

Effects of Particulate Matter on Obstructive Sleep Apnea and Obesity

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With accelerated global urbanization, understanding the impact of pollutant emissions and air pollution on obstructive sleep apnea (OSA) and obesity has become increasingly important. Particulate matter (PM) is a major component of air pollution. Recent studies have reported that PM influences OSA, obesity, and obesity-related metabolic disorders. The primary mechanisms proposed to underlie the effects of PM on OSA involve chronic inflammation and oxidative stress in the nasal epithelia. Regarding obesity, PM induces chronic inflammation in the hypothalamus, adipose tissue, skeletal muscle, and mitochondria; oxidative stress in white adipose tissue, the lungs, and the thyroid; activation of lipogenesis genes; changes in adipose tissue distribution; dysbiosis of the intestinal microbiome; and disruption of circadian rhythms. Therefore, reducing air pollution, including PM concentrations, represents a potential strategy for treating OSA and obesity and preventing related complications. Further prospective longitudinal studies in human participants are needed to clarify the effects of PM on the risk of OSA and obesity and to elucidate the underlying mechanisms.

Keywords: Particulate matter; Air pollution; Obstructive sleep apnea; Obesity; Metabolic syndrome.

INTRODUCTION

Obstructive sleep apnea (OSA) is the most common sleep disorder, characterized by repeated airway obstruction during sleep [1]. This condition is recognized as a risk factor for multiple health complications, including cardiovascular disease (CVD), metabolic syndrome, depression, and impaired cognitive function [2,3].

Risk factors for OSA include craniofacial abnormalities, male sex, obesity, aging, and air pollution [4-6]. Of these, obesity has been rapidly increasing worldwide, becoming a major public health concern [5,6]. Among the factors influencing obesity, air pollution—a physical environmental risk factor—has emerged as a major contributor to the global disease burden [7]. This has prompted growing interest in the health impacts of particulate matter (PM), the primary component of air pollution. Recent studies suggest that PM plays

a significant role in overweight, obesity, and obesity-related metabolic diseases. Exposure to PM affects both central and peripheral tissues involved in energy metabolism regulation [8], and these metabolic changes can shift systemic energy balance toward storage [9]. However, some cross-sectional studies have found that exposure to pollutants such as PM does not significantly contribute to obesity [10].

Because the upper respiratory tract—including the nasal passages and upper airway—represents the first entry point for inhaled contaminants [11], air pollution, including PM, has also become recognized as a key risk factor for OSA. The proposed mechanisms by which PM may induce OSA are chronic inflammation and oxidative stress [11].

Both OSA and obesity are risk factors for CVD and share several pathophysiological mechanisms [1]. However, studies on the effects of PM on OSA and obesity have produced inconsistent results, and the underlying mechanisms remain unclear. Therefore, this review aims to comprehensively examine the effects of PM on OSA and obesity and to elucidate the associated mechanisms, aiming to improve awareness and understanding of this issue.

Received: March 19, 2025 **Revised:** April 14, 2025

Accepted: April 16, 2025

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PM

Definition and characteristics

PM, the main component of air pollutants, is composed of inorganic substances (e.g., metals, non-metals, transition metals), organic compounds (e.g., carbon, polycyclic aromatic hydrocarbons, quinones), and aqueous components [10]. PM is classified based on its diameter into $PM_{0.1}$, $PM_{2.5}$, PM_{10} , and PM_{100} [12]. Among these, $PM_{2.5}$ —particles with a diameter of 2.5 μm or less—constitutes the majority of ambient PM [13]. Due to its large surface area relative to particle size and high chemical reactivity, $PM_{2.5}$ readily carries toxic substances and remains suspended in air for extended periods [14]. Furthermore, once inhaled, $PM_{2.5}$ deposits efficiently in the alveoli and can penetrate capillaries to enter the systemic circulation [15]. Reflecting these harmful properties, the US Environmental Protection Agency and the European Union use PM concentrations as key indicators when assessing the health risks of air pollution [16], and the World Health Organization includes PM in its revised guidelines on air pollutants [17]. Moreover, in 2013, the International Agency for Research on Cancer classified outdoor air pollution and PM as Group 1 carcinogens [18].

Human inhalation process

During inspiration, inhaled PM enters the lungs and activates alveolar macrophages [19], inducing an inflammatory response [8]. These particles can then traverse the epithelial-capillary barrier to enter systemic circulation and reach peripheral tissues via endocytosis [20]. Quantifying and clearing PM deposition in the respiratory tract is crucial for assessing health risks [21]. A previous study reported $PM_{2.5}$ deposition rates of 80% in the head and nasal region, 7% in the tracheo-bronchial region, and 13% in the alveolar region [22]. Thus, the relatively high deposition of $PM_{2.5}$ in the nasal passages has been suggested to correlate with OSA.

PM AND OSA

Impact of PM on OSA

PM exposure has been linked to an increased risk of sleep-breathing disorders, including OSA [23], although findings remain inconsistent [1]. For instance, one study found that long-term exposure to $PM_{2.5}$ was significantly associated with increased time spent with arterial oxygen saturation (SpO_2) below 90% ($T < 90$; $\Delta\% = 10.2$, $p = 0.04$) and a lower nadir SpO_2 ($\Delta\% = -0.9$, $p = 0.03$) [1]. In a large US cohort, an interquartile range increase of 14.5 $\mu g/m^3$ in mean PM_{10} exposure corresponded to a 13% rise in the respiratory disturbance index [24]. Another study reported that short-term (1 month) ex-

posure to $PM_{2.5}$ and PM_{10} was significantly associated with greater odds of OSA manifestation, with odds ratios (ORs) of 1.47 (95% confidence interval [CI], 1.34–1.62) for $PM_{2.5}$ and 1.17 (95% CI, 1.02–1.34) for PM_{10} [25]. Moreover, several investigations have suggested that air pollutants aggravate OSA severity. A review found that nitrogen dioxide (NO_2), ozone, and PM were each associated with elevated apnea-hypopnea index (AHI) and oxygen desaturation index [26]. In another analysis, each 1- $\mu g/m^3$ increase in average $PM_{2.5}$ level was linked to a 1.04–1.08-fold increase in the OR for AHI—across 1-, 7-, and 30-day exposure windows—in both mild-to-moderate and severe OSA cases [27]. However, heterogeneity in exposure duration, season, climate, and nation of study (as indicated in a systematic review covering various air pollutants, such as $PM_{2.5}$, PM_{10} , and NO_2), likely contributes to the conflicting results observed among studies [28]. Another systematic review and meta-analysis concluded that the effects of $PM_{2.5}$ and NO_2 on the risk of OSA are ambiguous [3]. Moreover, studies that have shown correlations between PM and OSA exhibit limitations, including the use of univariable analyses or inadequate adjustment for confounders. These potential confounders include seasonal variations in temperature and humidity, which can impact air pollution levels; differences between developing and developed countries, indoor air quality, and exposure to other pollutants [1,24,29,30]. Additionally, upper airway irritants and seasonal allergic reactions may both exert effects [16]. Diseases such as allergic rhinosinusitis can modulate the severity of sleep apnea, a factor that should be considered in future examinations of the relationship between air pollution and OSA [16]. Future time-series analyses with multiple follow-up points are required to clarify the impact of PM on OSA.

