

Original Article

Environmental monitoring and smoking exposure before and after the designation of non-smoking areas in indoor sports facilities

Sung Ho Hwang¹, Wha Me Park^{2,3*}¹Department of Health, Environment and Safety, Yong In University, South Korea²The Institute for Occupational Health, College of Medicine, Yonsei University, Seoul, South Korea³Graduate School of Public Health, Yonsei University, Seoul, South Korea*Correspondence: wmpark2045@hanmail.net

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Abstract

This study evaluated the effectiveness of smoke-free legislation in reducing indoor air pollutants, specifically PM_{2.5}, NO₂, and TVOC, in recreational facilities in Korea. A quasi-experimental before-and-after study was conducted in selected indoor venues, with pollutant levels compared pre- and post-designation of non-smoking areas. Monitoring was performed in three billiard halls and three screen golf ranges in Seoul. PM_{2.5}, NO₂, and TVOC were measured using a Grimm 1.108 aerosol spectrometer (Germany), MEZUS-210/ANA-2 and Teledyne M200E (Korea/USA), and a Sibata MP-Σ30 sampler (Japan). Sampling occurred during operating hours, and results were analyzed using non-parametric tests against Korean standards. After implementation, PM_{2.5} decreased from 42.8 to 18.6 μg/m³, and NO₂ from 148.3 to 57.9 μg/m³, though reductions were not statistically significant. TVOC showed the clearest improvement, falling significantly from 29.2 to 18.4 ppb (*p* < 0.01). Smoke-free policies substantially reduced indoor pollutants, particularly TVOC, in recreational facilities. While PM_{2.5} and NO₂ declines were less consistent, the results highlight both the benefits of smoke-free laws and the need for complementary interventions such as improved ventilation and continuous monitoring.

Keywords: Non-smoking policy, TVOC, Nitrogen dioxide, PM_{2.5}, billiard hall, screen golf range

Introduction

Tobacco smoke contains more than 7,000 chemicals and about 70 identified carcinogens [1]. These tobacco components include nicotine, 3-EP, respiratory dust, etc. as indicators representing the level of exposure to cigarette smoke caused by secondhand smoke (SHS) [2]. SHS refers to involuntary exposure to cigarette smoke and can cause a type of health effect similar to direct smoking [3]. SHS is associated with the development of neurological diseases including cardiovascular diseases and stroke, starting with respiratory diseases, which are the routes of exposure, including lung cancer [4-6]. One of the most widely used methods to reduce exposure to cigarette smoke from SHS in public places is the implementation of smoking cessation policies [7]. There have been reports of 86%-91% reduction in PM_{2.5} concentrations in the United States and Europe after smoking cessation policies were implemented in places such as restaurants, bars, and bowling alleys [8, 9].

Korea's policy on smoking cessation in public places is being implemented through the National Health Promotion Act. Article 9, Paragraph 4 of the National Health Promotion Act lists the facilities that should designate the entire facility as a non-smoking area and install a sign announcing the non-smoking area, including the Internet game room. This smoking cessation policy was gradually strengthened starting with the distinction between smoking and non-smoking areas in 2003, and from January 1, 2014, it included full-scale smoking cessation [10]. In the recent revision, Article 9, Paragraph 4 of the National Health Promotion Act included sports facilities installed indoors among sports facilities corresponding to the sports facility business, and this policy came into force from December 3, 2017. Among these indoor sports facilities, places where smoking has been frequent include indoor golf practice and billiard room businesses [10].

In Korea, studies on the effectiveness evaluation of public facilities in relation to smoking cessation policies have been conducted primarily in PC cafes and restaurants, with limited evaluation of other indoor public places. Exposure to these common indoor air pollutants, such as Total Volatile Organic Compounds (TVOC), can cause eye, nose, and throat irritation, headaches, and damage to various organs, while Nitrogen Dioxide (NO₂) is known to cause respiratory inflammation and exacerbate existing conditions like asthma and chronic obstructive pulmonary disease. Furthermore, Particulate Matter (PM_{2.5}), due to its small size, penetrates deeply into the lungs and is strongly linked to long-term cardiovascular and respiratory diseases, including lung cancer [11]. The purpose of this study is to evaluate the TVOC, NO₂,

PM_{2.5} concentration level before and after the smoking cessation policy was implemented for billiard halls and screen golf ranges in Seoul.

