Association between air pollutants and the risk of sleep disorders: A systematic review and meta-analysis

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Abstract:

Background: Sleep disorders have become prevalent, but the association between air pollutants and the risk of sleep disorders remains unclear. In this study, a meta-analysis was carried out to examine this relationship.

Methods: A systematic review and meta-analysis for publications from January 1, 2000 to February 1, 2023 was conducted to clarify the association between air pollutants and
the risk of sleep disorders.

Results: We identified 18027 articles from ScienceDirect, Web of Science, PubMed, and Embase, and 10 met our inclusion criteria. The results suggested that there were significant positive associations between PM$_{2.5}$, PM$_{10}$, NO$_2$ exposure and sleep disorders (for each 10 $\mu g$ m$^{-3}$ increment of PM$_{2.5}$, PM$_{10}$ and NO$_2$, OR: 2.50, 95% CI: 1.87–3.32; OR: 1.15, 95% CI: 1.06–1.24; OR: 1.36; 95% CI: 1.17–1.59 respectively).

Conclusions: Exposure to PM$_{2.5}$, PM$_{10}$, and NO$_2$ can lead to an increased risk of sleep disorders. Further studies with other pollutants are needed to clarify the association between air pollutants and sleep disorders.

Keywords: air pollutants; sleep disorders; insomnia; systematic review; meta-analysis

1. Introduction

Sleep accounts for one-third of human life and is vital for maintaining a healthy mental and physical state. Few physiological processes are so crucial to the health and function of the body as sleep (Tractenberg and Singer, 2007). Sleep disorders nowadays have become a widespread problem (Hong, 2013). According to WHO (World Health Organization), 27% of the world’s population suffers from it. Moreover, the Chinese Sleep Research Society survey suggests that 38.2% of Chinese adults have symptoms of sleep disorders, which has led to China being one of the countries with the highest number of sleep problems (Zhou et al., 2023). Due to difficulty falling and maintaining
asleep, snoring, and sleep apnea, sleep disorders lead to mental and physical health problems such as endocrine, metabolic, higher cortical function, and neurological disorders (Baker, 1985; Hong, 2013; Pavlova and Latreille, 2018). Furthermore, it is becoming one of the most severe health problems that have grave consequences on quality of life (Au et al., 2014; Pavlova and Latreille, 2018).

Sleep disorders can occur in many forms, of which insomnia is the most common. It also involves poor sleep quality, sleep duration problems, abnormal behavior of sleep, Obstructive sleep apnea (OSA), and so on (Zhou et al., 2023; Tung et al., 2021). Studies have shown that genetic factors can cause sleep disorders, and environmental exposure is also considered a risk factor (Dauvilliers and Tafti, 2008; Liu et al., 2021). In addition, the health effects of air pollution have become a topical issue because growing evidence has found that air pollutants can be related to sleep disorders (Hu and Guo, 2021; Li et al., 2022; Tenero et al., 2017). According to relevant studies, air pollution exposure may trigger sleep disorders by altering inflammation or affecting autonomic nervous system pathways (Perez et al., 2015; Thompson et al., 2010).

The combined effects of air pollutant exposure on the development of sleep disorders have been controversial. Several studies have found that air pollution has been related to a number of sleep disorders, such as insomnia, excessive daytime sleepiness, and prolonged sleep latency (Tsai et al., 2022; Wang et al., 2020a; Wang et al., 2020b). However, relevant data from previous studies were scattered and lack of comparison. Thus, a summary of the association between air pollution exposure and sleep disorders
in various areas is of great necessity. In this study, we reviewed the relevant literature and conducted a meta-analysis of air pollutants exposure and the risk of sleep disorders.

2. Materials and methods

2.1. Data searches and sources

We searched related publications from January 1, 2000 to February 1, 2023 using a detailed set of terms, including “air pollutants,” “sleep disorders,” “particulate matter,” “carbon monoxide,” “sulfur dioxide,” “nitrogen dioxide,” “ozone,” “poor sleep quality,” “sleep-breathing disorders,” and “insomnia,” with synonymous and truncation operators adapted to each database in ScienceDirect, Web of Science, PubMed, and Embase. Besides, there are no restrictions on air pollutants, and the detailed search strategy was provided in supplemental Table S1. The references of all included studies were also checked to avoid leaving out relevant literature.

