

Long-term exposure to ambient air pollution and prevalence of lower urinary tract symptoms suggestive of benign prostatic hyperplasia: A nationwide study in China

Kai Ma

Sichuan University West China Hospital

Zhufeng Peng

381193647@qq.com

Sichuan University West China Hospital

Research Article

Keywords: Aging population, Air pollution, Benign prostatic hyperplasia, Lower urinary tract symptoms

Posted Date: July 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10230282/v1>

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Additional Declarations: No competing interests reported.

Abstract

Purpose

Ambient air pollution is a major health concern with adverse effects on multiple physiological systems. Its association with benign prostatic hyperplasia (BPH) remains understudied. We investigated links between long-term air pollution exposure and prevalence of lower urinary tract symptoms suggestive of BPH (LUTS/BPH).

Methods

This nationwide cross-sectional study included 7,066 males (≥ 45 years) from the China Health and Retirement Longitudinal Study (2018). LUTS/BPH was defined via physician-diagnosed self-report. City-level annual average concentrations (2013–2018) of CO, NO₂, O₃, SO₂, PM₁, PM_{2.5}, and PM₁₀ were estimated using AI models. Multivariable logistic regression assessed per-unit pollutant increases, and Weighted Quantile Sum (WQS) regression evaluated mixture effects. Subgroup analyses tested age modifications.

Results

Among participants, 11.8% reported LUTS/BPH. Fully adjusted models showed each 1 mg/m³ CO increase associated with 35% higher odds of LUTS/BPH (OR = 1.35, 95%CI:1.00-1.82). Per 1 µg/m³ increase, PM₁ (OR = 1.012, 95%CI: 1.00-1.02), PM_{2.5} (OR = 1.007, 95%CI: 1.00-1.01), and PM₁₀ (OR = 1.004, 95%CI: 1.00-1.01) were significantly associated with higher odds of LUTS/BPH. The associations of NO₂, O₃, and SO₂ were non-significant. WQS indicated a joint mixture effect (OR = 1.12 per quartile, 95%CI: 1.01–1.25), with CO (weight = 0.41) and PM₁₀ (weight = 0.36) contributing most to the mixture association.

Conclusions

This nationwide study suggests that long-term exposure to ambient air pollution, particularly CO and particulate matter (PM₁, PM_{2.5}, PM₁₀), which is associated with higher LUTS/BPH prevalence among Chinese men. WQS regression indicated that CO and PM₁₀ contributed most to the observed mixture effect.

1. Introduction

Benign prostatic hyperplasia (BPH) is one of the most prevalent conditions observed in aging males. It is characterized by the excessive proliferation of stromal and epithelial tissues of the prostate and leads to

lower urinary tract symptoms (LUTS), including urgency, frequency, straining, weak stream, dribbling, and other related symptoms [1]. In China, the prevalence of LUTS/BPH among men aged over 40 years was 36.6%, increasing to 69.2% among those aged over 80 years [2, 3]. Although LUTS/BPH rarely causes mortality, it is associated with severe critical complications, such as acute urinary retention, renal insufficiency and failure, urinary tract infection, and imposes substantial healthcare expenses [4].

Known risk factors for LUTS/BPH include age, sedentary lifestyle, lack of exercise, smoking, excessive alcohol consumption [5]. Importantly, emerging evidence suggests that environmental pollutants, particularly ambient air pollution, may contribute to BPH development [6, 7]. However, epidemiological evidence linking air pollution to LUTS/BPH remains limited and geographically restricted. For example, a prior ecological study in South Korea reported an association between aggregated air pollution metrics and BPH risk, but did not examine pollutants such as PM₁, PM_{2.5} or comprehensively address confounding [7]. No large-scale studies have evaluated this relationship in China, where rapid industrialization and population aging coexist, creating a substantial public health burden.

Air pollutants are increasingly recognized as important environmental exposures associated with systemic diseases. They comprise multifaceted environmental toxicants that may adversely affect humans, animals, vegetation, and materials, including gases, particulate matter, and other harmful components. This study focused on seven major air pollutants: carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), sulfur dioxide (SO₂), and particulate matter with different aerodynamic diameters (PM₁, PM_{2.5}, and PM₁₀). CO and NO₂ are primarily emitted from motor vehicle exhaust and fossil fuel combustion; SO₂ mainly originates from industrial emissions and coal burning; and O₃ is a secondary pollutant formed through photochemical reactions in the atmosphere. Particulate matter, including PM₁, PM_{2.5}, and PM₁₀, is produced from various sources such as industrial processes, construction activities, and road dust [8]. Regulatory agencies such as the World Health Organization (WHO) have established guideline thresholds for these pollutants, and levels above these thresholds are considered harmful to human health [9].

Although most research has focused on respiratory and cardiovascular effects, recent evidence has implicated air pollution in urological disorders through biological mechanisms such as oxidative stress, systemic inflammation, hormonal imbalance, which may also contribute to prostate tissue remodeling and LUTS/BPH [10–12]. Despite this mechanistic plausibility, important gaps remain: The role of air pollutants in LUTS/BPH is still unclear.

