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Effect of indoor air quality on potential risk of obstructive sleep apnea: results from Korea National Health and Nutrition Examination Survey

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Abstract

Background Using nationally representative data from the 2020–2021 Korea National Health and Nutrition Examination Survey, we examined associations between indoor air pollutant exposure and potential obstructive sleep apnea (OSA) risk, estimated by STOP-BANG questionnaire scores.

Methods We included 1,501 participants who completed the STOP-BANG questionnaire and consented to in-home air quality measurements per Korea's Indoor Air Quality (IAQ) standards. Data were weighted for national representativeness, and multivariate logistic regression models identified determinants of potential OSA risk with adjusted odds ratios and 95% confidence intervals.

Results From our adjusted model, odds ratios (95% CI) for OSA risk with a unit increase in age were 1.07 (1.05–1.09) for men and 1.04 (1.01–1.07) for women, respectively. The ratios with systolic blood pressure were 1.05 (1.03–1.06) and 1.01 (0.99–1.02), and those with body mass index (BMI, Kg/m²) were 1.12 (1.01–1.24) and 1.08 (0.95–1.22) respectively. Unit increase in indoor formaldehyde (HCHO) exposure raised OSA risk by 1.02 (1.00–1.02) fold in men, after controlling for socioeconomic and behavioural factors as well as other common indoor pollutants (CO₂, PM_{2.5} and Toluene) and outdoor PM_{2.5}. No significant association was obtained from women's data.

Conclusions Our study found a potential association between elevated indoor HCHO levels and increased OSA risk in men. These findings highlight the importance of indoor air quality in OSA prevention, supporting the future development of more effective prevention models and interventions.

Keywords Obstructive sleep apnea, Indoor air quality, Formaldehyde, South Korea

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Background

Obstructive sleep apnea (OSA) is a prevalent sleep disorder characterized by repeated interruptions in breathing, affecting approximately one billion people globally, especially those aged 30–65 years [1]. This widespread condition significantly contributes to healthcare demands and costs. In South Korea, 15.8% of the population is estimated to be at high risk of OSA [2]. A recent survey found that approximately one-fifth of respondents were at high risk, although few had undergone medical intervention, underscoring a gap in awareness and management [3]. Despite these implications, regulatory frameworks or guidelines for identifying the determinants of OSA risk are limited [4] previous studies have reported that sociodemographic factors, such as age, sex, and obesity, and environmental factors, including air pollution, were positively associated [5–7].

The relationship between outdoor air pollution and sleep health has been extensively studied over the years. For instance, several epidemiological studies have reported the effects of exposure to ambient PM_{2.5} and PM₁₀ on sleep disorders, particularly among children and young adults, including university students [8–11]. Recent studies have also provided additional insights. Parks et al. [12] observed that interquartile range (IQR) increases in light-at-night (LAN) intensity and SO₂ levels were associated with a 1.07-fold (95% CI: 1.03–1.11) and 1.04-fold (95% CI: 1.02–1.07) increase, respectively, in the odds of reporting insufficient sleep duration. Similarly, Zhang et al. [13] reported that traffic-related ambient black carbon exposure was positively associated with impaired sleep quality. Individuals in the highest quartile of black carbon exposure had a 1.26-fold (95% CI: 1.11–1.43) increased risk of poor sleep quality compared with those in the lowest quartile, even after adjusting for potential confounders.

However, research on the effects of indoor air pollution on sleep health remains limited globally [7, 14]. Most previous studies have primarily focused on the long-term effects of ambient air pollutants, leaving a notable gap in understanding the impact of short-term exposure to indoor air pollutants on sleep health.

Given that people spend a significant amount of time indoors, variations in indoor air quality (IAQ) may have distinct regional effects on health. However, there are limited data on how the IAQ influences the risk of obstructive sleep apnea (OSA), particularly across diverse geographic and cultural contexts. This study aimed to address this gap by exploring the association between indoor air quality and OSA risk, adjusting for socioeconomic status and behavioral factors, using nationally representative data from South Korea.

Methods

Study design

This cross-sectional study used data from the 2020–2021 Korean National Health and Nutrition Examination Survey (KNHANES). Among the 1,980 participants with available IAQ measurements, individuals aged ≥ 40 years who had completed the STOP-BANG questionnaire ($n = 1,501$) were included in the analysis.

Data collection from KNHANES: health outcome

The Korea Centres for Disease Control and Prevention (KCDC) conducts the KNHANES annually using a nationally representative sample selected through stratified and cluster random sampling. Stratified sampling accounts for sex and age, whereas multi-stage cluster sampling considers geographic residence based on household registries. KNHANES data were collected through three surveys: health interviews, health examinations, and nutritional surveys. Health interviews and examinations were conducted at mobile examination centers. All participants provided written informed consent before participation. For this study, a subset of KNHANES data was used without direct participant contact. The KCDC follows the Personal Information Protection Act and Statistics Act and supplies only deidentified data to ensure anonymity. These data are available for academic research via approval by KNHANES office through the KNHANES website (<https://knhanes.cdc.go.kr/knhanes/main.do>).

