INTRODUCTION

The effect of air pollution on mortality and the burden of disease increases as air pollution increases, although estimates can vary from region to region. According to the Global Burden of Disease Study, ambient air pollution accounted for 7.5% of deaths globally in 2016 and was the sixth leading contributor to attributable disability-adjusted life years (DALYs) in that year. Korea has experienced rapid economic growth in the last century, and the quality of the atmosphere has worsened. Air pollution reduction policies, such as the Special Law on Air Quality in the Seoul metropolitan area, have had limited effect on particulate matter (PM) pollution, and the overall air quality remains poor. Concentrations of PM with aerodynamic diameter less than 10 μm (PM10) have improved over the past decade, reaching the lowest national average of 45 μg/m3 in 2012, and then rebounding to a level of 47 μg/m3 in 2016. However, the concentration of nitrogen dioxide (NO2) has remained relatively constant, with no large changes. The average values of ozone (O3) concentration are continuously increasing.

Epidemiological studies on the health effects of air pollution have been actively conducted in many countries. In particular, time series studies to examine the short-term effects of air pollution have been conducted worldwide and have yielded relatively consistent results. However, cohort studies to assess the long-term effects of air pollution have been primar-
ily conducted in Western countries that have relatively low concentrations of air pollutants. Due to a lack of direct evidence at higher global concentrations, the integrated expose–response (IER) model was developed. The IER combines information on PM-mortality associations from non-outdoor sources, including secondhand smoke, active smoking, and household air pollution, and has been used to estimate the disease burden attributable to PM with aerodynamic diameter less than 2.5 µm (PM_{2.5}). As the use of IER requires a strict assumption of equal toxicity per unit dose across these non-outdoor sources, cohort studies are needed that reflect the different air pollution concentrations in different regions.

The health effects of air pollution can vary regionally depending on the composition of pollutants or characteristics of the population at risk. The regional differences in PM_{2.5} mortality risk estimates can likely be attributed to geographic variation in particle composition or the spatial heterogeneity of constituents, as well as differences in the total air pollution mixture. Regional differences of topography, which may lead to regional differences of exposure error, can contribute to regional differences in PM risk estimates.

To accurately understand the impact of air pollution on health in Korea, the results of research performed specifically for Korea are needed. Since the publication of time series research starting in 1999 in Korea, many epidemiological studies have been conducted; however, the results of these studies have not been systematically summarized. To accurately assess the impact of air pollution in Korea and to clarify future research directions, systematic sorting of epidemiological studies on air pollution conducted in Korea is required. The aim of the present analysis was to comprehensively review previous epidemiological studies on air pollution and health conducted in Korea to identify future study needs.

LITERATURE SEARCH

We conducted a literature search in PubMed using the search terms (“air pollution”[MeSH Terms] OR (“air”[All Fields] AND “pollution”[All Fields]) OR “air pollution”[All Fields]) AND (“mortality”[Subheading] OR “mortality”[All Fields] OR “mortality”[MeSH Terms]) AND (“Korea”[MeSH Terms] OR “Korea”[All Fields]) and ((“air pollution”[MeSH Terms] OR “air”[All Fields] AND “pollution”[All Fields]) OR “air pollution”[All Fields] AND (“epidemiology”[Subheading] OR “epidemiology”[All Fields] OR “morbidity”[All Fields] OR “morbidity”[MeSH Terms]) AND (“Korea”[MeSH Terms] OR “Korea”[All Fields]) NOT (“mortality”[Subheading] OR “mortality”[MeSH Terms]) to find published studies on the associations of air pollution with mortality and morbidity respectively in Korea, between January 1990 and July 2018.

We also searched for health impact assessment studies using the same search engine and the search terms (“number” [All Fields] AND (“death”[MeSH Terms] OR “death”[All Fields] OR “deaths”[All Fields]) OR “burden of disease”[All Fields] OR “health impact assessment”[All Fields] AND “Korea”[All Fields] AND (“air pollution”[All Fields] OR “ambient”[All Fields]).

After reviewing the title and abstract of each article, we selected epidemiological studies that reported associations between exposure to air pollution and mortality or morbidity. We then summarized these articles according to their characteristics and results.

The initial search for mortality and morbidity returned 87 and 195 results, respectively. After excluding articles that did not meet the inclusion criteria (Fig. 1), there remained 27 (Table 1) and 37 studies (Table 2) on mortality and morbidity, respectively. One of the mortality study also reported morbidity results, so a total of 38 studies were included in the present review. The search for health impact analyses returned 22 studies; four articles remained after a review of titles and abstracts.

![Fig. 1. Selection of papers.](https://doi.org/10.3349/ymj.2019.60.3.243)
Table 1. Epidemiological Studies on Air Pollution and Mortality in Korea between 1999 and 2018