Materials and Methods

Facility types and monitoring design

The study targeted two categories of indoor leisure facilities prevalent in urban Korea: billiard halls and screen golf ranges. Both facility types are characterized by prolonged occupant stay times, limited natural ventilation, and potential pollutant sources such as tobacco smoke, building materials, and cleaning agents. Facilities were selected to represent typical small-to-medium-sized operations, with floor areas ranging from approximately 150 to 350 m², located in mixed-use commercial buildings. A total of three billiard halls and three screen golf ranges were monitored. To ensure a representative sample of indoor sports facilities in Seoul, a total of six venues—three billiard halls and three screen golf ranges—were selected from three distinct administrative districts within Seoul. The selection process was based on non-probabilistic sampling, targeting venues that were willing to participate in the quasi-experimental before-and-after monitoring study. The facilities were chosen to reflect the typical operational characteristics and size common to urban commercial areas in Seoul. The monitored facilities are considered representative of the general environment of similar indoor sports venues in the city. Measurements were conducted before and after the designation of non-smoking areas under the National Health Promotion Act, enabling a quasi-before-after comparative study design. Within each facility, sampling was performed at a central location in the main activity area, positioned away from direct ventilation outlets, windows, and localized pollutant-emitting appliances to ensure representative indoor air sampling. During each sampling session, TVOC, NO₂, and PM_{2.5} were measured concurrently using calibrated instruments (Table 1). Monitoring was performed over multiple days to account for operational variability and was conducted during typical business hours (14:00–22:00) to capture peak occupancy periods. In addition, outdoor temperature, relative humidity, and qualitative observations of occupant activity were recorded to aid in interpreting the variability of indoor pollutant levels.

Table 1. Measurement and analysis methods for target parameters.

	Sampler information	Method
TVOC	<ul style="list-style-type: none"> · Model: MP-Σ30 · Company: Sibata Co. · Manufactured in: Japan 	<ul style="list-style-type: none"> · Flow rate: 50-100 mL/min (once for 30 min) · Solid sorbent tube with gas chromatography-MS/FID
NO ₂	<ul style="list-style-type: none"> · Model: MEZUS-210, ANA-2 and M200E · Company: KEMIK Co., Total Engineering Co. LTD and Teledyne Technologies · Manufactured in: South Korea and USA 	<ul style="list-style-type: none"> · 60 min for each sampling point · Chemiluminescence method
PM _{2.5}	<ul style="list-style-type: none"> · Model: Grimm 1.108 · Company: Grimm Aerosol Technik GmbH & Co. KG · Manufactured in: Germany 	<ul style="list-style-type: none"> · Flow rate: 1.2L/min (6 hour) · Gravimetric continuous monitoring method

Sampling timeline in relation to smoke-free policy

To ensure a clear temporal relationship with the smoke-free policy, the sampling timeline was precisely structured. The policy mandating smoke-free indoor sports facilities, including billiard halls and screen golf ranges, officially took effect on December 3, 2017. The pre-designation (Before) sampling was conducted in a quasi-experimental design during September to November 2017, which was prior to the policy's effective date. The post-designation (After) sampling was subsequently conducted in September 2018, approximately 9 to 10 months after the policy implementation, thereby allowing adequate time for the policy to be fully enforced and for changes in smoking behavior and air quality to manifest.

Sampling and analysis

Indoor air quality measurements were conducted in selected billiard halls and screen golf ranges before and after the designation of non-smoking areas. Three target pollutants—TVOC, NO₂, and PM_{2.5}—were measured following standardized protocols. For TVOC, air samples were collected using a MP-Σ30 sampler (Sibata Co., South Korea) operated at a calibrated flow rate of 50–100 mL/min for a 30-minute period at each sampling location. Samples were captured in solid sorbent tubes and subsequently analyzed using gas chromatography. A split was made between the two detectors to fulfill both qualitative and quantitative requirements. A mass spectrometry (GC-MS) detector was employed for qualitative