Mechanisms by which PM affects OSA

Long-term exposure to environmental pollutants has cumulative adverse effects that contribute to the development of chronic diseases, including obesity and OSA [31]. Although the exact mechanisms linking PM exposure to OSA remain to be fully defined, evidence points to two principal mechanisms: chronic inflammation and oxidative stress.

Chronic inflammation

High levels of inhaled PM are believed to disrupt the nasal mucociliary clearance system, which normally traps and eliminates particles [16]. Young adults who relocate from rural to urban settings have been shown to exhibit inflammatory changes in their nasal epithelia [32]. In animal models, PM exacerbates pulmonary inflammation and increases mucus secretion, leading to upper airway edema and elevated airway resistance [33]. PM can also induce inflammatory reactions

in nasal epithelial cells, contributing to chronic rhinosinusitis and upper airway obstruction [34,35]. Moreover, the patency of the upper airway is influenced by the disruption of the sinonasal epithelial cell barrier [36]. This disruption triggers a persistent inflammatory process through the activation of pro-inflammatory pathways, further degrading barrier integrity and perpetuating inflammation [37]. Increased nasal resistance from this inflammation has been implicated in the pathogenesis of OSA [37]. Furthermore, the relationship between upper airway inflammation and OSA may be bidirectional, where the oxygen desaturation and altered lung ventilation seen in OSA can themselves sustain a low-grade inflammatory state [38].

Oxidative stress

As one study reported, exposure to $PM_{2.5}$ and PM_{10} can increase oxidative stress, exacerbating nocturnal hypoxia [39]. PM contains pro-oxidant molecules that disrupt mitochondrial respiratory chains, generating reactive oxygen species (ROS) [40] and inducing oxidative damage in nasopharyngeal and other cells. These mechanisms may impact ventilation and perfusion, aggravating the hypoxia associated with OSA.

PM AND OBESITY

Impact of PM on obesity

PM adversely affects both environmental quality and human health. Epidemiological and animal studies indicate that exposure to PM—especially $PM_{2.5}$ —promotes weight gain, suggesting that PM acts as an obesogen (a substance that promotes obesity) and a risk factor for obesity [41,42]. A meta-analysis found that each $10 \mu g/m^3$ increase in PM concentration corresponded to a 1.16-fold higher risk of obesity (95% CI, 1.11–1.21) [43]. In an 8-year longitudinal cohort study of 3.9 million US veterans, every $10 \mu g/m^3$ increase in annual average PM concentration was linked to an average weight gain of 10 pounds (approximately 4.54 kg; hazard ratio [HR], 1.07; 95% CI, 1.06–1.08) and an increased clinical risk of obesity (HR, 1.08; 95% CI, 1.06–1.11) [44]. Similarly, a cross-sectional study of over 47,000 Chinese adults reported that each $10 \mu g/m^3$ increase in PM concentration was associated with higher odds of general obesity (OR, 1.12; 95% CI, 1.09–1.14) and abdominal obesity (OR, 1.10; 95% CI, 1.07–1.13) [45]. In animal studies, PM-exposed mice developed greater subcutaneous and visceral fat mass than control animals breathing filtered air [42]. However, some cross-sectional analyses have found no significant association between PM exposure and obesity or markers of lipid metabolism [46]. These inconsistencies may reflect limited cumulative PM exposure in younger adults (aged 17–22 years) or methodological constraints, such as the reliance on area-level administrative data on PM concentrations,

despite the fact that approximately 70% of the participants were university students, with no verification of whether they lived in dormitories and no data regarding time spent outside of their residence [46].

Mechanisms by which PM affects obesity

Although the precise mechanisms linking PM exposure to obesity remain unclear, considerable research suggests that chronic inflammation and oxidative stress play major roles in this relationship. In addition, several other potential mechanisms have been proposed (Fig. 1) [47].

Chronic inflammation

PM can induce both local and systemic chronic inflammatory responses, contributing to obesity and metabolic disorders. Evidence indicates that PM exposure is associated with a greater increase in markers of systemic inflammation (such as C-reactive protein [CRP] level and white blood cell count) among individuals with obesity than in controls without obesity [48]. Moreover, a study of 52 children (mean age, 8.6 ± 0.1 years) from Mexico City—an area with high PM levels—reported significant elevations in inflammatory mediators compared with Polotitlán, a city with low levels. These mediators included tumor necrosis factor alpha (TNF- α), prostaglandin E₂, CRP, interleukin-1 beta, and endothelin-1 [49].

Through various mechanisms, this chronic inflammation impacts the hypothalamus, adipose tissue, skeletal muscles, and mitochondria, causing functional impairments that ultimately lead to obesity.

First, PM can induce hypothalamic inflammation. The hypothalamus integrates hormonal, environmental, and neural signals to regulate systemic energy balance and metabolic efficiency [50]. Three pathways have been proposed for PM entry into the central nervous system: 1) translocation via olfactory epithelial neurons; 2) disruption of the gut microbiota and the gut-brain axis; and 3) upregulation of pro-inflammatory mediators in the bloodstream.

The resulting hypothalamic inflammation then increases appetite, reduces energy expenditure, and induces leptin resistance, ultimately contributing to obesity [51]. Hypothalamic inflammation is also linked to insulin resistance [52] and inhibits thermogenesis and energy expenditure in brown adipose tissue [53], promoting weight gain [54]. In one animal study, PM exposure increased the expression of inflammatory markers such as TNF- α , inhibitor of nuclear factor kappa-B kinase- β , and nuclear factor kappa B in the paraventricular nucleus [55].