Therefore, we hypothesized that long-term exposure to elevated concentrations of these air pollutants is associated with a higher prevalence of LUTS/BPH. By addressing these hypotheses using nationwide data, this study provides new insights into potentially modifiable environmental drivers of LUTS/BPH, which is a growing concern in aging societies.

2. Materials and methods

2.1 Study population

This study used publicly available data from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative survey conducted in China [13]. The present analysis focused on participants from the fourth wave of CHARLS, 2018. Male individuals aged 45 years or older who completed standardized questionnaires on basic information, health status and function, and who provided information on LUTS/BPH were included. We excluded individuals who had moved during the study period. Ultimately, 7,066 participants were included in the final analysis. A flowchart of the participant selection process is provided in the Supplementary Materials.

2.2. The definition of LUTS/BPH

LUTS/BPH was defined based on a self-reported physician diagnosis in the CHARLS questionnaire. Participants were classified as having LUTS/BPH if they reported that a doctor had diagnosed them with benign prostatic hyperplasia or related lower urinary tract symptoms. Because IPSS data were not available in CHARLS, this definition, consistent with previous studies [13–14], was used as the best available outcome measure in this nationally representative dataset.

2.3. Estimation of air pollution exposure

Individuals' full-coverage ground-level air pollution concentrations (including CO, NO₂, O₃, SO₂, PM₁, PM_{2.5}, and PM₁₀) were estimated using artificial intelligence techniques at a spatial resolution of approximately 0.1° (≈ 10 km) from 2013 to 2018. These data were obtained from the CHAP dataset (<https://weijing-rs.github.io/product.html>). The assessment involved integrating ground-based measurements, remote sensing products, atmospheric reanalysis, and model simulations. The space-time extremely randomized trees (STET) model was applied to estimate daily ambient concentrations of PM₁, PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃. Detailed information on air pollution estimation can be found in previous studies [15–17]. To determine CHARLS participants' annual air pollution exposure, their city-level residential addresses were used.

2.4. Covariates

Variables included as covariates were selected based on prior literature identifying them as risk factors for both air pollution exposure and LUTS/BPH, including: age, education level (less than lower secondary, upper secondary & vocational training, and tertiary), marital status (married or partnered, and others), residence (urban, rural), body mass index (BMI), smoking (non-smoker, former smoker, and current smoker), drinking (non-drinker, former drinker, and current drinker), hypertension (no, yes), diabetes (no, yes), dyslipidemia (no, yes), kidney disease (no, yes) [5, 10, 14]. We compared our covariate selection process with that of previous studies to ensure consistency.

2.5. Statistical analyses

Continuous variables and categorical variables were expressed as mean ± standard deviation (SD) and number (percentage), respectively. To compare participants with and without LUTS/BPH, we used the

Student's t-test and Chi-square test for continuous variables and categorical variables, respectively. Pearson correlation coefficients were used to explore correlations among air pollutants.

We applied logistic regression models (R package stats) to examine the associations between 6-year mean concentrations of air pollutants and prevalence of LUTS/BPH. Three models were constructed: a crude model (model I), a base model (model II) and a main model (model III). The crude model was adjusted for age only. In the base model, five covariates were adjusted (age, BMI, education level, marital status, residence) and the main model additionally adjusted for smoking, drinking, hypertension, dyslipidemia, diabetes, kidney disease. Furthermore, to address the high correlation among pollutants and evaluate the joint effect of the air pollution mixture, we performed Weighted Quantile Sum (WQS) regression analysis. This approach accounts for co-exposure effects by generating a weighted index of multiple pollutants, where weights reflect each pollutant's relative contribution to the mixture association [18].

Given the established age-dependent increase in LUTS/BPH incidence, we conducted (a) Bivariate Global Moran's I analysis to assess spatial co-distribution of elderly males (> 65 years) and air pollutants; (b) age-stratified interaction tests to determine whether age modifies pollutant associations with LUTS/BPH.

All analyses were performed using R software (version 4.1.1). Two-sided P values < 0.05 were considered statistically significant.

3. Results

3.1. Description of study population

The characteristics of the study population are summarized in Table 1 and Fig. 1. The analytical cohort included 7,066 Chinese men aged ≥ 45 years, of whom 830 (11.8%) reported LUTS/BPH and 6,236 did not. Participants with LUTS/BPH were significantly older than those without LUTS/BPH (mean age, 66.70 ± 10.18 vs. 62.31 ± 9.83 years; $P < 0.001$), whereas no significant difference in BMI was observed (23.99 ± 3.58 vs. 23.75 ± 4.36 kg/m²; $P = 0.563$). Participants with LUTS/BPH also had a higher proportion of tertiary education (4.70% vs. 2.18%; $P < 0.001$) and were more likely to live in urban areas (46.8% vs. 35.0%; $P < 0.001$). In addition, they were more likely to be former smokers (37.4% vs. 28.3%) and former drinkers (24.1% vs. 18.5%; both $P < 0.001$). Comorbidity burdens were also more common among participants with LUTS/BPH, including hypertension (49.4% vs. 38.3%; $P < 0.001$), diabetes (21.2% vs. 10.7%; $P < 0.001$), dyslipidemia (38.1% vs. 18.7%; $P < 0.001$), and notably kidney disease (26.8% vs. 9.4%; $P < 0.001$).