| No. | Author (year) | Study design | Study period | Location | Outcome | Pollutant Unit | Effect size |
|-----|---------------|--------------|--------------|----------|----------|----------------|-------------|
| 1   | Lee, et al. (1999) | Time series | 1991–1995 | Seoul | Non-accidental | SO\textsubscript{2} | 50 ppb | RR 1.078 (1.057, 1.099) |
|     |               |              |             | Ulsan | Non-accidental | SO\textsubscript{2} | 50 ppb | RR 1.051 (0.991, 1.115) |
|     |               |              |             | Seoul | Non-accidental | TSP | 100 µg/m\textsuperscript{3} | RR 1.051 (1.031, 1.072) |
|     |               |              |             | Ulsan | Non-accidental | TSP | 100 µg/m\textsuperscript{3} | RR 0.999 (0.961, 1.039) |
|     |               |              |             | Seoul | Non-accidental | 1 hr max O\textsubscript{3} | 50 bpp | RR 1.015 (1.005, 1.025) |
|     |               |              |             | Ulsan | Non-accidental | 1 hr max O\textsubscript{3} | 50 bpp | RR 1.020 (0.989, 1.170) |
| 2   | Hong, et al. (1999) | Time series | 1995 | Incheon | Total | TSP | 10 µg/m\textsuperscript{3} | RR 1.2% (0.2, 2.2) |
|     |               |              |             | Total | PM\textsubscript{10} | 10 µg/m\textsuperscript{3} | RR 1.2% (0.2, 2.1) |
| 3   | Lee, et al. (1998) | Case-crossover | Seoul | Non-accidental | SO\textsubscript{2} | 50 ppb | RR 1.023 (0.991, 1.048) |
|     |               |              |             | Non-accidental | Maximum O\textsubscript{3} | 50 ppb | RR 1.010 (0.988, 1.032) |
|     |               |              |             | Non-accidental | TSP | 100 µg/m\textsuperscript{3} | RR 1.001 (0.999, 1.003) |
|     |               |              |             | Seoul | Non-accidental | 1 hr max O\textsubscript{3} | 50 bpp | RR 1.015 (1.005, 1.025) |
|     |               |              |             | Incheon | Non-accidental | Total PM\textsubscript{10} | 10 µg/m\textsuperscript{3} | RR 1.007 (1.001, 1.0007) |
|     |               |              |             | Total CO | RR 1.004 (1.000, 1.008) |
|     |               |              |             | Total NO\textsubscript{2} | RR 1.0009 (1.0007, 1.0011) |
|     |               |              |             | Total SO\textsubscript{2} | RR 1.0002 (1.0001, 1.0004) |
|     |               |              |             | Total O\textsubscript{3} | RR 0.9995 (0.9990, 0.9999) |
| 5   | Lee, et al. (2000) | Time series | 1991–1997 | 7 cities | Total | TSP | 100 µg/m\textsuperscript{3} | RR 0.5–4% |
|     |               |              |             | Total SO\textsubscript{2} | 50 ppb | RR 1.03 (1.01, 1.05) |
| 6   | Kwon, et al. (2001) | Time series | 1994–1998 | Seoul | Non-accidental | PM\textsubscript{10} | IQR (42.1 µg/m\textsuperscript{3} | OR 1.014 (1.006, 1.022) |
|     |               |              |             | Non-accidental | CO | IQR (0.59 ppm) | OR 1.022 (1.017, 1.029) |
|     |               |              |             | Non-accidental | NO\textsubscript{2} | IQR (14.6 ppb) | OR 1.021 (1.014, 1.029) |
|     |               |              |             | Total O\textsubscript{3} | IQR (20.5 ppb) | OR 1.010 (1.002, 1.017) |
| 7   | Hong, et al. (2002) | Time series | 1995–1998 | Seoul | Stroke | PM\textsubscript{10} | IQR (42.1 µg/m\textsuperscript{3} | RR 1.5% (1.3, 1.8) |
|     |               |              |             | Stroke | O\textsubscript{3} | IQR (0.59 ppm) | RR 2.9% (0.3, 5.5) |
|     |               |              |             | Stroke | NO\textsubscript{2} | IQR (14.6 ppb) | RR 3.1% (1.1, 5.1) |
|     |               |              |             | Stroke | CO | IQR (20.5 ppb) | RR 4.1% (1.1, 7.2) |
| 8   | Hong, et al. (2002) | Time series | 1991–1997 | Seoul | Ischemic stroke | TSP | IQR | RR 1.03 (1.00, 1.06) |
|     |               |              |             | Ischemic stroke | SO\textsubscript{2} | IQR | RR 1.04 (1.01, 1.08) |
|     |               |              |             | Ischemic stroke | NO\textsubscript{2} | IQR | RR 1.04 (1.01, 1.07) |
|     |               |              |             | Ischemic stroke | CO | IQR | RR 1.06 (1.02, 1.09) |
|     |               |              |             | Ischemic stroke | O\textsubscript{3} | IQR | RR 1.06 (1.02, 1.10) |
| 9   | Ha, et al. (2003) | Cohort | | | Total (postneonates) | PM\textsubscript{10} | IQR (42.9 µg/m\textsuperscript{3} | RR 1.142 (1.096, 1.190) |
|     |               |              |             | Respiratory (postneonates) | PM\textsubscript{10} | IQR (42.9 µg/m\textsuperscript{3} | RR 2.018 (1.784, 2.283) |
| 10  | Kim, et al. (2003) | Time series | 1995–1999 | Seoul | Non-accidental | PM\textsubscript{10} | IQR (43.1 µg/m\textsuperscript{3} | RR 3.7% (2.1, 5.4) |
|     |               |              |             | Respiratory | PM\textsubscript{10} | IQR (43.1 µg/m\textsuperscript{3} | RR 13.9% (6.8, 21.5) |
|     |               |              |             | Cardiovascular | PM\textsubscript{10} | IQR (43.1 µg/m\textsuperscript{3} | RR 4.4% (-1.0, 9.0) |
|     |               |              |             | Cerebrovascular | PM\textsubscript{10} | IQR (43.1 µg/m\textsuperscript{3} | RR 6.3% (2.3, 10.5) |
| 11  | Kim, et al. (2004) | Time series | 1997–2004 | Seoul | Non-accidental | PM\textsubscript{10} (mean) | IQR (42.1 µg/m\textsuperscript{3} | RR 1.021 (1.009, 1.035) |
|     |               |              |             | Non-accidental | PM\textsubscript{10} (SD) | IQR (11.93 µg/m\textsuperscript{3} | RR 1.025 (1.000, 1.028) |
| 12  | Lee, et al. (2007) | Time series | 2000–2004 | Seoul | Non-accidental | Asian dust event | Larger effect sizes in the model without Asian dust event |
| 13  | Cho, et al. (2008) | Time series | 2001 | Seoul | Respiratory | Fine particle count | IQR (10.321 number/cm\textsuperscript{3} | OR 5.73% (5.03, 6.45) |
|     |               |              |             | Respiratory | Respiratory particle count | IQR (10.38 number/cm\textsuperscript{3} | OR 5.82% (5.13, 6.53) |
### Table 1. Epidemiological Studies on Air Pollution and Mortality in Korea between 1999 and 2018 (Continued)