Data collection from KNHANES: indoor air quality

We used indoor air pollutant concentration data measured at each participant's home, as provided by the Korea National Health and Nutrition Examination Survey (KNHANES) for 2020–2021. Indoor pollutants were measured in a living room following the testing protocols and standards outlined in Korea's Indoor Air Quality Control Act (Article 5, Mandatory Standards for Maintaining Indoor Air Quality). The targeted pollutants included particulate matter which has less than 2.5 μm as aerodynamic diameter (PM_{2.5}), carbon dioxide (CO₂), formaldehyde (HCHO), and volatile organic compounds such as benzene and toluene. PM_{2.5} concentrations were measured by a 24-hour filter-based methodology using a mini-volume sampler (KMS-4100, KEMIK), with subsequent gravimetric analysis. CO₂ levels were determined using a non-dispersive infrared spectrometer (IQ-610Xtra, GRAYWOLF). HCHO was collected through a 2,4-dinitrophenylhydrazine cartridge coupled with an ozone scrubber and analyzed using liquid chromatography (LC/MS2030-Plus, Shimadzu). Benzene and toluene concentrations were assessed using solid thermal desorption

tubes (Tenax TA), followed by gas chromatography-mass spectrometry (GC/MS-QP2020 with TC-20, Shimadzu) [15]. The method detection limits (MDL) for HCHO, benzene, and toluene were 0.0004 $\mu\text{g}/\text{m}^3$, 0.0005 $\mu\text{g}/\text{m}^3$, and 0.0008 $\mu\text{g}/\text{m}^3$, respectively. Gravimetric analyzer for PM_{2.5} and gas analyzer for CO₂ do not have MDLs provided. Further details on the sampling and analysis methodologies are available in the sampling guideline [15].

STOP-BANG score

The gold standard for diagnosing OSA is laboratory-based polysomnography, which is often inconvenient and costly [16]. According to a recent review, moderate and severe OSA can be detected using a STOP-BANG questionnaire score of ≥ 3 , with sensitivities of 93% and 100%, respectively [17]. The STOP-BANG tool includes four self-reported items (STOP: snoring, daytime tiredness, observed apnea, and treatment for hypertension) and four demographic items (BANG: BMI $\geq 35 \text{ kg}/\text{m}^2$, age > 50 years, neck circumference ≥ 16 inches, and male sex). Based on validation test results for the global population [17].

Additionally, in a validation study conducted by Jeon et al. in 2019 [15], the diagnostic accuracy among three well known obstructive sleep apnea (OSA) screening questionnaires, i.e., Berlin Questionnaire (BQ), STOP-BANG Questionnaire, and Four-Variable Screening Tool (Four-V)—was assessed in a Korean community sample, the STOP-BANG questionnaire demonstrated the largest area under the receiver operating characteristic (ROC) curve for both overall OSA (0.752) and moderate to severe OSA (0.750), making it a useful screening tool for OSA.

In this study, according to the global definition of severity, we categorized STOP-BANG scores of 3–4 as indicating moderate OSA (corresponding to apnea-hypopnea index, AHI ≥ 15 of clinical version) and scores of 5–8 as indicating severe OSA (AHI ≥ 30 of clinical version), while scores of 0–2 indicated low OSA risk [15, 16].

Statistical analysis

This study employed a cross-sectional design. Survey weights for the KNHANES indoor air data set were applied to enhance statistical power and account for the complex sampling design [18]. A chi-square test was conducted to compare the proportions (%) of participants across three OSA risk groups—low (0–2), moderate (3–4), and severe (5–8)—based on the STOP-BANG questionnaire (snoring, tiredness, observed apnea, hypertension, BMI, age, neck circumference, and gender) and categorical variables such as monthly income (low, low-mid, mid, mid-high, and

high) and education status (elementary, middle, high school, and university or higher).

We also compared proportions of participants by smoking status (everyday, sometimes, former, non-smoker, and “don’t know” based on lifetime smoking amounts) and monthly drinking frequency (none over last one year, < 1 , 3, 6, 10, ≥ 16 times, “never drink”, “don’t know”) We also compared level of secondhand smoking exposure at home (yes/no) using KNHANES database. Differences in the distributions of the continuous variables (age, systolic blood pressure [mmHg], BMI [kg/m^2], and neck circumference [inches]) among the three OSA risk groups were assessed using the Kruskal-Wallis test.

The distribution of indoor air pollutants—including indoor and outdoor PM_{2.5}, indoor carbon monoxide, formaldehyde (HCHO), benzene, and toluene—designated as monitoring targets under Korea’s Indoor Air Quality Act (Article 5), was presented across the three OSA risk groups.

To identify the association between exposure to indoor air pollutants and OSA risk, multivariate logistic regression models were used, adjusting for demographic characteristics, socioeconomic status (SES), and behavioral factors. Recognizing that OSA is influenced by systolic blood pressure, body mass index (BMI), age, neck circumference, and gender, we included these demographic variables to account for potential confounding effects. SES was evaluated using participants’ educational attainment and monthly household income levels as provided by the KNHANES dataset. Behavioral factors included daily smoking amount, secondhand smoke exposure, and monthly drinking status [19].

In our logistic regression analysis, the binary dependent variable was defined as OSA risk groups (STOP-BANG score of 3–8) versus the low-risk group (STOP-BANG score of 0–2) according to previous validation study for Korean [15] and for other global population [16]. Independent variables representing indoor air pollutants were initially analyzed as continuous variables, centred around their median value [20].