analysis (identification) of individual VOC species and their semi-quantitative determination. Concurrently, a flame ionization detector (GC-FID) was used for the accurate quantification of the aggregate TVOC concentration. The FID provides a stable and reliable response proportional to the total carbon mass, which is critical for quantifying TVOCs against a standard equivalent. For the TVOC analysis, the total concentration was quantified using the GC-FID signal and expressed as toluene equivalent, a standard methodology in ambient air quality assessment. The TVOC measurement included more than 50 individual VOC species (including benzene, toluene, ethylbenzene, and xylene (BTEX)) ranging from C6 to C16, as determined by the initial GC-MS identification sweeps. The final TVOC concentration was calculated by summing the FID responses and converting the total area into a Toluene equivalent concentration (ppb). Rigorous quality assurance and quality control procedures were applied to both GC-MS and GC-FID analyses. Prior to analysis, all sampling tubes were conditioned with high-purity nitrogen. Calibration curves for both detectors were established using certified gas standards (e.g., Toluene for TVOC/FID; multi-component standards for individual VOCs/MS). Field blanks and laboratory blanks were analyzed for every batch of samples to ensure no cross-contamination. The Limits of Detection (LODs) were determined for all target compounds; the LOD for TVOC (Toluene Equivalent) via GC-FID was determined to be 1.0 ppb. For NO₂, measurements employed MEZUS-210 (KEMIK Co., South Korea), ANA-2 (Total Engineering Co. LTD, South Korea), and M200E (Teledyne Technologies, USA) instruments. Sampling was conducted for 60 minutes per site using the chemiluminescence method, in accordance with established atmospheric NO₂ monitoring standards. For PM_{2.5}, real-time monitoring was performed using a Grimm 1.108 aerosol spectrometer (Grimm Aerosol Technik GmbH & Co. KG, Germany) at a flow rate of 2–7 mL/min over a 6-hour continuous measurement period. The gravimetric continuous monitoring method was applied to ensure high temporal resolution and accuracy. All instruments were calibrated according to the manufacturers' specifications before deployment. Measurements were performed at breathing-zone height (1.2–1.5 m) and under typical operating conditions of the facilities. Environmental parameters, including indoor temperature and relative humidity, were concurrently recorded to support interpretation of pollutant variability.

Statistical analysis

Statistical analyses were performed using Python 3.11 (Python Software Foundation, Wilmington, DE, USA). Descriptive statistics, including the mean \pm standard deviation (SD), median, and range, were calculated for TVOC, NO₂, and PM_{2.5}, stratified by facility type and sampling period. The Shapiro–Wilk test was applied to assess data normality. Paired comparisons between pre- and post-designation measurements were conducted using the paired t-test for normally distributed variables or the Wilcoxon signed-rank test for non-normally distributed variables. The proportion of samples exceeding the Korean Ministry of Environment indoor air quality guidelines (NO₂: 60 $\mu\text{g}/\text{m}^3$; PM_{2.5}: 35 $\mu\text{g}/\text{m}^3$; no general TVOC standard) was compared using Fisher's exact test. All statistical tests were two-tailed, and a p-value < 0.05 was considered statistically significant.

Results

Table 2 presents the indoor air pollutant concentrations measured in billiard halls and screen golf ranges. For TVOC, the mean concentration was 23.8 ± 7.4 ppb, with a median of 17.5 ppb and a range of 12.0–40.0 ppb. NO₂ concentrations averaged 103.1 ± 175.4 $\mu\text{g}/\text{m}^3$, with a median of 35.7 $\mu\text{g}/\text{m}^3$ and a range of 3.4–838.1 $\mu\text{g}/\text{m}^3$. PM_{2.5} concentrations had a mean of 30.7 ± 25.1 $\mu\text{g}/\text{m}^3$, a median of 20.7 $\mu\text{g}/\text{m}^3$, and ranged from 5.1 to 119.8 $\mu\text{g}/\text{m}^3$.

Table 2. Level of indoor air pollutants and measurement results in parameterized form at billiard hall and screen golf range with temperature and relative humidity.

	No. of samples ^a	Mean \pm SD ^b	Median	Range	Temperature range (°C)	Relative humidity range (%)
TVOC (ppb)	12	23.8 \pm 7.4	17.5	12.0 – 40.0		
NO ₂ ($\mu\text{g}/\text{m}^3$)	12	103.1 \pm 175.4	35.7	3.4 – 838.1	18.1 – 30.8	25.7 – 52.6
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	12	30.7 \pm 25.1	20.7	5.1–119.8		

^a: The total sample size (n = 12) was derived from the monitoring design, which included six selected facilities (three billiard halls and three screen golf ranges) \times two sampling sites within each facility;

