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REVIEW
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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 µg 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

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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, 2019). 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, 2019).

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, 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 literatures and conducted a meta-analysis of air pollutant 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 Science Direct, 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 literatures.

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), 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 studies 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 formulas in the same increments: 10 μg m^{-3} for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO (Yang *et al.*, 2018). The formulas for standardized ORs, RRs, HRs, LCIs (low confidence intervals), and HCIs (high confidence interval) are as follows:

$$OR_{\text{standardized}} = OR_{\text{original}}^{\text{increment(standardized)/increment(original)}} \quad (1)$$

$$RR_{\text{standardized}} = RR_{\text{original}}^{\text{increment(standardized)/increment(original)}} \quad (2)$$

$$HR_{\text{standardized}} = HR_{\text{original}}^{\text{increment(standardized)/increment(original)}} \quad (3)$$

$$LCI_{\text{standardized}} = LCI_{\text{original}}^{\text{increment(standardized)/increment(original)}} \quad (4)$$

$$HCI_{\text{standardized}} = HCI_{\text{original}}^{\text{increment(standardized)/increment(original)}} \quad (5)$$

Owing to the differences between study years, study designs, exposure assessments, study areas, and populations, 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. 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 Fig. 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.*, 2020; Liu *et al.*, 2023; Nakhjirgan *et al.*, 2019; Tsai *et al.*, 2022; Wang *et al.*, 2020a, 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 Tables 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.