Three models were constructed for our logistic regression analysis. The first model had continuous variables of indoor air pollutants and demographic characteristics. The second and third model evaluated the association after further controlling for SES and behavioral factors on top of SES, respectively. Indoor benzene was excluded from our models due to its substantial number of missing values and its relatively high correlation with indoor toluene ($r = 0.608$).

Variance inflation factors (VIF) for each variable in the model ranged from 1 to 6, indicating no collinearity

issues. Statistical analyses were performed using SAS software (SAS Institute Inc., Cary, NC, USA), with a two-sided significance level of 0.05.

Ethical consideration

The KNHANES was approved by the Institutional Review Board (IRB) of the KCDC and conformed to the principles of the Declaration of Helsinki, revised in 2000. The KNHANES data used in this study are public, but the identities of all respondents remain anonymous. The study protocol was exempt from the research ethics review process of the Soonchunhyang University Research Ethics Review Committee. Ethical approval for this study was waived by the IRB of Soonchunhyang University in accordance with the waiver reason “research using information open to the general public” (no. SCH-2024-08-002).

Results

Proportion of participants according to potential OSA risk level evaluated using the STOP-BANG questionnaire

Our weighted frequency analysis indicated a relatively higher proportion of positive responses (“Yes”) for most STOP-BANG variables such as snoring, tiredness, observed apnea, high blood pressure (doctor-diagnosed), age (> 50 years), neck circumference (> 16 inches), and male sex, except BMI, in the moderate (score: 3–4) and severe (score: 5–8) OSA risk groups than in the low risk group (score: 0–2). Male participants were more predominant in the severe (92.0%) and moderate (66.7%) risk groups than in the low-risk group (30.8%) ($p < 0.05$) (Table 1).

Demographic and socioeconomic characteristics according to potential OSA risk group

Our weighted frequency analysis indicated a relatively higher proportion of positive responses (“Yes”) for most STOP-BANG variables such as snoring, tiredness, observed apnea, high blood pressure (doctor-diagnosed), age (> 50 years), neck circumference (> 16 inches), and male sex, except BMI, in the moderate (score: 3–4) and severe (score: 5–8) OSA risk groups than in the low risk group (score: 0–2). Male participants were more predominant in the severe (92.0%) and moderate (66.7%) risk groups than in the low-risk group (30.8%) ($p < 0.05$) (Table 1).

Demographic and socioeconomic characteristics according to OSA risk group

In our study, the geometric mean (GM) and 95% confidence interval (95% CI) of age was higher in both the moderate (63.9, (62.6–65.2) years) and severe (61.4, (59.4–63.5) years) OSA groups compared to the low OSA group (57.1, (56.0–58.3) years). The GM and

Table 1 Number and proportion of participants by STOP-BANG questionnaire and demographic and socioeconomic characteristics according to potential OSA risk group										
Variable	Response	Overall		Low (0–2) J		Moderate (3–4) J		Severe (5–8) J		Rao Chi p-value L: M:H
		n = 1,501* 26,119,883**	%	n = 946 (63.0%) 15,579,102	%	n = 482 (32.1%) 8,343,679	%	n = 73 (4.9%) 1,197,102	%	
Snoring	Yes	288	20.4	53	6.7	176	38.3	59	79.6	<0.001
Tiredness (day time)	Yes	432	30.5	157	17.6	222	44.8	53	73.7	<0.001
Observed apnea	Yes	131	9.3	15	2.0	74	14.7	42	63.0	<0.001
Hypertension	Yes	618	41.2	221	22.5	337	70.8	60	79.3	<0.001
BMI: >35 kg/m ²	Yes	6	0.4	1	0.1	3	0.6	2	1.8	<0.001
Age: >50 years	Yes	1144	76.2	638	65.1	438	88.8	68	93.0	<0.001
Neck: >16 inches	Yes	88	5.9	14	1.5	41	10.5	33	43.7	<0.001
Gender (men)	Yes	673	44.8	285	30.8	320	66.7	68	92.0	<0.001

J Potential OSA risk group (low, moderate and severe) was based on STOP-BANG screening scores (0–2, 3–4, and 5–8, respectively)
* number of samples before weighting, ** number of samples after weighting

95% CI of BMI was also higher in the moderate (24.7, (24.4–25.0) kg/m²) and severe (26.9, (25.9–28.0) kg/m²) OSA groups than in the low OSA group (23.3, (23.1–23.5) kg/m²) ($p < 0.05$).

Furthermore, the GM and 95% CI of neck circumference in the moderate and severe OSA groups was approximately one and two inches greater, respectively, than in the low OSA group (13.3, (13.2–13.4) inches) ($p < 0.05$). Additionally, the GM and 95% CI of systolic blood pressure in both the moderate (127.8, (126.1–129.4) mmHg) and severe (127.5, (123.6–131.5) mmHg) OSA groups was significantly higher ($p < 0.05$) than in the low OSA group (117.8, (116.6–119.0) mmHg) (Table 2).

Household income was categorized into five levels (low, low-middle, middle, middle-high, and high) as defined by K-NHANES. The moderate and severe OSA risk groups had significantly higher proportions of participants in the low and low-middle income brackets (22.2% and 24.1%; 19.0% and 36.8%, respectively) compared to the low OSA risk group (13.1% and 20.6%) ($p < 0.05$) (Table 2).

