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ORIGINAL ARTICLE

# Long-Term Exposure to Outdoor Air Pollutant Mixture and Cardiovascular Health Assessed by the American Heart Association's Life's Essential 8 Metric in Korean Adults

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***Background:*** Outdoor air pollutants are known to have adverse health impacts, but knowledge of the relationship between exposure to air pollutant mixtures and cardiovascular health (CVH) remains limited.

***Methods and Results:*** We examined the association of air pollutant mixtures with CVH using the American Heart Association's Life's Essential 8 (LE8), which is based on 4 health behaviors and 4 biometric health factors. Data from a nationally representative sample of 27,763 adults were analyzed. One-year moving average concentrations of $PM_{10}$, $PM_{2.5}$, $SO_2$, $NO_2$, CO, and $O_3$ were estimated through air pollution modeling. CVH was evaluated using LE8 scores (range 0–100), with higher scores indicating superior CVH. The association of a 1-quantile increment in air pollutant mixture with the expected change in LE8 score was evaluated using Quantile g-computation. The mean LE8 score in study participants was 63.7. In the adjusted model, a 1-quantile increment in air pollutant mixture was linked to a 1.67-point (95% confidence interval −2.18, −1.16) decrease in LE8 score. CO, $O_3$, $PM_{2.5}$, and $NO_2$ accounted for 43.7%, 28.7%, 23.9%, and 3.7%, respectively, of the inverse association of the air pollutant mixture with the overall LE8 score.

***Conclusions:*** Our study revealed that long-term exposure to outdoor air pollutants is associated with poor CVH, suggesting the need for supporting policy interventions to reduce air pollutant levels and mitigate their health impacts.

**Key Words:** Air pollution; Air quality; Cardiovascular health; Mixture analysis; Particulate matter

The adverse health impacts of outdoor air pollutants are well documented.[1–3] In 2019, the World Health Organization (WHO) reported that 99% of the global population lived in regions where air quality did not meet its recommended standards, contributing to an estimated 4.2 million premature deaths.[4] South Korea also faces a substantial health burden from air pollution.[5] For example, long-term exposure to outdoor particulate matter smaller than 2.5 $\mu$m ($PM_{2.5}$) was estimated to contribute to approximately 6.4% of all deaths in the country,[6] and this burden is expected to rise due to rapid population aging.[7]

Promoting cardiovascular health (CVH) requires addressing both behavioral factors, including physical activity and sleep, and cardiometabolic biomarkers, including blood glucose and blood pressure.[8–12] The American Heart Association (AHA) has proposed the Life's Essential 8 (LE8) to evaluate CVH using 4 health behaviors and 4 cardiometabolic biomarkers.[13] Rather than evaluating these components in isolation, LE8 emphasizes a comprehensive approach to CVH assessment and serves as a tool for stratifying cardiovascular disease (CVD) risk at the population level. LE8 scores have been inversely associated with the risks of both all-cause and CVD mortality in prospective studies conducted in the US and South Korea.[14–16] Therefore, LE8 can be regarded as a validated measure that reflects an individual's CVH status.

Previous research has established a link between exposure to outdoor air pollutants and elevated CVD risk. Long-term $PM_{2.5}$ exposure is linked to ischemic heart disease and stroke.[17–19] In addition, exposure to air pollutants is associated with poor cardiometabolic profiles, such as hypertension, diabetes, and obesity, which may contribute to the development of CVDs.[20] Health behaviors also play a role in modifying the effects of air pollution on CVDs.[21] High ambient pollution levels have been associated with reduced physical activity and shorter sleep duration.[22,23] Evidence from a large administrative dataset indicates that exposure to high concentrations of air pollutants is linked

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**Long-term exposure to outdoor air pollutant mixture and cardiovascular health assessed by the American Heart Association's "Life's Essential 8" metric: A study of Korean adults**