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only

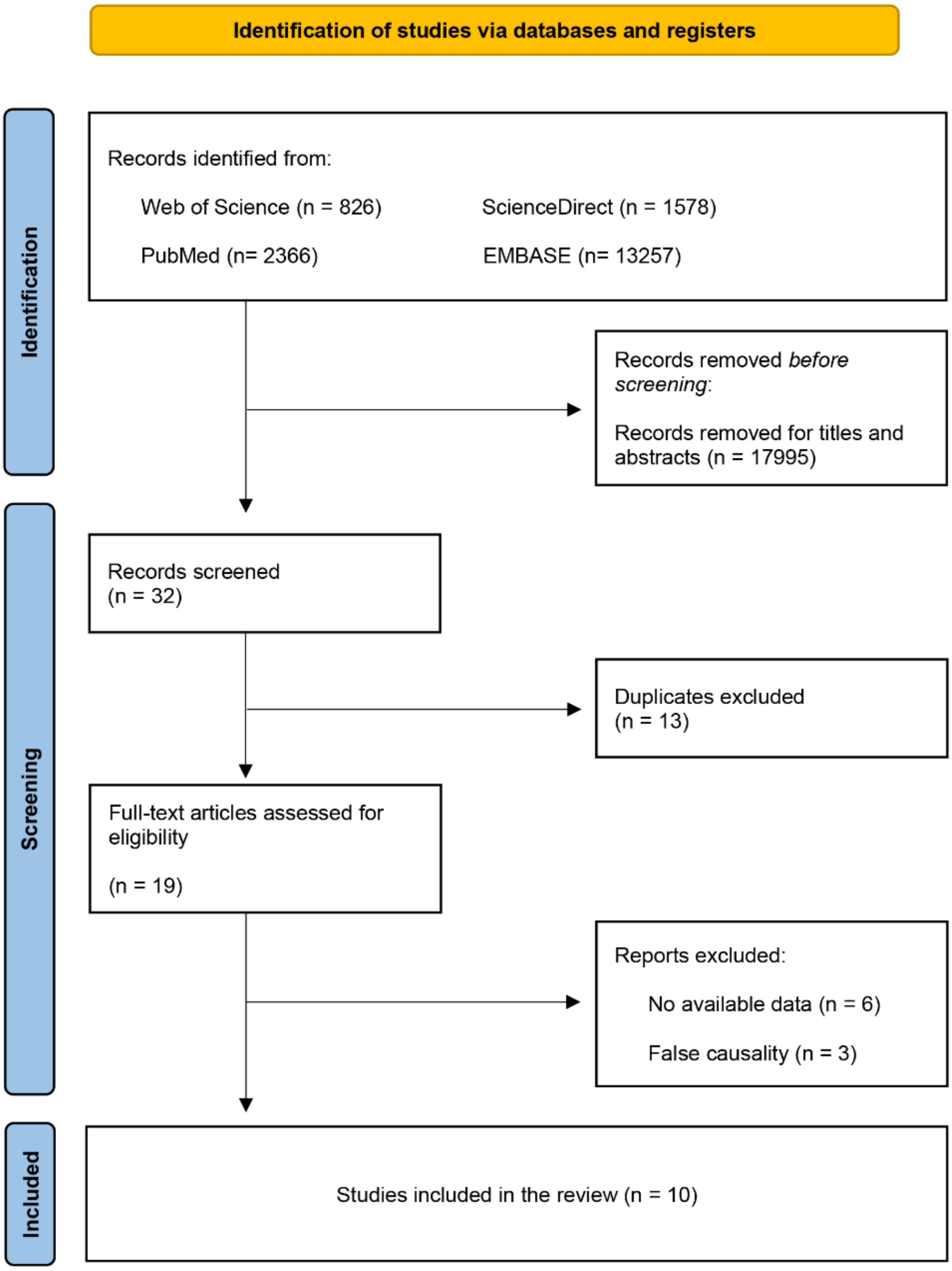

Fig. 1. Flowchart of systematic literature search and study selection.

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, 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, 2020b; Xu *et al.*, 2021;

Table 1. Basic characteristics of the included studies.

ID	Study	Location	Design	Sample size	Age (years)	Pollutants	Outcome	Sleep measures	Adjustment variables
1	Chen *et al.* (2019)	China	Cohort	27417	18–79	$PM_{2.5}$, PM_{10}, NO_2	Poor sleep quality	Pittsburgh Sleep Quality Index	age, gender, BMI, educational attainment, smoking, drink, physical activity intensity, income
2	Lawrence *et al.* (2018)	China	Cross-sectional	59754	2–17	PM_1, $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, CO	Sleep disorder, sleep-wake transition disorders, disorders of initiating and maintaining sleep, disorders of excessive somnolence, disorders of arousal, sleep hyperhidrosis, sleep-breathing disorders	Sleep Disturbance Scale for Children	age, gender, parental education, low birth weight, premature birth, breastfeeding, income, passive smoking exposure, home coal use, house pet, district
3	Li *et al.* (2020)	UK	Cross-sectional	103136	40–69	$PM_{2.5}$, PM_{10}, NO_2, NO_x	Sleep disorders	Touchscreen questionnaire	ethnicity, sex, age, BMI, the lifestyle risk factors of smoking, alcohol consumption
4	Liu *et al.* (2023)	China	Cohort	39580	≥ 45	PM_1, $PM_{2.5}$, PM_{10}, NO_2	Sleep disorders	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	age, sex, residence, marital status, education level, smoking, alcohol consumption, heating, cooking, disability, pension insurance
5	Nakhjirgan *et al.* (2019)	Iran	Cohort	31	23.65 ± 9.66	$PM_{2.5}$, PM_{10}	Sleep disturbance	Daily living questionnaire	–
6	Tsai *et al.* (2022)	China	Case-control	5108	≥ 18	$PM_{2.5}$, NO_x, O_3	Insomnia	International Statistical Classification of Diseases and Related Health Problems diagnosis record	age, gender, educational level, noise-related variables, major chronic diseases

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Table 1. (*continued*).

