations of PM imply a reduced risk of infection from COVID-19. Furthermore, although research has shown that cloth and surgical masks are generally ineffective in forming a tight seal and offer variable protection [28,29], our observations indicate that mask-wearing may not only block particle emission, e.g., droplets and coagulated fine PM due to exhalation moisture [30] but also indirectly reduce particulate matter agitation due to lower spectator movement [2] or better behavior compliance [31].

Moreover, the present study supports the conclusions of Tran et al. [31], who observed that mask-wearing behavior varies dynamically across game phases. Although we did not record mask-wearing at the individual level, our PM readings and observational notes align with their findings—mask usage declined during active play and increased during breaks, potentially explaining fluctuations in particulate concentrations between periods.

4.2. Interpretation and Practical Implications

The study also demonstrated that relative humidity (RH) patterns can serve as useful proxies for occupancy and ventilation demand. In both games, RH levels peaked during high-occupancy intervals and dropped afterward, reinforcing earlier research that links humidity spikes to crowd density and human activity. These insights support the idea that RH monitoring, coupled with low-cost PM sensors, can serve as a real-time environmental alert system in enclosed facilities [30]. Another important implication is that short-term PM spikes during high-density phases may pose health risks to athletes and spectators, even when average pollutant levels remain within acceptable ranges. This is especially relevant in environments where physical exertion increases respiratory intake, as noted by Szulc et al. [6] and others have noted, PM exposure in athletic settings frequently exceeds health-based guidelines. In our study, $PM_{2.5}$ and PM_{10} levels temporarily surpassed WHO thresholds during periods of peak occupancy, validating these concerns.

The results also underscore the value of utilizing low-cost sensor networks in sports venues. Our deployment enabled continuous monitoring and fine-grained data collection across multiple environmental parameters, highlighting how such systems can inform real-time decisions about ventilation, space occupancy, and public health interventions. Given the cost-effectiveness and accessibility of these tools, broader adoption could support public health goals without imposing significant financial burdens on facility operators.

4.3. Recommendations for Facility Design and Policy

To mitigate indoor air quality risks in athletic environments, several targeted measures are recommended. First, consistent and early use of face masks by spectators should be encouraged, as our findings demonstrate clear reductions in acceptable PM levels when masks are worn throughout the event. While N95-type masks offer superior protection, even surgical masks make a meaningful contribution to reducing aerosol presence in the air.

Second, humidity should be incorporated as a control variable within environmental monitoring systems. Since RH levels reliably track with human activity and crowding, they can be used to trigger adaptive ventilation strategies or inform occupancy limits during live events.

Third, facilities should adopt short-term PM exposure thresholds for high-density indoor zones. Traditional exposure guidelines often rely on long-term averages; however, our findings, along with prior literature, indicate that short-duration spikes can pose meaningful health risks in physically active populations.

Finally, policies governing mask distribution and education at sporting events must be transparent, equitable, and evidence-based. As noted by Epstein [28], logistical and legal challenges exist in distributing and maintaining mask compliance among spec-

tators, but these can be mitigated through proactive planning, public messaging, and consistent monitoring.

4.4. Broader Implications and Future Research

This study is, to our knowledge, the first to directly measure the effects of spectator mask use on real-time PM levels in a sports facility using low-cost environmental sensors. While the results are promising, they underscore the need for further investigation. Future research should:

- Expand the number of monitored venues and event types.
- Evaluate long-term exposure risks in athletes.
- Test targeted interventions, such as CO_2-triggered HVAC systems or high-efficiency particulate filtration.
- Integrate behavioral monitoring (e.g., automated mask detection) to more closely link environmental data with compliance patterns.

Given the global burden of air pollution-related illness, including millions of disability-adjusted life years (DALYs), these directions are timely and necessary. Indoor sports facilities provide a unique and controlled environment for modeling the interaction between human behavior, technology, and public health policy.

4.5. Limitations

Several limitations should be acknowledged when interpreting the findings of this study. First, while the optical particle counter used was factory pre-calibrated and demonstrated responsiveness to changes in pollutant concentrations, potential baseline drift cannot be completely excluded. Although this does not invalidate the relative comparisons presented, future work would benefit from parallel calibration against reference-grade instruments to further strengthen accuracy.

Second, the study design involved only two basketball games within a single facility, limiting the generalizability of the results. Differences in building characteristics, ventilation systems, crowd behavior, and climate conditions may influence air quality dynamics in other sports venues.

Third, the study relied on indirect evidence of mask compliance (inferred from PM trends and observational notes) rather than systematic behavioral monitoring. This may introduce uncertainty into the interpretation of the exact relationship between mask-wearing behavior and pollutant dynamics.

Finally, the analysis presented here is descriptive in nature and does not include inferential statistical testing. As such, the findings should be interpreted as exploratory observations that highlight trends in particulate matter concentrations, rather than as definitive statistical conclusions.

5. Conclusions

This study presents, for the first time, an in-depth evaluation of indoor air quality in a small athletic facility during competitive basketball events. The findings reveal that match play usage generates elevated levels of particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}), frequently surpassing international health guidelines, especially in confined zones with poor ventilation. Importantly, the results demonstrate that introducing surgical masks—even partway through a game—can significantly reduce fine particle concentrations. However, the data strongly support that early and consistent mask enforcement from the start of the event yields more stable and lower pollutant profiles, reinforcing the critical need for proactive rather than reactive protective strategies. In addition, humidity and temperature trends served as reliable indicators of occupancy-driven ventilation demand, particularly

in changing rooms, where intense breathing and post-activity routines further degrade air quality. These insights underscore the pressing need for customized environmental control measures in such enclosed spaces, including dynamic ventilation, humidity monitoring, and establishing short-term exposure thresholds. Overall, this study underscores the importance of integrating real-time environmental monitoring with behavioral insights to inform effective policies that safeguard the health of athletes and spectators in small- to medium-sized sports facilities. Future research should continue to refine zone-specific interventions and assess their long-term impact on respiratory and cardiovascular outcomes in athletic populations.