Table 1
Baseline characteristics of the participants.

		LUTS/BPH not reported (n = 6,236)	LUTS/BPH reported (n = 830)	P
Age, years (mean $\pm$ SD)		62.31 (9.83)	66.70 (10.18)	< 0.001
BMI (mean $\pm$ SD)		23.75 (4.36)	23.99 (3.58)	0.563
Education (%)				< 0.001
	Less than lower secondary	5333 (85.52)	649 (78.19)	
	Upper secondary & vocational training	767 (12.30)	142 (17.11)	
	tertiary	136 (2.18)	39 (4.70)	
Marital (%)				0.163
	Married or partnered	5609 (89.95)	733 (88.31)	
	Others	627 (10.05)	97 (11.69)	
Residence (%)				< 0.001
	Urban	2184 (35.02)	388 (46.75)	
	Rural	4052 (64.98)	442 (53.25)	
Smoking Status (%)				< 0.001
	Never	1171 (18.83)	180 (21.71)	
	Former	1757 (28.25)	310 (37.39)	
	Current	3292 (52.93)	339 (40.89)	
Alcohol Use (%)				< 0.001
	Never	1585 (25.48)	230 (27.74)	
	Former	1153 (18.54)	200 (24.13)	
	Current	3482 (55.98)	399 (48.13)	

Abbreviations: LUTS/BPH: lower urinary tract symptoms suggestive of benign prostatic hyperplasia; SD: standard deviation; BMI: body mass index; Mean $\pm$ SD for continuous variables: P value was calculated by Student's t-test; Number (%) for categorical variables: P value was calculated by chi-square test.

	LUTS/BPH not reported (n = 6,236)	LUTS/BPH reported (n = 830)	P
Hypertension (%)			< 0.001
No	3845 (61.75)	420 (50.60)	
Yes	2382 (38.25)	410 (49.40)	
Diabetes (%)			< 0.001
No	5564 (89.28)	654 (78.80)	
Yes	668 (10.72)	176 (21.20)	
Dyslipidemia (%)			< 0.001
No	5065 (81.33)	514 (61.93)	
Yes	1163 (18.67)	316 (38.07)	
Kidney disease (%)			
No	5649 (90.63)	608 (73.25)	
Yes	584 (9.37)	222 (26.75)	
Abbreviations: LUTS/BPH: lower urinary tract symptoms suggestive of benign prostatic hyperplasia; SD: standard deviation; BMI: body mass index; Mean $\pm$ SD for continuous variables: P value was calculated by Student's t-test; Number (%) for categorical variables: P value was calculated by chi-square test.			

Table 2 and Fig. 1 show the concentration ranges of CO (0.48–1.82 mg/m³), NO₂ (13.42–48.73 µg/m³), O₃ (72.48–106.61 µg/m³), SO₂ (8.47–53.81 µg/m³), PM₁ (9.68–47.61 µg/m³), PM_{2.5} (20.88–83.09 µg/m³), and PM₁₀ (41.10–248.53 µg/m³).

3.2. Association between air pollution and the risk of LUTS/BPH

Table 3 summarizes the ORs and 95% CIs for LUTS/BPH per 1 mg/m³ increase in CO and per 1 µg/m³ increase NO₂, O₃, SO₂, PM₁, PM_{2.5} and PM₁₀. In the fully adjusted models (Main model), long-term exposure to CO was significantly associated with LUTS/BPH prevalence, with each 1 mg/m³ increase corresponding to a 35.2% higher odds (OR = 1.352, 95%CI: 1.003–1.823; P = 0.048). In the main model, PM₁ exposure was associated with a 1.2% higher odds per 1 µg/m³ increment (OR = 1.012, 95%CI: 1.003–1.022; P = 0.011), while PM_{2.5} (OR = 1.007, 95%CI: 1.002–1.012; P = 0.008) and PM₁₀ (OR = 1.004, 95%CI: 1.001–1.007; P = 0.003) were also statistically significant. Notably, all particulate matter pollutants remained statistically significant across all adjustment models: PM₁ (Crude model P = 0.003;

Base model $P = 0.024$; Main model $P = 0.011$), $PM_{2.5}$ (Crude model $P = 0.001$; Base model $P = 0.011$; Main model $P = 0.008$), and PM_{10} (Crude model $P < 0.001$; Base model $P = 0.002$; Main model $P = 0.003$), suggesting consistent dose-response patterns across models. For gaseous pollutants, CO transitioned from non-significant in the base model ($OR = 1.27$, $P = 0.106$) to statistically significant in the main model ($OR = 1.35$, $P = 0.048$). This change suggests that the association may be influenced by metabolic comorbidities (such as diabetes). NO_2 showed a borderline association in the fully adjusted model ($OR = 1.009$, 95%CI: 0.999–1.018; $P = 0.064$), whereas ozone (O_3 : $OR = 1.007$, $P = 0.216$) and sulfur dioxide (SO_2 : $OR = 1.006$, $P = 0.167$) were not significantly associated with LUTS/BPH. This suggests that particulate matter may be the main contributing component.