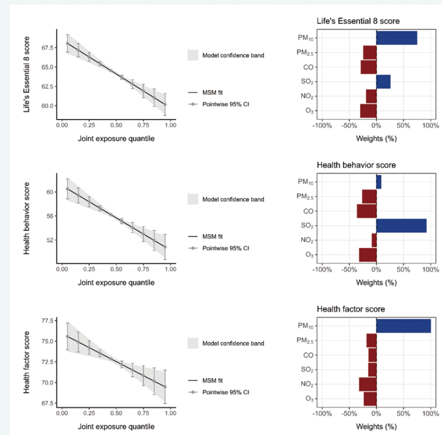
**Background**

- The burden of air pollutants has been a major public health concern globally.
- Recently, the American Heart Association introduced "Life Essential 8" (LE8) metric that encompasses four health behaviors (diet, physical activity, nicotine exposure, sleep health) and biometric factors (BMI, blood lipids, blood glucose, blood pressure).

**Methods**

**Data:** Nationwide sample of Korean adults (n=27,763)
**Design**: Cross-sectional study
**Measurements**: One-year moving average concentrations of $PM_{10}$, $PM_{2.5}$, $SO_2$, $NO_2$, CO, and $O_3$
**Outcomes**: Cardiovascular health measured by the LE8 score
**Statistical analysis**: Quantile G-computation method

**Results**




**Conclusions** Long-term exposure to outdoor air pollutants is associated with poor cardiovascular health status

**Central Figure**

to increased cigarette smoking and drinking, and reduced exercise.[24]

Although most studies have evaluated the impacts of individual air pollutants, people are exposed to complex mixtures of air pollutants that may have synergistic or additive effects on health. There is increasing recognition of the importance of studying multipollutant exposure to better reflect real-world conditions.[25,26] In addition, although much research has examined individual CVH risk factors, few studies have assessed overall CVH using integrated metrics like LE8. Accordingly, this study examined the association between long-term exposure to a mixture of outdoor air pollutants and CVH, as evaluated by the LE8 metric.

## Methods

### Study Design

The study sample was obtained from the Korea National Health and Nutrition Examination Survey (KNHANES), a cross-sectional study administered annually by the Korean government.[27] A nationally representative sample of South Korean residents was selected each year using a multistage clustered probability sampling method.[27] For the selected households, trained personnel conducted face-to-face interviews and health examinations via mobile health examination vehicles. The response rate for the survey ranged from 71.0% to 74.1% during the study period.[28]

Because all survey items and laboratory tests for the LE8 assessment were implemented starting in 2014, we used data from the 2014 to 2019 KNHANES cycles; 31,525 individuals aged >18 years participated during this period. After the exclusion of observations with missing values, data from 27,763 adults were included in the present study.

The data used in this study are available at https://knhanes.kdca.go.kr/. All participants provided written informed consent. The study protocol was approved by the Institutional Review Board of Yonsei Health System (4-2024-0675).

### LE8 Score

CVH was quantified using the LE8 score, which incorporates 4 health behaviors (diet, physical activity, nicotine exposure, and sleep health) and 4 biometric factors (body mass index [BMI], blood lipids, blood glucose, and blood pressure). The scoring system followed guidelines from the AHA.[13] The specific operationalization of the scoring system is detailed in **Supplementary Table 1**. Diet status was assessed using the Korean Healthy Eating Index. Physical activity was assessed based on the Global Physical Activity Questionnaire, covering leisure time and occupational- and transportation-related physical activity. Nicotine exposure included current and former smoking status, the use of alternative tobacco products, and exposure to secondhand smoke. Sleep health was determined by the self-reported average daily sleep duration. BMI was determined based on the measured weight and height. Blood lipid levels were assessed using non-high-density lipoprotein cholesterol levels and the use of lipid-lowering drugs. Blood glucose levels were evaluated based on HbA1c levels and the use of oral antidiabetic drugs or insulin. Blood pressure was measured at rest and included information on the use of antihypertensive medications.