2.2. Inclusion and exclusion criteria

The inclusion criteria for potentially eligible references were: (1) original articles that specified sleep disorders as the outcome; (2) observational/epidemiological studies, including cohort, cross-sectional and case-control studies that reported the association between air pollution exposure and sleep disorders; (3) studies which provided quantitative odds ratios (ORs) studies, relative risks (RRs), hazard ratios (HRs), and 95% confidence intervals (95% CIs). The exclusion criteria were: (1) duplicates, comments,
nonhuman studies, reviews, governmental reports, letters, or abstracts; (2) studies that did not investigate the association between air pollutants and sleep disorders. (3) studies with poor data quality or without original data.

Two independent reviewers (ZYZ, XM) screened the titles and abstracts first, and if there were no issues, the full texts were reviewed according to the criteria. Disagreements were adjudicated by consensus.

2.3. Data extraction and quality assessment

The included studies’ data were extracted by two investigators (ZYZ, XM). After filtering via titles and abstracts, we reviewed the full texts of potentially eligible articles that met the inclusion criteria. Title, authors, publication year, journal name, study design, study location, study duration, types of sleep disorders, sample size, study population, age, male proportion, the increment of air pollutants (PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, SO$_2$ and CO), odds ratios (ORs), relative risks (RRs), hazard ratios (HRs), and 95% confidence intervals (95% CIs) information were extracted from the study and recorded. Corresponding authors would be contacted if there was incomplete data. Two investigators (ZYZ, XM) independently pulled the information and estimations of included studies. The study results from all available data were extracted and recorded during data extraction. Meanwhile, we removed data from the subgroup if the article only reported subgroup results.
The quality of each cohort and case-control study was assessed using the Newcastle-Ottawa Scale (Wells et al., 2014) and cross-sectional study is evaluated with Joanna Briggs Institute checklist. The Newcastle-Ottawa Scale evaluates eight aspects of each study, with a total score of nine points. For this form of quality assessment, 0-3 points are poor, 4-6 points are medium, and 7-9 points are good. As for Joanna Briggs Institute checklist, it summarizes eight aspects of the article, with one point for each. And the corresponding article quality are assessed as low quality 0-2; moderate quality 3-5; high quality 6-8.

2.4. Statistical analysis

In this meta-analysis, we used adjusted odds ratios to evaluate the association between air pollutants and the risk of sleep disorders. Data for pollutants were standardized using a formula in the same increments: 10 μg m⁻³ for PM₂.₅, PM₁₀, O₃, NO₂, SO₂, and CO (Yang et al., 2018). The formulas for standardized ORs, RRs, HRs, LCIs, and HCIs are as follows:

\[
\text{OR}_{\text{standardized}} = \frac{\text{OR}_{\text{original}} \times \text{increment (standardized)}}{\text{increment (original)}} \quad (1)
\]

\[
\text{RR}_{\text{standardized}} = \frac{\text{RR}_{\text{original}} \times \text{increment (standardized)}}{\text{increment (original)}} \quad (2)
\]

\[
\text{HR}_{\text{standardized}} = \frac{\text{HR}_{\text{original}} \times \text{increment (standardized)}}{\text{increment (original)}} \quad (3)
\]

\[
\text{LCI}_{\text{standardized}} = \frac{\text{LCI}_{\text{original}} \times \text{increment (standardized)}}{\text{increment (original)}} \quad (4)
\]

\[
\text{HCl}_{\text{standardized}} = \frac{\text{HCl}_{\text{original}} \times \text{increment (standardized)}}{\text{increment (original)}} \quad (5)
\]

Owing to the differences between study year, study design, exposure assessment,
study area, and population, the overall effect estimates were expected to be significant variation and heterogeneity. A random effect model was applied to calculate pooled ORs due to the potential heterogeneity. Heterogeneity was tested through the $I^2$ statistics and Cochrane’s Q test. The degree of heterogeneity across trials was measured by the $I^2$ statistic, which ranges from 0% to 100%. It classified heterogeneity as low ($I^2 \leq 25\%$), moderate ($25 < I^2 < 75\%$), or high ($I^2 \geq 75\%$). A larger value of $I^2$ indicates greater heterogeneity. In general, there is heterogeneity when the P value of Q test is less than 0.05. After that, subgroup analysis was conducted to find the source of the high heterogeneity.