Table 2. Descriptive statistics of 6-year average levels of air pollution levels.					
	Mean	Median	Min.	Max.	IQR
CO	1.060	1.00	0.48	1.82	0.30
NO_2	28.71	27.51	13.42	48.73	13.90
O_3	88.11	88.23	72.48	106.61	13.46
SO_2	24.48	21.02	8.47	53.81	12.23
PM_1	27.44	26.33	9.68	47.61	12.74
$PM_{2.5}$	48.97	46.65	20.88	83.09	26.13
PM_{10}	84.90	80.90	41.10	248.53	48.54
Abbreviations: CO: Carbon Monoxide (mg/m^3); NO_2 : Nitrogen Dioxide ($\mu g/m^3$); O_3 : Ozone ($\mu g/m^3$); SO_2 : Sulfur Dioxide ($\mu g/m^3$); PM_1 : particulate matter with aerodynamic diameters $\leq 1.0 \mu m$ ($\mu g/m^3$); $PM_{2.5}$: particulate matter with aerodynamic diameters $\leq 2.5 \mu m$ ($\mu g/m^3$); PM_{10} : particulate matter with aerodynamic diameters $\leq 10 \mu m$ ($\mu g/m^3$); IQR, inter-quartile range.					

Table 3
Associations between air pollution and LUTS/BPH prevalence.

Air pollutant	Crude model OR (95%CI)	P value	Crude model OR (95%CI)	P value	Crude model OR (95%CI)	P value
CO (mg/m ³)	1.328 (1.019, 1.73)	0.036	1.270 (0.95, 1.696)	0.106	1.352 (1.003, 1.823)	0.048
NO ₂ (µg/m ³)	1.009 (1.001, 1.018)	0.023	1.006 (0.997, 1.015)	0.174	1.009 (0.999, 1.018)	0.064
O ₃ (µg/m ³)	1.009 (1, 1.018)	0.055	1.003 (0.993, 1.013)	0.520	1.007 (0.996, 1.017)	0.216
SO ₂ (µg/m ³)	1.006 (0.999, 1.013)	0.096	1.004 (0.996, 1.011)	0.360	1.006 (0.998, 1.014)	0.167
PM ₁ (µg/m ³)	1.012 (1.004, 1.021)	0.003	1.010 (1.001, 1.02)	0.024	1.012 (1.003, 1.022)	0.011
PM _{2.5} (µg/m ³)	1.008 (1.003, 1.012)	0.001	1.006 (1.001, 1.011)	0.011	1.007 (1.002, 1.012)	0.008
PM ₁₀ (µg/m ³)	1.005 (1.003, 1.007)	< 0.001	1.004 (1.001, 1.007)	0.002	1.004 (1.001, 1.007)	0.003
Crude model: adjusted for age.						
Base model: further adjusted for body mass index, education level, residence, and marital status.						
Main model: further adjusted for smoking, drinking, hypertension, dyslipidemia, diabetes, chronic lung diseases, liver disease, heart problems, stroke, kidney disease, digestive diseases, psychiatric problems, arthritis or rheumatism, asthma, and depression.						
OR, odds ratio; CI, confidence interval.						

3.3. Weighted Quantile Sum (WQS) analysis

Given the substantial inter-pollutant correlations revealed by Pearson analysis (Fig. 2A, all $P < 0.001$), particularly the near-collinearity between PM₁/PM_{2.5} ($r = 0.97$) and strong NO₂/PM₁ covariation ($r = 0.90$), WQS regression was employed to disentangle the joint effects of this highly correlated pollutant mixture.

WQS regression analysis showed a statistically significant joint association of the air pollution mixture on LUTS/BPH prevalence. For each quartile increase in the multi-pollutant index, the adjusted odds ratio (OR) was 1.12 (95%CI: 1.005–1.249; $P < 0.05$), corresponding to 12% higher odds of LUTS/BPH per quartile increment in cumulative pollution exposure. Figure 2B illustrates the relative contributions of individual pollutants to the mixture association, quantified by bootstrap-derived mean weights. Carbon monoxide contributed the most to the mixture association (weight = 0.41), followed by PM_{10} (0.36), collectively accounting for 77.2% of the total mixture weight. The remaining pollutants showed lower contributions: NO_2 (0.140), O_3 (0.044), PM_1 (0.034), SO_2 (0.007), and $PM_{2.5}$ (0.003). This weighting pattern was broadly consistent with the main logistic regression results (Table 3), in which CO showed the largest effect estimate.