Regarding educational attainment (elementary, middle, high school, and university), the distribution was similar between the low and severe OSA risk groups. However, the moderate OSA risk group showed significantly lower educational levels ($p < 0.05$) (Table 2).

The proportions of both current daily smokers and former smokers were higher in the moderate (18.3% and 36.4%) and severe (22.0% and 62.9%) OSA risk groups than in the low OSA risk group (9.5% and 19.5%) ($p < 0.05$). Moreover, the proportion of frequent drinkers (≥ 16 drinking occasions per month) was significantly higher in the moderate (8.1%) and severe (15.9%) OSA risk groups than in the low OSA risk group (4.9%) ($p < 0.05$) (Table 2).

Distribution of concentration of indoor air pollutants

We calculated the geometric means (GM) with 95% CIs for indoor PM_{2.5}, outdoor PM_{2.5}, indoor CO₂, indoor HCHO, indoor benzene, and toluene across different potential OSA risk groups, stratified by STOP-BANG scores (low [0–2], moderate [3–4] and severe [5–8]).

The GM and 95% CI of indoor PM_{2.5} were higher in the moderate and severe group (14.3, (13.1–15.6) $\mu\text{g}/\text{m}^3$ and 14.3, (12.0–17.1) $\mu\text{g}/\text{m}^3$) than in the low OSA risk group (13.5, (12.7–14.4) $\mu\text{g}/\text{m}^3$) but it was not statistically significant ($p = 0.0583$). In contrast, outdoor PM_{2.5} levels were comparable among the three groups (15.1, (13.8–16.5) $\mu\text{g}/\text{m}^3$ for low; 15.3, (13.9–16.8) $\mu\text{g}/\text{m}^3$ for moderate; 16.0, (13.8–18.6) $\mu\text{g}/\text{m}^3$ for severe) ($p = 0.6659$) (Table 3). Concentrations of indoor CO₂, HCHO, benzene, and toluene did not show significant differences among the three OSA risk groups

(p -values: 0.7153 for CO₂, 0.2736 for HCHO, 0.3309 for benzene, and 0.2923 for toluene).

Odds ratio (95% CI) for OSA risk with a unit increase in demographic factors and indoor air quality level

Logistic regression models were used to assess the association between indoor air pollutant exposure levels and OSA risk. Table 4 presents the final associations between demographic characteristics, indoor air quality, and OSA risk by comparing the crude and adjusted models. The final adjusted model (Model 3) incorporated adjustments for socioeconomic status (monthly household income and education level) and behavioural factors (daily smoking amount, second-hand smoke exposure, and monthly amount of alcohol consumption). Figure 1 shows the association between indoor air pollutant exposure and OSA risk across three models: Model 1 (demographic characteristics and indoor air pollutants as independent variables), Model 2 (adjusted for SES), and Model 3 (further adjusted for both SES and behavioural factors).

In the final adjusted model (Model 3), traditional OSA risk factors, including age (centered at 60 years), high blood pressure (centered at 120 mmHg), elevated BMI (centered at 24.0 kg/m²), neck circumference (centered at 13.5 inches), and male sex, remained statistically significant association with an increased risk of OSA.

Our final adjusted model demonstrated that unit increase in exposure level to HCHO elevated the OSA risk by 1.02 (95 CI: 1.003–1.029) fold among male participants. These associations remained robust after adjusting for socioeconomic status (monthly household income and education level) and behavioural factors (daily smoking amount, second-hand smoke, and monthly alcohol consumption) (Fig. 1).

Discussion

Our study investigated the association between potential OSA risk, calculated using the STOP-BANG questionnaire scores [16], and the exposure level to indoor air pollutants using a nationally representative database in South Korea. Our study found that male participants who exposed to indoor HCHO had highly susceptible for increase of OSA risk even after controlling for traditionally well known demographic, socioeconomic and behavioral factor; unit increase in exposure level to HCHO elevated the OSA risk by approximately 2% (95 CI: 0.3–2.9%).

A large volume of previous studies have reported an association between exposure to ambient air pollution and the risk of OSA. For example, A Taiwanese study by Shen et al. [21] reported that an interquartile range (IQR) increase of 3.4 $\mu\text{g}/\text{m}^3$ in the 1-year

Table 2 Summaries of demographic, socioeconomic and behavioral characteristics according to potential OSA risk group