Author Contributions: Conceptualization, E.K., A.A., M.M., I.K., P.S. and A.C.; Data curation, C.K., D.P., M.E., M.P. and N.O.R.; Formal analysis, C.K. and D.P.; Funding acquisition, A.A. and A.C.; Investigation, D.B., M.E., M.P., N.O.R., P.A. and P.F.; Methodology, E.K., A.A. and A.C.; Project administration, A.A. and A.C.; Resources, A.A., M.M., I.K. and P.S.; Software, C.K. and D.P.; Supervision, A.A., I.K., P.S. and A.C.; Validation, E.K., D.B., P.A., P.F., N.Z. and A.C.; Visualization, C.K. and D.B.; Writing—original draft, E.K., C.K. and D.P.; Writing—review & editing, A.A., N.Z., M.M. and A.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study protocol was approved by the Ethics Committee of the Department of Physical Education and Sport Science, Democritus University of Thrace (Protocol No: DUTH/EHDE/29660/206-21/01/2022), in compliance with the 2024 Declaration of Helsinki (eighth revision, approved at the 75th Meeting in Helsinki).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the participants to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

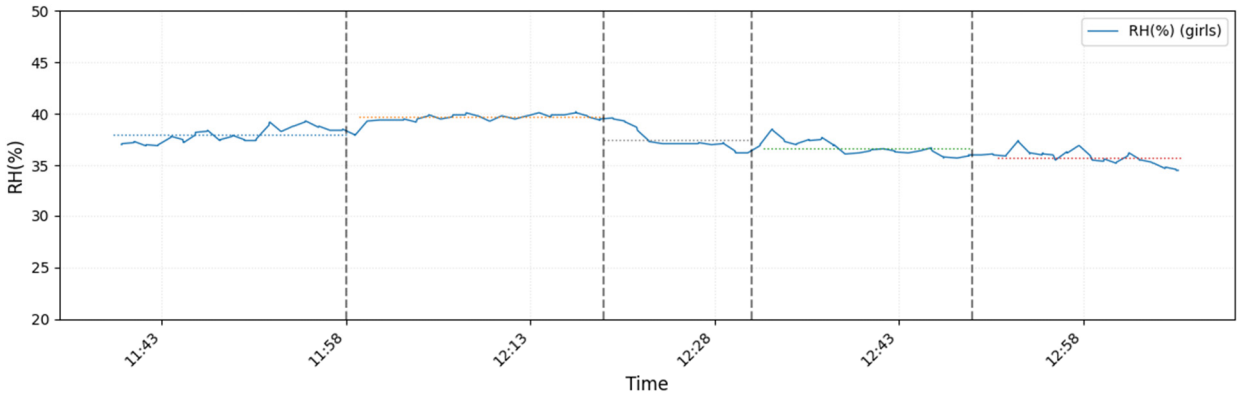


Figure A1. Humidity measurements at the spectators' area during the girls' game (11:39–13:06 27 May 2022). The colored horizontal lines denote mean humidity values for each phase of the girls' game, respectively.

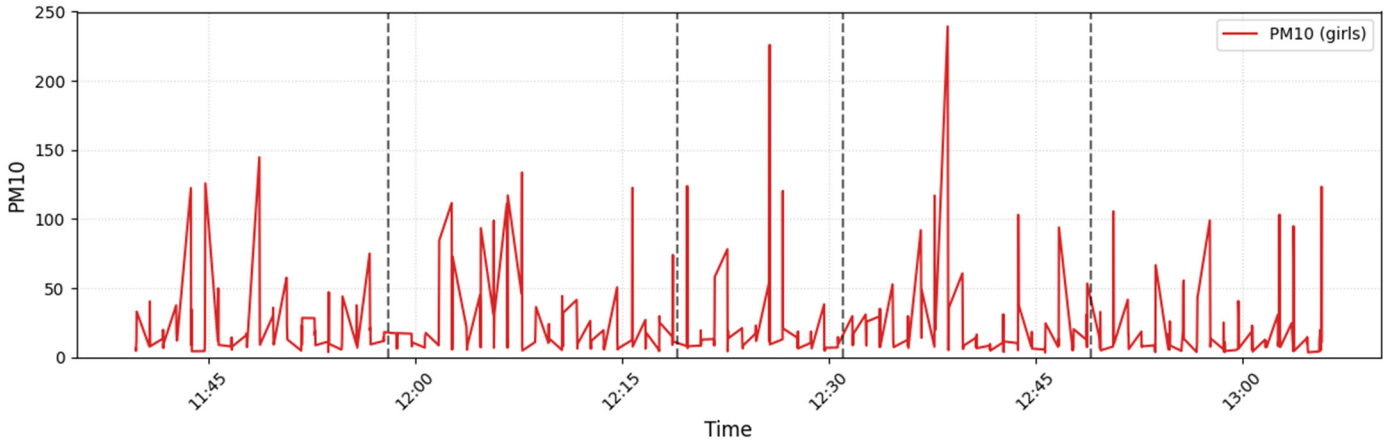


Figure A2. PM_{10} measurements at the spectators' area during the girls' game (11:39–13:06 27 May 2022).