3.4. Spatial clustering and age-stratified, interaction tests effects

To evaluate spatial autocorrelation between pollutant distributions and older male populations (aged ≥ 60 years), we performed bivariate Global Moran's I analysis. No significant spatial clustering was observed for any pollutant, indicating negligible spatial dependence in the exposure-outcome relationship.

Stratified analyses (Table 4) suggested age-related differences: long-term exposure to CO (OR = 1.57, 95%CI: 1.10–2.23), NO_2 (OR = 1.01, 95%CI: 1.00–1.02), PM_1 (OR = 1.01, 95%CI: 1.00–1.03), $PM_{2.5}$ (OR = 1.01, 95%CI: 1.00–1.01), and PM_{10} (OR = 1.00, 95%CI: 1.00–1.01) was significantly associated LUTS/BPH only among adults aged 60 years or older (all $P < 0.05$), whereas no significant associations were observed among middle-aged participants (45–59 years). Despite these age-related differences, multiplicative interaction terms for age and pollutant exposure were not statistically significant. Ozone and SO_2 showed no significant associations in either group, suggesting that particulate matter and combustion-derived pollutants (CO/ NO_2) may warrant particular attention in aging populations.

Table 4
Subgroup analysis between air pollution and LUTS/BPH.

Air pollution	Age Group	OR (95%CI)	P	P for interaction
CO				0.865
	middle	0.90 (0.50, 1.61)	0.724	
	old	1.57 (1.10, 2.23)	0.012	
NO ₂				0.914
	middle	1.00 (0.98, 1.02)	0.883	
	old	1.01 (1.00, 1.02)	0.041	
PM ₁				0.909
	middle	1.01 (0.99, 1.03)	0.393	
	old	1.01 (1.00, 1.03)	0.016	
PM _{2.5}				0.454
	middle	1.01 (1.00, 1.02)	0.211	
	old	1.01 (1.00, 1.01)	0.022	
PM ₁₀				0.332
	middle	1.00 (1.00, 1.01)	0.207	
	old	1.00 (1.00, 1.01)	0.007	
SO ₂				0.870
	middle	1.00 (0.98, 1.01)	0.814	
	old	1.01 (1.00, 1.02)	0.087	
O ₃				0.387
	middle	1.00 (0.98, 1.02)	0.858	
	old	1.01 (1.00, 1.02)	0.121	
Abbreviations: LUTS/BPH: lower urinary tract symptoms suggestive of benign prostatic hyperplasia; Middle age: 45 ≤ age <60 years old; Old age: age ≥ 60 years old; OR: odds ratio; 95%CI: 95% Confidence interval.; Model was adjusted for age, BMI, education level, marital status, residence, smoking, drinking, hypertension, dyslipidemia, diabetes, kidney disease. P for interaction was obtained using the log-likelihood ratio test.				

4. Discussion

To the best of our knowledge, this is the first nationwide epidemiological study to examine the association between long-term exposure to a comprehensive panel of ambient air pollutants and LUTS/BPH prevalence in China. Our main findings suggest significant positive associations between long-term exposure to higher concentrations of CO, PM₁, PM_{2.5}, and PM₁₀ and LUTS/BPH prevalence. Notably, the WQS analysis suggested that CO and PM₁₀ contributed most to the observed mixture association.

Our findings are consistent with broader evidence linking air pollution to male reproductive disorders. For instance, comprehensive meta-analyses have linked pollutants such as PM_{2.5}, PM₁₀, and SO₂ to impaired semen quality parameters, and several studies have suggested associations with prostate cancer incidence [19–21]. Notably, a recent investigation by Yuan et al. found that household use of solid fuels (a major source of ambient CO and PM) was significantly associated with LUTS/BPH (OR = 1.68, 95%CI: 1.31–2.15), supporting the biological plausibility of combustion-derived pollutant in relation to prostate pathology [22]. This finding is in line with Shim et al.'s earlier ecological study, which reported higher prevalence of BPH with greater aggregate pollution levels (OR = 2.23; 95%CI: 1.55–3.21) but was limited to age-adjusted associations across seven pollutants (CO, NO_x, SO_x, TSP, PM₁₀, VOC, and NH₃) [7]. Our study extends this evidence through three critical methodological enhancements: rigorous adjustment for lifestyle, socioeconomic, and comorbidity confounders, individual-level assessment of novel pollutants (PM₁/PM_{2.5}/O₃), and application of WQS regression to address co-exposure effects in our nationally representative Chinese cohort (n = 7,066). This comprehensive approach showed a divergence from prior findings: gaseous pollutants (NO₂, O₃, and SO₂) were not significantly associated with LUTS/BPH after full adjustment, whereas particulate matter (PM₁, PM_{2.5}, and PM₁₀) remained significantly associated with LUTS/BPH and exhibited consistent dose-response patterns.