Each component was scored on a scale of 0–100, with a higher score indicating better CVH. The composite LE8 score was calculated as the mean of all 8 component scores (range 0–100). Participants were then classified into CVH categories of low (0–49), intermediate (50–79), and high

**Table 1.  Participant Characteristics**

| | All participants (n=27,763) | Cardiovascular health categories[A] | | |
|---|---|---|---|---|
| | | High (n=6,624) | Intermediate (n=16,493) | Low (n=4,646) |
| **LE8 score** | 63.7±14.0 | 81.6±5.3 | 62.6±6.9 | 42.1±6.2 |
| Health behavior score | 56.6±18.9 | 74.0±11.2 | 55.7±15.4 | 34.6±14.4 |
| Health factor score | 70.9±19.0 | 89.3±10.4 | 69.5±15.7 | 49.5±13.9 |
| **Sex** | | | | |
| Male | 11,691 (42.1) | 1,492 (22.5) | 7,254 (44.0) | 2,945 (63.4) |
| Female | 16,072 (57.9) | 5,132 (77.5) | 9,239 (56.0) | 1,701 (36.6) |
| Age (years) | 51.4±16.6 | 43.9±15.5 | 53.2±16.5 | 56.1±15.1 |
| **Region** | | | | |
| Urban | 22,581 (81.3) | 5,868 (88.6) | 13,280 (80.5) | 3,433 (73.9) |
| Rural | 5,182 (18.7) | 756 (11.4) | 3,213 (19.5) | 1,213 (26.1) |
| **Education level** | | | | |
| Middle school or below | 8,639 (31.1) | 996 (15.0) | 5,615 (34.0) | 2,028 (43.7) |
| High school | 9,023 (32.5) | 2,350 (35.5) | 5,263 (31.9) | 1,410 (30.3) |
| College or above | 10,101 (36.4) | 3,278 (49.5) | 5,615 (34.0) | 1,208 (26.0) |
| **Income[B]** | | | | |
| Lowest | 6,699 (24.1) | 1,297 (19.6) | 3,981 (24.1) | 1,421 (30.6) |
| Low | 6,954 (25.0) | 1,534 (23.2) | 4,209 (25.5) | 1,211 (26.1) |
| High | 7,047 (25.4) | 1,788 (27.0) | 4,142 (25.1) | 1,117 (24.0) |
| Highest | 7,063 (25.4) | 2,005 (30.3) | 4,161 (25.2) | 897 (19.3) |
| **Marital status** | | | | |
| Married | 19,563 (70.5) | 4,549 (68.7) | 11,803 (71.6) | 3,211 (69.1) |
| Unmarried | 4,407 (15.9) | 1,608 (24.3) | 2,295 (13.9) | 504 (10.8) |
| Other | 3,793 (13.7) | 467 (7.1) | 2,395 (14.5) | 931 (20.0) |
| **Employment status** | | | | |
| Employed | 16,645 (60.0) | 3,801 (57.4) | 9,889 (60.0) | 2,955 (63.6) |
| Unemployed | 11,118 (40.0) | 2,823 (42.6) | 6,604 (40.0) | 1,691 (36.4) |

Data are given as the mean ± SD or n (%). [A]Participants were classified into cardiovascular health categories based on LE8 scores in line with American Heart Association guidelines[14] as follows: low, 0–49; intermediate, 50–79; and high, 80–100. LE8, Life's Essential 8. [B]Income level was categorized into four groups based on the quartile values of the annual household income for each year.

**Table 2.  Pearson's Correlation Coefficients for Individual Air Pollutants**

| | Mean (±SD) concentration | Pearson's correlation coefficient | | | | | |
|---|---|---|---|---|---|---|---|
| | | $PM_{10}$ | $PM_{2.5}$ | CO | $SO_2$ | $O_3$ | $NO_2$ |
| $PM_{10}$ (μg/m$^3$) | 47.5±5.5 | 1 | | | | | |
| $PM_{2.5}$ (μg/m$^3$) | 23.1±3.3 | 0.78 | 1 | | | | |
| CO (ppb) | 466.3±69.5 | 0.53 | 0.30 | 1 | | | |
| $SO_2$ (ppb) | 4.3±1.9 | 0.40 | 0.26 | 0.18 | 1 | | |
| $O_3$ (ppb) | 29.5±6.5 | −0.49 | −0.33 | −0.61 | −0.27 | 1 | |
| $NO_2$ (ppb) | 25.7±10.6 | 0.55 | 0.11 | 0.71 | 0.27 | −0.78 | 1 |

For all coefficients, $P<0.001$. $PM_{2.5}$, particulate matter smaller than 2.5 μm; $PM_{10}$, particulate matter smaller than 10 μm.