Second, PM induces inflammation in adipose tissue. As shown in a previous study, PM exposure suppresses the expression of anti-inflammatory M2 genes and promotes pro-

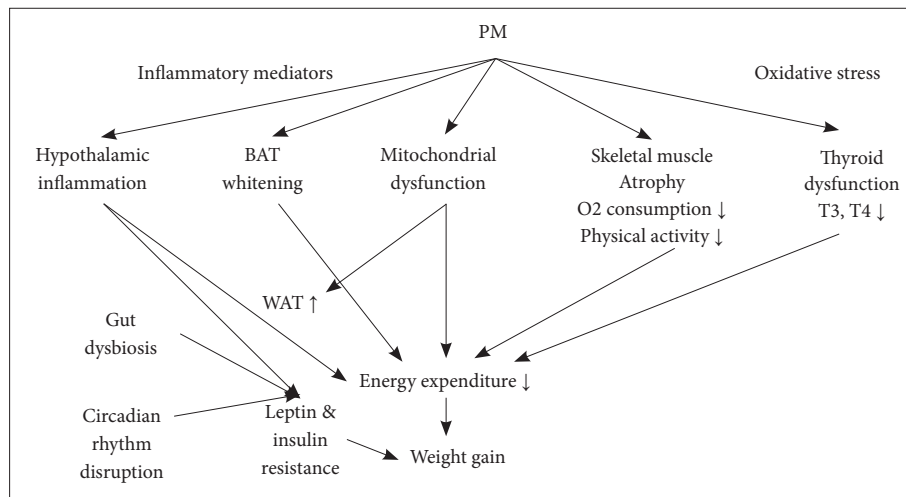


Fig. 1. Schematic diagram showing the mechanism by which PM affects obesity. The mechanisms by which PM impacts obesity appear to include chronic inflammation in organs associated with energy metabolism, oxidative stress, activation of adipogenic genes, changes in adipose tissue distribution, gut microbiota imbalance, and disruption of circadian rhythms. Adapted from Della Guardia L, Wang L. Fine particulate matter induces adipose tissue expansion and weight gain: pathophysiology. *Obes Rev* 2023;24(4):e13552 [47] under the terms of the Creative Commons License. BAT, brown adipose tissue; PM, particulate matter; T3, triiodothyronine; T4, thyroxine; WAT, white adipose tissue.

inflammatory (M1) gene expression, driving adipose inflammation and metabolic disturbance [42]. It also increases macrophage infiltration into adipose depots, exacerbating local inflammation [42]. Cross-sectional data indicate that people with obesity have higher baseline adipose inflammation and are more susceptible to PM-induced inflammatory responses [56]. Increased levels of pro-inflammatory factors due to PM exposure can lead to inflammation in white adipose tissue, increased fat production, and “whitening” of brown adipose tissue [57]. In particular, the last of these is believed to be caused by inflammation within the tissue [8].

Third, PM-induced inflammation can impair mitochondrial function in endothelial cells [58], cardiomyocytes [40], skeletal myocytes [59], and both white and brown adipocytes [60]. The proposed mechanism involves pro-inflammatory mediators disrupting mitochondrial respiratory chain complexes, leading to mitochondrial dysfunction [61,62]. This phenomenon impairs mitochondrial DNA replication [63] and alters fusion/fission dynamics [64]. Through inflammation, chronic PM exposure significantly reduces the number and size of mitochondria in both white and brown adipose tissue [61], impairing glucose and lipid oxidation, leading to triglyceride accumulation and adipocyte hypertrophy, and ultimately causing obesity [61,65].

Fourth, skeletal muscle plays a key role in energy metabolism [66]. Chronic PM-induced inflammation drives muscle protein degradation and mitochondrial dysfunction in these tissues [67,68]. Additionally, pro-inflammatory factors and dysfunction in white adipose tissue can increase insulin resis-

tance in muscles, contributing to muscle atrophy [69,70]. Recent human studies have demonstrated that chronic PM exposure adversely affects muscle mass and physical function [71,72]. Moreover, PM-related cardiopulmonary and neurophysiological effects increase sedentary behavior and discourage physical activity, furthering the deterioration of muscle mass and function [9]. A separate study similarly shows that increased PM concentrations can discourage outdoor activity, potentially leading to weight gain [73]. Animal studies also suggest that PM exposure induces inflammatory changes in the muscle microvasculature, causing functional impairment [74,75]. Specifically, PM exposure promotes inflammation in the microvascular endothelium and surrounding smooth muscle, impairing vasodilation, inducing mitochondrial dysfunction, and promoting muscle atrophy [76,77].

Oxidative stress

Oxidative stress plays a key mediating role in the development of PM-induced obesity [78]. PM contains various pro-oxidant molecules that disrupt mitochondrial respiratory chains, generating ROS [61] and causing oxidative injury in various tissues and cells, including white adipose tissue, the lungs, and the thyroid [79]. Elevated ROS levels in white adipose tissue promote triglyceride accumulation and inhibit breakdown, resulting in expansion of white fat depots and reduction of brown adipose tissue. These changes impair metabolism, decrease insulin sensitivity, and contribute to obesity [80]. In fact, exposure to air pollution has been associated with abnormalities in signaling pathways related to insulin re-

sistance [42,80]. In an animal study, PM exposure reduced Akt (protein kinase B) levels, increased endothelial nitric oxide synthase phosphorylation, and upregulated protein kinase C in endothelial cells [42]. Recent research also indicated that PM exposure elevates xanthine concentrations in murine white adipose tissue, further driving oxidative stress [80]. Furthermore, interventions that reduce pulmonary oxidative stress—such as antioxidant treatments or overexpression of extracellular superoxide dismutase—have been shown to alleviate PM-induced insulin resistance in mice, further suggesting that oxidative stress contributes to insulin resistance [76]. Additionally, PM-driven oxidative injury can impact thyroid function and reduce circulating levels of thyroid hormones [81,82]. The thyroid plays a central role in energy metabolism, and dysfunction in thyroid hormone synthesis and secretion can lead to obesity [50]. Epidemiological studies have linked chronic exposure to high levels of PM with thyroid dysfunction and reduced serum thyroid hormone levels [81,82]. In rodents, PM exposure induces oxidative stress in thyroid follicles, diminishing follicular epithelial cells and enlarging follicular cavities; consequently, thyroid hormone synthesis and secretion are impaired [83]. Moreover, thyroid dysfunction induced by PM exposure leads to the “whitening” of brown adipose tissue [84].