Variable	Percentile	Overall			Low (0–2)			Moderate (3–4)			Severe (5–8)			Kruskal-Wallis P-value (L: M:S)
		Estimate	95% CI		Estimate	95% CI		Estimate	95% CI		Estimate	95% CI		
Age (years)	Geometric Mean	59.4	58.3	60.5	57.1	56.0	58.3	63.9	62.6	65.2	61.4	59.4	63.5	<0.001
	P25	49.4	47.6	51.2	46.5	45.3	47.7	57.2	55.1	59.2	54.7	51.3	58.2	
	P50	60.6	59.3	61.9	57.8	55.9	59.6	65.4	63.3	67.6	61.6	59.1	64.1	
	P75	70.5	69.4	71.6	68.2	66.5	69.9	72.6	71.6	73.6	67.9	64.3	71.5	
Body Mass Index (Kg/m ²)	Geometric Mean	23.9	23.7	24.1	23.3	23.1	23.5	24.7	24.4	25.0	26.9	25.9	28.0	<0.001
	P25	21.8	21.5	22.0	21.4	21.0	21.7	22.8	22.3	23.2	24.8	23.7	25.9	
	P50	24.0	23.8	24.2	23.3	23.0	23.7	24.7	24.3	25.1	26.7	25.4	27.9	
	P75	26.2	25.9	26.5	25.5	25.2	25.9	27.1	26.7	27.6	29.7	28.2	31.1	
Neck circumference (in)	Geometric Mean	13.7	13.7	13.8	13.3	13.2	13.4	14.3	14.2	14.5	15.5	15.2	15.8	<0.001
	P25	12.7	12.6	12.8	12.4	12.4	12.5	13.4	13.2	13.7	14.5	14.1	15.0	
	P50	13.6	13.5	13.7	13.1	13.0	13.2	14.5	14.3	14.6	15.8	15.2	16.3	
	P75	14.7	14.6	14.8	14.1	14.0	14.2	15.2	15.0	15.4	16.3	16.1	16.6	
Systolic Blood Pressure (mmHg)	Geometric Mean	121.4	120.3	122.5	117.8	116.6	119.0	127.8	126.1	129.4	127.5	123.6	131.5	<0.001
	P25	110.7	109.7	111.7	107.8	106.4	109.2	116.9	115.3	118.5	118.6	114.6	122.6	
	P50	120.6	119.3	121.9	116.5	115.1	117.8	126.8	125.1	128.4	127.3	123.3	131.4	
	P75	132.1	130.8	133.4	128.5	126.1	130.9	137.6	134.8	140.4	136.8	131.9	141.8	
		N	%		N	%		N	%		N	%		Rao Chi P-value (L: M:S)
Monthly income level	Low	265	16.3		145	13.1		105	22.2		15	19.0		<0.001
	Low mid	334	22.5		197	20.6		116	24.1		21	36.8		
	Mid	287	20.0		183	21.0		91	18.8		13	15.4		
	Mid-high	287	19.3		200	21.5		76	15.9		11	12.7		
Educational attainment	High	321	21.9		216	23.8		92	19.0		13	16.1		<0.001
	Elementary	350	22.8		198	20.1		138	27.9		14	21.1		
	Middle	178	12.3		91	11.2		77	14.4		10	11.1		
	High	414	31.4		262	32.8		129	29.0		23	30.4		
Smoking status	University	474	33.5		310	35.9		138	28.6		26	37.4		<0.001*
	Everyday	189	12.9		88	9.5		83	18.3		18	22.0		
	Sometimes	25	1.8		17	2.0		8	1.9		0	.		
	Former	396	26.8		172	19.5		178	36.4		46	62.9		
	Nonsmoker	885	58.2		663	68.7		213	43.4		9	15.1		
	Don't know	6	0.3		6	0.4		0	.		0	.		
SHS	Yes	36	2.6		28	3.2		8	1.7		0	.		<0.0001

Table 2 (continued)

Variable	Percentile	Overall		Low (0–2)		Moderate (3–4)		Severe (5–8)		Kruskal-Wallis P-value (L: M:S)
		Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	
Monthly Drinking Frequency (Times)	None over last 1 year	352	23.5	207	22.6	127	24.9	18	29.1	<0.0001*
	<1	230	15.3	167	17.3	59	12.4	4	6.2	
	3	123	8.2	85	8.5	34	8.0	4	6.5	
	6	291	19.4	180	20.0	96	18.9	15	18.7	
	10	172	11.5	90	10.2	65	15.5	17	19.1	
	≥ 16	89	5.9	40	4.9	39	8.1	10	15.7	
	Never drink	238	15.9	171	16.1	62	12.2	5	4.7	
	Don't know	6	0.4	6	0.4	0		0		

SHS: secondhand smoke at home, * obtained from the test conducted without those group answered "Don't know" and/or "Never drink"

mean PM_{2.5} concentration was associated with a 2.5% increase in the oxygen desaturation index (ODI) and a 4.7% increase in the apnea-hypopnea index (AHI). Billings et al.'s [6] multi-ethnic study, which included participants with an average age of 68 years, 48% of whom had sleep apnea and 25% had a sleep efficiency of $\leq 88\%$, demonstrated that individuals with higher annual NO₂ and PM_{2.5}, exposure levels had greater odds of developing sleep apnea. Cheng et al. [22] found that PM₁₀, ozone, sulfur dioxide, and relative humidity were significantly associated with apnea-hypopnea index (AHI) in patients with severe obstructive sleep apnea. Lappharat et al. [23] also reported that a unit increase in the 1-year mean bedroom PM₁₀ concentration was significantly associated with a 4% increase in AHI ($p < 0.021$) in a cohort of 63 participants enrolled for overnight polysomnography.

Some of recent studies have reported the effects of IAQ on sleep disorders. For example, a study conducted in Sweden by Silverforsen et al. suggested that exposure to home air pollution was associated with a higher prevalence of snoring [24]. Liao et al. reported that a decrease in subjectively rated sleep problems occurred with a decrease in perceived IAQ levels among participants in Denmark [25]. In addition, studies in Belgium by Fan et al. [26] and in China by Kang et al. (2023) [27] demonstrated that elevated indoor CO₂ levels were associated with poor sleep quality, whereas Strom-Tejsen et al. reported that lower CO₂ levels correlated with improved sleep quality in Denmark [28].