^b: Standard deviation

Measurements of TVOC, NO₂, and PM_{2.5} were conducted in three billiard halls and three screen golf ranges before and after the designation of non-smoking areas (Table 3). In billiard halls, mean ± SD concentrations were 22.9 ± 5.2 ppb for TVOC (range: 12.0–40.0 ppb), 154.9 ± 200.4 µg/m³ for NO₂ (3.4–838.1 µg/m³), and 29.1 ± 14.0 µg/m³ for PM_{2.5} (5.5–60.3 µg/m³). Against Korean Ministry of Environment 24-h guidelines (NO₂: 60 µg/m³; PM_{2.5}: 35 µg/m³; no general TVOC limit), exceedances occurred in 16.7 % of NO₂ samples and 66.7 % of PM_{2.5} samples; no TVOC exceedances were observed. In screen golf ranges, mean ± SD concentrations were 24.6 ± 4.3 ppb for TVOC (12.0–33.0 ppb), 51.3 ± 40.2 µg/m³ for NO₂ (15.6–166.3 µg/m³), and 32.4 ± 24.3 µg/m³ for PM_{2.5} (5.1–119.8 µg/m³). No TVOC or NO₂ samples exceeded guideline values, whereas 16.7 % of PM_{2.5} samples exceeded the 35 µg/m³ limit.

Table 3. Overall levels of TVOC, NO₂, and PM_{2.5} (combined before and after policy implementation) in the billiard hall and screen golf range.

Facility ^a	No. of sample ^s _a	Pollutant (Unit)	Mean ± SD ^b	Range	Recommended criteria ^c	Samples exceeding recommended levels (%)
Billiard hall	4	TVOC (ppb)	22.9 ± 5.2	12.0 – 40.0	No official general indoor air standard; facility-specific limits may apply (~400 ppb in some cases)	Exceeded (0)
	4	NO ₂ (µg/m ³)	154.9 ± 200.4	3.4 – 838.1	24-h mean: 60 µg/m ³	Exceeded (25.0)
	4	PM _{2.5} (µg/m ³)	29.1 ± 14.0	5.5 – 60.3	24-h mean: 35 µg/m ³	Exceeded (50.0)
Screen golf range	4	TVOC (ppb)	24.6 ± 4.3	12.0 – 33.0	No official general indoor air standard; facility-specific limits may apply (~400 ppb in some cases)	Exceeded (0)
	4	NO ₂ (µg /m ³)	51.3 ± 40.2	15.6 – 166.3	24-h mean: 60 µg/m ³	Exceeded (0)
	4	PM _{2.5} (µg/m ³)	32.4 ± 24.3	5.1 – 119.8	24-h mean: 35 µg/m ³	Exceeded (25.0)

^a: Note on sample size: The n=4 represents the total number of samples (or measurement results used for the mean ± SD) reported for each facility category in this combined analysis. This sample size was derived from two measurements taken before the policy implementation and two measurements taken after the policy implementation for each facility category, resulting in 2 (Before) + 2 (After) = 4 samples total per pollutant per facility type; ^b: Standard deviation; ^c: Recommended criteria: Ministry of Environment, Korea

For the combined category of billiard halls and screen golf ranges, the mean ± SD concentration of TVOC decreased markedly from 29.2 ± 4.5 ppb (range: 21.0–40.0 ppb) before the designation of non-smoking areas to 18.4 ± 5.0 ppb (range: 12.0–29.0 ppb) after designation, a statistically significant difference (p < 0.01) (Table 4). Mean NO₂ concentrations declined from 148.3 ± 186.3 µg/m³ (range: 9.3–838.1 µg/m³) before designation to 57.9 ± 54.2 µg/m³ (range: 3.4–188.8 µg/m³) afterward; however, this reduction was not statistically significant (p > 0.05). Similarly, PM_{2.5} levels decreased from 42.8 ± 29.4 µg/m³ (range: 6.9–119.8 µg/m³) to 18.6 ± 8.8 µg/m³ (range: 5.1–33.9 µg/m³) following the policy implementation, but the change did not reach statistical significance (p > 0.05).

Fig. 1 presents the mean concentrations of TVOC, NO₂, and PM_{2.5} in billiard halls and screen golf ranges before and after the designation of non-smoking areas. For TVOC, both facility types exhibited a marked reduction after designation, with mean levels decreasing from 28.9 ppb to 17.9 ppb in billiard halls and from 30.5 ppb to 18.8 ppb in screen golf ranges. NO₂ concentrations were initially higher in billiard halls (245.7 µg/m³) compared to screen golf ranges (66.3 µg/m³). After designation, these levels declined to 72.3 µg/m³ and 48.2 µg/m³, respectively, with a greater relative reduction observed in billiard halls. Similarly, PM_{2.5} concentrations decreased following designation in both facility types, from 36.8 µg/m³ to 20.5 µg/m³ in billiard halls and from 48.6 µg/m³ to 16.7 µg/m³ in screen golf ranges.