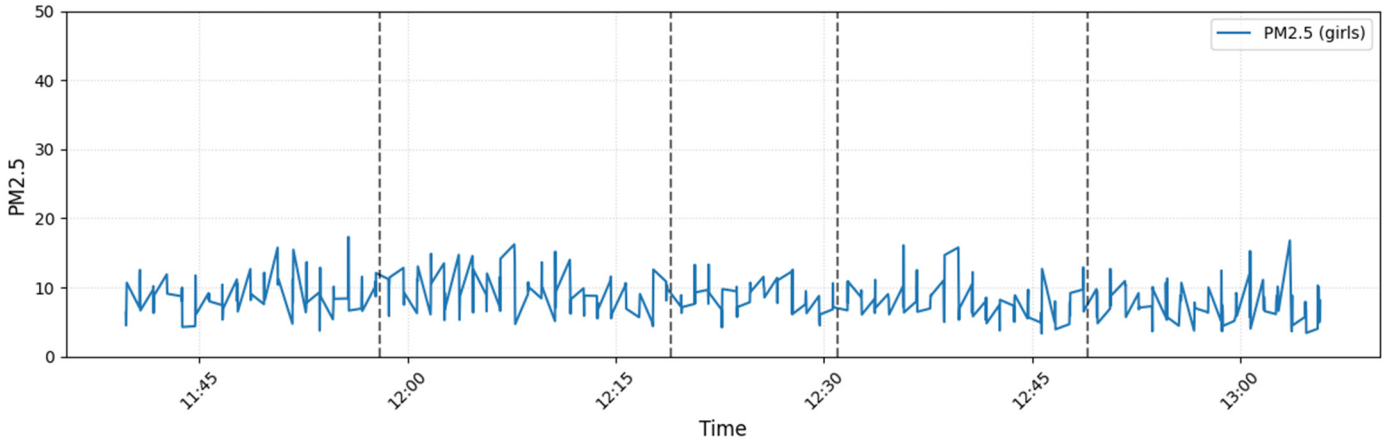


Figure A3. PM2.5 measurements at the spectators' area during the girl's game (11:39–13:06 27 May 2022).

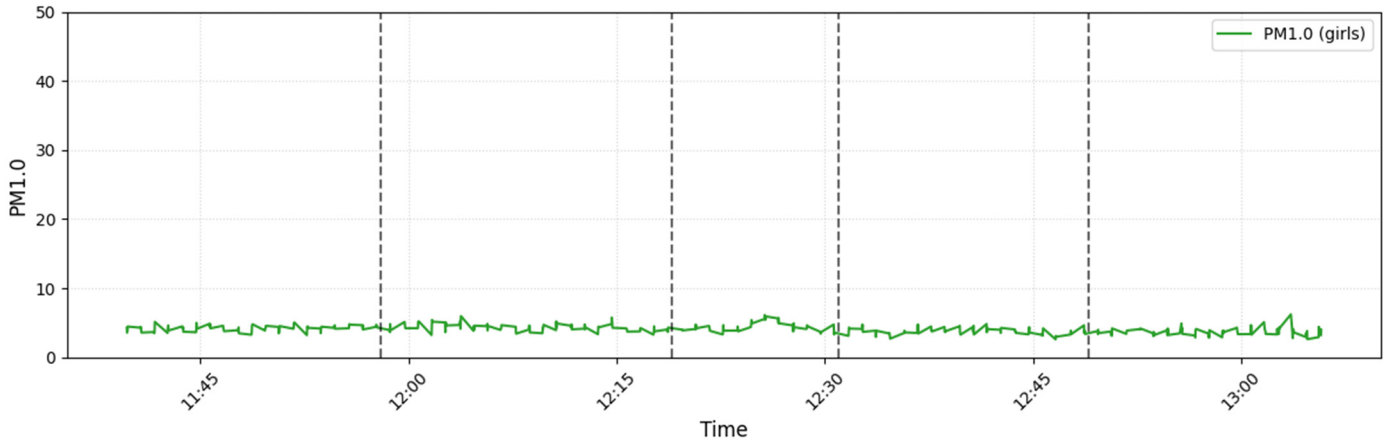


Figure A4. PM1.0 measurements at the spectators' area during the girl's game (11:39–13:06 27 May 2022).

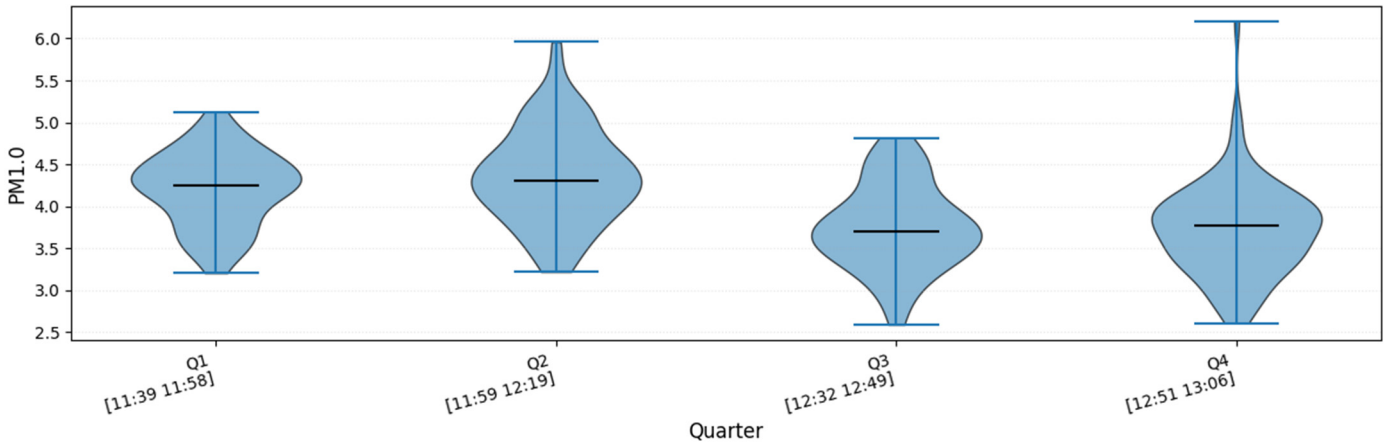


Figure A5. Violin plots for PM1.0 for each period. It can be inferred that the median value in Q3 and Q4 is smaller, and the number of samples in higher concentrations is smaller (the plot is narrower).