Model 1, which accounted for IAQ and demographic variables, and Model 2, which additionally controlled for SES, both indicated a significant positive odds ratio ($p < 0.05$) for OSA risk per one-unit increase in indoor PM_{2.5}. However, in Model 3—further adjusted for both behavioral factors and SES—the odds ratio was no longer statistically significant. Although these findings suggest that indoor PM_{2.5} may be a potential risk factor for OSA, it was not deemed as significant as HCHO, which demonstrated consistently robust associations regardless of how confounding factors were controlled. Furthermore, because of methodological differences between this study and previous ones [21, 22]—such as sampling locations and methods—we did not conduct further discussion on the effect of PM_{2.5} on OSA.

To the best of our knowledge, this is the first study to report the association between elevated indoor formaldehyde (HCHO) levels and the risk of obstructive sleep apnea (OSA) in men, even after accounting for other commonly detected indoor air pollutants, such as PM_{2.5}, CO₂, and toluene, as potential confounders

Table 3 Comparison of GM with 95% CI of air pollutant concentrations according to potential OSA risk group

	Overall			Low (0–2)			Moderate (3–4)			Severe (5–8)			p-value
	Estimate	95% CI		Estimate	95% CI		Estimate	95% CI		Estimate	95% CI		
Indoor PM2.5 (µg/m³)	GM	13.8	13.0	14.7	12.7	14.4	14.3	13.1	15.6	14.3	12.0	17.1	0.0583
	P25	9.0	8.3	9.6	8.2	9.5	9.1	8.2	10.1	9.8	8.3	11.4	
	P50	12.6	11.6	13.6	11.5	13.5	12.9	11.6	14.2	13.6	10.5	16.6	
	P75	19.8	17.7	21.8	17.0	21.3	19.9	17.6	22.1	22.7	18.0	27.3	
CO ₂ (ppm)	GM	712.5	681.2	745.2	684.0	750.6	708.8	671.6	748.0	683.4	616.8	757.1	0.7153
	P25	514.7	495.3	534.2	492.5	541.4	511.5	487.0	535.9	503.7	469.2	538.2	
	P50	660.9	612.2	709.6	664.5	714.4	655.2	595.6	714.8	590.9	522.2	659.6	
	P75	937.3	890.2	984.5	943.7	990.8	909.1	835.7	982.6	835.4	681.6	989.1	
HCHO (µg/m³)	GM	20.1	18.7	21.5	20.2	21.9	20.2	18.5	22.0	17.0	14.2	20.4	0.2736
	P25	12.3	11.3	13.3	12.6	11.5	12.2	10.9	13.5	10.4	7.5	13.2	
	P50	20.1	18.5	21.7	20.3	22.1	20.2	17.8	22.6	16.4	12.1	20.7	
	P75	33.0	29.5	36.5	32.7	36.4	35.1	31.1	39.1	30.4	23.0	37.7	
Benzene (µg/m³)	GM	2.7	2.3	3.1	2.7	3.2	2.6	2.1	3.3	2.6	1.8	3.7	0.3309
	P25	1.3	1.0	1.6	1.3	1.6	1.3	0.7	1.8	1.5	0.9	2.1	
	P50	2.6	2.3	2.9	2.6	2.9	2.6	2.2	3.1	2.3	1.0	3.5	
	P75	4.7	3.7	5.6	4.6	5.7	5.0	3.7	6.3	4.7	2.1	7.3	
Toluene (µg/m³)	GM	10.5	9.4	11.9	10.4	11.7	11.2	9.5	13.2	8.5	6.1	12.0	0.2923
	P25	5.1	4.5	5.8	5.2	5.9	5.3	4.3	6.3	3.9	2.5	5.2	
	P50	10.0	8.4	11.5	10.4	12.1	9.7	7.9	11.4	7.6	5.4	9.9	
	P75	21.5	17.8	25.2	21.1	25.3	22.6	17.2	28.0	15.8	3.5	28.1	
Outdoor PM2.5 (µg/m³)	GM	15.2	14.0	16.5	15.1	16.5	15.3	13.9	16.8	16.0	13.8	18.6	0.6659
	P25	10.4	9.4	11.4	10.4	11.4	10.1	8.9	11.2	10.7	9.0	12.4	
	P50	15.0	13.6	16.3	14.7	16.1	15.2	13.3	17.1	15.7	13.2	18.2	
	P75	22.3	19.0	25.7	22.5	26.0	22.1	18.4	25.7	22.8	16.9	28.6	

GM, geometric means; CI, confidence interval;; HCHO, formaldehyde; OSA, obstructive sleep apnea; PM, particulate matter
p-value from Kruskal-Wallis test

on top of socioeconomic, behavioral and demographic confounders.

Formaldehyde (HCHO) is one of the most prevalent indoor air pollutants originating from various sources including carpets, paint, and construction materials [29, 30]. As a sensory irritant, HCHO adversely affects the respiratory tract by compromising airway epithelial integrity and function, which can lead to airway narrowing or blockage and breathing difficulties. These effects are particularly concerning in the context of conditions like obstructive sleep apnea (OSA) [31, 32]. Our findings align with those of the previously proposed mechanisms. Liu et al. [7] highlighted how pollutants can damage respiratory cells, trigger inflammation that restricts airflow and increases the risk of apnea, ultimately disrupting the sleep cycle. Similarly, Castaneda et al. [33] suggested that air pollutants may worsen OSA by contributing to adenotonsillar hypertrophy.

