Environment International 182 (2023) 108319

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Short-term association of fine particulate matter and its constituents with oxidative stress, symptoms and quality of life in patients with allergic rhinitis: A panel study

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ARTICLE INFO

Handling Editor: Hanna Boogaard

Keywords:
Particulate matter
$PM_{2.5}$ constituents
Allergic rhinitis
Oxidative stress
Symptoms
Quality of life

ABSTRACT

Background: Short-term exposure to fine particulate matter ($PM_{2.5}$) and its specific constituents might exacerbate allergic rhinitis (AR) conditions. However, the evidence is still inconclusive.

Method: We conducted a panel study of 49 patients diagnosed with AR $>$ 1 year prior to the study in Taiyuan, China, to investigate associations of individual exposure to $PM_{2.5}$ and its constituents with oxidative parameters, symptoms, and quality of life among AR patients. All participants underwent repeated assessments of health and PM exposure at 4 time points in both the heating and nonheating seasons from June 2017 to January 2018. AR patients' oxidative parameters were assessed using nasal lavage, and their subjective symptoms and quality of life were determined through in-person interviews using a structured questionnaire. Short-term personal exposure to $PM_{2.5}$ and its constituents was estimated using the time-microenvironment-activity pattern and data from the nearest air sampler, respectively. We applied mixed-effects regression models to estimate the short-term effects of $PM_{2.5}$ and its constituents.

Results: The results showed that exposure to $PM_{2.5}$ and its constituents, including BaP, PAHs, SO_4^{2-}, NH_4^+, V, Cr, Cu, As, Se, Cd, and Pb, was significantly associated with increased oxidative stress, as indicated by an increase in the malondialdehyde (MDA) index. Exposure to $PM_{2.5}$ and its components (V, Mn, Fe, Zn, As, and Se) was associated with decreased antioxidant activity, as indicated by a decrease in the superoxide dismutase (SOD) index. Additionally, increased visual analog scale (VAS) and rhinoconjunctivitis quality of life questionnaire (RQLQ) scores indicated that exposure to $PM_{2.5}$ and its constituents exacerbated inflammatory symptoms and affected quality of life in AR patients.

Conclusion: Exposure to $PM_{2.5}$ and specific constituents, could exacerbate AR patients' inflammatory symptoms and adversely affect their quality of life in the heavily industrialized city of Taiyuan, China. These findings may have potential biological and policy implications.

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https://doi.org/10.1016/j.envint.2023.108319
Received 23 June 2023; Received in revised form 10 October 2023; Accepted 9 November 2023

1. Introduction

Allergic rhinitis (AR) is an immunoglobulin E (IgE)-mediated inflammatory and type I allergic disease of the respiratory system triggered by allergen exposure with symptoms including nasal irritation, congestion, and sneezing (Passali et al., 2018). AR affects up to 40 % of the world's population, and its prevalence varies across age and geographic regions (Chen et al., 2019, Greiner and Meltzer, 2011). AR not only impacts an individual's quality of life (Naclerio et al., 2020) but is also associated with bronchial asthma, sinusitis, nasal polyps, otitis media, and allergic conjunctivitis (Kim et al., 2019).

An increasing number of epidemiological, experimental, and toxicological studies have investigated the adverse effect of exposure to fine particulate matter (PM$_{2.5}$) on AR (Fuertes et al., 2013, Guo et al., 2019, Chen et al., 2018), and recent *meta*-analyses have also synthesized findings regarding the association between PM$_{2.5}$ exposure and the risk of AR (Rosario Filho,Satoris and Scala, 2021, Li et al., 2022a, Zhang et al., 2022). However, the results of previous studies have been mixed, and some studies have reported contradictory findings regarding the impacts of PM exposure (Gehring et al., 2015, Burte et al., 2018, Li et al., 2020).

Numerous factors could contribute to the heterogeneity among previous findings, and the spatiotemporal differences in PM$_{2.5}$ chemical composition might be one of the key contributors. Indeed, PM$_{2.5}$ is a complex mixture of constituents, including elemental carbon, organic compounds, and metallic compounds, and these constituents vary spatially and temporally depending on the local source of origin and interactions with local climate and other factors (Bell et al., 2007). The evidence for PM$_{2.5}$ constituents on AR risk is largely unknown. A recent prospective cohort study first reported that long-term exposure to six PM$_{2.5}$ constituents (NH_4^+, NO_3^-, SO_4^{2-}, organic matter, black carbon) increased the risk of AR (Jia et al., 2023), which warrants further studies exploring the biological mechanisms and pathophysiology of this association.