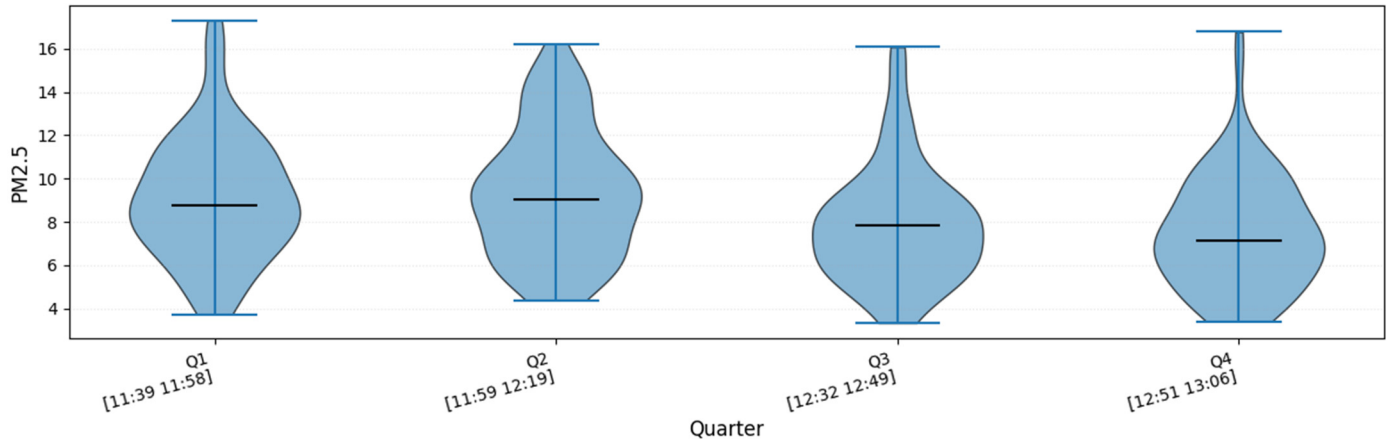


Figure A6. Violin plots for PM2.5 for each period. It can be inferred that the median value in Q3 and Q4 is smaller, and the number of samples in higher concentrations is smaller (the plot is narrower).

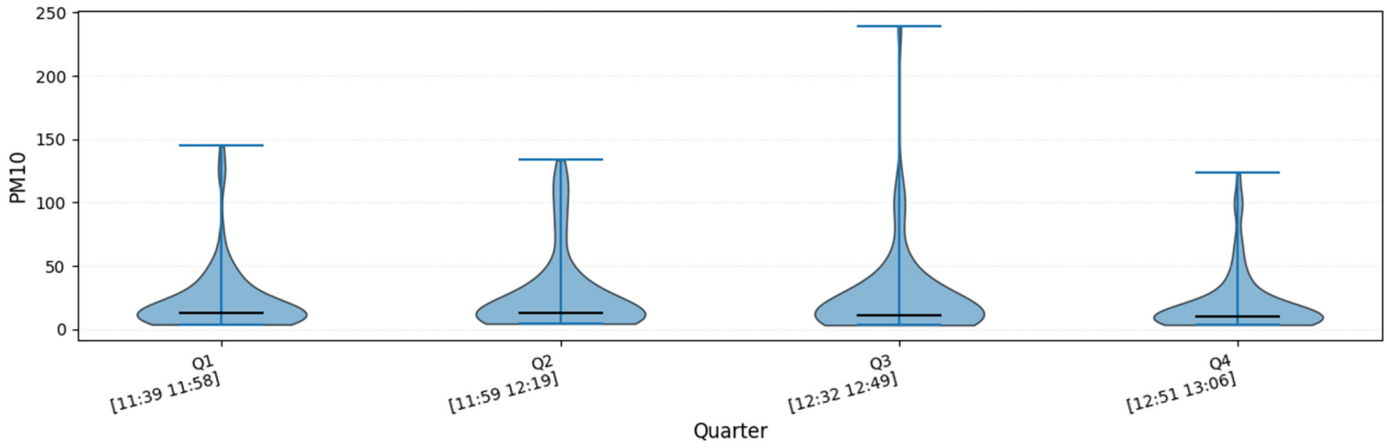


Figure A7. Violin plots for PM10 for each period. It can be inferred that the median value in Q3 and Q4 is smaller, and the number of samples in higher concentrations is smaller (the plot is narrower). However, in Q3, there are a few outliers with high values, possibly due to spectators fidgeting with their masks.