ID	Study	Location	Design	Sample size	Age (years)	Pollutants	Outcome	Sleep measures	Adjustment variables
7	Wang *et al.* (2020a)	China	Cohort	27935	18–79	PM_1, $PM_{2.5}$, PM_{10}, NO_2	Prolonged sleep latency	Pittsburgh sleep quality index	demographic characteristics, behavioral lifestyle, the history of disease and medication, and mental health
8	Wang *et al.* (2020b)	China	Cohort	27935	18–79	PM_1, $PM_{2.5}$, NO_2	Excessive daytime sleepiness	Questionnaire through face to face interviews	demographic characteristics, behavioral lifestyle, the history of disease and medication, mental health
9	Xu *et al.* (2021)	China	Cohort	70668	52.2 (11.4)	PM_1, $PM_{2.5}$, PM_{10}, NO_2, O_3	Insomnia	Subscales to assess sleep quality	health behaviors, demographic and socioeconomic information, health-related variables and environmental factors
10	Yu *et al.* (2021)	China	Cohort	38775	≥ 18	$PM_{2.5}$, PM_{10}, NO_2	Incident sleep disorders	Electronic medical records	demographic and lifestyle information

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 Figs. 2–4, the overall meta-analysis results prove a significant positive association between $PM_{2.5}$, PM_{10},

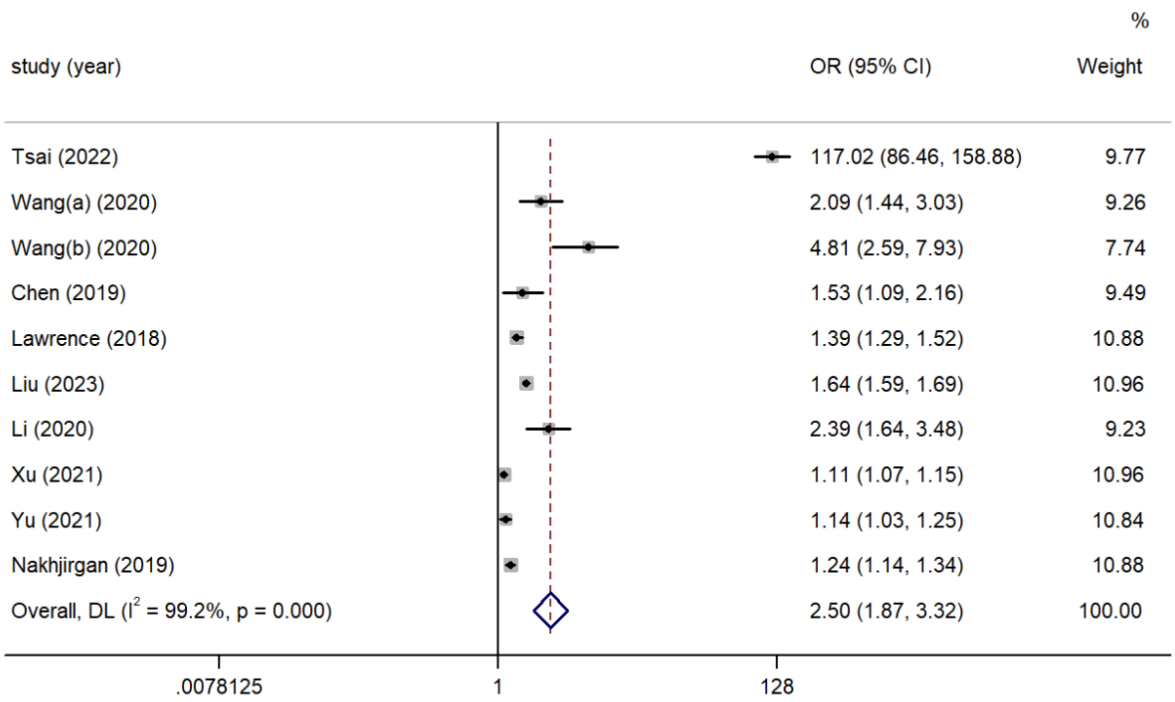

Fig. 2. Combined estimates of sleep disorders with 10 µg m^{-3} increase in exposure to $PM_{2.5}$.

