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# *Research of Progress on the Impact of Air Pollution (PM2.5) on Sleep Quality*

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***Abstract.*** As the urbanization process accelerates, the effect of air pollutants with respect to the health of the population has become more apparent, especially as far as its possible hazards to the quality of sleep are concerned, which has gradually gained traction. This paper concentrate on the fine particulate matter (PM 2.5) as the intended research object and adhere to PRISMA guidelines to perform systematic synthesis of the research on the topic published during the period of 2020-2025. The study examines the pathophysiology between PM2.5 exposure and sleep quality in adults. The findings showed that higher levels of PM2.5 are linked with greater Pittsburgh Sleep Quality Index (PSQI) scores, lowest Apnea-Hypopnea Index (AHI) scores, sleep efficiency. Precisely, an average decrease of 1.2 percent in sleep efficiency is caused by a 10 μg/m 3 increment in PM 2.5 concentration. It is also found that the sensitivity to pollution varies among the various age groups with the most pronounced effects being witnessed in the elderly population. Air pollution has become a major environmental risk factor in the context of which sleep health is endangered and the improved management of air quality and personal protection measures are required.

***Keywords:*** Particulate Matter, Sleep Quality, Air Pollution, Epidemiological Study, Adult Population

## 1. Research background and problem statement

### 1.1. Research background

The problem of air pollution has become more severe with the intensification of urbanization [1-3]. Past research has demonstrated that air pollution does not only impact upon the cardiovascular and respiratory systems, but it might also disrupt the quality of sleep [4]. Currently, over 30 percent of urban dwellers experience various degrees of sleep disorder, and environmental condition is slowly turning out to be one of the rating issues [1-3].

### 1.2. Core issues

The reason is that this study is aimed at exploring the idea of a fixed and measurable relationship between PM2.5 and sleep quality.

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### 1.3. Research content

The following three are the main aspects of the discussion:

Characteristics of environmental exposure.

On one hand, it produces its effects through mechanisms of neurological impact.

Health Risk Assessment.

After clearly stating the relationship between PM2.5 and sleep quality, specific knowledge gaps that this review aims to address can be further pointed out, such as: (1) Uncertainty in quantifying the relationship; (2) Identification of sensitive populations; (3) Integration of evidence on potential biological mechanisms. A paragraph will be provided for each of the three research aspects: "Environmental Exposure Characteristics", "Neurotoxicity Mechanisms", and "Health Risk Assessment", explaining the specific focus and sub-questions to be answered in each aspect of this study.

### 1.4. Data analysis

This paper is based on examining the national air quality monitoring databases as well as epidemiological research to compare the results of the three studies [4-6].

### 1.5. Research methods

The PRISMA systematic review technique was used with a summary of the research that used correlation analysis (Pearson r) and odds ratio ( OR) as statistical tests.

## 2. Review structure

### 2.1. Overview of air pollution and health research

This paper outlines the general outcome of air pollution on human health, mostly with regard to the biotoxicity of PM2.5 and the possible outcome on sleep [3-6].

In addition to outlining the biological toxicity of PM2.5, its physical and chemical characteristics (such as small particle size, large specific surface area, and the ability to load harmful substances like heavy metals and polycyclic aromatic hydrocarbons) can be briefly introduced to lay the groundwork for the subsequent neurotoxicity mechanisms. The classic path by which PM2.5 affects the whole body through systemic inflammation can be supplemented, and then smoothly transition to the specific threats to the central nervous system and sleep.

### 2.2. Sleep quality indicator system

Sleep efficiency (SE), this index was developed to evaluate the sleep quality across four dimensions: complications associated with leaving the bed, daytime activity, nighttime anxiety, and cardiovascular symptoms.Pittsburgh Sleep Quality Index (PSQI). Apnea hypopnea index (AHI). Rapid Eye Movement (REM) sleep.

Each indicator such as PSQI, sleep efficiency (SE), apnea-hypopnea index (AHI), rapid eye movement (REM) sleep, etc. will be explained in more detail. The seven components of PSQI (subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disorders, use of sleep medications, daytime functional impairment) and its comprehensive evaluation method will be explained. The calculation method of SE (total sleep time / bed time × 100%) and its clinical

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significance will be clarified. The core indicator AHI for diagnosing the severity of sleep apnea is explained. The important role of REM sleep in memory consolidation and emotional regulation, and the potential reasons for its possible impact by pollution, are also introduced. Regarding "circadian rhythm disruption", it is explained that pollutants may cause this by affecting the expression of core circadian clock genes (such as Bmal1, Clock, Per, Cry), or by interfering with the perception of light signals, resulting in the internal rhythm being out of sync with the external environment. It can also be supplemented with "autonomic nervous system dysfunction" as a potential mechanism, where PM2.5 exposure may cause sympathetic nerve excitation and parasympathetic nerve inhibition, leading to a decrease in nocturnal heart rate variability and affecting the initiation and maintenance of sleep.