Biologically, exposure to PM$_{2.5}$ and its constituents may be associated with an increased risk of AR by the triggering of oxidative stress and inflammatory responses. In humans, exposure to PM$_{2.5}$ may trigger oxidative stress and inflammation in nasal epithelial cells, exacerbating allergic airway disease and increasing organ reactivity, thus contributing to the development of AR (Peden, 2001). Using the ovalbumin (OVA)-induced allergic rhinitis mouse model, Piao et al. also reported that exposure to PM$_{2.5}$ and its constituents enhanced oxidative stress and the inflammatory response via the Nrf2/HF-κB pathway (Piao et al., 2021). Nevertheless, most prior studies primarily focused on the role of

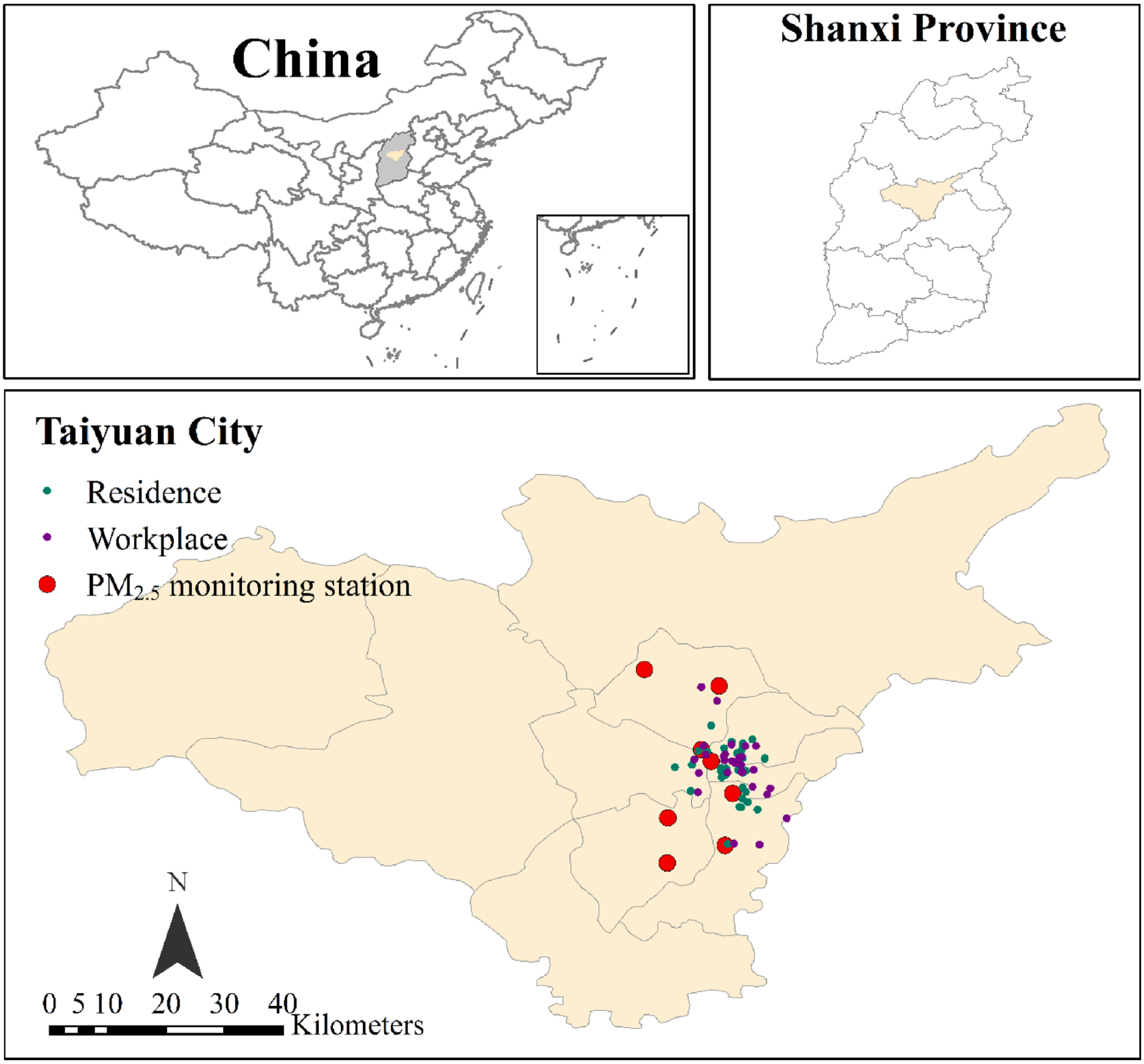


Fig. 1. Map showing the location of Taiyuan in Shanxi Province, China, and geographical distributions of PM$_{2.5}$ monitoring stations and participants' residences and workplaces. For confidentiality reasons, all participants were only geo-coded to the corresponding community or street.

air pollution in the onset of AR but overlooked its potential impact in exacerbating AR conditions and the underlying mechanisms involved.