We performed sensitivity analyses to examine the stability of the pooled effect size by removing each study successively. And the sensitivity analyses were only conducted for the meta-analyses that included more than five studies. The forest plots summarized the ORs of each included study. Funnel plot, Begg’s and Egger’s tests were performed to examine the potential publication bias of included studies. All statistical analyses were performed using STATA version 12.

3. Results

A systemic methodology was applied for the literature search and study selection, as shown in Figure 1. From four databases, a total of 18027 articles were found. After viewing the titles and abstracts, 17995 articles were excluded. 13 duplicates were deleted. Of the other 19 articles, 10 (Chen et al., 2019; Lawrence et al., 2018; Li et al.,
Wang et al., 2020b; Xu et al., 2021; Yu et al., 2021) met our inclusion criteria after full texts were screened. Characteristics of included studies in this meta-analysis are shown in Table 1. The details of quality evaluation are shown in supplemental Table S2-S4. The average score of the cohort studies and cross-sectional studies quality evaluation were 5.86 (Newcastle-Ottawa Scale) and 6 (Joanna Briggs Institute checklist), respectively. In addition, the only case-control study included scores 6 of 9 (Newcastle-Ottawa Scale). According to the quality assessment criteria, 6 studies were rated as good, 3 as medium, and 1 as poor.
Figure 1. Flowchart of systematic literature search and study selection.
<table>
<thead>
<tr>
<th>ID</th>
<th>Study</th>
<th>Location</th>
<th>Design</th>
<th>Sample size</th>
<th>Age (years)</th>
<th>Pollutants</th>
<th>Outcome</th>
<th>Sleep measures</th>
<th>Adjustment variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chen 2019</td>
<td>China</td>
<td>Cohort</td>
<td>27417</td>
<td>18-79</td>
<td>PM$<em>{2.5}$, PM$</em>{10}$, NO$_2$</td>
<td>Poor sleep quality</td>
<td>Pittsburgh Sleep Quality Index</td>
<td>age, gender, BMI, educational attainment, smoking, drink, physical activity intensity, income</td>
</tr>
<tr>
<td>2</td>
<td>Lawrence 2018</td>
<td>China</td>
<td>Cross-sectional</td>
<td>59754</td>
<td>2-17</td>
<td>PM$<em>1$, PM$</em>{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, O$_3$, CO</td>
<td>Sleep disorder, sleep-wake transition disorders, disorders of initiating and maintaining sleep, disorders of excessive somnolence, disorders of arousal, sleep hyperhidrosis, sleep-breathing disorders</td>
<td>Sleep Disturbance Scale for Children</td>
<td>age, gender, parental education, low birth weight, premature birth, breastfeeding, income, passive smoking exposure, home coal use, house pet, district</td>
</tr>
<tr>
<td>3</td>
<td>Li 2020</td>
<td>UK</td>
<td>Cross-sectional</td>
<td>103136</td>
<td>40-69</td>
<td>PM$<em>{2.5}$, PM$</em>{10}$, NO$_2$, NOx</td>
<td>Sleep disorders</td>
<td>Touchscreen questionnaire</td>
<td>ethnicity, sex, age, BMI, the lifestyle risk factors of smoking, alcohol consumption</td>
</tr>
<tr>
<td></td>
<td>Study Year</td>
<td>Country</td>
<td>Study Type</td>
<td>Sample Size</td>
<td>Age Range</td>
<td>PM1, PM2.5, PM10, NO2</td>
<td>Sleep Disorders</td>
<td>Methodology</td>
<td></td>
</tr>
<tr>
<td>---</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>Liu 2023</td>
<td>China</td>
<td>Cohort</td>
<td>39580</td>
<td>≥45</td>
<td>PM1, PM2.5, PM10, NO2</td>
<td>Sleep disorders</td>
<td>Standard guidelines proposed by Exercise and Sleep White Paper 2021 (Chinese Sleep Research Association, 2021) and the latest evidence of sleep health proposed by Nature Ageing</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Nakhjirgan 2019</td>
<td>Iran</td>
<td>Cohort</td>
<td>31</td>
<td>23.65±9.66</td>
<td>PM2.5, PM10</td>
<td>Sleep disturbance</td>
<td>Daily living questionnaire</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Tsai 2022</td>
<td>China</td>
<td>Case-control</td>
<td>5108</td>
<td>≥18</td>
<td>PM2.5, NO2, O3</td>
<td>Insomnia</td>
<td>International Statistical Classification of Diseases and Related Health Problems diagnosis record</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wang 2020a</td>
<td>China</td>
<td>Cohort</td>
<td>27935</td>
<td>18-79</td>
<td>PM1, PM2.5, PM10, NO2</td>
<td>Prolonged sleep latency</td>
<td>Pittsburgh sleep quality index</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Wang 2020b</td>
<td>China</td>
<td>Cohort</td>
<td>27935</td>
<td>18-79</td>
<td>PM1, PM2.5, PM10, NO2</td>
<td>Excessive daytime sleepiness</td>
<td>Questionnaire through face to face interviews</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Xu 2021</td>
<td>China</td>
<td>Cohort</td>
<td>70668</td>
<td>52.2 (11.4)</td>
<td>PM1, PM2.5, PM10, NO2</td>
<td>Insomnia</td>
<td>Subscales to assess sleep quality</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Yu 2021</td>
<td>China</td>
<td>Cohort</td>
<td>38775</td>
<td>≥18</td>
<td>PM2.5, PM10, NO2</td>
<td>Incident sleep disorders</td>
<td>Electronic medical records</td>
<td></td>
</tr>
</tbody>
</table>