Activation of adipogenesis-related genes and changes in adipose tissue distribution

PM exposure activates genes involved in adipogenesis and alters adipose tissue distribution [85–87]. Animal studies have demonstrated that long-term exposure to PM upregulates genes governing lipogenesis, adipocyte differentiation, and lipid droplet formation in adipose tissue [85], resulting in larger adipocytes, increased visceral fat mass, and obesity [85,86]. In particular, PM exposure increases the expression of key adipogenic markers, such as acetyl-CoA carboxylase and diacylglyceride acyltransferase-2, in white adipose tissue [87]. It also increases the expression of pro-adipogenic transcription factors, including peroxisome proliferator-activated receptor- γ and cyclic adenosine monophosphate response element-binding protein- α , in murine models [87].

Gut microbiota imbalance

Imbalances in the gut microbiota may play a mediating role in the relationship between PM and obesity, as well as other metabolic diseases [88–91]. Previous studies have shown that inhalation of air pollutants, including PM, can alter microbial diversity and relative abundance, compromise intestinal barrier integrity, and trigger increased gastrointestinal inflammation via chronic endotoxemia [88]. Moreover, certain gut microbiota patterns have been observed in patients with obesity and disorders of glucose and lipid metabolism, implicating

the gut microbiome in metabolic processes [89]. Population-based analyses further indicate that the gut microbiota partially mediates the association between PM exposure and obesity or metabolic diseases, such as disorders of glucose and lipid metabolism [90,91].

Disruption of circadian rhythms

PM exposure can influence circadian rhythms, indirectly leading to obesity [92,93]. Recent data have shown that circadian rhythm disruption leads to metabolic syndrome, including the dysregulation of energy homeostasis and insulin resistance, and is linked to PM exposure [92]. Another study reported that 10 weeks of PM exposure disrupted the oscillations of clock genes in both white and brown adipose tissues [92]. A separate investigation also observed changes in major clock genes (*Per1-3*, *Rev-erba*, and *Bmal1*), accompanied by increased inflammation and oxidative stress in the plasma and lungs [93].

Factors affecting exposure to PM

When analyzing the effects of PM on obesity, it is important to consider factors such as the age of exposure, cumulative effects, and regional variations.

Age of exposure and cumulative effects

Multiple studies indicate that the obesogenic impact of PM varies by age, with children and adolescents being especially vulnerable [43,46]. A meta-analysis reported that the risk of obesity from PM exposure was higher among those under 18 years (relative risk [RR], 1.24; 95% CI, 1.09–1.38) than in adults (RR, 1.10; 95% CI, 1.09–1.20) [43]. This heightened susceptibility in youth likely reflects incomplete lung development and greater time spent engaging in outdoor activities [43,46]. However, research has indicated that older adults may be more adversely affected by aspects of PM exposure [44], potentially from the cumulative effects of heavy metals in these pollutants [94]. Most human studies on the impact of PM on obesity have focused on short-term PM exposure (<1 month), and although long-term exposure is hypothesized to exert a stronger obesogenic influence [95], reports on the cumulative effects of long-term exposure are rare. One cross-sectional study indicated a correlation between 1 year of PM exposure and higher blood insulin and total cholesterol levels, although no significant correlation with obesity was found [96].

Regional variations

The health impact of PM exposure varies by region. A meta-analysis found a statistically significant association between PM and obesity in Asia (RR, 1.09; 95% CI, 1.06–1.12), whereas results for Europe (RR, 1.12; 95% CI, 0.99–1.27) and the

Table 1. Key findings from human studies on the effects of particulate matter on OSA and obesity

OSA	OSA manifestations ↑ [25] OSA symptoms and severity ↑ [26] - Time spent with SpO ₂ <90% (T<90) ↑ [1] - Lowest SpO ₂ (Δ%=-0.9, p=0.03) ↑ [1] - Respiratory disturbance index ↑ [24] - Apnea-hypopnea index ↑ [26] - Oxygen desaturation index ↑ [26]
Obesity	Risk of obesity ↑ [43] Increased risk of weight gain (10 lb, approximately 4.54 kg) ↑ [44] Abdominal obesity ↑ [45]

OSA, obstructive sleep apnea; SpO₂, arterial oxygen saturation

United States (RR, 1.36; 95% CI, 0.85–2.18) did not reach significance [43]. Additionally, the effects of PM were stronger in developing countries (RR, 1.17; 95% CI, 1.12–1.23) than in developed nations (RR, 1.10; 95% CI, 1.03–1.18) [43]. These regional differences likely stem from the impacts of industrialization and development.

Interaction between PM and obesity

Although PM exposure promotes obesity, obesity may also magnify the harmful effects of PM. Epidemiological evidence suggests that individuals with obesity exhibit greater sensitivity to PM-related health risks [46]. In this population, PM exposure shows stronger associations with chronic obstructive pulmonary disease [97], hypertension [98], CVDs [99,100], and coronavirus disease 2019 severity [101]. This increased vulnerability may stem from elevated baseline proinflammatory cytokine levels in those with obesity following PM exposure, making them particularly vulnerable to PM-induced inflammation [102].

Table 1 summarizes key findings from human studies regarding the effects of PM on OSA and obesity.

CONCLUSION

With accelerated global urbanization, growing industrial and vehicular emissions have contributed to air pollution, which is increasingly impacting OSA and obesity [12]. Current evidence details PM exposure as a newly identified risk factor for these conditions. Discrepancies among studies likely stem from differences in research design; methods of measuring and quantifying PM, OSA, and obesity; regional and participant characteristics; sample size biases; and residual confounding.

Accordingly, strategies to tackle the global burden of OSA and obesity must consider exposure to air pollution, includ-

ing PM, and incorporate measures to reduce PM concentrations. Improving air quality could become a key strategy in the treatment of OSA and obesity and in the prevention of related complications. At a policy level, national public health initiatives and preventive measures that lower human exposure to PM—and thus its associated health risks—are urgently needed to lessen the socioeconomic and medical impact of these disorders. However, most current research relies on animal models. Large-scale, long-term human studies are necessary to clarify the impact of PM on the risk of OSA and obesity and to elucidate the underlying mechanisms. Future work should also examine whole-body impacts, extending beyond individual organs, and explore how PM interacts with energy metabolism pathways and hormonal regulation.

Ultimately, however, as indicated by the maxim “you are where you live,” one’s risk of OSA or obesity is likely shaped by their surrounding environment.