Sleep health is an important aspect of human life and OSA is one major health concerns in sleep health. OSA not only causes sleep disturbances and nighttime gasping for air but also leads to acute daytime effects such as sleepiness and loss of focus, as well as chronic impacts on cardiovascular and other related health conditions. This study highlighted the need for improved IAQ management to mitigate the risk of OSA. Controlling IAQ, particularly HCHO levels, may substantially enhance sleep quality by controlling other traditional OSA risk factors. Future studies should explore these relationships in detail, including other potential environmental risk factors, such as light or noise, to develop effective public health strategies.

Although this study used nationally representative data, it had several limitations that warrant consideration. First, its cross-sectional nature implies the potential for an inverse causal relationship, necessitating caution in the interpretation. Additionally, the measurement of IAQ conducted in the living room rather than in the bedroom and at a single or limited time point as a standard process of the KNHANES may not fully reflect its dynamic nature, which is influenced by seasonal variation. Because indoor air investigators operated a filter-based PM2.5, sampler connected to a low-volume pump for 24 h as a federal reference methodology, they could not avoid the noise produced by the pump. Due to this issue, the KNHANES indoor air quality investigator could not install the device in the living room and bedroom, so as not to interfere with the participant's daily sleeping condition.

The authors also acknowledge that the Korea National Health and Nutrition Examination Survey (KNHANES) employs active sampling methods for indoor air quality (IAQ) assessments, as recommended by the Korean Indoor Air Quality Control Act. This approach assumes that indoor air quality exhibits less temporal variability than outdoor air pollution. Previous studies have shown that outdoor pollutants, such as PM2.5, can vary substantially across seasons, whereas indoor levels tend to remain more stable [34].

Relying on a single year database of KNHANES may not fully capture the complexities of long-term exposure. Measuring indoor air quality (IAQ) is undeniably important; however, it demands significant time spent at participants' homes and substantial financial resources. Currently, the 2020–2021 KNHANES

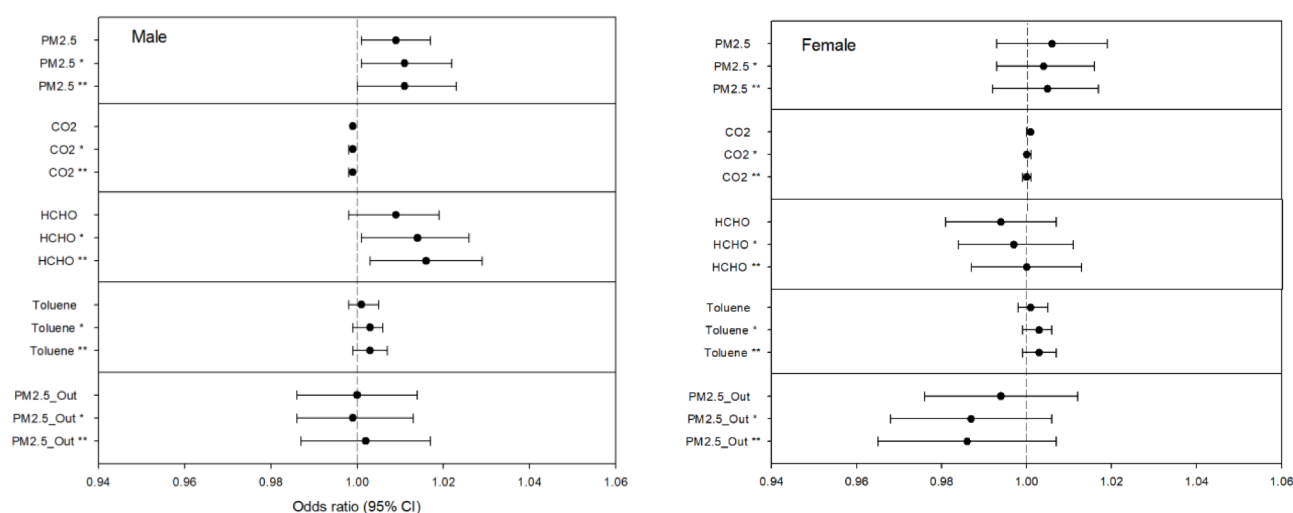


Fig. 1 Association of OSA risk with unit increases in exposure to indoor air pollutants (PM2.5, CO2, formaldehyde [HCHO], and toluene) and outdoor PM2.5. Results were obtained from multivariate logistic regression models under three adjustment levels: (1) Model including indoor air pollutants and demographic characteristics. (2) Model further adjusted for socio-economic status (household income level and education level) (*). (3) Model additionally adjusted for behavioral factors (daily smoking and monthly alcohol consumption) on top of socio-economic status (**)

Table 4 Logistic regression on effect of indoor air pollutants on OSA risk after controlling for demographic factors (gender, age, systolic blood pressure, body mass index, and neck circumference), socio-economic status (monthly household income level and education level) and behavioural factors (daily smoking level, daily second-hand smoke exposure and monthly drinking level)