| Additional Variables | Age, sex, residence, marital status, education level, smoking, alcohol consumption, heating, cooking, disability, pension insurance | Age, gender, educational level, noise-related variables, major chronic diseases | Demographic characteristics, behavioral lifestyle, the history of disease and medication, mental health | Demographic characteristics, behavioral lifestyle, the history of disease and medication, mental health | Health behaviors, demographic and socioeconomic information, health-related variables and environmental factors | Demographic and lifestyle information |
The ten included studies that were published between 2018 and 2023, with eight
from China (Chen et al., 2019; Lawrence et al., 2018; Liu et al., 2023; Tsai et al., 2022;
Wang et al., 2020a; Wang et al., 2020b; Xu et al., 2021; Yu et al., 2021), one from Iran
(Nakhjirgan et al., 2019), and one from the UK (Li et al., 2020). Among them, five
studies reported sleep disorders (Lawrence et al., 2018; Li et al., 2020; Liu et al., 2023;
Nakhjirgan et al., 2019; Yu et al., 2021), and two studies reported insomnia as the
outcome (Tsai et al., 2022; Xu et al., 2021), the other three reported poor sleep quality
(Chen et al., 2019), excessive daytime sleepiness (Wang et al., 2020b), and prolonged
sleep latency (Wang et al., 2020a), respectively. In terms of study design, seven of them
are cohort studies (Chen et al., 2019; Liu et al., 2023; Nakhjirgan et al., 2019; Wang et
al., 2020a; Wang et al., 2020b; Xu et al., 2021; Yu et al., 2021), two are cross-sectional
(Lawrence et al., 2018; Li et al., 2020) and the last is case-control study (Tsai et al.,
2022). The air pollutants that have been studied the most are PM$_{2.5}$, PM$_{10}$, and NO$_{2}$. All
included studies investigated the relationship between multiple single pollutants and
sleep disorders.

A random-effects model was performed to estimate the overall risk effect. As
shown in Figures 2-4, the overall meta-analysis results prove a significant positive
association between PM$_{2.5}$, PM$_{10}$, NO$_{2}$ exposure and sleep disorders (for each 10 µg m$^{-3}$
PM$_{2.5}$, OR: 2.50, 95% CI: 1.87–3.32, I$^2$: 99.2%; each 10 µg m$^{-3}$ PM$_{10}$, OR: 1.15, 95%
CI: 1.06–1.24, I$^2$: 96.5%; and each 10 µg m$^{-3}$ NO$_{2}$, OR: 1.36; 95% CI: 1.17–1.59, I$^2$:}
95.3%). Due to insufficient relevant studies, meta-analyses for the association between other air pollutants (SO₂, O₃, CO) and sleep disorders were not conducted.