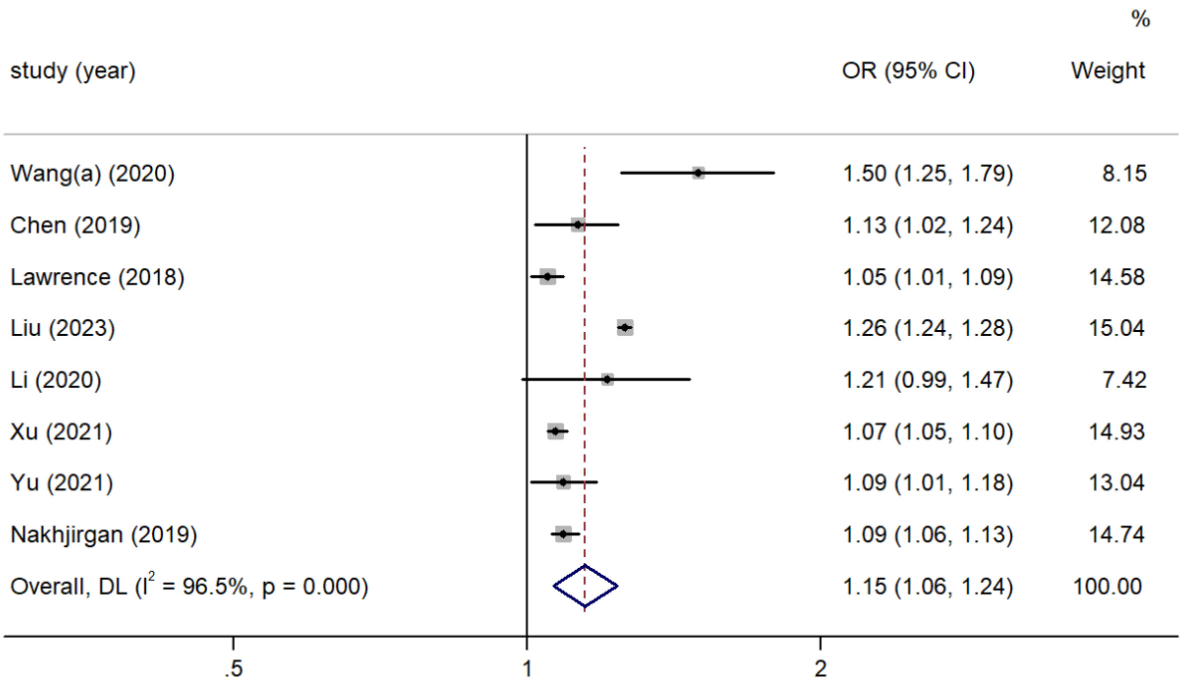

Fig. 3. Combined estimates of sleep disorders with 10 µg m^{-3} increase in exposure to PM_{10}.