Ethics Statement

Not applicable

Availability of Data and Material

Data sharing not applicable to this article as no datasets were generated or analyzed during the study.

Conflicts of Interest

The author has no potential conflicts of interest to disclose.

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Funding Statement

This research was supported by the Chung-Ang University Research Grant in 2025.

Acknowledgments

None

REFERENCES

- 1) Pengo MF, Iodice S, Parati G, Meriggi P, Bollati V, Lombardi C. Fine particulate matter and sleep-disordered breathing severity in a large Italian cohort. *Sleep Breath* 2024;28(1):371-5.
- 2) Eastwood PR, Malhotra A, Palmer LJ, Kezirian EJ, Horner RL, Ip MS, et al. Obstructive sleep apnoea: from pathogenesis to treatment: current controversies and future directions. *Respirology* 2010;15(4):587-95.
- 3) Alrahbeni T, Gupta JK, Alkhouri A, Kumar LA, Mahal A, Al-Mugeheed K, et al. Association of air pollution with risk and severity of obstructive sleep apnea: a systematic review and meta-analysis. *Neurotoxicology* 2024;102:106-13.
- 4) Senaratna CV, Perret JL, Lodge CJ, Lowe AJ, Campbell BE, Matheson MC, et al. Prevalence of obstructive sleep apnea in the general population: a systematic review. *Sleep Med Rev* 2017;34:70-81.
- 5) Lee SD, Kang SH, Ju G, Han JW, Kim TH, Lee CS, et al. The prevalence of and risk factors for sleep-disordered breathing in an elderly Korean population. *Respiration* 2014;87(5):372-8.
- 6) Young T, Peppard PE, Taheri S. Excess weight and sleep-disordered

- breathing. *J Appl Physiol* (1985) 2005;99(4):1592-9.
- 7) World Health Organization. WHO ambient air pollution: a global assessment of exposure and burden of disease. Geneva: World Health Organization; 2016.
 - 8) Della Guardia L, Shin AC. White and brown adipose tissue functionality is impaired by fine particulate matter (PM_{2.5}) exposure. *J Mol Med (Berl)* 2022;100(5):665-76.
 - 9) An R, Xiang X. Ambient fine particulate matter air pollution and leisure-time physical inactivity among US adults. *Public Health* 2015;129(12):1637-44.
 - 10) Jia YY, Wang Q, Liu T. Toxicity research of PM_{2.5} compositions in vitro. *Int J Environ Res Public Health* 2017;14(3):232.
 - 11) Senaratna CV, English DR, Currier D, Perret JL, Lowe A, Lodge C, et al. Sleep apnoea in Australian men: disease burden, co-morbidities, and correlates from the Australian longitudinal study on male health. *BMC Public Health* 2016;16(Suppl 3):1029.
 - 12) Pryor JT, Cowley LO, Simonds SE. The physiological effects of air pollution: particulate matter, physiology and disease. *Front Public Health* 2022;10:882569.
 - 13) Yang J, Zhou M, Li M, Yin P, Hu J, Zhang C, et al. Fine particulate matter constituents and cause-specific mortality in China: a nationwide modelling study. *Environ Int* 2020;143:105927.
 - 14) Pope CA 3rd, Coleman N, Pond ZA, Burnett RT. Fine particulate air pollution and human mortality: 25+ years of cohort studies. *Environ Res* 2020;183:108924.
 - 15) Li D, Li Y, Li G, Zhang Y, Li J, Chen H. Fluorescent reconstitution on deposition of PM_{2.5} in lung and extrapulmonary organs. *Proc Natl Acad Sci U S A* 2019;116(7):2488-93.
 - 16) Künzli N, Kaiser R, Medina S, Studnicka M, Chanel O, Filliger P, et al. Public-health impact of outdoor and traffic-related air pollution: a European assessment. *Lancet* 2000;356(9232):795-801.
 - 17) World Health Organization. WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021.
 - 18) Straif K, Cohen A, Samet J. Air Pollution and Cancer. IARC Scientific Publication No. 161. Lyon: International Agency for Research on Cancer; 2013.
 - 19) Champion JA, Mitragotri S. Role of target geometry in phagocytosis. *Proc Natl Acad Sci U S A* 2006;103(13):4930-4.
 - 20) Su R, Jin X, Li H, Huang L, Li Z. The mechanisms of PM_{2.5} and its main components penetrate into HUVEC cells and effects on cell organelles. *Chemosphere* 2020;241:125127.
 - 21) Manoj Kumar N, Srimuruganandam B, Shiva Nagendra SM. Quantification of size segregated particulate matter deposition in human airways. *Journal of Advanced Research in Alternative Energy, Environment and Ecology* 2018;5(4):15-22.
 - 22) Gupta SK, Elumalai SP. Size-segregated particulate matter and its association with respiratory deposition doses among outdoor exercisers in Dhanbad City, India. *J Air Waste Manag Assoc* 2017;67(10):1137-45.