We performed sensitivity analyses to assess our results’ robustness, and the results plots are shown in Figures S1-S3. The pooled effect estimates between PM₂.₅ exposure and the risk of sleep disorders could be obviously influenced by the studies of (Tsai et al., 2022) and (Wang et al., 2020b). After removing Tsai’s article, the pooled OR and 95% CI changed from 2.50 (1.87, 3.32) to 1.55 (1.30, 1.84). Conversely, after we deleted Xu’s article, the estimated values became 2.80 (1.92, 4.10). While the analysis result of PM₁₀ and NO₂ is relatively stable. Furthermore, we found significant heterogeneity in the association between PM₂.₅, PM₁₀, NO₂ exposure and the risk of sleep disorders (I²: 96.5%, 99.2%, and 95.3%, respectively, all P values of them are less than 0.0001). The heterogeneity of these studies might be explained by the differences in race, study year, average age, study design, sample size, and sex ratio. As such we conducted subgroup analyses to explore it. The overall results of subgroup analyses are shown in Table 2. For PM₂.₅, male ratio ≤50% subgroup have smaller effect estimates and I² value for OR than male ratio >50% (OR: 1.47, 95% CI: 1.40–1.74, I²: 97.6%; OR: 55.73, 95% CI: -55.55–171.01, I²: 97.4% respectively). In addition, the subgroup whose average age >55 is more dangerous when exposed to PM₂.₅ (OR: 3.84, 95% CI: 1.80–8.16, I²: 99.4%; OR: 1.33, 95% CI: 1.14–1.56, I²: 92.7% respectively). For three types of air pollutant exposure, the yellow race has higher effect estimates (PM₂.₅ for yellow race: OR: 2.78, 95% CI: 1.97–3.91, I²: 99.4%, for white race: OR: 1.68, 95%
CI: 0.88–3.18, $I^2$: 91.1%; PM$_{10}$ for yellow race: OR: 1.16, 95% CI: 1.05–1.27, $I^2$: 97.2%, for white race: OR: 1.10, 95% CI: 1.05–1.14, $I^2$: 4.3%; NO$_2$ for yellow race: OR: 1.45, 95% CI: 1.23–1.72, $I^2$: 92.5%, for white race: OR: 1.01, 95% CI: 0.97–1.06, $I^2$: 0.0%).

Moreover, the effect estimates of the studies after 2020 are higher than that before (PM$_{2.5}$ before 2020: OR: 1.33, 95% CI: 1.20–1.47, $I^2$: 55.9%, after 2020: OR: 3.32, 95% CI: 2.23–4.94, $I^2$: 99.5%; PM$_{10}$ before 2020: OR: 1.08, 95% CI: 1.04–1.11, $I^2$: 37.0%, after 2020: OR: 1.20, 95% CI: 1.07–1.33, $I^2$: 97.2%; NO$_2$ before 2020: OR: 1.17, 95% CI: 0.98–1.39, $I^2$: 64.3%, after 2020: OR: 1.50, 95% CI: 1.22–1.86, $I^2$: 96.8%).

In addition, no publication bias was found in the studies on the association between PM$_{2.5}$, PM$_{10}$, NO$_2$ exposure, and risk of sleep disorders (Egger’s test for asymmetry, $P=0.287, 0.518, 0.274$, respectively). The funnel plots and plots of Egger’s test are shown in Figures S4-S9.
Figure 2. Combined estimates of sleep disorders with 10 μg m$^{-3}$ increase in exposure to PM$_{2.5}$.

Figure 3. Combined estimates of sleep disorders with 10 μg m$^{-3}$ increase in exposure to PM$_{10}$.
4. Discussion

There are increasing studies investigating air pollutants exposure and sleep problems. However, the relationship between them remains unclear, and no meta-analysis was performed to examine that, so we tried to fill this gap. We included ten studies in this systematic review and meta-analysis after a series of screenings. The results show that the overall associations of exposure to PM$_{2.5}$, PM$_{10}$, and NO$_2$ with sleep disorders were significantly positive. That means that PM$_{2.5}$, PM$_{10}$, and NO$_2$ exposure can affect people’s sleep somehow, and PM$_{2.5}$ exposure has a more significant effect than the other two. Subgroup analyses suggest that study design, study time,
sample size, kinds of pollutants, and demographic characteristics may be potential sources of association heterogeneity. The result of sensitivity analysis shows that the pooled association between PM$_{10}$ and NO$_2$ exposure and risk of sleep disorder was robust. No significant publication bias was observed in all included studies.