The extent of tissue damage associated with gas exposure largely depends on its water solubility, concentration, and oxidizing potential [8]. SO₂ is highly soluble in water and largely damages the upper airways and skin. NO₂ and O₃ are less soluble but irritating, which may limit their penetration beyond the respiratory tract and reduce their ability to reach extrapulmonary organs. However, CO's hemoglobin-targeting mechanism may lead to systemic hypoxic effects. Chronic hypoxia activates proliferative pathways (e.g., HIF-1α/VEGF) in prostatic stromal cells, directly promoting hyperplasia and LUTS pathogenesis [23]. This fundamental distinction may explain the persistent significance of CO in fully adjusted models, where spatially restricted gases (SO₂/NO₂/O₃) showed non-significant associations. The toxicity of particulate matter is determined by factors such as particle size, structure, and chemical composition. Generally speaking, the smaller the particles, the more easily they can cross the alveolar-capillary membrane, be absorbed by cells, and be transported through the bloodstream to expose almost all cells in the body, resulting in greater toxicity [8]. This size-dependent bioactivity hierarchy may help explain our multiple logistic regression results, which showed that PM₁ had the highest per-unit risk for LUTS/BPH (adjusted OR = 1.016, 95%CI: 1.007–1.025), compared to PM_{2.5} (OR = 1.009) and PM₁₀ (OR = 1.005). The strong association observed for PM, which remained robust across all adjustment models, is particularly noteworthy. The application of WQS regression provided valuable insights beyond single-

pollutant models. The significant joint effect of the pollutant mixture (OR = 1.12 per quartile increase) and the identification of CO and PM₁₀ as primary contributors strengthen the overall evidence for an association with LUTS/BPH. This approach helps mitigate challenges posed by high inter-pollutant correlations, such as the near-collinearity observed between PM₁ and PM_{2.5}.

In general, the biological pathways linking air pollution exposure to LUTS/BPH development are likely multifactorial and may involve the following aspects: (a) Oxidative stress and systemic inflammation: Inhaled pollutants, particularly fine and ultrafine particulate matter (PM₁, PM_{2.5}), can induce local pulmonary inflammation and oxidative stress, leading to systemic dissemination of inflammatory cytokines and reactive oxygen species (ROS) [12, 24]. Chronic systemic inflammation is a recognized contributor to prostate tissue remodeling and BPH progression [25]. (b) Endocrine disruption: Certain air pollutants, including components of particulate matter and polycyclic aromatic hydrocarbons (PAHs), possess endocrine-disrupting properties [26]. Disruption of hormonal balance, particularly involving androgens and estrogens, is central to BPH pathogenesis [27]. (c) Neurogenic effects: Air pollution has documented neurotoxic effects [28]. Disruption of autonomic nervous system pathways involved in bladder control and prostate function could potentially manifest as LUTS [29]. (d) Vascular dysfunction: Pollutants like CO (which reduces oxygen-carrying capacity) and others promoting endothelial dysfunction and atherosclerosis might impair blood flow to the genitourinary tract, potentially contributing to tissue hypoxia and LUTS/BPH [30, 31].

Our subgroup analyses suggested that the positive associations between certain air pollutants and LUTS/BPH prevalence were more apparent among older adults (≥ 60 years) than among middle-aged participants (45–59 years). However, the multiplicative interaction terms between age and pollutant exposures were not statistically significant. The observed subgroup pattern may reflect either greater statistical power in the older subgroup, given the higher prevalence of LUTS/BPH in this group, or underlying age-related differences in biological vulnerability. Compared with younger individuals, older adults may spend more time indoors, where certain pollutants can accumulate; in addition, age-related changes in pharmacokinetics and reduced physiological reserve may influence internal dose and susceptibility to environmental stressors [32–34]. These possibilities warrant further investigation in longitudinal studies with formal interaction testing.

Several limitations of this study should be acknowledged. First, the cross-sectional design precludes causal inference and limits the ability to determine the temporal relationship between ambient air pollution exposure and LUTS/BPH prevalence. Prospective longitudinal studies are needed to further clarify these associations. Second, although WQS regression was used to address the high correlation among PM₁, PM_{2.5}, and PM₁₀, substantial collinearity may still limit the ability to distinguish the independent contribution of each particulate pollutant. Third, LUTS/BPH was defined based on self-reported physician diagnosis rather than symptom-based instruments such as the International Prostate Symptom Score (IPSS) or objective clinical measures, which may have introduced outcome misclassification and recall bias. Fourth, despite adjustment for multiple covariates, residual confounding cannot be excluded because some potentially relevant factors, such as physical activity,

medication use, occupational exposure, healthcare access, and hormone-related variables, were not sufficiently complete in the dataset. Finally, because this study was conducted exclusively among Chinese adults, the generalizability of the findings to other populations and geographic settings may be limited.

5. Conclusions

This nationwide study suggests that ambient air pollution, particularly carbon monoxide (CO) and particulate matter (PM₁, PM_{2.5}, PM₁₀), is associated with LUTS/BPH among Chinese men. WQS regression indicated that CO and PM₁₀ contributed most to the observed mixture association. These findings highlight the importance of air quality regulations targeting combustion-derived pollutants and particulate matter, especially in regions with aging populations.