 - 23) Billings ME, Gold D, Szpiro A, Aaron CP, Jorgensen N, Gassett A, et al. The association of ambient air pollution with sleep apnea: the multi-ethnic study of atherosclerosis. *Ann Am Thorac Soc* 2019;16(3):363-70.
 - 24) Zanobetti A, Redline S, Schwartz J, Rosen D, Patel S, O'Connor GT, et al. Associations of PM₁₀ with sleep and sleep-disordered breathing in adults from seven U.S. urban areas. *Am J Respir Crit Care Med* 2010;182(6):819-25.
 - 25) Lawrence WR, Yang M, Zhang C, Liu RQ, Lin S, Wang SQ, et al. Association between long-term exposure to air pollution and sleep disorder in Chinese children: the Seven Northeastern Cities study. *Sleep* 2018;41(9):zsy122.
 - 26) Cao B, Chen Y, McIntyre RS. Comprehensive review of the current literature on impact of ambient air pollution and sleep quality. *Sleep Med* 2021;79:211-9.
 - 27) Bai KJ, Liu WT, Lin YC, He Y, Lee YL, Wu D, et al. Ambient relative humidity-dependent obstructive sleep apnea severity in cold season: a case-control study. *Sci Total Environ* 2023;861:160586.
 - 28) Clark DPQ, Son DB, Bowatte G, Senaratna CV, Lodge C, Perret JL, et al. The association between traffic-related air pollution and obstructive sleep apnea: a systematic review. *Sleep Med Rev* 2020;54:101360.
 - 29) Weinreich G, Wessendorf TE, Pundt N, Weinmayr G, Hennig F, Moebus S, et al. Association of short-term ozone and temperature with sleep disordered breathing. *Eur Respir J* 2015;46(5):1361-9.
 - 30) Shen YL, Liu WT, Lee KY, Chuang HC, Chen HW, Chuang KJ. Association of PM_{2.5} with sleep-disordered breathing from a population-based study in Northern Taiwan urban areas. *Environ Pollut* 2018;233:109-13.
 - 31) Coogan PF, White LF, Jerrett M, Brook RD, Su JG, Seto E, et al. Air pollution and incidence of hypertension and diabetes mellitus in black women living in Los Angeles. *Circulation* 2012;125(6):767-72.
 - 32) Calderon-Garcidueñas L, Rodriguez-Alcaraz A, Garcia R, Sanchez G, Barragan G, Camacho R, et al. Human nasal mucosal changes after exposure to urban pollution. *Environ Health Perspect* 1994;102(12):1074-80.
 - 33) Fu C, Lu H, Wu X, Liu J, Liu C, Liu Z, et al. Chronic intermittent hypoxia decreases pulmonary clearance of 99mTc-labelled particulate matter in mice. *Am J Transl Res* 2017;9(6):3060-72.
 - 34) Tam WW, Wong TW, Ng L, Wong SY, Kung KK, Wong AH. Association between air pollution and general outpatient clinic consultations for upper respiratory tract infections in Hong Kong. *PLoS One* 2014;9(1):e86913.
 - 35) Teng B, Zhang X, Yi C, Zhang Y, Ye S, Wang Y, et al. The association between ambient air pollution and allergic rhinitis: further epidemiological evidence from Changchun, Northeastern China. *Int J Environ Res Public Health* 2017;14(3):226.
 - 36) Cho DY, Le W, Bravo DT, Hwang PH, Illek B, Fischer H, et al. Air pollutants cause release of hydrogen peroxide and interleukin-8 in a human primary nasal tissue culture model. *Int Forum Allergy Rhinol* 2014;4(12):966-71.
 - 37) Kim SH, Won HK, Moon SD, Kim BK, Chang YS, Kim KW, et al. Impact of self-reported symptoms of allergic rhinitis and asthma on sleep disordered breathing and sleep disturbances in the elderly with polysomnography study. *PLoS One* 2017;12(2):e0173075.
 - 38) Kheirandish-Gozal L, Gozal D. Obstructive sleep apnea and inflammation: proof of concept based on two illustrative cytokines. *Int J Mol Sci* 2019;20(3):459.
 - 39) Wang X, Chen M, Zhong M, Hu Z, Qiu L, Rajagopalan S, et al. Exposure to concentrated ambient PM_{2.5} shortens lifespan and induces inflammation-associated signaling and oxidative stress in *Drosophila*. *Toxicol Sci* 2017;156(1):199-207.
 - 40) Li R, Kou X, Geng H, Xie J, Tian J, Cai Z, et al. Mitochondrial damage: an important mechanism of ambient PM_{2.5} exposure-induced acute heart injury in rats. *J Hazard Mater* 2015;287:392-401.
 - 41) Madrigano J, Baccarelli A, Wright RO, Suh H, Sparrow D, Vokonas PS, et al. Air pollution, obesity, genes and cellular adhesion molecules. *Occup Environ Med* 2010;67(5):312-7.
 - 42) Sun Q, Yue P, Deiluiis JA, Lumeng CN, Kampfrath T, Mikolaj MB, et al. Ambient air pollution exaggerates adipose inflammation and insulin resistance in a mouse model of diet-induced obesity. *Circulation* 2009;119(4):538-46.
 - 43) Lin L, Li T, Sun M, Liang Q, Ma Y, Wang F, et al. Global association between atmospheric particulate matter and obesity: a systematic review and meta-analysis. *Environ Res* 2022;209:112785.
 - 44) Bowe B, Gibson AK, Xie Y, Yan Y, Donkelaar AV, Martin RV, et al. Ambient fine particulate matter air pollution and risk of weight gain