Studies have found a positive association between air pollutants and the risk of sleep disorders. The ten included studies that were published between 2018 and 2023 included eight from China (Chen et al., 2019; Lawrence et al., 2018; Liu et al., 2023; Tsai et al., 2022; Wang et al., 2020a; Wang et al., 2020b; Xu et al., 2021; Yu et al., 2021), the other two are from UK (Li et al., 2020) and Iran (Nakhjirgan et al., 2019). This study conducted a comprehensive assessment and quantified the association between air pollutant exposure and the risk of sleep disorders for the first time. The meta-analysis was performed by three types of air pollutants (PM$_{2.5}$, PM$_{10}$, NO$_2$). We found that sleep disorders were more affected by PM$_{2.5}$ exposure than by PM$_{10}$ and NO$_2$. As for the reason, fine particulate matter can penetrate into the lower respiratory tract, even alveoli, due to its smaller size and larger specific surface area, while PM$_{10}$ can only penetrate into the upper respiratory tract (Grzywa-Celińska et al., 2020; Kampa and Castanas, 2008; Ning et al., 2021). Therefore, PM$_{2.5}$ has a greater impact on human health than PM$_{10}$ (Ab. Rahman et al., 2022). Furthermore, PM$_{2.5}$ can penetrate the pulmonary epithelium and enter the circulation or interact with pulmonary receptors to induce cardiovascular responses, while inhalation of NO$_2$ does not impair vascular vasomotor or fibrinolytic function (Fiordelisi et al., 2017; Langrish et al., 2010). Moreover, PM$_{2.5}$
is the major contributor of atmospheric pollutants and can carry toxic and harmful substances, leading to more significant health effects (Chang et al., 2021; Rajagopalan et al., 2018; Li et al., 2023). This may explain the more significant effect estimates of PM$_{2.5}$ compared with PM$_{10}$ and NO$_2$.

No significant publication bias was observed in the included studies. The details of Begg’s and Egger’s tests are shown in supplemental Table S5. In addition, we conducted sensitivity analyses to assess the robustness of our results. It shows that the pooled estimates were generally robust except for the association between PM$_{2.5}$ and sleep disorders. This may be caused by different increments in included studies.

According to formula (1), minimal increment (original) may make effect estimates excessive. Then these effect estimates will have a large impact on the overall result.

We found significant heterogeneity in this meta-analysis and conducted subgroup analyses to explore the source of heterogeneity of included studies by dividing subgroups based on the study design, time, average age, sample size, race, gender ratio, and pollutant types. The subgroup analysis for average age found that older age (average age >55) subgroups are more affected by air pollution. This may be because of the more vulnerable nervous system of the elderly. In fact, air pollution can influence the central nervous system, while the central nervous system hyperarousal is considered to be associated with sleep initiation and maintenance problems (Cardinale et al., 2018; Serafini et al., 2022). Moreover, some researchers have suggested that the sympathetic tone of the human heart increases with age due to increased sympathetic nerve discharge.
and decreased neuronal uptake of noradrenaline (Esler et al., 1995; Moore et al., 2003).

The results were also striking in the subgroup with a male proportion of less than 50% in PM$_{10}$ and NO$_2$ subgroup analyses. One potential explanation is that owing to women’s smaller airways and greater airway reactivity, women are more vulnerable to air pollutant exposure (Clougherty, 2010). This makes sleep disorders more likely to occur in females. Meanwhile, women also have a higher prevalence of depression than men (Kioumourtzoglou et al., 2017). Krystal (2012) reported that the relationship between psychiatric problems and sleep disorders is interactive (Krystal, 2012). This means that emotional people, especially women, are more prone to sleep disorders.