(80–100) in line with the AHA guidelines.[13] In addition, subscores were calculated, namely a health behavior score (mean of the 4 behavior components) and a health factor score (mean of the 4 biometric health factor components); both these subscores ranged from 0 to 100. Previous research has demonstrated that the LE8 is inversely associated with the onset and mortality of CVD in both US and Korean populations,[14–16] thereby validating its effectiveness in assessing individual CVH.

## Air Pollutants

The concentrations of 6 air pollutants were estimated based on the Community Multiscale Air Quality model: particulate matter <10 μm ($PM_{10}$), $PM_{2.5}$, carbon monoxide (CO), sulfur dioxide ($SO_2$), ozone ($O_3$), and nitrogen dioxide ($NO_2$).[27] This model integrates meteorological and emission data, with meteorological inputs generated using the Weather Research and Forecasting model and emissions data from the Sparse Matrix Operator Kernel Emissions model.[27] Data assimilation techniques were used to improve the model's accuracy. The $PM_{10}$ and $PM_{2.5}$ concentrations were modeled at a 1-km spatial resolution, whereas gaseous pollutants were assessed at a 9-km grid resolution. Daily mean concentrations were calculated,

**Table 3. Linear Regression Models Examining Associations Between Air Pollutants and LE8 Scores Overall and for Its Subcomponents (Single-Pollutant Models)**

| Air pollutant | β (95% CI) | | |
|---|---|---|---|
| | LE8 score | Health behavior score | Health factor score |
| $PM_{10}$ (10 μg/m³) | −0.82 (−1.30, −0.34) | −1.30 (−2.05, −0.55) | −0.34 (−0.86, 0.18) |
| $PM_{2.5}$ (10 μg/m³) | −1.42 (−2.22, −0.63) | −2.65 (−3.89, −1.41) | −0.20 (−1.05, 0.65) |
| CO (100 ppb) | −1.02 (−1.46, −0.58) | −1.49 (−2.14, −0.84) | −0.55 (−1.05, −0.04) |
| $SO_2$ (1 ppb) | 0.02 (−0.09, 0.13) | 0.18 (0.03, 0.34) | −0.14 (−0.29, 0.00) |
| $O_3$ (10 ppb) | −0.08 (−0.55, 0.40) | −0.13 (−0.85, 0.58) | −0.02 (−0.60, 0.56) |
| $NO_2$ (10 ppb) | −0.30 (−0.65, 0.05) | −0.18 (−0.71, 0.34) | −0.41 (−0.80, −0.03) |

CI, confidence interval. Other abbreviations as in Tables 1,2.

**Table 4. Quantile G-computation Models Examining Associations Between Air Pollutant Mixtures and LE8 Scores Overall and for Its Subcomponents (Multipollutant Models)**

| | β (ψ) of mixtures (95% CI) | Coefficients | |
|---|---|---|---|
| | | Positive | Negative |
| **LE8 score** | | | |
| Air pollutant mixture[A] | −1.67 (−2.18, −1.16) | 0.069 | −1.740 |
| $PM_{10}$ | | 0.030 | |
| $PM_{2.5}$ | | | −0.417 |
| $SO_2$ | | 0.039 | |
| $NO_2$ | | | −0.064 |
| CO | | | −0.760 |
| $O_3$ | | | −0.499 |
| **Health behavior score** | | | |
| Air pollutant mixture[A] | −1.88 (−2.59, −1.17) | 0.727 | −2.610 |
| $PM_{10}$ | | | −0.249 |
| $PM_{2.5}$ | | | −0.577 |
| $SO_2$ | | 0.437 | |
| $NO_2$ | | 0.290 | |
| CO | | | −1.185 |
| $O_3$ | | | −0.598 |
| **Health factor score** | | | |
| Air pollutant mixture[A] | −1.45 (−2.15, −0.75) | 0.309 | −1.760 |
| $PM_{10}$ | | 0.309 | |
| $PM_{2.5}$ | | | −0.255 |
| $SO_2$ | | | −0.358 |
| $NO_2$ | | | −0.418 |
| CO | | | −0.331 |
| $O_3$ | | | −0.398 |