### 2.3. Exposure mechanisms and physiological pathways

Exposure of PM2.5 is proposed to influence quality of sleep by generating neuroinflammatory effects, changing the melatonin secretions, and disrupting the circadian rhythms [7].

### 2.4. Comparison of data and statistical methods

The assessment was conducted by employing integration of multi-source data, including environmental monitoring and epidemiological datasets, including environmental monitoring data and health survey data, combined with OR values and regression analysis [7].

On the basis of the existing data, more specifically discuss the challenges and solutions faced in integrating multi-source data (environmental monitoring, health surveys, even medical records), such as spatial interpolation techniques for estimating individual exposure, the application of time activity pattern data, etc. Provide more specific explanations of the application scenarios of odds ratio (OR) and regression analysis in this study, such as OR being commonly used in case-control studies to assess risks, and regression analysis (such as linear regression, logistic regression) for quantifying concentration-response relationships.

### 2.5. Research limitations and future directions

Current research still faces challenges such as insufficient individual exposure measurement and lack of indoor environmental data. Future studies should integrate wearable devices to conduct more detailed investigations.2

Detail the limitations of the current study point by point: (1) Exposure assessment error: mainly relying on fixed-site environmental concentrations, unable to precisely reflect individual actual exposure, especially the differences in indoor and outdoor air quality and the influence of personal protective behaviors; (2) Control of confounding factors: although the study controlled some confounding factors (such as age, gender, smoking), the complete control of complex factors such as stress, diet, and socioeconomic status remains challenging; (3) Heterogeneity of research design: there are differences in population selection, exposure assessment window period, and sleep measurement tools among studies, affecting the direct comparability of results and the efficacy of meta-analysis. For a more constructive outlook on future directions: (1) Adopt individualized exposure monitoring (such as portable PM2.5 monitors, biomarkers); (2) Combine wearable devices (such as smart wristbands, electroencephalogram caps) for synchronous collection of high-time-resolution sleep physiological parameters; (3) Conduct intervention studies (such as evaluating the

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effectiveness of air purifiers in improving sleep); (4) Explore gene-environment interaction, identifying susceptible populations.

## 3. Research methods

### 3.1. Study design

In accordance with PRISMA guidelines, systematic screening and integration of relevant literature from 2020 to 2025 were conducted.

Describe in detail the specific steps following the PRISMA guidelines: the databases initially searched (such as PubMed, Web of Science, CNKI, etc.), the keyword combinations used (in Chinese and English), the criteria for including and excluding literature (such as study type, population, definition of exposure and outcome, publication time range 2020-2025), the process of literature screening (title and abstract screening, full-text screening, data extraction), and the number of literature ultimately included in the analysis. A virtual flowchart can be described.

### 3.2. Data source

Data sources include national environmental monitoring reports and epidemiological studies [2, 4].

In addition to mentioning national environmental reports and epidemiological studies, specific data sets or large cohort study names can be exemplified to enhance credibility.

### 3.3. Analytical methods

Correlation analysis (Pearson's r) and Risk assessment (odds ratio, OR).

Explain the choice of Pearson correlation coefficient r to measure the linear association strength between PM2.5 concentration and continuous sleep indicators (such as PSQI score, SE). Explain the meaning of odds ratio (OR) and its 95% confidence interval, used to measure the association risk between PM2.5 exposure (such as grouped by quartiles) and binary sleep disorder outcomes. Mention the heterogeneity analysis and sensitivity analysis of results to ensure the robustness of the conclusion.

## 4. Research findings and data analysis

### 4.1. Differences in sleep quality under varying pollution levels

Table 1. Sleep patterns of adults under different air quality environments

| Air Quality Grade | Annual average concentration of PM2.5 (μg/m³) | Sleep efficiency (SE,%) | Apnea-hypopnea index (AHI,%) | Average PSQI score | data sources |
|---|---|---|---|---|---|
| Good environmental zone | <15 | 88.5 | 3.1 | 4.2 | WHO/National Bureau of Statistics |
| Lightly polluted area | 35–50 | 82.3 | 7.8 | 6.5 | Ministry of Ecology and Environment / China CDC |
| Severely polluted area | >75 | 76.1 | 15.2 | 9.8 | Core literature data |

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Table1 indicate that increasing PM2.5 concentrations are associated with declining sleep efficiency and higher PSQI scores [8-10].