However, owing to the large effect estimate after the standardization of Tsai’s study, the result of the PM$_{2.5}$ subgroup are opposite (Tsai et al., 2022). After removing Tsai’s article, the pooled ORs and 95% CIs became 1.47 (1.20, 1.74) (male ratio ≤50%) and 1.39 (1.27, 1.50) (male ratio >50%). The result also showed that yellow people were more likely to be affected than white people. As for race subgroup analyses, all of the studies whose samples are yellow race were conducted in China where is suffering from environmental pollution, especially ambient air pollution. Although implementing a series of emission reduction measures has effectively improved air quality, China’s air pollution is still severe (Guo et al., 2020; Zheng et al., 2018). Therefore, air pollution has a more significant impact on sleep in the yellow race. In addition, studies conducted after 2020 had even larger odds ratios. This could be explained by the fact that new coronavirus, which led to a pandemic in 2020 can damage the immune system in some
ways. In addition, the outbreak has caused mental health issues among individuals (Zhou et al., 2021). These factors make people more sensitive to air pollution exposure.

Then the state and trait type of sleep structure may be affected. (Horváth et al., 2016). We found that $I^2$ values with larger sample sizes are smaller. This shows that the research results with a large sample size are more robust. Therefore, we need more relevant studies with large samples in the future. In general, although we conducted the subgroup analyses from multiple aspects, the results did not clearly show the source of heterogeneity.

Despite great attention, the biological mechanisms between air pollutants and sleep disorders had not been clarified clearly yet. One possible mechanism is that air pollution may aggravate the obstruction of the upper respiratory tract and increase the possibility of apnea and hypoxia, affecting people’s sleep (Bourdrel et al., 2017; Losacco and Perillo, 2018). Another mechanism is that air pollutants can enter the body through the nose/smell, respiration, gastrointestinal tract, brain blood barrier, skin, mucous membrane, and placenta, then affect lymph and central nervous system after being transported in the blood and finally affect sleep (Argacha et al., 2018; Calderón-Garcidueñas and Ayala, 2022; Liu et al., 2023). In addition, inhaled “bad air” can affect body regulation, anxiety and depression (Thomson et al., 2013). From this, it is plausible that inhalation of air pollutants causes mental problems and thus sleep disorders.

This study provided scientific evidence for relevant research. The ten included
studies were all published in the past five years, which had good timeliness. We also conducted a subgroup analysis to analyze and discuss the influence of various factors. However, there are several limitations to our study. First, we did not consider the exposure duration, such as long-term and short-term exposure. Third, the methods of sleep measurement in all included studies are quite different, which may lead to inaccurate results of the pooled effect. Fourth, the heterogeneity between studies was pretty large. Nevertheless, the pooled effect shows a positive correlation between air pollutants and sleep disorders. Therefore, humans should increase their air pollution governance for their sleep health.

Table 2. Subgroup analyses based on study characteristics

<table>
<thead>
<tr>
<th>Male ratio</th>
<th>No. of estimates</th>
<th>OR (95% CI)</th>
<th>P value for OR</th>
<th>P value for heterogeneity</th>
<th>P value for subgroup differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<tr>
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<td>1.63 (1.31, 2.04) **</td>
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<td>Before 2020</td>
<td>1.33 (1.20, 1.47) **</td>
<td>0.000</td>
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<tr>
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<td>1.08 (1.04, 1.11) **</td>
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<td>1.17 (0.98, 1.39)</td>
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<td>Cohort</td>
<td>1.63 (1.31, 2.04) **</td>
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Our study illustrated that exposure to PM$_{2.5}$, PM$_{10}$, and NO$_2$ could increase the risk of sleep disorders. The ORs of PM$_{2.5}$, PM$_{10}$, and NO$_2$ were 2.50, 1.15, and 1.36, respectively, which indicated that for each additional unit of PM$_{2.5}$, PM$_{10}$, and NO$_2$ exposure, the risk of sleep disorders increased by 1.5, 0.15, and 0.36 times, respectively. Moreover, the ORs of people with an average age above 55 was 3.84, 1.21 and 1.63, respectively, which was higher than that of people with an average age below 55. This means that older people are at greater risk of sleep disorders when exposed to air pollution. The results of this study may help explain the prevalence of sleep disorders and the resulting diseases and provide scientific evidence for health hazard prevention and control of air pollution. More scientific approaches to sleep measurement are also needed for further analysis with greater accuracy.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at

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Association between long-term exposure to air pollution and sleep disorder in Chinese children: the Seven Northeastern Cities study. Sleep. 41, zsy122. https://doi.org/10.1093/sleep/zsy122


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