[A]Per 1-quantile increment in air pollutant mixture concentration. Abbreviations as in Tables 1–3.

and the model was validated against air quality monitoring station data.[27–29]

Air pollution estimates were linked to the KNHANES participants using their examination dates and residential addresses. Exposure was defined as the 1-year moving average of each pollutant concentration prior to the health examination date, calculated individually for each participant.[27]

## Statistical Analysis

The distribution of sample characteristics according to CVH category (low, intermediate, or high) was examined. Pearson correlation coefficients were calculated to examine interpollutant correlations.

For the single-pollutant model, we examined the association of each air pollutant with overall LE8, health behavior, and health factor scores using linear regression models. Models were adjusted for sociodemographic covariates, including sex, age (continuous scale), residential region (urban or rural), educational attainment (middle school or below, high school, college or above), income level (quartile, Q1–Q4), marital status (married, unmarried, others), economic activity (worker, unemployed), and survey years. In addition, the 1-year moving averages of relative humidity and temperature were adjusted as meteorological factors. Although we observed higher PM levels in winter and spring and peak $O_3$ levels in summer, which is consistent with previous Korean studies,[30,31] we used annual mean exposure estimates. This approach mitigated the influence of seasonal variation on exposure values. Furthermore, we observed a temporal trend of gradually decreasing pollutant concentrations over the study period, which was addressed through adjustment for survey year.

To account for the joint effects of multiple pollutants, we used Quantile g-computation (qgcomp) models, which estimate the change in the LE8 score associated with a simultaneous 1-quantile increase in all pollutants.[32] Effect sizes are presented as beta coefficients (β) and 95% confidence intervals (CIs). Survey weights were applied to enhance the generalizability of the findings. Analyses were conducted using R version 4.5.0 (R Foundation for Statistical Computing, Vienna, Austria), with qgcomp performed using the R package "qgcomp".[32]

## Additional Analyses

We conducted some additional analyses to assess the robustness of our results. First, qgcomp models with multinomial logistic regression were used to evaluate associations of air pollutant mixtures with CVH categories (low, intermediate, and high), and the results expressed as odds ratios (ORs) and 95% CIs. Second, multiple imputation via chained equations was performed to address missing data in the original dataset (n=31,525), generating 20 complete datasets. The qgcomp models were fitted to each dataset, and estimates were pooled. Multiple imputation was performed using the R package "mice".[33] Third, we compared the associations between each air pollutant and the outcome using 2-, 3-, 4-, and 5-year moving averages