| No. | Author (year) | Study design | Study period | Location | Outcome | Pollutant | Unit | Effect size |
|-----|---------------|--------------|--------------|----------|---------|-----------|------|-------------|
| 14  | Son, et al. (2008) | Case-crossover | 1999–2003 | Seoul | Infant | PM$_{10}$ | 1 µg/m$^3$ | OR 1.000 (0.998, 1.002) |
|     |                |              |             |          | Infant | NO$_2$ | 1 unit | OR 1.002 (0.994, 1.009) |
|     |                |              |             |          | Infant | SO$_2$ | 1 unit | OR 1.015 (0.973, 1.058) |
|     |                |              |             |          | Infant | CO     | 1 unit | OR 1.029 (0.833, 1.271) |
|     |                |              |             |          | Infant | O$_3$  | 1 unit | OR 0.984 (0.977, 0.992) |
| 15  | Yi, et al. (2010) | Case-crossover | 2000–2006 | Seoul | Non-accidental | PM$_{10}$ | 10 µg/m$^3$ | 0.28% (0.12, 0.44) |
|     |                |              |             |          | Cardiovascular | PM$_{10}$ | 10 µg/m$^3$ | 0.51% (0.19, 0.83) |
|     |                |              |             |          | Respiratory | PM$_{10}$ | 10 µg/m$^3$ | 0.59% (0.08, 1.26) |
| 16  | Kim, et al. (2010) | Case-crossover | 2004 | 7 cities | Suicide | PM$_{10}$ | IQR | 9.0% (2.4, 16.1) |
|     |                |              |             |          | Suicide | PM$_{2.5}$ | IQR | 10.1% (2.0, 19.0) |
| 17  | Park, et al. (2011) | Time-series | 1999–2007 | Seoul | Non-accidental (high temp. ≥26.2°C) | SO$_2$ | 0.5 ppb | 0.83% (0.42, 1.25) |
|     |                |              |             |          | Non-accidental (low temp. <26.2°C) | SO$_2$ | 0.5 ppb | 0.21% (0.07, 0.36) |
| 18  | Son, et al. (2011) | Birth cohort | 2004–2007 | Seoul | All-cause infant | TSP | IQR | HR 1.44 (1.06, 1.97) |
|     |                |              |             |          | All-cause infant | PM$_{10}$ | IQR | HR 1.65 (1.18, 2.31) |
|     |                |              |             |          | All-cause infant | PM$_{2.5}$ | IQR | HR 1.53 (1.22, 1.90) |
|     |                |              |             |          | Respiratory infant | TSP | IQR | HR 1.19 (0.83, 1.70) |
|     |                |              |             |          | Respiratory infant | PM$_{10}$ | IQR | HR 3.78 (1.18, 12.13) |
|     |                |              |             |          | Respiratory infant | PM$_{2.5}$ | IQR | HR 6.20 (1.50, 25.66) |
|     |                |              |             |          | Respiratory infant | PM$_{10,2.5}$ | IQR | HR 3.15 (1.26, 7.85) |
|     |                |              |             |          | Respiratory infant | PM$_{10,2.5}$ | IQR | HR 2.86 (0.76, 10.85) |
| 19  | Son, et al. (2012) | Case-crossover | 2000–2007 | Seoul | Total | PM$_{10}$ | IQR | 0.94% (0.25, 1.62) |
|     |                |              |             |          | Total | NO$_2$ | IQR | 2.27% (1.03, 3.53) |
|     |                |              |             |          | Total | SO$_2$ | IQR | 1.94% (0.80, 3.09) |
|     |                |              |             |          | Total | CO     | IQR | 2.21% (1.00, 3.43) |
|     |                |              |             |          | Total | O$_3$  | IQR | Positive/NS |
|     |                |              |             |          | Cardiovascular | PM$_{10}$ | IQR | 1.95% (0.64, 3.27) |
|     |                |              |             |          | Cardiovascular | NO$_2$ | IQR | 4.82% (2.18, 7.54) |
|     |                |              |             |          | Cardiovascular | SO$_2$ | IQR | 3.64% (1.46, 5.87) |
|     |                |              |             |          | Cardiovascular | CO     | IQR | 4.32% (1.77, 6.92) |
|     |                |              |             |          | Cardiovascular | O$_3$  | IQR | Positive/NS |
| 20  | Heo, et al. (2014) | Time-series | 2003–2007 | Seoul | Non-accidental, cardiovascular, respiratory | PM$_{2.5}$ and components | Percentage of excess risk by PM$_{10}$ and components |
| 21  | Lim, et al. (2014) | GWR | 2008–2010 | Seoul | Cardiovascular | PM$_{10}$ | IQR (48.3 µg/m$^3$) | Mean β (SE) 0.956 (0.102) |
|     |                |              |             |          | Unintentional injury | PM$_{10}$ | IQR (0.005 ppm) | NS |
|     |                |              |             |          | Unintentional injury | SO$_2$ | IQR (0.02 ppm) | OR 1.119 (1.022, 1.226) |
|     |                |              |             |          | Unintentional injury | NO$_2$ | IQR (0.03 ppm) | OR 1.208 (1.043, 1.400) |
|     |                |              |             |          | Unintentional injury | O$_3$  | IQR (0.36 ppm) | OR 1.012 (1.000, 1.024) |
| 22  | Ha, et al. (2015) | Case-crossover | 2002–2008 | 7 cities | Non-accidental | PM$_{10}$ | 10 µg/m$^3$ | 0.51% (0.01, 1.01) |
|     |                |              |             |          | Daily concentrations of ≥75 µg/m$^3$ | Mean β (SE) 0.48% (0.30, 0.60) |
| 23  | Kim, et al. (2017) | Time-series | 1993–2009 | 7 cities | Non-accidental | PM$_{10}$ | 10 µg/m$^3$ | 0.48% (0.14, 0.82) |
|     |                |              |             |          | Daily concentrations of ≥75 µg/m$^3$ | Mean β (SE) 1.13% (0.37, 1.89) |
| 24  | Kim, et al. (2018) | Time-series | 1993–2009 | 7 cities | Cardiovascular | PM$_{10}$ | 10 µg/m$^3$ | 0.48% (0.14, 0.82) |
|     |                |              |             |          | Daily concentrations of ≥75 µg/m$^3$ | Mean β (SE) 1.13% (0.37, 1.89) |
Air pollution and mortality
Among the included studies, the earliest reports regarding an association between air pollution and mortality in Korea were published in 1999.10-13 Three of these were time series studies and one was a case-crossover study. Both time series and case-crossover designs are suitable for analysis of acute effects (in days) of short-term exposure to air pollution. One time series analysis was conducted in Seoul and Ulsan. That study reported that the daily variation of ambient concentrations of sulfur dioxide (SO2), total suspended particles (TSP), and O3 in Seoul were significantly associated with increased non-accidental mortality.10 In the same year, the results of reanalysis of Seoul data from the previous time series using a case-crossover approach, in which each participant became its own control, were reported, showing that only SO2 was significantly associated with non-accidental mortality.12 Another time series study conducted in Incheon showed that, in addition to TSP, a 10-µg/m3 increase in the daily mean concentration of PM10 was also associated with a 1.2% increase in total mortality.13 The remaining study was the first to examine the effects of all five criteria pollutants [PM10, SO2, NO2, carbon monoxide (CO), and O3] on mortality in Seoul. That study reported that the previous day’s concentrations of PM10 and NO2 were significantly associated with increased daily mortality [relative risks (RRs) of 1.0007 and 1.0026 for PM10 and NO2, respectively].11

After 1999, most subsequent studies examined the associa-
tions between air pollutants and total or non-accidental mortality using time series analysis and a case-crossover design. However, the effect sizes varied according to different studies. For instance, the percent increase in mortality for an interquartile range (IQR) increment in PM$_{10}$ ranged between 0.9% and 3.7%. This may be due to different factors of these studies, including the study period and area, and a multi-city study may provide more robust effect size. There were few multi-city studies and even fewer reported associations with total mortality. The most recent such study stated that a 10-µg/m$^3$ increase in daily ambient PM$_{10}$ was associated with a 0.51% increase in mortality.