	Crude model			Adjusted model*					
	Overall		Male	Female		Male	Female		
	OR	95% CI		OR	95% CI		OR	95% CI	
Indoor PM2.5–13 (µg/m ³)	1.006	1.000	1.013	1.004	0.996	1.012	1.006	0.994	1.017
CO ₂ – 700 (ppm)	1.000	1.000	1.000	0.999	0.999	1.000	1.000	1.000	1.001
HCHO – 20 (µg/m ³)	1.001	0.994	1.007	1.003	0.994	1.013	0.998	0.987	1.010
Toluene – 10 (µg/m ³)	1.001	0.999	1.004	1.001	0.997	1.005	1.001	0.997	1.005
Outdoor PM2.5–15 (µg/m ³)	1.002	0.993	1.010	1.001	0.988	1.014	1.000	0.984	1.016

* controlling for demographic factors (gender, in case of overall, age, systolic blood pressure, body mass index, neck circumference), socio-economic status (monthly household income level and education level) and behavioral factors (daily smoking level, daily second-hand smoke exposure, and monthly drinking level)

database is the only dataset that provides IAQ information for participants’ of national survey program. Due to the COVID-19 pandemic, the Korea CDC had to suspend IAQ measurements after 2020–2021 term, which are expected to resume in 2025 or 2026. Authors sincerely hope that the K-NHANES team will prioritize restarting IAQ measurements in the near future, ideally as part of a long-term monitoring initiative.

Future research incorporating real-time IAQ monitoring over extended periods could provide a more comprehensive understanding of both acute and chronic environmental effects on sleep health. Longitudinal data could improve the precision of exposure assessments and their correlations with health outcomes.

Moreover, the KNHANES indoor air quality measurement database does not contain information on the details of ventilation conditions for bedrooms during indoor air sampling. Although the distribution (GM, 95% CI) of CO₂ concentrations were not statistically significantly different ($p=0.7153$) among OSA risk groups (716, (684.0~750.6) ppm for low (0–2); (708.8 (671.6~748.0) ppm for moderate (3–4); (683.4 (616.8~757.1) ppm for severe (5–8) $p=0.7153$), it is important to note that detailed information on ventilation conditions during the sampling period would be valuable. This would help develop strategies to optimize ventilation volume and frequency for better sleep, potentially reducing HCHO and PM_{2.5} concentrations.

Future research should consider these limitations and strive for more comprehensive data, including ventilation and air conditioning, and temporally extensive data collection methods, such as the application of air-monitoring sensors, to enhance the strength and generalizability of the findings. The authors understand that the KNHANE indoor air measurement methodology fully relies on the active sampling methods recommended by the Korean indoor air monitoring law. However, if real-time data from sensors were incorporated, it would be helpful to understand the acute effects of variations in environmental conditions on sleep health.

Conclusions

Our study found a potential association between exposure to increased level of indoor HCHO and OSA risk using nationally representative data. This result did not change after adjusting for demographic socioeconomic statuses and behavioral factors. Our findings provide potential insights into more advanced research and robust evidence regarding the effects of IAQ and other environmental factors on the risk of OSA, leading to effective preventive measures and interventions.

Ultimately, this will enhance our ability to mitigate the effects of environmental factors, especially indoors, on potential OSA risk or develop an upgraded model to predict or control its severity.

Abbreviations

µg/m ³	Micrograms per Cubic Meter (unit of concentration)
AHI	Apnea-Hypopnea Index
BMI	Body Mass Index
CI	Confidence Interval
CO ₂	Carbon Dioxide
GM	Geometric mean
HCHO	Formaldehyde
IAQ	Indoor Air Quality
IRB	Institutional Review Board
KCDC	Korea Centers for Disease Control and Prevention
mmHg	Millimeters of Mercury (unit of pressure)
NO ₂	Nitrogen Dioxide
OR	Odds Ratio
OSA	Obstructive Sleep Apnea
PM10	Particulate Matter with a diameter of 10 micrometers or smaller
PM2.5	Particulate Matter with a diameter of 2.5 micrometers or smaller
Q1	First Quartile
Q3	Third Quartile
SES	Socioeconomic Status
STOP-BANG	Snoring, Tiredness, Observed Apnea, high blood Pressure, Body mass index, Age, Neck circumference, Gender (a screening tool for OSA)
VOC	Volatile Organic Compounds

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12889-025-22127-2>.

Supplementary Material 1

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Author contributions

Conceptualization: SK, BG, and KY; methodology: SK, KY, and ML; software: SK, BG, CS, and MK; validation: SK and KY; formal analysis: SK, BG, and KY; resources: SK and BG; writing—original draft preparation: SK and BG; writing—review and editing: SK, KY, ML, CL, and AR; visualization: MK and CS; supervision: SK. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The KNHANES was approved by the Institutional Review Board (IRB) of the Korea Disease Control and Prevention Agency, which confirmed the principles of the Declaration of Helsinki, revised in 2000. The study protocol was exempt from the research ethics review process of the Soonchunhyang University Research Ethics Review Committee. Ethical approval for this study was waived by the IRB of Soonchunhyang University in accordance with the waiver reason “research using information open to the general public” (no. SCH-2024-08-002). All participants provided written informed consent before participating

in the KNHANES. The identities of all respondents remained anonymous even though the dataset was public.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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