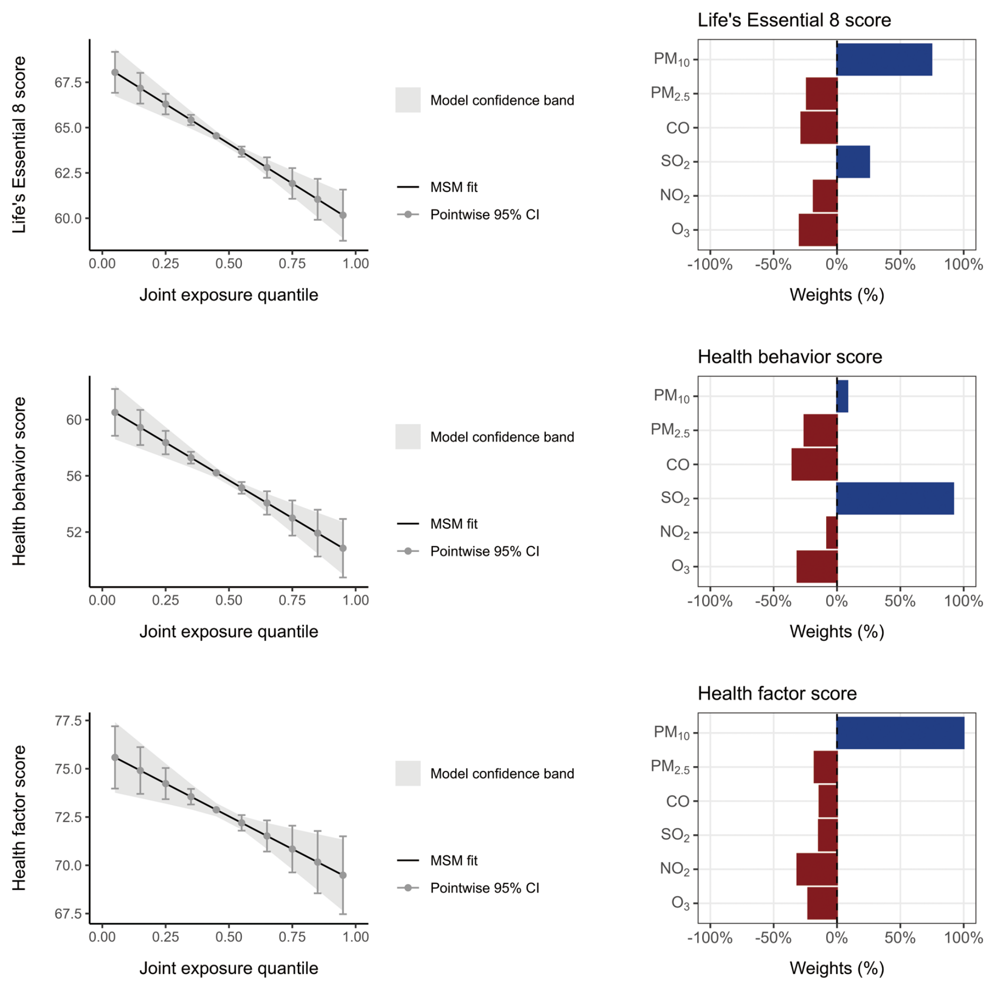



**Figure.** Results from the mixture analyses, showing relationships between Life's Essential 8 scores and exposure quantiles (**Left**) and the relative weights of air pollutants (**Right**). MSM, marginal structural model; $PM_{2.5}$, particulate matter smaller than 2.5 $\mu$m; $PM_{10}$, particulate matter smaller than 10 $\mu$m.

to examine how the associations varied across different exposure windows.

## Results

Among the samples, 23.9%, 59.4%, and 16.7% were categorized as having high, intermediate, and low CVH, respectively (**Table 1**). The mean scores for LE8, health behaviors, and biometric health factors were 63.7, 56.6, and 70.9, respectively. Compared with individuals with high CVH, those with low CVH were more likely to be male, older, less educated, and have lower incomes.

**Table 2** presents the 1-year moving averages and correlations of each air pollutant. The average concentrations were 47.5 $\mu$g/m$^3$ for $PM_{10}$, 23.1 $\mu$g/m$^3$ for $PM_{2.5}$, 466.3 ppb for CO, 4.3 ppb for $SO_2$, 29.5 ppb for $O_3$, and 25.7 ppb for $NO_2$. All pollutants were positively correlated with each other, except for $O_3$, which showed negative correlations with the others.

The results of the single-pollutant models are presented in **Table 3**. The adjusted $\beta$ coefficients for the associations between air pollutants and overall LE8 score were −0.82 (95% CI −1.30, −0.34) for $PM_{10}$, −1.42 (95% CI −2.22, −0.63) for $PM_{2.5}$, −1.02 (95% CI −1.46, −0.58) for CO, 0.02 (95% CI −0.09, 0.13) for $SO_2$, −0.08 (95% CI −0.55, 0.40) for $O_3$, and −0.30 (95% CI −0.65, 0.05) for $NO_2$. $PM_{10}$, $PM_{2.5}$, and CO were inversely associated with health behavior scores, whereas $PM_{10}$, CO, and $NO_2$ were inversely associated with health factor scores.