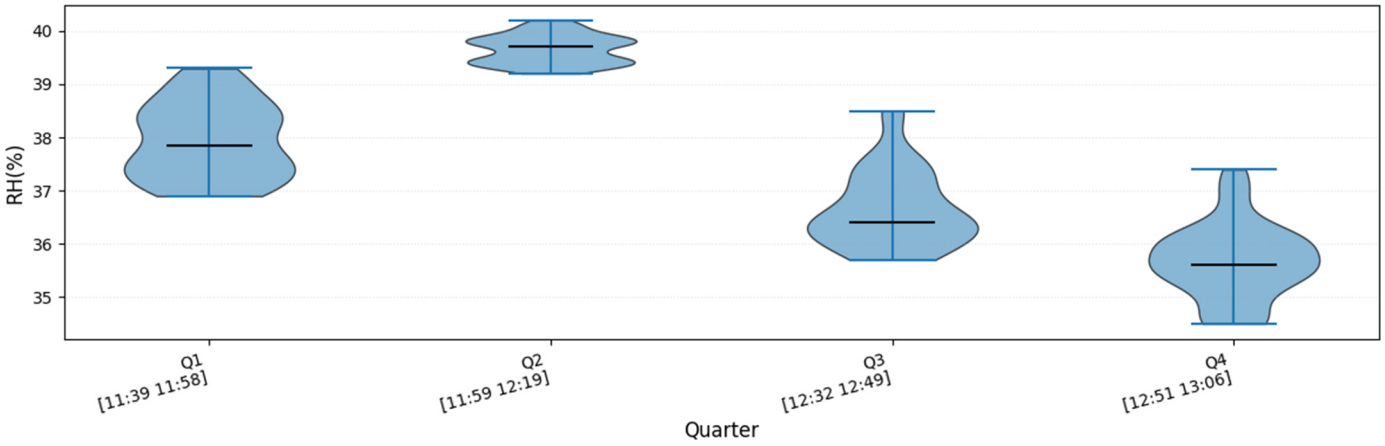


Figure A8. Violin plots for RH for each period. It can be inferred that the median value in Q3 and Q4 is smaller, and the number of samples in higher concentrations is smaller (the plot is narrower). The high density of high humidity values in Q2 could be attributed to a sterilisation spraying that took place during the break between Q1 and Q2. In Q4, the median value is lower than in Q3, and a large number of measurements are clustered around the median, indicating a decrease from before.

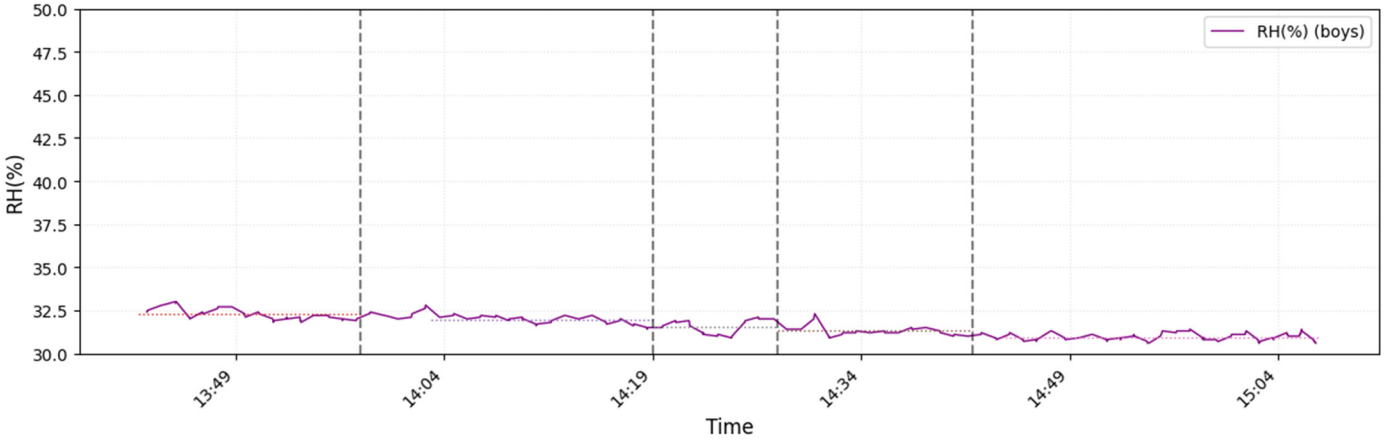


Figure A9. Humidity measurements at the spectators' area during the boy's game (13:42–15:07 27 May 2022). The colored horizontal lines denote mean humidity values for each phase of the boys' game, respectively.

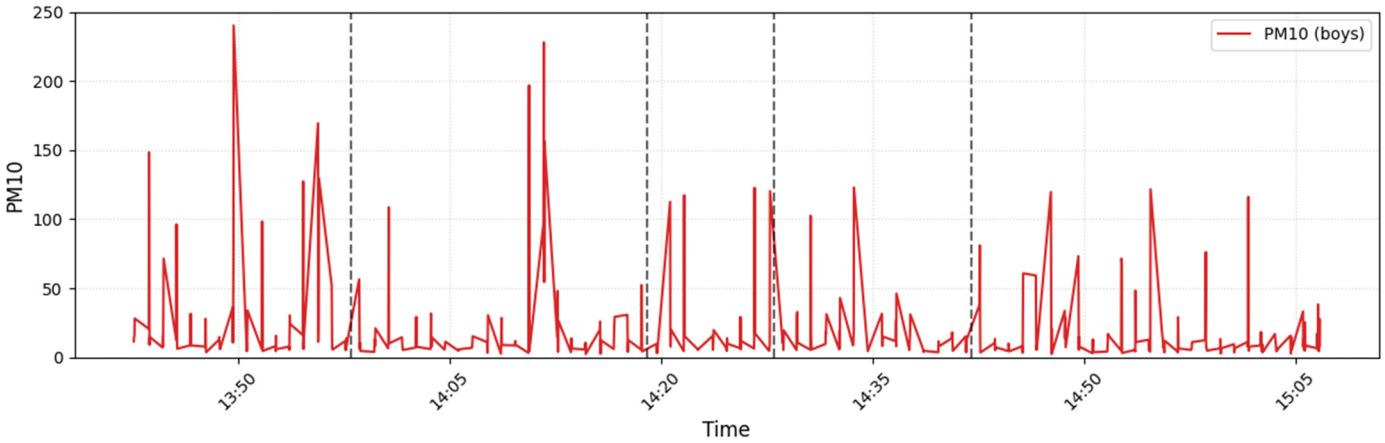


Figure A10. PM10 measurements at the spectators' area during the boy's game (13:42–15:07 27 May 2022).