The effects of air pollution are not only acute but also chronic, and long-term exposure is generally expected to have a much higher effect size than short-term exposure. However, the chronic effect of air pollution has rarely been examined in Korea. In fact, there were only two studies reporting long-term effects of PM exposure on mortality among our search results, one each for PM$_{10}$ and PM$_{2.5}$. Kim, et al. analyzed a sample cohort of the National Health Insurance Service and reported a marginally significant 5% increase in mortality per a 1-µg/m$^3$ increase in annual PM$_{10}$ concentration. Another study reported a hazard ratio (HR) of 1.32 for all-cause mortality with an increment of 1 µg/m$^3$ in PM$_{2.5}$. Long-term exposure to other gaseous pollutants was also found to be associated with increased risk of mortality, and CO, SO$_2$, and NO$_2$ showed HRs of 1.72, 1.73, and 1.79 for each IQR increase, respectively.

The effect of air pollution exposure on mortality is cause-specific, and the related cardiovascular and respiratory effects are well known. There have been several reports on cardiovascular and respiratory mortality owing to air pollution in Korea. An interesting cause of death that shows an association with air pollution is suicide. In a case-crossover study conducted using data from seven metropolitan cities in Korea (Seoul, Incheon, Daejeon, Gwangju, Daegu, Busan, and Ulsan), the authors reported that an IQR increase of PM$_{2.5}$ was associated with a 10.1% increase in the number of suicides.

Most gaseous air pollutants (SO$_2$, NO$_x$, and CO) showed consistently significant associations with increased mortality. For acute exposure, an IQR increase of SO$_2$, NO$_x$, and CO increased daily mortality about 2%, and an IQR increase in chronic exposure to those three pollutants showed consistent RRs of around 1.7 (Table 1). However, the association between ambient O$_3$ concentration and mortality seems inconclusive. Two studies reported significant positive associations of O$_3$ concentration with total mortality and ischemic stroke mortality. However, we also found reports of significant negative associations with all-cause, cardiovascular, and infant mortality.

**Air pollution and morbidity**

Asthma and respiratory diseases were among the first specific disorders analyzed in Korea. A time series analysis conducted in Seoul reported that an IQR increase in PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$ showed significant RRs for children’s asthma hospitalization of 1.07, 1.11, 1.15, 1.16 and 1.12, respectively. Another study reported the results of a children’s panel for NO$_2$ exposure showing an OR of 1.12 for upper respiratory symptoms and ORs for lower respiratory symptoms of 1.18, 1.12, and 1.16 for increased exposures to NO$_2$, SO$_2$, and CO, respectively. O$_3$ was also associated with children’s asthma hospitalization, especially in groups with lower socioeconomic status (RR: 1.32, 95% CI: 1.11, 1.58). In a cohort study, O$_3$ concentration was associated with a 12-month prevalence of wheeze and airway hyperresponsiveness in children. Other allergic disorders, such as allergic rhinitis and atopic dermatitis, were also associated with air pollution (Table 2).

Similar to the association between air pollution and cardiovascular mortality, the morbidity of cardiovascular and cerebrovascular diseases, such as stroke, myocardial infarction, and hypertension, were also significantly associated with increased exposure to air pollution. A time series analysis reported that NO$_2$ increased stroke (RR=1.2, p-value=0.001), and a cohort study reported that long-term exposure to PM$_{2.5}$, CO, SO$_2$, and NO$_2$ increased the risk of acute myocardial infarction, congestive heart failure, and stroke (Table 2).

We found two studies examining the association of air pollution with cancer. In these recent studies, indoor radon concentrations were associated with an increased risk of male lung cancer and non-Hodgkin’s lymphoma in girls, and conventional air pollutants (PM$_{10}$ and NO$_2$) were associated with lung cancer with marginal significance.

Similar to the association of suicide with air pollution, depressive symptoms were also found to be associated with air pollution in Korea. A panel study examining air pollution and depressive symptoms was one of the first to report such an association. An association between PM$_{15}$ and major depressive disorder was also found in a community-based urban cohort.

Birth outcome has been another subject of analysis. PM$_{10}$, SO$_2$, and CO exposures were reported to have significant associations with low birth weight in a cohort study.

**Health impact assessment**

Among four studies (Table 3), two calculated the attributable number of deaths, one calculated the attributable number of deaths and morbidity, and a fourth calculated DALYs. There were substantial differences in the attributable number of deaths among the study results. For instance, Leem, et al. estimated the number of deaths attributable to PM$_{15}$ to be 15346 in the Seoul metropolitan area, whereas Han, et al. estimated this number to be 1763. Yorifuji, et al. estimated the number of deaths attributable to PM$_{10}$ over 20 µg/m$^3$ at 5840 in Seoul. These numbers are substantially different, even when considering the differences in study area, study period, and pollutants investigated.
### Table 2. Epidemiological Studies on Air Pollution and Morbidity in Korea between 1999 and 2018