In the mixture analyses (**Table 4**), a 1-quantile increase in the air pollutant mixture was associated with a 1.67-point (95% CI −2.18, −1.16) decrease in the LE8 score, a 1.88-point (95% CI −2.59, −1.17) decrease in the health behavior score, and a 1.45-point (95% CI −2.15, −0.75) decrease in the health factor score.

The results of qgcomp models and the weights of each air pollutant are shown in the **Figure**. The associations between air pollutant mixtures and LE8 and its subcomponents exhibited a dose–response pattern, with higher levels of exposure linked to lower scores in both health behaviors and health factors. In addition, CO, $O_3$, $PM_{2.5}$, and $NO_2$ accounted for 43.7%, 28.7%, 23.9%, and 3.7%, respectively, of the negative association with the overall LE8 score. CO, $O_3$, $PM_{2.5}$, and $PM_{10}$ contributed 45.4%, 22.9%, 22.1%, and 9.5%, respectively, to the negative associations with health behavior scores. $NO_2$, $O_3$, $SO_2$, CO, and $PM_{2.5}$ contributed 23.8%, 22.6%, 20.3%, 18.8%, and 14.5%, respectively, to the negative associations with health factor scores.

As indicated in **Supplementary Table 2**, a 1-quantile increment in air pollutant mixture was associated with a 1.20-fold (95% CI 1.11, 1.31) increase in the odds of having intermediate CVH status and a 1.57-fold (95% CI 1.43, 1.73) increase in the odds of having low CVH status.

The results of sensitivity analyses using imputed datasets are presented in **Supplementary Table 3**; these analyses confirmed the inverse associations of the air pollutant mixture with the overall LE8 score ($\beta$ −1.73; 95% CI −2.59, −1.17), health behavior score ($\beta$ −1.97; 95% CI −2.69, −1.26), and health factor score ($\beta$ −1.49; 95% CI −2.22, −0.76).

**Supplementary Table 4** presents associations between 1- to 5-year moving average exposures and LE8, health behavior, and health factor scores. The results suggest that as the exposure window lengthens, the strength of the association between air pollutant exposure and LE8 score diminishes.

Finally, **Supplementary Table 5** presents associations between air pollutant mixtures and each LE8 component. Negative associations with exposure to air pollutant mixtures were most evident for physical activity, sleep health, BMI, and blood pressure.

## Discussion

This study investigated the association between outdoor air pollution and LE8 scores, demonstrating that long-term exposure to mixtures of air pollutants was linked to lower LE8 scores. Multipollutant analysis identified CO, $O_3$, and $PM_{2.5}$ as the contributors to the negative association with overall LE8 scores. Moreover, the relationship between air pollutant mixtures and LE8 followed a dose–response trend, whereby greater exposure levels were associated with lower scores across both health behaviors and health factors. These findings provide insights into the potential mechanisms by which exposure to air pollution may contribute to the development of CVDs, stressing the need for policy interventions to reduce air pollution and its health implications.

The findings of our study are consistent with those of previous studies. For example, long-term exposure to mixtures of outdoor air pollutants has been associated with an elevated risk of CVDs.[34–36] It has also been linked to cardiometabolic risk factors, including obesity,[37] diabetes,[38] and hypertension.[39] Although research examining the association between air pollutant mixtures and health behaviors is limited, some studies have shown that $PM_{2.5}$ concentrations are inversely associated with physical activity and sleep duration, and directly associated with smoking prevalence.[22–24] Overall, most previous studies indicate that chronic exposure to a mixture of outdoor air pollutants is linked to a poorer status across various components of the LE8, including both health behaviors and biomarkers.