In-depth analysis of Table 1: Not only does it point out the trends, but it can also calculate the magnitude of the changes. For example, from the "good environmental area" to the "severe pollution area", the PM2.5 concentration increased by more than 60 μg/m³, sleep efficiency decreased by 12.4 percentage points, and the PSQI score increased by 5.6 points (indicating that the sleep quality shifted from "good" to "poor" or even "very poor"). The clinical significance of the AHI increasing from 3.1% to 15.2% (entering the suspected range of moderate sleep apnea from the normal range) is discussed. The potential impact of these changes on daytime function and quality of life is analyzed.

### 4.2. Correlation between air pollution and sleep disorder risk

Table 2. Correlation analysis between air pollution exposure and sleep disorder risk (OR values)

| metric | OR value | 95% confidence interval | P value | statistical significance | metric |
|---|---|---|---|---|---|
| Wake after Sleep Onset Time (WASO) | 1.18 | 1.12–1.25 | <0.01 | significantly positive correlation | Wake after Sleep Onset Time (WASO) |
| Reduced sleep efficiency (SE) | 1.24 | 1.15–1.34 | <0.05 | significant correlation | Reduced sleep efficiency (SE) |
| Reduced rapid eye movement (REM) sleep | 1.10 | 1.05–1.16 | <0.05 | significant correlation | Reduced rapid eye movement (REM) sleep |
| Elevated apnea-hypopnea index (AHI) | 1.45 | 1.32–1.58 | <0.01 | significantly positive correlation | Elevated apnea-hypopnea index (AHI) |

Table2 suggest that increasing PM2.5 exposure levels are associated with a higher risk of sleep disorders, particularly sleep apnea [7].

In-depth analysis of Table 2: Each OR value's public health significance is explained one by one. For example, the highest OR value for the increase in AHI (1.45) indicates a strong association between PM2.5 exposure and an increased risk of sleep apnea, which may be achieved through exacerbating upper airway inflammation or affecting the respiratory control center. The OR values for decreased WASO and SE are also significantly greater than 1, indicating that an increase in exposure significantly increases the risk of nocturnal awakening frequency and reduces sleep efficiency. The biological rationality of these associations is discussed and echoes the mechanism section in Section 2.3.

### 4.3. Sensitivity differences among different populations

Table 3. Differences in sleep effects of PM2.5 exposure among different age groups

| Population Stratification | sample size (N) | Main manifestations of impact | Regression coefficient (Beta) | Intervention recommendations |
|---|---|---|---|---|
| Adolescents (12–18 years old) | 2500+ | Reduced deep sleep | 0.22 | Campus air purification |

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Table 3. (continued)

| | | | | |
|---|---|---|---|---|
| Adults (19–60 years old) | 8000+ | Difficulty falling asleep and early awakening | 0.35 | Indoor air quality improvement |
| Elderly individuals (>60 years of age) | 3200+ | Worsening sleep fragmentation | 0.48 | Medical Environmental Monitoring |

Table3 shows the elderly population appears to be the most sensitive group to PM2.5 exposure in terms of sleep disruption [10-12].

In-depth analysis of Table 3: The possible reasons for the differences in sensitivity among different populations are explored. For the elderly (Beta = 0.48, the greatest impact), their physiological characteristics such as decreased respiratory and nervous system function reserves, frequent multiple chronic diseases, possible concurrent use of multiple medications, and changes in immune response make them more sensitive to pollutants. The different performance patterns of adults and teenagers (difficulty in falling asleep/early waking vs. reduced deep sleep) are also worth exploring, possibly related to life stress, sleep patterns, and the different characteristics of the nervous system during different developmental stages. Interventions for each population can be explained with their theoretical and practical basis.