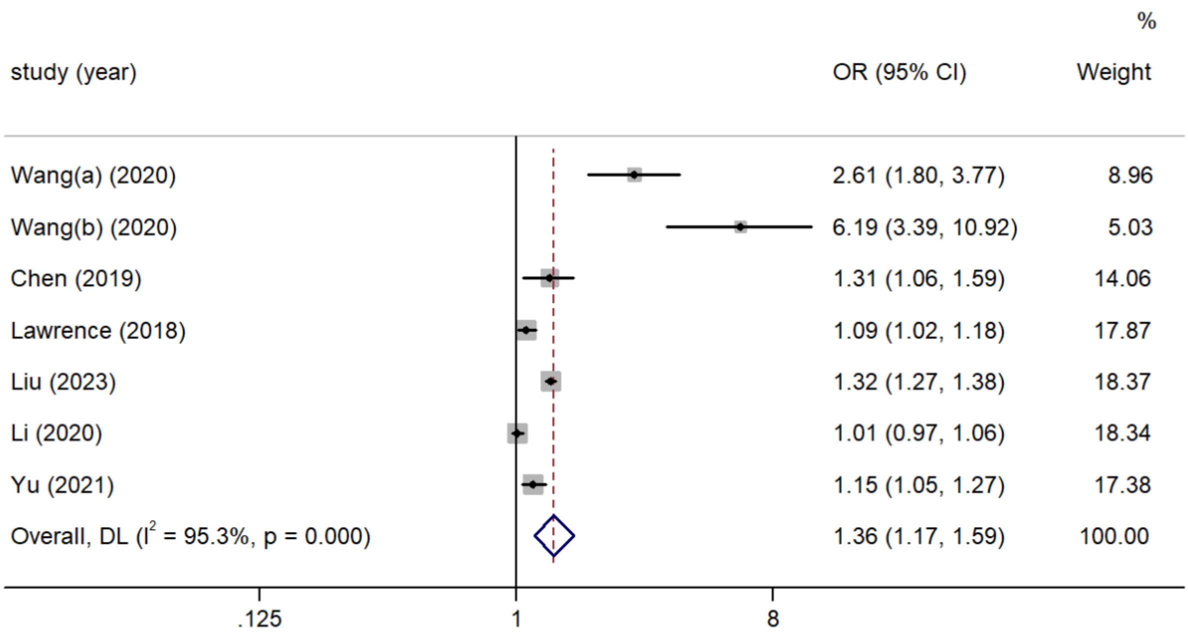

Fig. 4. Combined estimates of sleep disorders with 10 µg m^{-3} increase in exposure to NO_2.

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 (SO_2, O_3, CO) and sleep disorders were not conducted.

We performed sensitivity analyses to assess our results' robustness, and the results plots are shown in Figs. S1–S3. The pooled effect estimates between $PM_{2.5}$ 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 results of PM_{10} and NO_2 is relatively stable. Furthermore, we found significant heterogeneity in the association between $PM_{2.5}$, PM_{10}, NO_2 exposure and the risk of sleep disorders (I^2: 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 $PM_{2.5}$, male ratio $\leq$ 50% subgroup have smaller effect estimates and I^2 value for OR than male ratio > 50% (OR: 1.47, 95% CI: 1.40–1.74, I^2: 97.6%; OR: 55.73, 95% CI: -55.55–171.01, I^2: 97.4% respectively). In addition, the subgroup whose average age > 55 is more dangerous when exposed to $PM_{2.5}$ (OR: 3.84, 95% CI: 1.80–8.16, I^2: 99.4%; OR: 1.33, 95% CI: 1.14–1.56, I^2: 92.7% respectively). For three types of air pollutant exposure, the yellow race has higher effect estimates ($PM_{2.5}$ for yellow race: OR: 2.78, 95% CI: 1.97–3.91, I^2: 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 the 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 Figs. S4–S9.

Table 2. Subgroup analyses based on study characteristics.