Complex mechanisms may underlie the relationship between chronic exposure to combinations of air pollutants and low LE8 scores. First, oxidative stress and systemic inflammation are considered key mechanisms. Studies have demonstrated that exposure to air pollutants is linked to elevated circulating levels of inflammatory markers including C-reactive protein and interleukin-6.[40,41] Chronic inflammation induces metabolic dysfunction and contributes to impaired CVH.[42] In addition, chronic exposure to outdoor air pollutants may lead to structural changes in the heart and promote atherosclerosis, thereby increasing blood pressure.[43] Second, high levels of outdoor air pollutants may be associated with undesirable health behaviors. For example, ambient concentrations of $PM_{2.5}$ have been inversely associated with physical activity and sleep duration.[22,44] Furthermore, research suggests that exposure to air pollutants can increase airway resistance or induce neuroinflammation, potentially leading to sleep disturbances.[45] Chronic exposure to air pollutants has been associated with poor mental health, such as psychological distress, depressive symptoms, and anxiety,[46] which may serve as indirect pathways contributing to maladaptive behaviors such as nicotine use or poor dietary habits.[24] However, further investigations are needed to better understand these underlying mechanisms.

The associations between air pollutant mixtures and individual LE8 components varied across components. Notably, air pollutant mixture exposure was associated with poorer scores in the domains of physical activity, sleep duration, BMI, and blood pressure. Although the exact mechanisms are not fully understood, this may reflect the influence of air pollution on outdoor activity patterns, given the close relationship of these components with leisure-time physical activity. For example, high levels of air pollutants may reduce leisure-time physical activity, thereby contributing to increased BMI and elevated blood pressure, as well as poorer sleep quality.[47]

Although the negative association between air pollutant mixture exposure and LE8 was mostly preserved across exposure windows, the strength of the association weakened as the exposure window lengthened, as indicated in **Supplementary Table 4**. Several factors may explain this observation. First, components of LE8 may be more sensitive to recent concentrations of air pollutants, with diminishing influence as the temporal distance increases. Second, the possibility of increased misclassification over longer periods should be considered. For example, because our exposure estimates were based on residential addresses,[27] a longer exposure window is more susceptible to errors arising from residential mobility. Therefore, longer exposure windows may fail to adequately capture associations of air pollutants with LE8 components, contributing to an underestimation of the relationship.

This study has several limitations. First, we relied on cross-sectional data, which hinders our ability to assess the causal influence of air pollutants on LE8 components. Future longitudinal studies are needed to investigate the temporal relationship between air pollutant exposure and LE8 scores. Second, our analysis assumed that participants did not change their residential addresses in the year prior to the health examination, which may not have been accurate. Due to a lack of information, we could not account for participants' residential mobility, which may have introduced measurement error in estimating exposure. Therefore, more comprehensive residential history data are needed to improve the accuracy of cumulative exposure assessments. Third, the use of the Community Multiscale Air Quality model could not exclude the possibility of exposure misclassification. For example, factors such as residential mobility, time spent on indoor activities, and workplace exposures may contribute to inaccuracies in assessing air pollutant exposure.[48] Therefore, future research should incorporate individual-level activity tracking to improve the accuracy of exposure assessment. Fourth, we were unable to account for several factors. For example, potential residual confounding may arise from unmeasured variables such as family history of CVD, time spent on outdoor activities, indoor air pollution (e.g., cooking smoke), and traffic-related or occupational exposures, due to the lack of available information.

Nevertheless, our study has several notable strengths. We used validated and objective measurements of both health behaviors and biomarkers to enhance the accuracy of outcome assessment. In addition, the analyses of a nationally representative sample strengthen the generalizability of our findings.

## Conclusions

The results of this study indicate that long-term exposure to outdoor air pollutant mixtures is associated with poor CVH, as measured by the AHA's LE8 framework. Although future longitudinal studies are required to confirm a causal relationship, this study suggests that exposure to a mixture of outdoor air pollutants may be associated with both adverse health behaviors and unfavorable biomarker profiles.

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### Disclosures

None.

### IRB Information

The study protocol was approved by the Institutional Review Board of Yonsei Health System (4-2024-0675).

### Data Availability

The data used in this study are are available at https://knhanes.kdca.go.kr/.

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## Supplementary Files

Please find supplementary file(s);
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