Declarations

Ethical Approval and consent to participate

CHARLS was approved by the Institutional Review Board of Peking University (approval number: IRB00001052-11015 for the household survey and IRB00001052-11014 for blood samples), and all participants provided written informed consent. This study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Competing Interests

The authors declare no conflicts of interests.

Funding

No funds, grants, or other support was received.

Author Contribution

KM conceived and designed the study. KM and PZ extracted and checked the data. KM performed the statistical analysis. KM drafted the manuscript. PZ revised the manuscript. All authors read and approved the final manuscript.

Acknowledgments

None.

Data Availability

Publicly available datasets were analyzed in this study, which can be found at: <http://charls.pku.edu.cn/> and <https://weijing-rs.github.io/product.html>.

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Figures

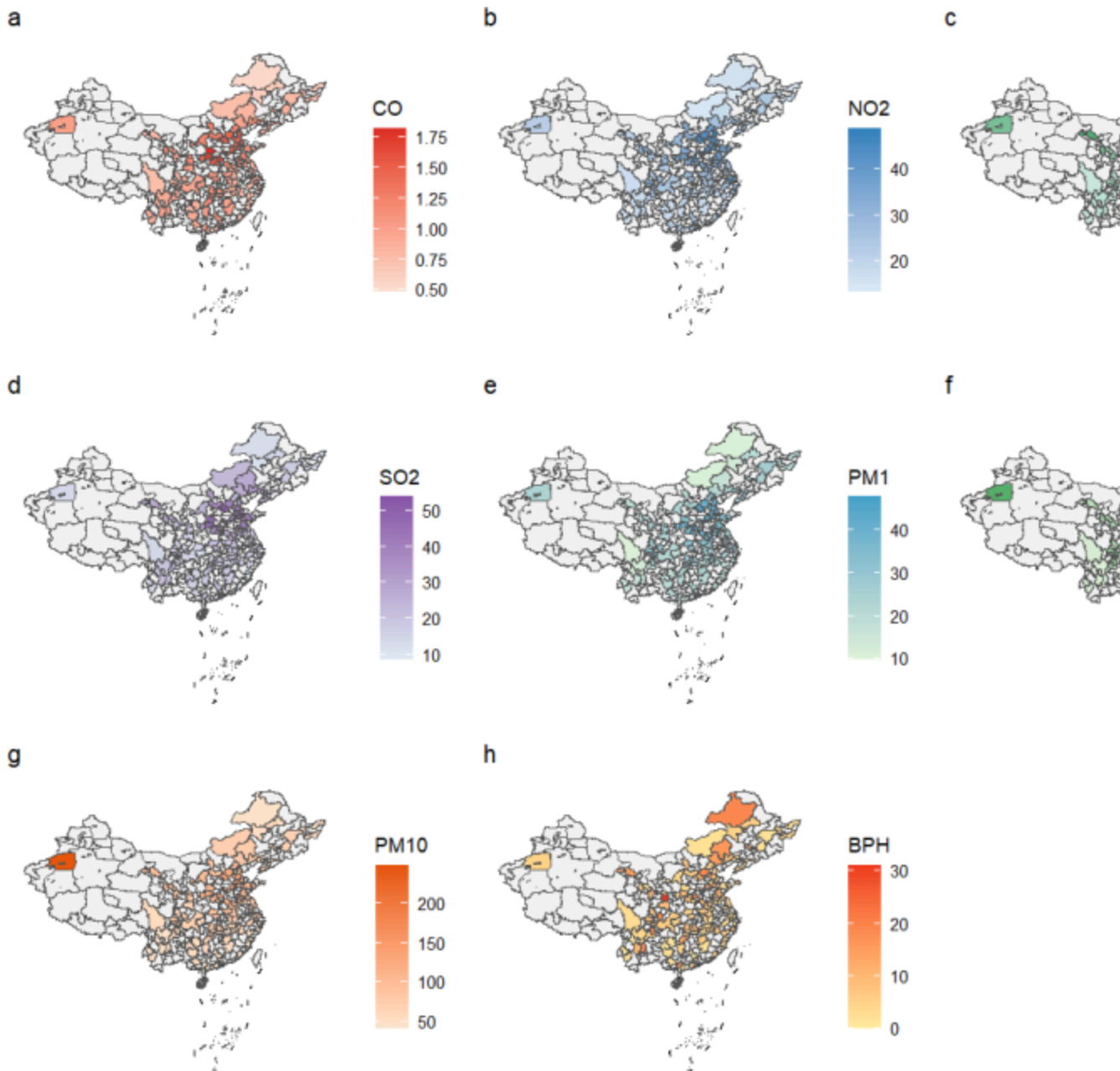


Figure 1