	No. of estimates	OR (95% CI)	*p* value for OR	I^2 value	*p* value for heterogeneity	*p* value for subgroup differences
Male ratio						
$PM_{2.5}$						
≤ 50%	8	1.47 (1.40, 1.74) **	0.000	97.6%	0.000	0.330
> 50%	2	57.73 (–55.55, 171.01)	0.318	97.4%	0.000	
PM_{10}						
≤ 50%	7	1.16 (1.07, 1.26) **	0.000	96.4%	0.000	0.031
> 50%	1	1.05 (1.01, 1.09) **	0.000	0.0%	–	
NO_2						
≤ 50%	6	1.26 (1.05, 1.46) **	0.000	94.5%	0.000	0.139
> 50%	1	1.09 (1.01, 1.17) **	0.000	0.0%	–	
Average age						
$PM_{2.5}$						
≤ 55	4	1.33 (1.14, 1.56) **	0.000	92.7%	0.000	0.007
> 55	6	3.84 (1.80, 8.16) **	0.000	99.4%	0.000	
PM_{10}						
≤ 55	4	1.07 (1.05, 1.09) **	0.000	17.6%	0.303	0.019
> 55	4	1.21 (1.10, 1.34) **	0.000	85.7%	0.000	
NO_2						
≤ 55	2	1.04 (0.97, 1.12)	0.261	67.4%	0.080	0.000
> 55	5	1.63 (1.31, 2.04) **	0.000	99.6%	0.000	
Sample size						
$PM_{2.5}$						
< 40000	7	3.22 (1.93, 5.38) **	0.000	99.3%	0.000	0.005
> 40000	3	1.42 (1.12, 1.80) **	0.004	94.8%	0.000	
PM_{10}						
< 40000	5	1.18 (1.08, 1.30) **	0.000	94.9%	0.000	0.033
> 40000	3	1.07 (1.04, 1.09) **	0.000	12.4%	0.319	
NO_2						
< 40000	5	1.63 (1.31, 2.04) **	0.000	91.6%	0.000	0.000
> 40000	2	1.04 (0.97, 1.12) **	0.261	67.4%	0.080	
Race						
$PM_{2.5}$						
Yellow	8	2.78 (1.97, 3.91) **	0.000	99.4%	0.000	0.173
White	2	1.68 (0.88, 3.18)	0.114	91.1%	0.001	
PM_{10}						
Yellow	6	1.16 (1.05, 1.27) **	0.002	97.2%	0.000	0.305
White	2	1.10 (1.05, 1.14) **	0.000	4.3%	0.307	
NO_2						
Yellow	6	1.45 (1.23, 1.72) **	0.000	92.5%	0.000	0.000
White	1	1.01 (0.97, 1.06)	0.660	0.0%	–	
Time						
$PM_{2.5}$						
Before 2020	3	1.33 (1.20, 1.47) **	0.000	55.9%	0.104	0.000
After 2020	7	3.32 (2.23, 4.94) **	0.000	99.5%	0.000	
PM_{10}						
Before 2020	3	1.08 (1.04, 1.11) **	0.000	37.0%	0.205	0.072
After 2020	5	1.20 (1.07, 1.33) **	0.001	97.2%	0.000	
NO_2						
Before 2020	2	1.17 (0.98, 1.39)	0.084	64.3%	0.094	0.068
After 2020	5	1.50 (1.22, 1.86) **	0.000	96.8%	0.000	

** $0 < p < 0.01$; * $0.01 < p < 0.05$.

Table 2. *(continued).*

	No. of estimates	OR (95% CI)	*p* value for OR	I^2 value	*p* value for heterogeneity	*p* value for subgroup differences
Design						
$PM_{2.5}$						
Cohort	7	1.52 (1.24, 1.86) **	0.000	98.1%	0.000	0.000
Cross-sectional	2	1.76 (1.04, 2.99) *	0.035	86.9%	0.006	
Case-control	1	117.02 (86.32, 158.63) **	0.000	0.0%	–	
PM_{10}						
Cohort	6	1.16 (1.07, 1.27) **	0.001	97.0%	0.000	0.395
Cross-sectional	2	1.09 (0.96, 1.23)	0.169	47.6%	0.167	
NO_2						
Cohort	5	1.63 (1.31, 2.04) **	0.000	91.6%	0.000	0.000
Cross-sectional	2	1.04 (0.97, 1.12)	0.261	67.4%	0.080	
Pollutants						
$PM_{2.5}$						
≤ 3	5	4.11 (1.44, 11.71) **	0.008	99.5%	0.000	0.081
> 3	5	1.58 (1.24, 2.01) **	0.000	98.5%	0.000	
PM_{10}						
≤ 3	3	1.09 (1.06, 1.12) **	0.000	0.0%	0.787	0.165
> 3	5	1.18 (1.06, 1.32) **	0.002	97.7%	0.000	
NO_2						
≤ 3	3	1.85 (1.12, 3.07) *	0.017	93.7%	0.000	0.170
> 3	4	1.27 (1.05, 1.53) *	0.012	96.9%	0.000	

** $0 < p < 0.01$; * $0.01 < p < 0.05$.

4 DISCUSSION

There are increasing studies investigating air pollutant 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 $PM_{2.5}$, 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 the risk of sleep disorders 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, 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 $\leq$ 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 researches. The ten included studies were all published in the past five years, which had good timeliness. We also conducted subgroup analyses 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. Second, the methods of sleep measurement in all included studies are quite different, which may lead to inaccurate results of the pooled effect. Third, 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.

5 CONCLUSION

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 analyses with greater accuracy.

ADDITIONAL INFORMATION AND DECLARATIONS

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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Supplementary Material

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