Given the rising prevalence of AR and the absence of a definitive treatment offering complete efficacy, there is an urgent need to prioritize the relief of allergic rhinitis symptoms and the improvement of quality of life for AR patients. Therefore, this study aimed to investigate the association between short-term exposure to $PM_{2.5}$ and its constituents and oxidative stress, subjective symptoms, and quality of life in patients with AR in Taiyuan City, Shanxi Province, China, a major coal-mining and burning region.

2. Methods

2.1. Study population

Taiyuan, one of the leading industrial provincial capital cities in China, is located roughly in the center of the North China Plain (Fig. 1). Taiyuan has six districts and three counties and hosts a county-level city with a total area of 6,988 square kilometers (km^2) and a permanent population of 5,390,957. Taiyuan has long, warm, partly overcast summers and cold, snowy, generally clear winters. Taiyuan is one of the most polluted cities in China due to the air pollution released from coal smoke and traffic exhaust (Wang et al., 2023). This study was approved by The Ethics Committee of Shanxi Province People's Hospital.

In this study, participants meeting the following two inclusion criteria were recruited: 1) patients from Shanxi Provincial People's Hospital who had been diagnosed with AR for at least one year prior to the commencement of the study and 2) individuals residing in six urban areas within Taiyuan city. The diagnosis was made according to the Guidelines for the Diagnosis and Treatment of Allergic Rhinitis in China (2015, Tianjin, China). The AR diagnosis was confirmed by a preliminary screening questionnaire, a skin prick test for allergic reactions, positive results in the allergy profile, and clinician examination for over two typical symptoms (lasting 1 h/d). We excluded participants who were active smokers ($n = 6$), those on long-term or continuous medication ($n = 2$), those with occupational exposure to dust or organic matter ($n = 3$), those who lived outside the six main districts in Taiyuan ($n = 7$), and patients who refused to attend the follow-up sessions ($n = 4$), resulting in 49 remaining participants. All participants underwent four repeated measurements (Fig S1).

2.2. Assessment of symptoms, quality of life and oxidative stress

In-person interviews with each participant were performed by trained nurses using a structured questionnaire. The following information was collected: (1) demographic characteristics and residential environment, including the addresses of the subjects' homes and workplaces, residential types and architectural features, indoor particulate matter source information, the use of air conditioning purifiers and heating equipment, indoor allergen information and window ventilation during the study period; (2) lifestyle and activities, including use of alcohol, exercise, sleep, family history of allergic diseases, medication, travel time, and general health information during the study period; and (3) health scale survey, including the allergic rhinitis symptom rating scale (SRS), visual analog scale (VAS), and rhinoconjunctivitis quality of life questionnaire (RQLQ), which was targeted to collect patients' self-perceived scores of allergic rhinitis symptoms, severity, and impact on daily life. The SRS is a symptom scale for AR that is primarily used to rate the patient's nasal symptoms. The VAS is primarily used to assess the intensity of nasal and ocular symptoms in patients. The RQLQ measures the impact of nasal and ocular symptoms on a patient's daily life.

Participants signed informed consent forms provided in advance. We collected nasal lavage fluid samples. The participants were instructed to open their jaws slightly while seated, hold their breath, and inject 5 ml of normal saline into one side of their nasal cavity. The patients were then advised to drop their heads after 10 s to collect the lavage solution using the nasal lavage solution-collecting centrifuge tube. The aforementioned procedures were repeated on the opposite side of the nasal cavity. The centrifuge tubes were then inserted into a centrifuge with the rotating speed set to 4000 rpm. After 10 min of centrifugation, the supernatant and lower precipitate were separated using a sterile pipette, and the supernatant was placed in a -40 °C refrigerator for analysis of the oxidative parameters of malondialdehyde (MDA) and superoxide dismutase (SOD). Finally, the MDA concentration was measured using the thiobarbituric acid (TBA) method, while SOD activity was measured using the xanthine oxidase method (hydroxylamine method). MDA is useful as an oxidative stress marker, and SOD represents antioxidant enzymes (Camkurt et al., 2017). The test was conducted in accordance with the manufacturer instructions (Nanjing Jianguo Bioengineering Institute, China).