- and obesity in United States Veterans: an observational cohort study. *Environ Health Perspect* 2021;129(4):47003.
- 45) Chen R, Yang C, Li P, Wang J, Liang Z, Wang W, et al. Long-term exposure to ambient PM_{2.5}, sunlight, and obesity: a nationwide study in China. *Front Endocrinol (Lausanne)* 2022;12:790294.
 - 46) Sacks JD, Stanek LW, Luben TJ, Johns DO, Buckley BJ, Brown JS, et al. Particulate matter-induced health effects: who is susceptible? *Environ Health Perspect* 2011;119(4):446-54.
 - 47) Della Guardia L, Wang L. Fine particulate matter induces adipose tissue expansion and weight gain: pathophysiology. *Obes Rev* 2023; 24(4):e13552.
 - 48) Dubowsky SD, Suh H, Schwartz J, Coull BA, Gold DR. Diabetes, obesity, and hypertension may enhance associations between air pollution and markers of systemic inflammation. *Environ Health Perspect* 2006;114(7):992-8.
 - 49) Calderón-Garcidueñas L, Villarreal-Calderon R, Valencia-Salazar G, Henríquez-Roldán C, Gutiérrez-Castrellón P, Torres-Jardón R, et al. Systemic inflammation, endothelial dysfunction, and activation in clinically healthy children exposed to air pollutants. *Inhal Toxicol* 2008;20(5):499-506.
 - 50) Tran LT, Park S, Kim SK, Lee JS, Kim KW, Kwon O. Hypothalamic control of energy expenditure and thermogenesis. *Exp Mol Med* 2022;54(4):358-69.
 - 51) Ying Z, Xu X, Bai Y, Zhong J, Chen M, Liang Y, et al. Long-term exposure to concentrated ambient PM_{2.5} increases mouse blood pressure through abnormal activation of the sympathetic nervous system: a role for hypothalamic inflammation. *Environ Health Perspect* 2014;122(1):79-86.
 - 52) Sáinz N, Barrenetxe J, Moreno-Aliaga MJ, Martínez JA. Leptin resistance and diet-induced obesity: central and peripheral actions of leptin. *Metabolism* 2015;64(1):35-46.
 - 53) Campolim CM, Weissmann L, Ferreira CKO, Zordão OP, Dornellas APS, de Castro G, et al. Short-term exposure to air pollution (PM_{2.5}) induces hypothalamic inflammation, and long-term leads to leptin resistance and obesity via Tlr4/Ikbke in mice. *Sci Rep* 2020;10(1):10160.
 - 54) Scherer T, Sakamoto K, Buettner C. Brain insulin signalling in metabolic homeostasis and disease. *Nat Rev Endocrinol* 2021;17(8):468-83.
 - 55) Liu C, Fonken LK, Wang A, Maiseyeu A, Bai Y, Wang TY, et al. Central IKK β inhibition prevents air pollution mediated peripheral inflammation and exaggeration of type II diabetes. *Part Fibre Toxicol* 2014;11:53.
 - 56) Pan WW, Myers MG Jr. Leptin and the maintenance of elevated body weight. *Nat Rev Neurosci* 2018;19(2):95-105.
 - 57) Cheru L, Saylor CF, Lo J. Gastrointestinal barrier breakdown and adipose tissue inflammation. *Curr Obes Rep* 2019;8(2):165-74.
 - 58) Hill BG, Rood B, Ribble A, Haberzettl P. Fine particulate matter (PM_{2.5}) inhalation-induced alterations in the plasma lipidome as promoters of vascular inflammation and insulin resistance. *Am J Physiol Heart Circ Physiol* 2021;320(5):H1836-50.
 - 59) Stephenson EJ, Ragauskas A, Jaligama S, Redd JR, Parvathareddy J, Peloquin MJ, et al. Exposure to environmentally persistent free radicals during gestation lowers energy expenditure and impairs skeletal muscle mitochondrial function in adult mice. *Am J Physiol Endocrinol Metab* 2016;310(11):E1003-15.
 - 60) Xu Z, Xu X, Zhong M, Hotchkiss IP, Lewandowski RP, Wagner JG, et al. Ambient particulate air pollution induces oxidative stress and alterations of mitochondria and gene expression in brown and white adipose tissues. *Part Fibre Toxicol* 2011;8:20.
 - 61) Soberanes S, Urich D, Baker CM, Burgess Z, Chiarella SE, Bell EL, et al. Mitochondrial complex III-generated oxidants activate ASK1 and JNK to induce alveolar epithelial cell death following exposure to particulate matter air pollution. *J Biol Chem* 2009;284(4):2176-86.
 - 62) Costa Beber LC, da Silva MOAF, Dos Santos AB, Mai AS, Goettsme-
 - Fiorin PB, Frizzo MN, et al. The association of subchronic exposure to low concentration of PM_{2.5} and high-fat diet potentiates glucose intolerance development, by impairing adipose tissue antioxidant defense and eHSP72 levels. *Environ Sci Pollut Res Int* 2020;27(25): 32006-16.
 - 63) Breton CV, Song AY, Xiao J, Kim SJ, Mehta HH, Wan J, et al. Effects of air pollution on mitochondrial function, mitochondrial DNA methylation, and mitochondrial peptide expression. *Mitochondrion* 2019;46:22-9.
 - 64) Li R, Kou X, Geng H, Xie J, Yang Z, Zhang Y, et al. Effect of ambient PM(2.5) on lung mitochondrial damage and fusion/fission gene expression in rats. *Chem Res Toxicol* 2015;28(3):408-18.
 - 65) Giordano A, Frontini A, Cinti S. Convertible visceral fat as a therapeutic target to curb obesity. *Nat Rev Drug Discov* 2016;15(6):405-24.
 - 66) Zurlo F, Larson K, Bogardus C, Ravussin E. Skeletal muscle metabolism is a major determinant of resting energy expenditure. *J Clin Invest* 1990;86(5):1423-7.
 - 67) Meng SJ, Yu LJ. Oxidative stress, molecular inflammation and sarcopenia. *Int J Mol Sci* 2010;11(4):1509-26.
 - 68) Lang CH, Frost RA, Nairn AC, MacLean DA, Vary TC. TNF-alpha impairs heart and skeletal muscle protein synthesis by altering translation initiation. *Am J Physiol Endocrinol Metab* 2002;282(2):E336-47.
 - 69) Abbatecola AM, Paolisso G, Fattoretti P, Evans WJ, Fiore V, Dicio-cio L, et al. Discovering pathways of sarcopenia in older adults: a role for insulin resistance on mitochondria dysfunction. *J Nutr Health Aging* 2011;15(10):890-5.
 - 70) Kalinkovich A, Livshits G. Sarcopenic obesity or obese sarcopenia: a cross talk between age-associated adipose tissue and skeletal muscle inflammation as a main mechanism of the pathogenesis. *Ageing Res Rev* 2017;35:200-21.
 - 71) Nurkiewicz TR, Porter DW, Barger M, Castranova V, Boegehold MA. Particulate matter exposure impairs systemic microvascular endothelium-dependent dilation. *Environ Health Perspect* 2004; 112(13):1299-306.
 - 72) Chen CH, Huang LY, Lee KY, Wu CD, Chiang HC, Chen BY, et al. Effects of PM_{2.5} on skeletal muscle mass and body fat mass of the elderly in Taipei, Taiwan. *Sci Rep* 2019;9(1):1176.
 - 73) An R, Zhang S, Ji M, Guan C. Impact of ambient air pollution on physical activity among adults: a systematic review and meta-analysis. *Perspect Public Health* 2018;138(2):111-21.
 - 74) Rundell KW, Hoffman JR, Caviston R, Bulbulian R, Hollenbach AM. Inhalation of ultrafine and fine particulate matter disrupts systemic vascular function. *Inhal Toxicol* 2007;19(2):133-40.
 - 75) Nurkiewicz TR, Porter DW, Barger M, Millecchia L, Rao KM, Marvar PJ, et al. Systemic microvascular dysfunction and inflammation after pulmonary particulate matter exposure. *Environ Health Perspect* 2006;114(3):412-9.
 - 76) Haberzettl P, O'Toole TE, Bhatnagar A, Conklin DJ. Exposure to fine particulate air pollution causes vascular insulin resistance by inducing pulmonary oxidative stress. *Environ Health Perspect* 2016; 124(12):1830-9.
 - 77) Ho CC, Chen YC, Tsai MH, Tsai HT, Weng CY, Yet SF, et al. Ambient particulate matter induces vascular smooth muscle cell phenotypic changes via NOX1/ROS/NF- κ B dependent and independent pathways: protective effects of polyphenols. *Antioxidants (Basel)* 2021; 10(5):782.
 - 78) Xu X, Yavar Z, Verdin M, Ying Z, Mihai G, Kampfrath T, et al. Effect of early particulate air pollution exposure on obesity in mice: role of p47phox. *Arterioscler Thromb Vasc Biol* 2010;30(12):2518-27.
 - 79) Ghio AJ, Carraway MS, Madden MC. Composition of air pollution particles and oxidative stress in cells, tissues, and living systems. *J Toxicol Environ Health B Crit Rev* 2012;15(1):1-21.
 - 80) Chen L, Li H, Ru Y, Song Y, Shen Y, Zhao L, et al. Xanthine-derived