| No. | Author (year) | Study design | Study period | Location | Outcome | Pollutant | Unit | Effect size |
|-----|---------------|--------------|--------------|----------|---------|----------|------|-------------|
| 1   | Lee, et al. (2002)<sup>23</sup> | Time series | Seoul | | Asthma hospitalization | PM<sub>10</sub> | IQR (40.4 µg/m<sup>3</sup>) | RR 1.07 (1.04, 1.11) |
|     |                |              |              |          |          | SO<sub>2</sub> | IQR (4.4 ppb) | RR 1.11 (1.06, 1.17) |
|     |                |              |              |          |          | NO<sub>2</sub> | IQR (14.6 ppb) | RR 1.15 (1.10, 1.20) |
|     |                |              |              |          |          | O<sub>3</sub> | IQR (21.7 ppb) | RR 1.12 (1.07, 1.16) |
|     |                |              |              |          |          | CO       | IQR (1.0 ppm) | RR 1.16 (1.10, 1.22) |
| 2   | Lee, et al. (2005)<sup>24</sup> | Panel study | 2003 | Seoul | Upper respiratory symptoms | NO<sub>2</sub> | OR 1.12 (1.01, 1.24) |
|     |                |              |              |          | Lower respiratory symptoms | NO<sub>2</sub> | OR 1.18 (1.06, 1.31) |
|     |                |              |              |          | Lower respiratory symptoms | SO<sub>2</sub> | OR 1.12 (1.01, 1.25) |
|     |                |              |              |          | Lower respiratory symptoms | CO       | OR 1.16 (1.02, 1.32) |
| 3   | Son, et al. (2006)<sup>25</sup> | Time series | 2002 | Seoul | Asthma hospitalization (highest SES) | O<sub>3</sub> | RR 1.12 (1.00, 1.25) |
|     |                |              |              |          | Asthma hospitalization (moderate SES) | O<sub>3</sub> | RR 1.24 (1.08, 1.43) |
|     |                |              |              |          | Asthma hospitalization (lowest SES) | O<sub>3</sub> | RR 1.32 (1.11, 1.58) |
| 4   | Lee, et al. (2007)<sup>22</sup> | Natural experiment | 2002 | Busan | Childhood asthma hospitalization | PM<sub>10</sub> | IQR | RR post Asian game period/RR baseline 0.73 (0.49, 1.11) |
| 5   | Lee, et al. (2006)<sup>23</sup> | Time series | 2002 | Seoul | Asthma hospitalization | PM<sub>10</sub> | IQR | 31% (14, 51) |
|     |                |              |              |          | Asthma hospitalization | SO<sub>2</sub> | IQR | 29% (8, 53) |
|     |                |              |              |          | Asthma hospitalization | NO<sub>2</sub> | IQR | 29% (5, 58) |
| 6   | Seo, et al. (2007)<sup>23</sup> | Cohort | 2002–2003 | Seoul | Low birth weight | CO       | IQR | RR 1.081 (1.002, 1.166) |
|     |                |              |              |          | Low birth weight | SO<sub>2</sub> | IQR | RR 1.145 (1.038, 1.267) |
|     |                |              |              |          | Low birth weight | NO<sub>2</sub> | IQR | RR 1.053 (1.002, 1.108) |
|     |                |              |              |          | Low birth weight | PM<sub>10</sub> | IQR | RR 1.003 (0.954, 1.055) |
| 7   | Moon, et al. (2009)<sup>24</sup> | Cohort | 2002–2003 | Seoul | Low birth weight | PM<sub>10</sub> | IQR | OR 1.08 (0.99, 1.18) |
|     |                |              |              | Busan | Low birth weight | PM<sub>10</sub> | IQR | OR 1.24 (1.02, 1.52) |
|     |                |              |              | Daegu | Low birth weight | PM<sub>10</sub> | IQR | OR 1.19 (1.04, 1.37) |
|     |                |              |              | Incheon | Low birth weight | PM<sub>10</sub> | IQR | OR 1.12 (0.98, 1.28) |
|     |                |              |              | Gwangju | Low birth weight | PM<sub>10</sub> | IQR | OR 1.22 (0.98, 1.52) |
|     |                |              |              | Daejeon | Low birth weight | PM<sub>10</sub> | IQR | OR 1.06 (1.00, 1.11) |
|     |                |              |              | Ulsan | Low birth weight | PM<sub>10</sub> | IQR | OR 1.19 (1.03, 1.38) |
| 8   | Seo, et al. (2010)<sup>24</sup> | Cohort | 2004 | Seoul | Low birth weight | PM<sub>10</sub> | IQR | OR 1.08 (0.99, 1.18) |
|     |                |              |              | Busan | Low birth weight | PM<sub>10</sub> | IQR | OR 1.24 (1.02, 1.52) |
|     |                |              |              | Daegu | Low birth weight | PM<sub>10</sub> | IQR | OR 1.19 (1.04, 1.37) |
|     |                |              |              | Incheon | Low birth weight | PM<sub>10</sub> | IQR | OR 1.12 (0.98, 1.28) |
|     |                |              |              | Gwangju | Low birth weight | PM<sub>10</sub> | IQR | OR 1.22 (0.98, 1.52) |
|     |                |              |              | Daejeon | Low birth weight | PM<sub>10</sub> | IQR | OR 1.06 (1.00, 1.11) |
|     |                |              |              | Ulsan | Low birth weight | PM<sub>10</sub> | IQR | OR 1.19 (1.03, 1.38) |
| 9   | Yi, et al. (2010)<sup>25+</sup> | Case-crossover | 2001–2006 | Seoul | Cardiovascular hospitalization | PM<sub>10</sub> | 0.01 µg/m³ | 0.77% (0.53, 1.01) |
|     |                |              |              | Busan | Respiratory hospitalization | PM<sub>10</sub> | 0.01 µg/m³ | 1.19% (0.94, 1.44) |
| 10  | Kim, et al. (2011)<sup>26</sup> | Cohort | 12-month prevalence of wheeze | 2005 | O<sub>3</sub> | 5 ppb | OR 1.372 (1.016, 1.852) |
| 11  | Lim, et al. (2012)<sup>27</sup> | Panel study | Seoul | Depression (SGDS-K) | PM<sub>10</sub> | IQR | 17.0% (4.9, 30.5) |
|     |                |              |              | Depression (SGDS-K) | NO<sub>2</sub> | IQR | 32.8% (1.6, 65.6) |
|     |                |              |              | Depression (SGDS-K) | O<sub>3</sub> | IQR | 43.7% (11.5, 85.2) |
| 12  | Kim, et al. (2012)<sup>28</sup> | Panel study | Seoul | Insulin resistance | PM<sub>10</sub>, NO<sub>2</sub> | IQR | Significantly increased |