Table 4. Levels of TVOC, NO₂, and PM_{2.5} in the billiard hall and screen golf range.

Facility	No. of samples ^a	Pollutant (Unit)	Before the designation of non-smoking areas		After the designation of non-smoking areas		P value
			Mean ± SD ^b	Range	Mean ± SD ^b	Range	
Billiard hall and screen golf range	12	TVOC (ppb)	29.2 ± 4.5	21.0–40.0	18.4 ± 5.0	12.0–29.0	< 0.01
	12	NO ₂ (µg/m ³)	148.3 ± 186.3	9.3–838.1	57.9 ± 54.2	3.4–188.8	> 0.05
	12	PM _{2.5} (µg/m ³)	42.8 ± 29.4	6.9–119.8	18.6 ± 8.8	5.1–33.9	> 0.05

^a: Note on sample size: The reported n = 12 represents the total number of individual data points used for the statistical comparison in each time period (Before/After). This was derived from monitoring six facilities in total (three billiard halls and three screen golf ranges). Therefore, the overall statistical comparison was based on 6 facilities × 2 time points = 12 points used for the paired analysis; ^b: Standard deviation

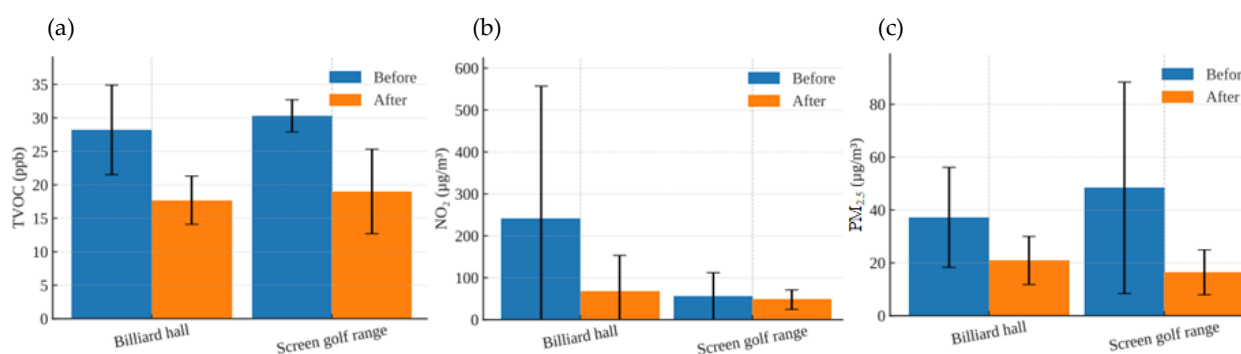


Figure 1. Concentrations of air pollutants measured before and after the designation of non-smoking areas in indoor sports facilities (billiard halls and screen golf ranges). (a) TVOC concentrations; (b) NO₂ concentrations; (c) PM_{2.5} concentrations. Error bars indicate the Standard Deviation (SD) of the mean.

Discussion

The analysis of indoor air pollutants in billiard halls and screen golf ranges prior to and following the designation of non-smoking areas revealed distinct patterns across different pollutants. Although the mean concentrations of TVOC in both facility types (Table 3) were well below the Korean Ministry of Environment's reference value for certain indoor facilities (~400 ppb), the observed ranges indicate substantial variability. This variability supports previous findings by Jang et al., [12] who reported that TVOC levels in hospitality environments can fluctuate considerably depending on ventilation conditions, occupant density, and smoking behaviors, even when official ventilation standards such as ASHRAE 62-1989 are met. In contrast, NO₂ levels in billiard halls before the implementation of non-smoking regulations averaged 148.3 ± 186.3 µg/m³, with a wide range (9.3–838.1 µg/m³), and 16.7 % of samples exceeded the Korean 24-h mean guideline value of 60 µg/m³ [13]. This contrasts with post-designation measurements (Table 3), which showed a reduction and no samples exceeding the guideline, suggesting that smoking bans can effectively lower NO₂ exposure. Meanwhile, PM_{2.5} concentrations decreased in both settings after the designation. However, despite the reductions, the proportion of PM_{2.5} samples exceeding the 24-h Korean standard of 35 µg/m³ [13-16] remained notable in both facility types. These results highlight that while policy interventions can significantly reduce certain pollutant levels, comprehensive measures, including improved ventilation and continuous monitoring, are essential to meet stringent indoor air quality targets.