2.3. Exposure assessment

Based on the investigation of the spatial and temporal distribution characteristics of air pollution and the literature on air pollen content in Taiyuan from 2013 to 2016, we selected the time axis of four repeated measurements of $PM_{2.5}$ and constituents: twice in the nonheating season (the first and second measurements: June to August 2017), when air pollution is relatively less severe, and twice in the heating season (the third and fourth measurements: December 2017 to January 2018), when air pollution is severe. To better investigate whether this difference in $PM_{2.5}$ and constituents has an impact on the exacerbation of chronic AR patients, these collection times were selected to best avoid peak seasons with relatively high AR incidence because the main potential ambient allergens in Taiyuan have a peak season during August and September. The process of exposure assessment is displayed in **Fig S2**. First, the real-time ambient $PM_{2.5}$ concentrations of eight monitoring stations in six Taiyuan urban areas (Jiancaoping District, Xinghualing District, Wanbailin District, Yingze District, Jinyuan District, and Xiaodian District) (Fig. 1) were collected from the China National Environmental Monitoring Center (https://www.cnemc.cn/). Additionally, we obtained the daily mean ambient temperature from the China Meteorological Data Sharing System (https://data.cma.cn/). Second, to understand the constituent characteristics of $PM_{2.5}$ in the external environment of Taiyuan at the time of the four repeated measurements to assess the personal exposure to $PM_{2.5}$ constituents of the study participants, we selected three representative external environment sampling points and installed two medium flow particle samplers (TH-150, Wuhan Tianhong Instrument and Meter Co., Ltd., 100 L/ml, >20 h/d) at each sampling point. Then, techniques including inductively coupled plasma-mass spectrometry (ICP-MS), ion chromatography, and high-performance liquid chromatography were utilized to determine the concentrations of metal elements, water-soluble ions (WSIs), and polycyclic aromatic hydrocarbons (PAHs) in daily $PM_{2.5}$ samples, respectively. We obtained the concentrations of 17 $PM_{2.5}$ constituents (BaP, benzopyrene; PAHs; Cl^-, chloride; NO_3^-, nitrate; SO_4^{2-}, sulfate; NH_4^+, ammonium; V, vanadium; Cr, chromium; Mn, manganese; Fe, ferrum; Ni, nickel; Cu, copper; Zn, zinc; As, arsenic; Se, selenium; Cd, cadmium; Pb, lead).

Next, to assess individual $PM_{2.5}$ exposure, we used the time-microenvironment-activity pattern in this study. This method is considered one of the most advanced approaches for assessing individual exposure (Schweizer et al., 2007) encompassing considerations for outdoor and indoor $PM_{2.5}$ concentrations, diverse microenvironments, and time-activity patterns of survey participants. The indoor-outdoor (I/O) ratio is the ratio of indoor $PM_{2.5}$ concentration to outdoor concentration and reflects the concentration relationship between indoor and outdoor $PM_{2.5}$. This coefficient has been used in many previous studies to explore the relationship between indoor and outdoor $PM_{2.5}$ concentrations (Chen and Zhao, 2011, Qi et al., 2017). By utilizing the obtained indoor and outdoor $PM_{2.5}$ concentrations of the building and integrating the time spent by individuals in different environments (time-activity pattern survey), the time-weighted concentration of different microenvironments can be calculated as the individual $PM_{2.5}$ exposure level. Briefly, we estimated time-microenvironment-activity $PM_{2.5}$ exposure with the following steps: 1) using the inverse distance weighted (IDW) interpolation method (Choi and Chong, 2022) and ambient $PM_{2.5}$ monitoring station measurements to estimate outdoor $PM_{2.5}$ concentration in all residential and work buildings for the 49 participants; 2) for each measurement period, a small flow $PM_{2.5}$ sampler (MicroPEM^{TM}) was installed indoors and outdoors in 30 selected typical residentials and 10 workplaces (grouped by the geographical locations of the 60 candidate participants) to monitor indoor and outdoor $PM_{2.5}$ concentrations. The average I/O ratios of residentials and workplaces were then calculated; 3) estimating indoor $PM_{2.5}$ concentrations for all buildings using the outdoor $PM_{2.5}$ concentrations estimated by IDW and the I/O ratio; 4) conducting a unified questionnaire survey, including a time-activity pattern survey completed by the study participants during each measurement period. This was used to gather information on their activity status (including weekdays and weekends, time spent in workplaces, residences, and indoor and outdoor activities). Based on the responses to the questionnaire survey and the dates of biological sample collection, the daily time activity schedule was calculated for the seven days prior to the biological sample collection, including the time spent in various microenvironments such as residence, workplace, and indoor and outdoor activities; 5) calculating the daily (24-hour) individual $PM_{2.5}$ exposure concentrations for the study participants using the following formula:

$$\rho_{individualPM2.5exposure(\mu g/m3)} = (\rho_{out}{}^{*}\iota_1 + \rho_{home\_in}{}^{*}\iota_2 + \rho_{work\_in}{}^{*}\iota_3)/24_h$$

Where $\iota_{1,}\iota_{2,}\iota_{3,}$ represents the time spent in different locations within a day, ρ represents the $PM_{2.5}$ concentrations at specific environment.

To assess individual exposure to $PM_{2.5}$ constituents, the constituent-specific concentration of the nearest fixed sampling point was used as the proxy for the exposure level of the corresponding $PM_{2.5}$ constituent.

2.4. Statistical analysis

We used Spearman's rank correlation coefficients (r_s) to evaluate the correlations between exposure to $PM_{2.5}$ and its constituents. We used mixed-effects regression models with a random subject-specific intercept to examine the short-term effects of exposure to $PM_{2.5}$ and 17 of its constituents on MDA, SOD, SRS, VAS, and RQLQ. Box–Cox transformation was applied to ensure that these two parameters of oxidative stress (MDA and SOD) were normally (or approximately normally) distributed, followed by a standardized procedure setting the standardized deviation (SD) of the transformed data to 1, thereby improving the interpretability and comparability of the regression model (Wu et al., 2021). We applied linear mixed-effects models (LMMs) for MDA and SOD. SRS, VAS, and RQLQ exhibited a Poisson distribution, so we built Poisson mixed-effects models (PMMs) for those outcomes.

We first adopted a sequential adjustment approach with various levels of adjustment: Model A was adjusted for demographic information (gender, age, body mass index (BMI)); Model B was additionally adjusted for ambient temperature; Model C was further adjusted for lifestyle factors (smoking status, drinking status, medication use, home pets, exercise, and cooking status); Model D (fully adjusted model) was additionally adjusted for living environment (the duration since last house renovation, status of opening area of bedroom/living room windows number, humidifier usage in the house). Models A-D were performed on the $PM_{2.5}$ single-pollutant model across outcomes, which showed consistent effect estimations, especially when additionally adjusting for lifestyle variables and/or living environment (Table 3). Thus, the fully adjusted model was used as the primary model in subsequent main analyses for $PM_{2.5}$ and its constituents.

In the main analyses, to examine the constituent-specific effects of $PM_{2.5}$, we applied three fully adjusted models (Huang et al., 2019): (1) Model 1 included a single constituent without additionally adjusting for $PM_{2.5}$ concentration; (2) Model 2 included a single constituent with additionally adjusting for $PM_{2.5}$ mass; and (3) Model 3 included a single constituent residual calculated by fitting a simple linear regression model with constituent exposure as the dependent variable and $PM_{2.5}$ concentration as the independent variable. For the analysis of MDA and SOD, the three LMMs are referred to as LMM 1, LMM 2 and LMM 3. For the analysis of SRS, VAS and RQLQ, the three PMMs are referred to as PMM 1, PMM 2 and PMM 3. We expressed the results as effect coefficients per interquartile range (IQR) increase in $PM_{2.5}$ and its constituents.

We also conducted a sensitivity analysis to assess the influence of ambient allergens on effect estimations by additionally adjusting for the score of potential ambient allergens in the regression model. The potential ambient allergens included dust mites, artemisia (mainly found in northern China, especially in Inner Mongolia and Shanxi Province), and pollen, which are the main potential ambient allergens in previous studies (Li et al., 2009, Gao et al., 2019). To construct the ambient allergen score, we assigned a score of 1 to each participant if they were exposed to a specific ambient allergen (dust mites, artemisia, or pollen). The sum of these scores represented the final ambient allergen score, ranging from 0 to 3. Only the final ambient allergen score was included in the regression model, rather than three separate scores, to preserve the power of the analysis.