| 13  | Kim, et al. (2013)<sup>29</sup> | Cross sectional | Allergic diseases | Traffic related pollutants | PM<sub>10</sub>, NO<sub>2</sub> | IQR | OR 2.12 (1.41, 3.19) |
| 14  | Kim, et al. (2013)<sup>29</sup> | Cohort | Airway hyperresponsiveness | New episodes of wheezing | O<sub>3</sub> | OR 1.60 (1.13, 2.27) |
|     |                |              |              | New episodes of wheezing | O<sub>3</sub> | OR 1.92 (0.96, 3.83) |
| No. | Author (year) | Study design | Study period | Location | Outcome | Pollutant | Unit | Effect size |
|-----|---------------|--------------|--------------|----------|---------|-----------|------|-------------|
| 15  | Han, et al. (2013) |          |              |          | Hemorrhagic fever with renal syndrome | PM$_{10}$ | 1 µg/m$^3$ | 0.013 increase of monthly cases |
| 16  | Son, et al. (2013) | 2003–2008 | 8 cities |          | Allergic disease hospital admission | PM$_{10}$ | IQR (30.7 µg/m$^3$) | 2.2% (0.5, 3.9) |
|     |               |          |              |          | Asthma hospital admission | PM$_{10}$ | IQR (30.7 µg/m$^3$) | 2.8% (1.3, 4.4) |
|     |               |          |              |          | Respiratory hospital admission | PM$_{10}$ | IQR (30.7 µg/m$^3$) | 1.7% (0.9, 2.6) |
|     |               |          |              |          | Cardiovascular hospital admission | PM$_{10}$ | IQR (30.7 µg/m$^3$) | 0.7% (0.0, 1.4) |
|     |               |          |              |          | Allergic disease hospital admission | NO$_2$ | IQR (12.2 ppb) | 2.3% (0.6, 4.0) |
|     |               |          |              |          | Asthma hospital admission | NO$_2$ | IQR (12.2 ppb) | 2.2% (0.3, 4.1) |
|     |               |          |              |          | Respiratory hospital admission | NO$_2$ | IQR (12.2 ppb) | 2.2% (0.6, 3.7) |
|     |               |          |              |          | Cardiovascular hospital admission | NO$_2$ | IQR (12.2 ppb) | 2.2% (1.1, 3.4) |
| 17  | Park, et al. (2013) | Time series | 7 cities |          | Asthma admission | PM$_{10}$, CO, O$_3$, NO$_2$ | Children vs. adult | Lower risk in children for PM$_{10}$ and CO |
| 18  | Kim, et al. (2014) | Cohort |          |          | Neurodevelopment (MDI) | PM$_{10}$ | IQR | $\beta$=2.83; $p$=0.003 |
|     |               |          |              |          | Neurodevelopment (PDI) | PM$_{10}$ | IQR | $\beta$=3.00; $p$=0.002 |
| 19  | Hwang, et al. (2014) | Retrospective cohort | Seoul |          | Tuberculosis | SO$_2$ | IQR | RR 1.07 (1.03, 1.12) |
| 20  | Han, et al. (2015) | Time series | 2004–2013 |          | Stroke | NO$_2$ | IQR | RR 1.262, $p$=0.001 |
| 21  | Kim, et al. (2015) | Case-crossover | Korea |          | Hourly asthma ED visit | PM$_{10}$ | IQR | OR 1.95 (1.00, 1.11) |
|     |               |          |              |          | Hourly asthma ED visit | O$_3$ | IQR | OR 1.10 (1.04, 1.16) |
| 22  | Jang, et al. (2015) | Ecological | Korea |          | Monthly malaria incidence | NO$_2$ | | $\beta$=0.884, $p$=0.01 |
| 23  | Shim, et al. (2016) | Cross sectional | 2010–2013 | Korea | Benign prostate hyperplasia | NO$_2$ | IQR | OR 2.23 (1.56, 2.39) |
|     |               |          |              |          | Benign prostate hyperplasia | SO$_2$ | IQR | OR 2.02 (1.42, 2.88) |
| 24  | Kang, et al. (2016) | Time series | 2006–2013 | Seoul | Cardiac arrest | PM$_{2.5}$ | 10 µg/m$^3$ | 1.30% (0.20, 2.41) |
| 25  | Kim, et al. (2016) | Cross sectional |          |          | Allergic rhinitis | CO (during the first year of life) | 100 ppb | OR 1.10 (1.03, 1.19) |
|     |               |          |              |          | Atopic dermatitis | CO (past 12 months) | 1 ppm | OR 8.11 (1.06, 62.12) |
| 26  | Kim, et al. (2016) | Cross sectional |          |          | Asthma | NO$_2$ | | OR 1.67 (1.03, 2.71) |
|     |               |          |              |          | Allergic rhinitis | Black carbon | | OR 1.60 (1.36, 1.90) |
|     |               |          |              |          | Allergic rhinitis | SO$_2$ | | OR 1.09 (1.01, 1.17) |
|     |               |          |              |          | Allergic rhinitis | NO$_2$ | | OR 1.18 (1.07, 1.30) |
| 27  | Han, et al. (2016) | Time series | 2004–2014 | Seongdong-gu, Seoul | Intracerebral hemorrhage | PM$_{10}$ | IQR | RR 1.09 (1.02, 1.15) |
|     |               |          |              |          | Subarachnoid hemorrhage | O$_3$ | | RR 1.32 (1.10, 1.58) |
| 28  | Kim, et al. (2016) | Cohort | 2002–2010 | Korea | Major depressive disorder | PM$_{2.5}$ | 10 µg/m$^3$ | HR 1.44 (1.17-1.78) |
|     |               |          |              |          | Hypertension | PM$_{10}$ | 10 µg/m$^3$ | OR 1.942 (1.009, 1.077) |
|     |               |          |              |          | Hypertension in >30 years old | PM$_{10}$ | 10 µg/m$^3$ | OR 1.044 (1.009, 1.079) |
|     |               |          |              |          | Stroke | PM$_{10}$ | 10 µg/m$^3$ | OR 1.044 (0.979, 1.114) |
|     |               |          |              |          | Angina | PM$_{10}$ | 10 µg/m$^3$ | OR 0.977 (0.901, 1.069) |
|     |               |          |              |          | Hypertension | NO$_2$ | 10 ppb | OR 1.077 (1.044, 1.112) |
| 29  | Lee, et al. (2016) | Cross sectional | 2008–2010 | Korea | Hypertension in >30 years old | NO$_2$ | 10 ppb | OR 1.080 (1.043, 1.118) |
|     |               |          |              |          | Stroke | NO$_2$ | 10 ppb | OR 1.073 (0.994, 1.157) |
|     |               |          |              |          | Angina | NO$_2$ | 10 ppb | OR 1.047 (0.968, 1.134) |
|     |               |          |              |          | Hypertension | CO | 10 ppb | OR 1.123 (0.963, 1.310) |
|     |               |          |              |          | Hypertension in >30 years old | CO | 10 ppb | OR 1.129 (0.963, 1.387) |
|     |               |          |              |          | Stroke | CO | 10 ppb | OR 1.336 (0.987, 2.011) |
DISCUSSION