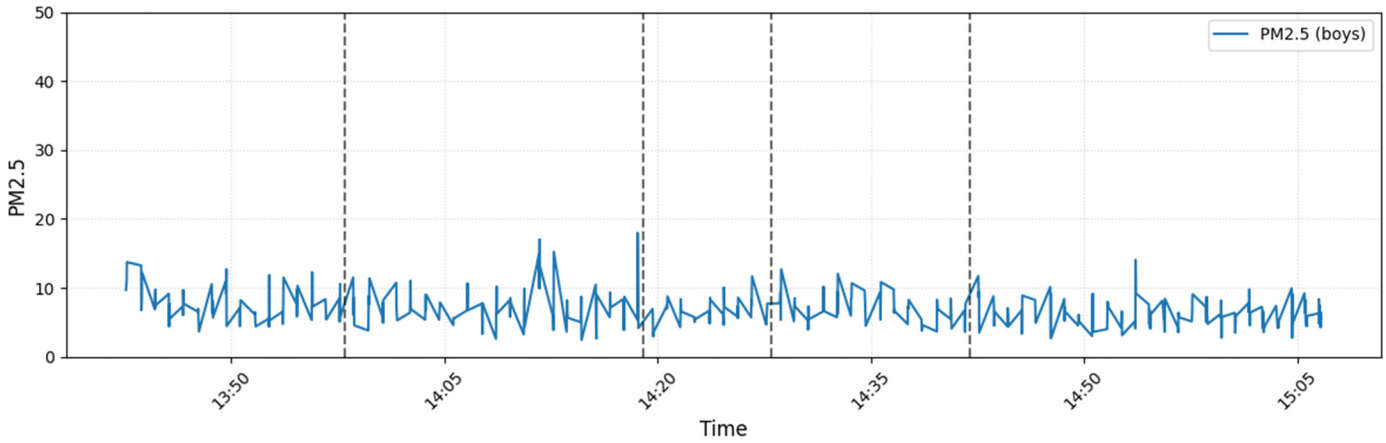


Figure A11. PM2.5 measurements at the spectators' area during the boy's game (13:42–15:07 27 May 2022).

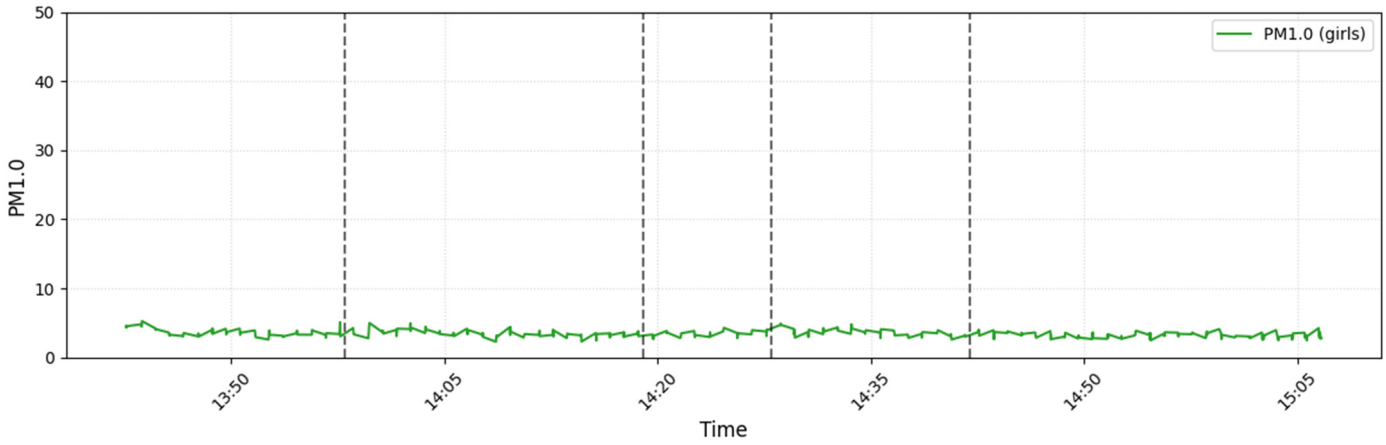


Figure A12. PM1.0 measurements at the spectators' area during the boy's game (13:42–15:07 27 May 2022).

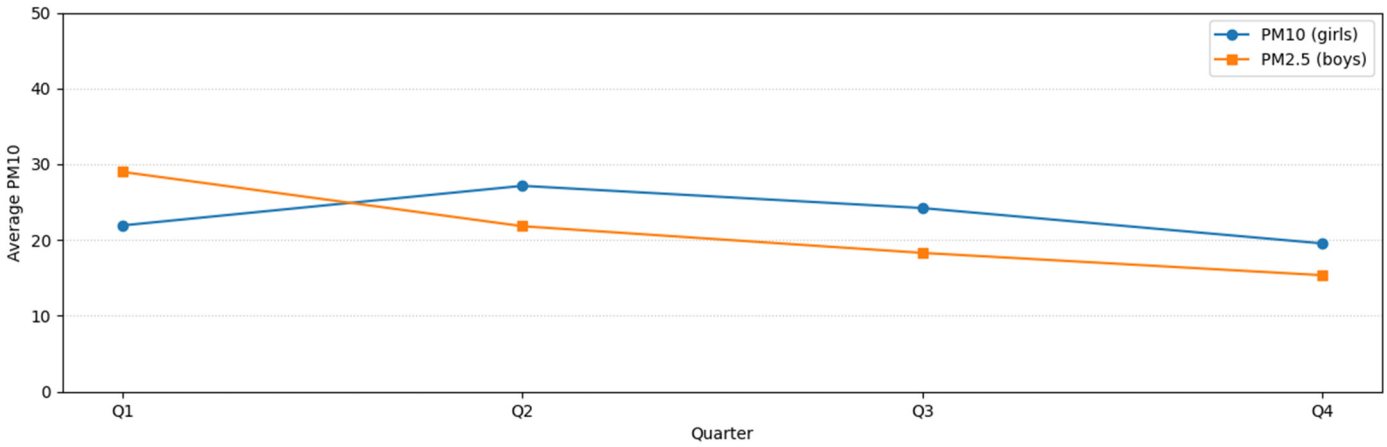


Figure A13. PM10 averages per period for girls (blue line) and boys (orange line). It is clear that after the protective face masks are on (from Q3 on for the girls and from Q1 for the boys), there is a constant decrease in PM10 concentration. On the contrary, during the period when the protective face masks are off (during Q1 and Q2 for the girls), there is a clear increase in PM10.