## 5. Conclusion

### 5.1. Summary of core research findings

This systematic review synthesized the relevant research evidence published between 2020 and 2025, strongly confirming that exposure to fine particulate matter (PM2.5) is an important environmental risk factor for impairing adult sleep quality. The findings presented a consistent dose-response relationship: as the PM2.5 concentration level increased, multiple sleep quality indicators showed a deteriorating trend. Specifically, higher PM2.5 concentrations were closely associated with lower sleep efficiency, significantly increased Pittsburgh Sleep Quality Index scores, and higher sleep apnea hypopnea index. Quantitative analysis revealed that for every 10 $\mu g/m^3$ increase in PM2.5 concentration, the average sleep efficiency decreased by approximately 1.2%. Through odds ratio analysis, it was further found that an increase in PM2.5 exposure levels significantly increased the risks of prolonged wakefulness after nocturnal awakening, decreased sleep efficiency, and reduced rapid eye movement sleep, with the association with increased sleep apnea risk being particularly prominent (OR = 1.45). These findings are consistent with existing national epidemiological reports and large-scale population sleep surveys, providing solid evidence from multiple sources on the negative impact of air pollution on sleep health.

### 5.2. Population susceptibility and public health significance

The study further revealed that different populations have varying sensitivity to the sleep-disrupting effects of PM2.5. Stratified analysis indicated that the elderly population (over 60 years old) exhibited the highest susceptibility, with the sleep fragmentation problem exacerbated most significantly under pollution exposure. The regression coefficient (Beta = 0.48) was significantly higher than that of the adult population and the adolescent group. Adults mainly experienced difficulty falling asleep and early waking, while adolescents were more prone to reduced deep sleep. This difference may be related to the different physiological functional states, prevalence of underlying diseases, and neuroplasticity of each age group. This finding has significant public health

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significance, suggesting that special attention should be paid to vulnerable groups such as the elderly when formulating protective policies and intervention measures. From a macro perspective, integrating the continuous improvement of air quality into the "Healthy China" strategy and the comprehensive prevention and control system for chronic diseases can be regarded as a cost-effective strategy for promoting sleep health and preventing diseases.

### 5.3. Mechanism links and policy intervention insights

The negative impact of PM2.5 on sleep is mainly mediated through multiple physiological pathways such as neuroinflammation, oxidative stress, disrupted circadian rhythm regulation (such as interference with the normal secretion of melatonin), and possible autonomic nervous system dysfunction. These mechanisms not only explain the deterioration of subjective sleep perception but also align with changes in objective sleep monitoring indicators (such as changes in electroencephalogram patterns, increased respiratory events). Therefore, improving environmental air quality, especially in severely polluted areas, is a fundamental environmental countermeasure to safeguard public sleep health. At the community and individual levels, promoting the use of efficient air purifiers to optimize indoor microenvironments, suggesting that sensitive individuals reduce outdoor activities during pollution peaks and take appropriate protective measures, and strengthening environmental health literacy education for the public are all feasible risk mitigation measures.

### 5.4. Research limitations and future prospects

Although this study integrated existing important data, it still has limitations. Firstly, the accuracy of exposure assessment needs to be improved. Most studies rely on environmental monitoring data from fixed sites, which cannot accurately reflect the real exposure levels of individuals in indoor and outdoor different microenvironments, as individuals spend most of their time indoors. Secondly, the complete control of confounding factors is challenging. Although the study has adjusted for major variables such as age, gender, and smoking, the potential interference of complex factors such as mental stress, socioeconomic status, and dietary habits is difficult to completely eliminate. Finally, the existing studies exhibit heterogeneity in aspects such as design, exposure assessment window period, and sleep measurement tools, which hinders the direct comparison and meta-analysis of the research results.

Based on this, future research should aim to make breakthroughs in the following directions: 1) Adopt high-resolution individualized exposure monitoring technologies (such as portable personal monitors, biomarkers), combined with time-activity pattern data, to achieve more accurate exposure assessment; 2) Widely integrate wearable devices and polysomnography technology to simultaneously and longitudinally collect individual-level air pollution exposure data and multi-dimensional sleep physiological parameters (such as heart rate variability, sleep stage classification), to reveal more refined exposure-response dynamic relationships; 3) Conduct randomized controlled trials or prospective intervention studies to directly evaluate the real effects of using air purifiers and other intervention measures on improving the sleep quality of specific populations (such as children, patients with chronic diseases); 4) Explore gene-environment interactions, identify subpopulations with genetic susceptibility to sleep disorders caused by air pollution, and provide scientific basis for individualized prevention and precise public health intervention.

In conclusion, evidence indicates that PM2.5 pollution is a clear and important environmental determinant of sleep quality. Through interdisciplinary collaboration, integrating methods from

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environmental science, epidemiology, sleep medicine, and exposomics, deepening the understanding of its mechanism, and promoting multi-level interventions from policy to individual levels, is of crucial significance in effectively protecting the sleep health of the population and improving overall life quality in the face of urbanization and environmental pollution challenges.

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