Beginning in 1999, many studies have been conducted to elucidate the health effects of air pollution in Korea. These studies have reported associations with mortality (all-cause, respiratory, cerebrovascular, cardiovascular, infant, injury, and suicide) and morbidity (allergic, respiratory, cardiovascular, cerebrovascular, adverse birth outcomes, depression, and cancer). Most studies examined the short-term effects of air pollution using a time series or case-crossover study design; we found only three cohort studies that examined long-term effects. There were four studies that estimated the health impacts of air pollution, and except for one study that reported DALYs, three studies had inconsistent estimations of the attributable number of deaths.

Estimating health impacts is usually conducted later than other research as previously estimated associations between exposure and outcome, or concentration-response function (C-R function) are required. Naturally, the estimated health impact depends on the C-R function used. We suspect that differences in the attributable number of deaths estimated in the three studies reviewed here is partly due to the different

Table 2. Epidemiological Studies on Air Pollution and Morbidity in Korea between 1999 and 2018 (Continued)

| No. | Author (year) | Study design | Study period | Location | Outcome | Pollutant | Unit | Effect size |
|-----|---------------|--------------|--------------|----------|---------|-----------|------|-------------|
| 30  | Lee, et al. (2017) | Cross sectional | 2008–2011 | Korea | Pterygium | PM$_{10}$ | 5 µg/m$^3$ | OR 1.23 $p<0.023$ |
| 31  | Chung, et al. (2017) | Randomized intervention trial | 2008–2011 | | Cardioembolic stroke | PM$_{10}$ | | |
|     |                |              |              |          | Cardioembolic stroke | SO$_2$ | | |
| 32  | Kim, et al. (2016) | Randomized intervention trial | 2008–2011 | | Atopic dermatitis | Indoor VOC | | |
| 33  | Ha, et al. (2017) | Ecological | 1999–2008 | | Male lung cancer | Indoor radon | 10 Bq/m$^3$ | 1% |
|     |                |              |              |          | Female children non-Hodgkin's lymphoma | Indoor radon | 10 Bq/m$^3$ | 7% |
| 34  | Hwang, et al. (2017) | Time series | Cardiovascular ED visit | | | NH$_4^+$ (PM$_{2.5}$ component) | RR 1.05 (1.01, 1.09) |
| 35  | Kim, et al. (2017) | Cohort | 2007–2013 | Seoul | Acute myocardial infarction | PM$_{2.5}$ | 1 µg/m$^3$ | 1.36 (1.19, 1.56) |
|     |                |              |              |          | Congestive heart failure | PM$_{2.5}$ | 1 µg/m$^3$ | 1.44 (1.29, 1.61) |
|     |                |              |              |          | Stroke | PM$_{2.5}$ | 1 µg/m$^3$ | 1.39 (1.27, 1.52) |
|     |                |              |              |          | Acute myocardial infarction | CO | IQR (0.25 ppm) | 2.12 (1.72, 2.61) |
|     |                |              |              |          | Congestive heart failure | CO | IQR (0.25 ppm) | 1.86 (1.56, 2.21) |
|     |                |              |              |          | Stroke | CO | IQR (0.25 ppm) | 2.00 (1.73, 2.30) |
|     |                |              |              |          | Acute myocardial infarction | SO$_2$ | IQR (2.54 ppb) | 1.82 (1.52, 2.19) |
|     |                |              |              |          | Congestive heart failure | SO$_2$ | IQR (2.54 ppb) | 2.00 (1.73, 2.32) |
|     |                |              |              |          | Stroke | SO$_2$ | IQR (2.54 ppb) | 2.25 (2.00, 2.54) |
|     |                |              |              |          | Acute myocardial infarction | NO$_2$ | IQR (18.4 ppb) | 1.81 (1.46, 2.25) |
|     |                |              |              |          | Congestive heart failure | NO$_2$ | IQR (18.4 ppb) | 2.40 (2.02, 2.85) |
|     |                |              |              |          | Stroke | NO$_2$ | IQR (18.4 ppb) | 2.65 (2.29, 3.06) |
|     |                |              |              |          | Acute myocardial infarction | O$_3$ | IQR (15.9 ppb) | 0.71 (0.63, 0.82) |
|     |                |              |              |          | Congestive heart failure | O$_3$ | IQR (15.9 ppb) | 0.64 (0.58, 0.71) |
|     |                |              |              |          | Stroke | O$_3$ | IQR (15.9 ppb) | 0.60 (0.55, 0.65) |
| 36  | Lamichhane, et al. (2017) | Case-control | Lung cancer | Korea | | PM$_{10}$ | 10 µg/m$^3$ | OR 1.09 (0.96, 1.23) |
|     |                |              |              |          | | NO$_2$ | 10 ppb | OR 1.10 (1.00, 1.22) |
| 37  | Yi, et al. (2017) | Cross sectional | Children's atopic eczema | | | Road density | | OR 1.08 (1.01, 1.15) |
|     |                |              |              | Seoul |          | Road proximity | | OR 1.15 (1.01, 1.31) |
| 38  | Lamichhane, et al. (2018) | Birth cohort | Fetal growth (BPD) | | | PM$_{10}$ | 10 µg/m$^3$ | -0.26 mm (-0.41, -0.11) |
|     |                |              |              |          | | NO$_2$ | 10 µg/m$^3$ | -0.30 mm (-0.59, -0.03) |

SES, socioeconomic status; SGDS-K, Short Geriatric Depression Scale-Korean; MDI, mental developmental index; PDI, psychomotor developmental index; BPD, biparietal diameter; VOC, volatile organic carbon; PVC, polyvinyl chloride; IQR, interquartile range; OR, odds ratio; RR, relative risk; HR, hazard ratio; 7 cities, Seoul, Incheon, Daejeon, Gwangju, Daegu, Busan, Ulsan.

*From the search results of mortality studies.
C-R functions applied by the authors. Specifically, Yorifuji, et al.\textsuperscript{35} and Leem, et al.\textsuperscript{37} used C-R functions for mortality derived from epidemiological studies conducted in the United States (U.S.), whereas Han, et al.\textsuperscript{36} used an IER function developed for the Global Burden of Disease 2010 and 2013. The C-R function derived from U.S. studies only accounted for a relatively low level of PM; thus, it may be inadequate for estimation of health impacts in Korea where exposure to higher concentrations of PM is observed. The IER function was developed by integrating various C-R functions of other exposures, such as tobacco smoke and burning of indoor solid fuel, to fill the gap in exposure range.\textsuperscript{36} However, it remains uncertain whether the C-R function is comparable to the higher exposure range observed in Korea. Considering this, it is important to produce C-R functions using Korean data to accurately estimate the health impacts of exposure to air pollution.

As mentioned above, the effect of air pollution exposure can be divided into short-term and long-term effects. Typically, short-term effects are examined using time series and case-crossover studies, and long-term effects are investigated in cohort studies. The most recent time series study in Korea reported a 0.51% increase in mortality for each 10-µg/m\(^3\) increase in PM\(_{10}\).\textsuperscript{16} This is comparable to the results of a recent meta-analysis of studies from East Asian cities, including Seoul and Incheon, which reported a 0.47% increase in total mortality for the same amount of increase in PM\(_{10}\).\textsuperscript{40} Similarly, although we could not find health impact assessment studies regarding air pollutants other than PM, we believe that previous epidemiological studies can provide relatively robust C-R functions for NO\(_2\) and SO\(_2\) to estimate health impacts.