The results in Table 3 indicate distinct patterns of indoor air pollutant concentrations between billiard halls and screen golf ranges. TVOC levels in both facility types were considerably lower than the facility-specific limits sometimes applied in Korea (~400 ppb), suggesting that active smoking was not the sole determinant of VOC burden. Instead, these compounds are likely influenced by multiple non-tobacco sources, including building and furnishing materials, adhesives, cleaning products, and emissions from human activity. Such findings are consistent with earlier studies showing that VOC concentrations can vary widely depending on ventilation efficiency, occupancy rates, and indoor activities [17, 18].

The combined analysis of billiard halls and screen golf ranges revealed a substantial decline in TVOC concentrations from 29.2 ± 4.5 ppb before the designation of non-smoking areas to 18.4 ± 5.0 ppb afterward, representing a

statistically significant reduction ($p < 0.01$) (Table 4). This magnitude of decrease is consistent with previous findings showing that smoking bans in hospitality and recreational venues can effectively reduce indoor VOC levels by limiting emissions from environmental tobacco smoke (ETS) and related sources [18, 19]. The significant reduction in TVOC directly reflects the elimination of combustion byproducts, including specific volatile organic compounds and potentially semi-volatile organic compounds (such as polycyclic aromatic hydrocarbons, PAHs) associated with tobacco smoke particles. Given the lack of a specific South Korean regulatory standard for TVOC, the significance of this finding for policymakers lies in the observed relative change, which provides conclusive evidence that the policy successfully eliminated a major source of VOC pollution. Policymakers can interpret this result as strong validation for continued enforcement and use the post-intervention level as a baseline for future indoor air quality management. Although mean NO_2 levels decreased from $148.3 \pm 186.3 \mu\text{g}/\text{m}^3$ to $57.9 \pm 54.2 \mu\text{g}/\text{m}^3$ after implementation, the change was not statistically significant ($p > 0.05$). Similar non-significant reductions have been observed in other post-ban studies, suggesting that factors such as outdoor infiltration, combustion appliances, and traffic-related emissions may limit the effect of smoking restrictions on NO_2 concentrations [13]. Likewise, $\text{PM}_{2.5}$ levels decreased from $42.8 \pm 29.4 \mu\text{g}/\text{m}^3$ to $18.6 \pm 8.8 \mu\text{g}/\text{m}^3$, but without statistical significance ($p > 0.05$). While several studies have reported significant $\text{PM}_{2.5}$ declines after smoking bans [14], our findings indicate that in some facilities, additional particulate sources—such as cooking, heating, and infiltration from outdoor air—may attenuate the measurable impact of policy interventions.

Fig. 1 illustrates the mean \pm SD concentrations of TVOC, NO_2 , and $\text{PM}_{2.5}$ measured in billiard halls and screen golf ranges before and after the designation of non-smoking areas. Among the pollutants, TVOC exhibited the most substantial and statistically significant reduction; however, the considerable overlap in standard deviations indicates pronounced inter-facility variability. This heterogeneity is likely attributable to differences in ventilation system design and operation, maintenance practices, occupant density, and the contribution of non-smoking-related VOC sources such as cleaning agents, air fresheners, and off-gassing from building materials [20, 21]. The reduction in NO_2 concentrations did not reach statistical significance, which may be explained by its multiple sources. Beyond environmental tobacco smoke (ETS), indoor NO_2 levels can be substantially affected by outdoor infiltration from vehicular emissions, emissions from gas-fired appliances, and seasonal variations in ventilation rates [22, 23]. These findings suggest that smoking bans alone are insufficient to ensure compliance with NO_2 guidelines, and that additional measures—such as source elimination, enhanced ventilation strategies, and improved filtration—are required. For $\text{PM}_{2.5}$, mean concentrations decreased following policy implementation; however, substantial inter-facility variability persisted. The high $\text{PM}_{2.5}$ levels measured prior to the policy implementation were primarily attributed to active indoor smoking, which generates significant amounts of particulate matter. After the policy, residual $\text{PM}_{2.5}$ concentrations were likely sustained by other facility-specific and environmental factors, including the generation of chalk dust from billiard cues and particle resuspension due to vigorous human movement, as well as the infiltration of outdoor air pollution, particularly fine dust, as these facilities typically do not utilize open-flame cooking or heating equipment. The continued occurrence of exceedances after the smoking ban highlights the necessity for a comprehensive indoor air quality (IAQ) management approach that integrates smoking restrictions with broader environmental and operational controls [24]. Overall, the results indicate a consistent reduction in pollutant concentrations across all measured parameters after the implementation of non-smoking policies, with the most pronounced improvements observed for TVOC and $\text{PM}_{2.5}$.