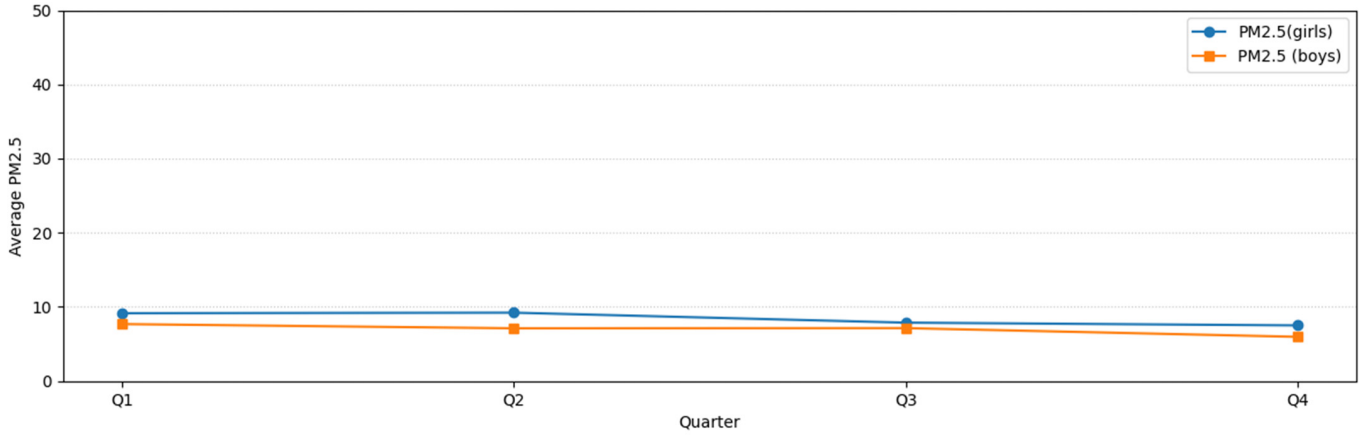


Figure A14. PM2.5 averages per period for girls (blue line) and boys (orange line). It is clear that after the protective face masks are on (from Q3 on for the girls and from Q1 for the boys), there is a constant decrease in PM2.5 concentration. On the contrary, during the period when the protective face masks are off (during Q1 and Q2 for the girls), there is a clear increase in PM2.5. Furthermore, the transition from Q2 to Q3 when masks are applied (girls).

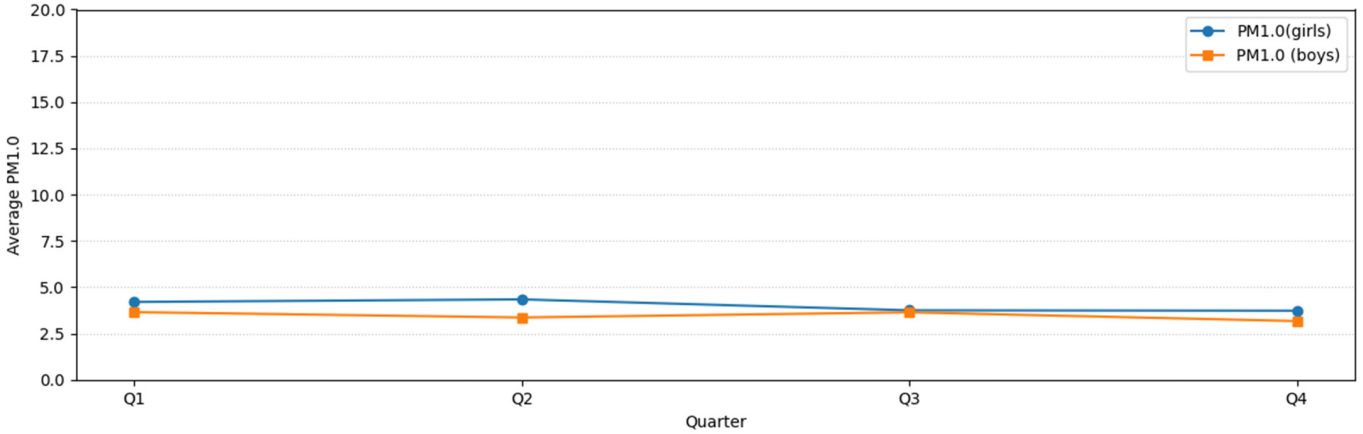


Figure A15. PM1.0 averages per period for girls (blue line) and boys (orange line). It is clear that after the protective face masks are on (from Q3 on for the girls and from Q1 for the boys), there is a constant decrease in PM1.0 concentration (here the boys' PM1.0 increases very slightly from Q2 to Q3. On the contrary, during the period when the protective face masks are off (during Q1 and Q2 for the girls), there is a clear increase in PM1.0.