Distribution of the 6-year mean concentrations of air pollutants and LUTS/BPH in different cities of China. (a: CO mg/m³; b: NO₂ μg/m³; c: O₃ μg/m³; d: SO₂ μg/m³; e: PM₁ μg/m³; f: PM_{2.5} μg/m³; g: PM₁₀ μg/m³; h: LUTS/BPH cases)._x0010_Abbreviations: CO: Carbon Monoxide; NO₂: Nitrogen Dioxide; O₃: Ozone; SO₂: Sulfur Dioxide; PM₁: particulate matter with aerodynamic diameters ≤ 1.0 μm; PM_{2.5}: particulate matter with aerodynamic diameters ≤ 2.5 μm; PM₁₀: particulate matter with aerodynamic diameters ≤ 10 μm; the gray areas on the map represent regions that were not surveyed.

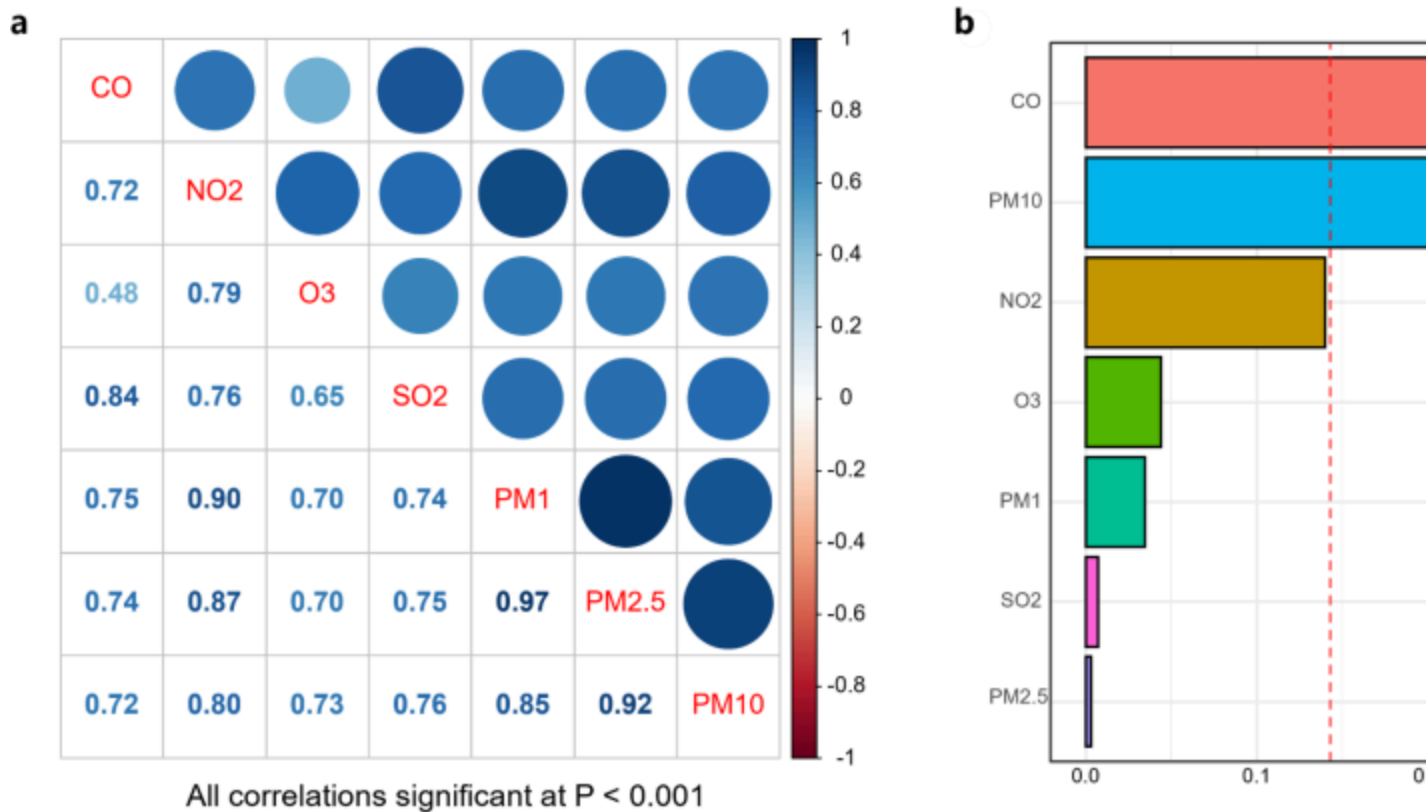


Figure 2

Correlation analysis and weighted quantile sum (WQS) regression results for air pollutants.

a) Pearson correlation matrix of long-term exposure to seven ambient air pollutants.

b) Relative contribution weights of individual pollutants to the mixture association with LUTS/BPH prevalence derived from WQS regression. The weights represent the relative importance of each pollutant within the mixture model and do not indicate independent effects. A larger weight indicates a greater contribution to the overall mixture association. Weights were estimated using bootstrap analysis with 10,000 iterations.

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