Previous studies have reported inconsistent associations between O\(_3\) exposure and mortality. Some published studies have reported a negative association, and the cause of this negative association has been an intriguing subject for additional analysis. One hypothesis is that the C-R function between O\(_3\) concentration and mortality is not linear.\textsuperscript{41} Time series analyses conducted in Korea and Japan support this hypothesis in short-term associations.\textsuperscript{42,43} However, such non-linearity has not been observed in other studies,\textsuperscript{44,45} and the shape of the C-R function between O\(_3\) concentration and acute mortality is still controversial. Nevertheless, studies analyzing the C-R function for long-term exposure of O\(_3\) and mortality consistently report no evidence of a threshold.\textsuperscript{46,47} However, these studies may not have accounted for lower concentrations of O\(_3\); this may be the reason for not observing a non-linear association, as the reported threshold of non-linear associations tends to

| No. | Autor (year) | Study period | Location | Outcome | Pollutant | Health impact (person) |
|-----|-------------|--------------|----------|---------|-----------|------------------------|
| 1   | Leem, et al. (2015)\textsuperscript{37} | 2010 | Seoul metropolitan area | Attributable number of deaths | PM\(_{2.5}\) | 15346 |
|     |             |              |          |         | PM\(_{10}\) | 12511 |
|     |             |              |          |         | PM\(_{10}\) | 12351 |
|     |             |              |          |         | Attributable number of lung cancer incidence | PM\(_{10}\) | 1403 |
|     |             |              |          |         | Attributable number of asthma attack (children) | PM\(_{10}\) | 11389 |
|     |             |              |          |         | Attributable number of asthma attack (adults) | PM\(_{10}\) | 44006 |
|     |             |              |          |         | Attributable number of chronic bronchitis | PM\(_{10}\) | 20490 |
|     |             |              |          |         | Attributable number of acute bronchitis | PM\(_{10}\) | 278346 |
| 2   | Yorifuji, et al. (2015)\textsuperscript{35} | 2009 | Seoul | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 5840 |
|     |             |              | Busan | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 2465 |
|     |             |              | Daegu | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 1466 |
|     |             |              | Incheon | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 1931 |
|     |             |              | Daejeon | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 599 |
|     |             |              | Gwangju | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 698 |
|     |             |              | Ulsan | Attributable number of deaths | PM\(_{10}\) over 20 µg/m\(^3\) | 539 |
| 3   | Yoon, et al. (2015)\textsuperscript{38} | 2007 | Korea | Disability-adjusted life years | Out door air pollution | 6.89/1000 person |
| 4   | Han, et al. (2018)\textsuperscript{36} | 2015 | Seoul | Attributable number of deaths | PM\(_{2.5}\) | 11924 |
|     |             |              | Busan | Attributable number of deaths | PM\(_{2.5}\) | 1763 |
|     |             |              | Daegu | Attributable number of deaths | PM\(_{2.5}\) | 947 |
|     |             |              | Incheon | Attributable number of deaths | PM\(_{2.5}\) | 672 |
|     |             |              | Gwangju | Attributable number of deaths | PM\(_{2.5}\) | 309 |
|     |             |              | Daejeon | Attributable number of deaths | PM\(_{2.5}\) | 657 |
|     |             |              | Ulsan | Attributable number of deaths | PM\(_{2.5}\) | 342 |
|     |             |              | Sejong | Attributable number of deaths | PM\(_{2.5}\) | 222 |
|     |             |              |          |         |          | 49 |
be at lower concentrations. The negative association reported in a cohort study conducted by Kim, et al.18 may suggest the existence of a non-linear C-R function between long-term exposure to O₃ and mortality because Korea has lower concentrations of O₃ than the U.S.,43 however, no analysis has been conducted using Korean data, as far as we know.

Among the two cohort studies on air pollution and mortality, one study examined the long-term health effects of PM₁₀ exposure. Although it is a valuable addition to the current knowledge, the results of that study seem inconsistent with previous reports. For instance, Kim, et al.18 reported an HR of 1.32 for all-cause mortality for a 1-μg/m³ increment of PM₁₀, in a cohort constructed using the National Health Insurance Service database, and a recent U.S. study analyzing a cohort constructed from a Medicare database reported an HR of 1.073 for a 10-μg/m³ increment of PM₁₀.47 Kim, et al.18 suggested possible differences in the effect and composition of PM₁₀, genetic characteristics, and range of exposure between these studies, although we find a more than 30-fold greater HR difficult to explain. The largest difference between these two studies was in exposure assessment. Kim, et al.18 linked the concentration measured at a fixed monitoring station to the addresses of participants, whereas Di, et al.47 used a model-based estimation of individual exposure. Another cohort study examined the long-term effect of PM₁₀ exposure.17 Those authors reported similar effects for PM₁₀ exposure, although the association was not statistically significant. However, this latter study applied an exposure assessment strategy, which could alleviate the effect of misclassification caused by participant mobility and exposure measurement at fixed monitoring stations.

Conventionally, air pollution studies use concentrations measured at fixed monitoring stations for exposure, which is an advantage for providing a large amount of data for a wide range of pollutants. However, data linked to study participants’ addresses may not reflect individual exposure, especially when the mobility pattern of individuals is not accounted for.46 This limitation may lead to misclassification, which may have substantial implications for the interpretation of results.46 In recent years, advanced sensor and modeling technologies have facilitated individual exposure measurement in air pollution studies with the use of personal sensors and various exposure models based on dispersion models, geographical information, and satellite images.48–51 Estimation of exposure using these methods in Korea has been reported recently,52 and these individual exposure estimation methods should be applied in future studies to reduce uncertainty.

In addition to observational studies, there have been many intervention studies on air pollution and its health effects. Recent intervention studies have explored the benefits of exposure reduction using devices, such as an air purifier53,54 and facemasks,55 in randomized controlled trials. The strength of intervention studies is two-fold: First, intervention studies may provide more robust evidence regarding the health effects of exposure to air pollution. Second, these trials may provide evidence regarding the effectiveness of personal measures that can be used to reduce the effects of air pollution. However, due to ethical and practical limitations, randomized controlled trials can only be applied to evaluate acute effects of exposure to air pollution. For instance, it may be unethical to design a study in which a portion of study participants are asked to wear facemasks for a long period (e.g., years). Causal modeling is a method that has been proposed to mitigate the shortcomings of observational studies without the need to conduct a randomized trial. This approach includes marginal structural modeling, instrumental variable analysis, and negative exposure control.56 The causal modeling approach provides associations that are free of confounding under certain assumptions, which can be interpreted as causal, similar to the results of a trial. To date, there had been reports on the causal associations of PM₂₅, black carbon, and NO₂ in various circumstances.57–59 Such experimental studies are necessary so as to correctly assess the effects of air pollution on health and to facilitate more effective interventions through which to reduce exposure and to mitigate the health effects of air pollution.

Finally, despite our best efforts to comprehensively summarize the study results regarding the health effects of air pollution exposure in Korea, it is possible that we did not compile a complete list of all relevant research, which should be considered a limitation of the present review.

CONCLUSION

In the present review, we presented epidemiological studies conducted in Korea examining the health effects of exposure to air pollution. For the past 2 decades, there has been a considerable accumulation of knowledge regarding air pollution and health in Korea. However, the present review highlights that additional studies, especially cohort and experimental studies, are needed to provide more robust and accurate evidence that can be used to promote evidence-based policymaking.

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AUTHOR CONTRIBUTIONS

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