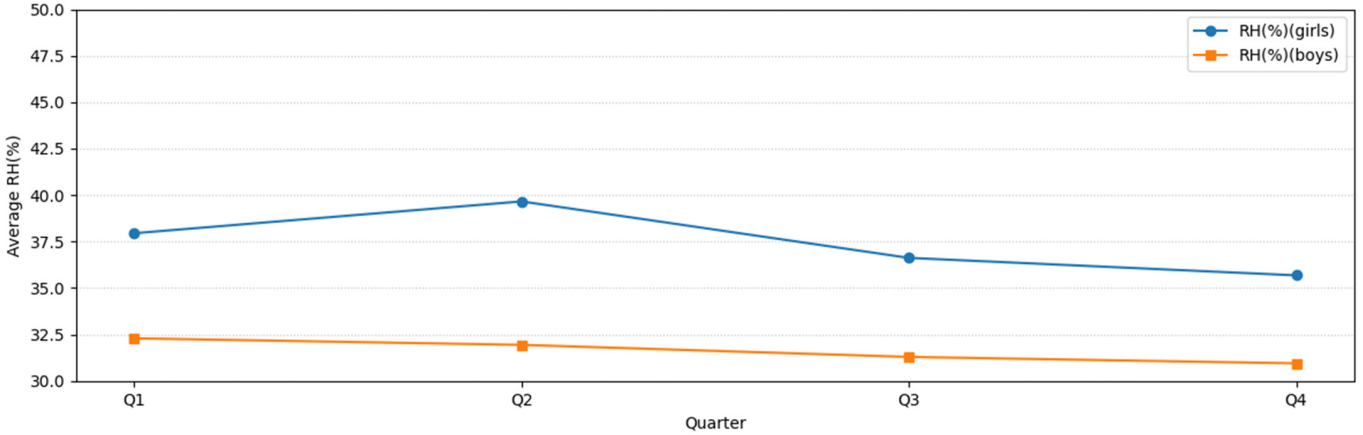


Figure A16. Humidity averages per period for girls (blue line) and boys (orange line). It is clear that after the protective face masks are on (from Q3 on for the girls and from Q1 for the boys) there is a constant decrease in humidity concentration. On the contrary, during the period when the protective face masks are off (during Q1 and Q2 for the girls), there is a clear increase in humidity.

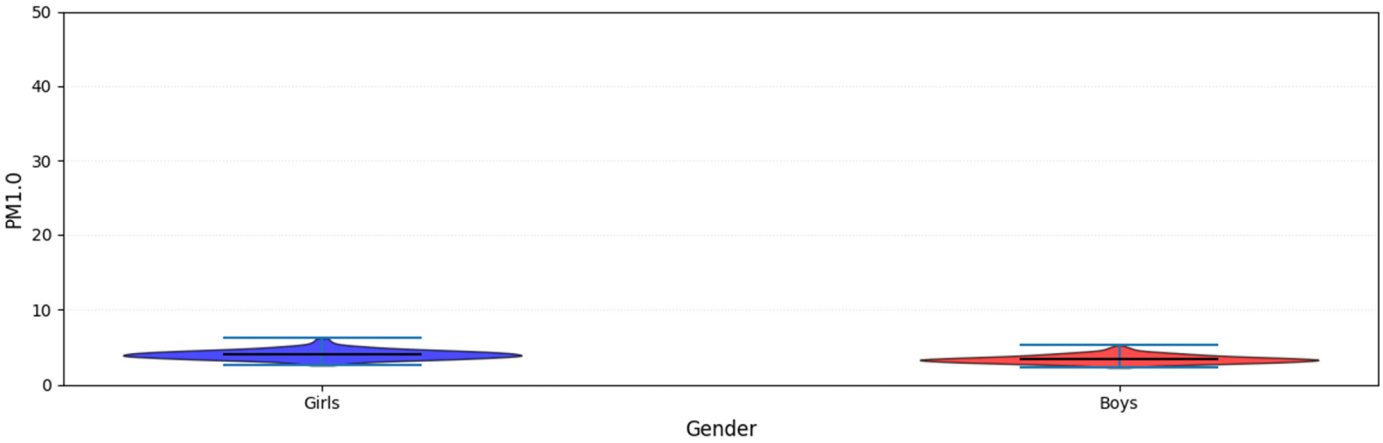


Figure A17. Violin plot that shows that during the boy's game (portrayed in red) PM1.0 concentrations are lower, the overall PM1.0 density is higher while both the min and max values are lower compared to the girls' game (portrayed in blue).

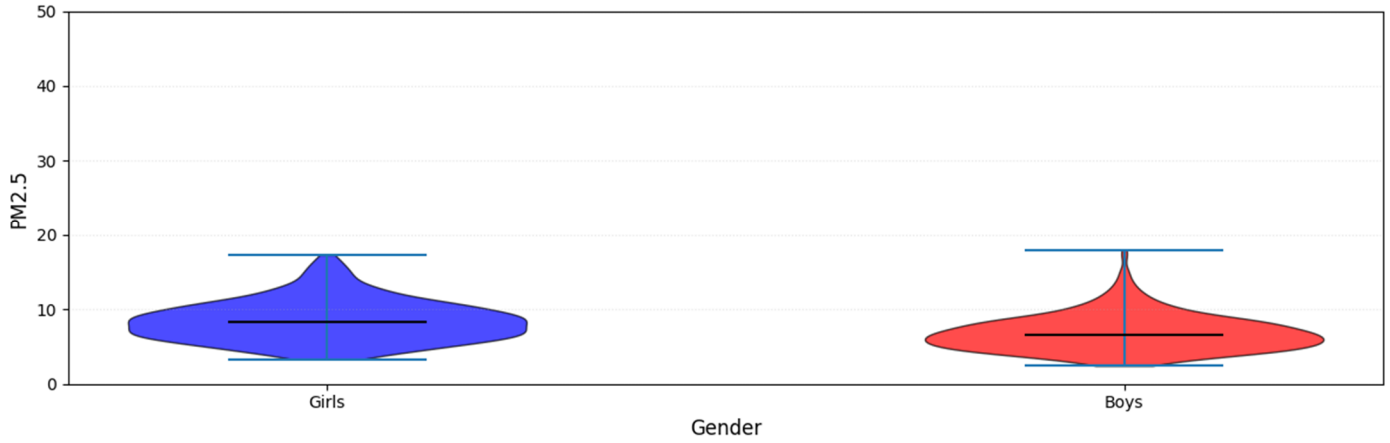


Figure A18. Violin plot that shows that during the boy's game (portrayed in red) PM2.5 concentrations are lower, the overall PM2.5 density is higher while both the min and max values are lower compared to the girls' game (portrayed in blue).

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