- reactive oxygen species exacerbates adipose tissue disorders in male db/db mice induced by real-ambient PM_{2.5} exposure. *Sci Total Environ* 2023;882:163592.
- 81) Janssen BG, Saenen ND, Roels HA, Madhloum N, Gyselaers W, Lefebvre W, et al. Fetal thyroid function, birth weight, and in utero exposure to fine particle air pollution: a birth cohort study. *Environ Health Perspect* 2017;125(4):699-705.
 - 82) Wang X, Liu C, Zhang M, Han Y, Aase H, Villanger GD, et al. Evaluation of maternal exposure to PM_{2.5} and its components on maternal and neonatal thyroid function and birth weight: a cohort study. *Thyroid* 2019;29(8):1147-57.
 - 83) Dong X, Wu W, Yao S, Li H, Li Z, Zhang L, et al. PM_{2.5} disrupts thyroid hormone homeostasis through activation of the hypothalamic-pituitary-thyroid (HPT) axis and induction of hepatic transthyretin in female rats 2.5. *Ecotoxicol Environ Saf* 2021;208:111720.
 - 84) Volke L, Krause K. Effect of thyroid hormones on adipose tissue flexibility. *Eur Thyroid J* 2021;10(1):1-9.
 - 85) Mendez R, Zheng Z, Fan Z, Rajagopalan S, Sun Q, Zhang K. Exposure to fine airborne particulate matter induces macrophage infiltration, unfolded protein response, and lipid deposition in white adipose tissue. *Am J Transl Res* 2013;5(2):224-34.
 - 86) Hamanaka RB, Mutlu GM. Particulate matter air pollution: effects on the cardiovascular system. *Front Endocrinol (Lausanne)* 2018;9:680.
 - 87) Wang N, Ma Y, Liu Z, Liu L, Yang K, Wei Y, et al. Hydroxytyrosol prevents PM_{2.5}-induced adiposity and insulin resistance by restraining oxidative stress related NF- κ B pathway and modulation of gut microbiota in a murine model. *Free Radic Biol Med* 2019;141:393-407.
 - 88) Bailey MJ, Naik NN, Wild LE, Patterson WB, Alderete TL. Exposure to air pollutants and the gut microbiota: a potential link between exposure, obesity, and type 2 diabetes. *Gut Microbes* 2020;11(5):1188-202.
 - 89) Aron-Wisnewsky J, Warmbrunn MV, Nieuwdorp M, Clément K. Metabolism and metabolic disorders and the microbiome: the intestinal microbiota associated with obesity, lipid metabolism, and metabolic health-pathophysiology and therapeutic strategies. *Gastroenterology* 2021;160(2):573-99.
 - 90) Liu T, Chen X, Xu Y, Wu W, Tang W, Chen Z, et al. Gut microbiota partially mediates the effects of fine particulate matter on type 2 diabetes: evidence from a population-based epidemiological study. *Environ Int* 2019;130:104882.
 - 91) Alderete TL, Jones RB, Chen Z, Kim JS, Habre R, Lurmann F, et al. Exposure to traffic-related air pollution and the composition of the gut microbiota in overweight and obese adolescents. *Environ Res* 2018;161:472-8.
 - 92) Wang Y, Li R, Chen R, Gu W, Zhang L, Gu J, et al. Ambient fine particulate matter exposure perturbed circadian rhythm and oscillations of lipid metabolism in adipose tissues. *Chemosphere* 2020;251:126392.
 - 93) Song P, Li Z, Li X, Yang L, Zhang L, Li N, et al. Transcriptome profiling of the lungs reveals molecular clock genes expression changes after chronic exposure to ambient air particles. *Int J Environ Res Public Health* 2017;14(1):90.
 - 94) Wang X, Mukherjee B, Park SK. Associations of cumulative exposure to heavy metal mixtures with obesity and its comorbidities among U.S. adults in NHANES 2003-2014. *Environ Int* 2018;121(Pt 1):683-94.
 - 95) Yang BY, Guo Y, Markevych I, Qian ZM, Bloom MS, Heinrich J, et al. Association of long-term exposure to ambient air pollutants with risk factors for cardiovascular disease in China. *JAMA Netw Open* 2019;2(3):e190318.
 - 96) Kim JS, Chen Z, Alderete TL, Toledo-Corral C, Lurmann F, Berhane K, et al. Associations of air pollution, obesity and cardiometabolic health in young adults: the meta-AIR study. *Environ Int* 2019;133(Pt A):105180.
 - 97) Doiron D, de Hoogh K, Probst-Hensch N, Fortier I, Cai Y, De Matteis S, et al. Air pollution, lung function and COPD: results from the population-based UK Biobank study. *Eur Respir J* 2019;54(1):1802140.
 - 98) Dong GH, Wang J, Zeng XW, Chen L, Qin XD, Zhou Y, et al. Interactions between air pollution and obesity on blood pressure and hypertension in Chinese children. *Epidemiology* 2015;26(5):740-7.
 - 99) Qin XD, Qian Z, Vaughn MG, Trevathan E, Emo B, Paul G, et al. Gender-specific differences of interaction between obesity and air pollution on stroke and cardiovascular diseases in Chinese adults from a high pollution range area: a large population based cross sectional study. *Sci Total Environ* 2015;529:243-8.
 - 100) Weichenthal S, Hoppin JA, Reeves F. Obesity and the cardiovascular health effects of fine particulate air pollution. *Obesity (Silver Spring)* 2014;22:1580-9.
 - 101) Lubrano C, Risi R, Masi D, Gnessi L, Colao A. Is obesity the missing link between COVID-19 severity and air pollution? *Environ Pollut* 2020;266(Pt 3):115327.
 - 102) Hu D, Jia X, Cui L, Liu J, Chen J, Wang Y, et al. Exposure to fine particulate matter promotes platelet activation and thrombosis via obesity-related inflammation. *J Hazard Mater* 2021;413:125341.