This study has several limitations that should be considered when interpreting the findings. First, the sample size for both billiard halls and screen golf ranges was relatively small, which may limit the statistical power and generalizability of the results. Specifically, the findings should be interpreted cautiously as reflecting the immediate impact of the policy within the monitored facilities, and they may not fully represent the heterogeneity of ventilation or operational practices across all similar venues in Seoul. Future studies with a larger, more representative sample size across different regions and facility sizes would be necessary to establish broader generalizability. Second, measurements were conducted during a single season, precluding assessment of seasonal variability in pollutant concentrations; previous research has shown that factors such as heating practices, reduced ventilation rates in cold weather, and seasonal outdoor air quality changes (which strongly influence indoor NO_2 and $\text{PM}_{2.5}$ levels) can cause substantial seasonal fluctuations in indoor air pollutants. Third, a significant limitation lies in the uncontrolled nature of potential confounding factors. Although pollutant levels were measured before and after the policy, we did not perform a detailed, quantitative characterization of mechanical ventilation system parameters (e.g., air exchange rate or airflow) or collect quantitative data on occupant density or activity levels. Consequently, several potential confounders—including heterogeneity in ventilation effectiveness, changes in occupant-driven particle resuspension, cleaning practices, building maintenance, and influence from nearby outdoor pollution sources—were not systematically controlled, which may have attenuated or masked the true impact of the smoking restrictions on air quality. Finally, while the study focused on TVOC, NO_2 , and $\text{PM}_{2.5}$, other relevant indoor pollutants (e.g., CO, formaldehyde, ultrafine particles) were not measured, limiting the comprehensiveness of indoor air quality assessment. Furthermore, the aggregate nature of the TVOC measurement prevented the speciation and quantification of individual volatile compounds, thereby limiting our ability to conclusively identify which specific tobacco smoke constituents

contributed most to the observed overall reduction. Future studies with larger sample sizes, year-round monitoring, and broader pollutant coverage are warranted to validate and expand upon these findings.

Conclusions

This study evaluated indoor air quality in billiard halls and screen golf ranges, focusing on TVOC, NO₂, and PM_{2.5} concentrations before and after the designation of non-smoking areas. The results demonstrated a statistically significant reduction in TVOC levels following the policy implementation, suggesting that smoking-related emissions are a major source of VOCs in these venues. While reductions in NO₂ and PM_{2.5} concentrations were also observed, these changes were not statistically significant, indicating that other sources—such as outdoor infiltration, combustion appliances, cooking activities, and resuspension of settled particles—continue to influence indoor pollutant levels. These findings underscore the effectiveness of smoking bans in reducing certain indoor pollutants, particularly VOCs, but also highlight the need for comprehensive indoor air quality management strategies that include improved ventilation, source control, and regular maintenance. Future research efforts are warranted to fully address the limitations of this study and develop more robust, evidence-based interventions. Expanding pollutant monitoring to include additional chemical and particulate species is also essential to characterize the full health impact. We specifically prioritize the inclusion of ultrafine particles defined as particles smaller than 0.1 µg, as they are a more sensitive marker for ETS combustion than PM_{2.5}, and carbon monoxide, a robust marker that would help differentiate between the pollutant contributions of smoking and vehicular emissions. Such comprehensive monitoring, combined with year-round, multi-season data collection and systematic control of ventilation parameters, is essential to definitively quantify the long-term effectiveness of smoke-free policies in complex urban environments.

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Conflict of interest

No potential conflict of interest was reported by the authors.

CRedit author statement

SH H: Writing – original draft, Visualization, Resources, Funding acquisition, Conceptualization. P, WM: Writing – review & editing, Project administration.

ORCID

Sung Ho Hwang : 0000-0002-2304-719X

Wha Me Park: 0000-0002-7499-0663

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