Notably, including both $PM_{2.5}$ and its constituents simultaneously in a model might lead to multicollinearity, potentially resulting in unstable estimates. To assess multicollinearity, we used the variance inflation factor (VIF) for all the LMMs and PMMs constructed in this study. According to the rule of thumb, a specific-exposure VIF greater than 4 warrants further investigation, and a specific-exposure VIF greater than 10 suggests significant multicollinearity.

All data analyses were performed using R software version 4.1.0 (R Foundation for Statistical Computing). The statistical tests were two-sided, and $P < 0.05$ was considered statistically significant.

3. Results

During June 2017 and January 2018, we recruited 49 patients with four measurements for each participant. Table 1 shows the demographic characteristics of the study participants. Most participants were females (75.5 %), and their mean age was 36.7 (SD: 8.4) years, with a range of 23 to 59 years. A total of 32.7 % of participants had a BMI larger than 24 kg/m^2, and 32.7 % reported that they or their family members smoke in the house. On the other hand, most participants did not drink alcohol (71.9 %), and only 23.0 % generally drank alcohol one or two times per week. Over 80 % of the participants did not take medication. Additionally, 44.4 % of participants reported almost no exercise activities, followed by 31.1 % who engaged in light-level exercise such as running, swimming, and resistance training at gym for less than 30 min, and only the remaining participants reported that medium-level (12.2 %) or high-level (12.2 %) exercise was performed frequently. Regarding the living environment of the participants, more than half of them did not cook at home (55.1 %), and most of them (77.6 %) had not undergone house renovation for the past two years. They also reported that the opening areas of bedroom windows and living room windows were generally approximately 11 % to 20 %. Notably, only 11.7 % of families reported humidifier usage in the house.

Table 2 shows the median (IQR) of outcomes and individual exposures to $PM_{2.5}$ and its 17 constituents 0 to 1 day before each measurement time point. SRS was the only one that exhibited marginal statistical significance ($P = 0.057$) among different measurement time points, while all other outcome parameters and exposures showed significant differences among different measurement time points ($P < 0.05$). The highest median value of MDA was observed at the last measurement time point (January 2018), while that of SOD was observed at the first

Table 1
Characteristics of the study subjects and their observations at all measurement time points.

Characteristic	N (%)
Subjects	49
Observations	196
Gender	
Female	148 (75.5)
Male	48 (24.5)
Age (years)	
$\leq$ 35	104 (53.1)
>35	92 (46.9)
Body Mass Index (BMI; kg/m^2)	
< 24	132 (67.3)
$\geq$ 24	64 (32.7)
Smoking status in the house (including family members)	
No	132 (67.3)
Yes	64 (32.7)
Drinking frequency (Times/week)	
Never	141 (71.9)
1–2 times	45 (23.0)
3–7 times	8 (4.1)
> 7 times	2 (1.0)
Medications usage	
No	159 (81.1)
Yes	37 (18.9)
House pets	
No	176 (89.8)
Yes	20 (10.2)
Cooking status	
Patient-self	88 (44.9)
Other family members	108 (55.1)
The duration since last house renovation	
< 2 years	44 (22.4)
> 2 years	152 (77.6)
Status of opening area of bedroom windows	
< 10 %	6 (3.1)
11 % – 20 %	157 (80.1)
21 % – 50 %	30 (15.3)
>50 %	3 (1.5)
Status of opening area of living room windows	
< 10 %	45 (23.0)
11 % – 20 %	126 (64.3)
21 % – 50 %	24 (12.2)
>50 %	1 (0.5)
Humidifier usage in the house	
No	173 (88.3)
Yes	23 (11.7)
Exercise Status	
Never	87 (44.4)
Light level	61 (31.1)
Medium level	24 (12.2)
High-level	24 (12.2)

Note: Light level (e.g., General Walking), Medium level (e.g., Running, Swimming, Gym in less than 30 min), High level (e.g., Running, Swimming, Gym in over 30 min).

measurement time point (June 2017). The highest median values of SRS, VAS, and RQLQ simultaneously occurred in July 2017, the second measurement time point. The median PM$_{2.5}$ exposure ranged from 21.43 to 65.93 μg/m^3, with the median being highest in January 2018 and lowest in June 2017.

Spearman's rank correlations among PM$_{2.5}$ and its constituents are presented in Fig. 2. The correlations between exposure to PM$_{2.5}$ and most metal/metalloid constituents were strong ($r_s > 0.70$), with the strongest correlation observed between exposure to PM$_{2.5}$ and V at 0.91. We also observed that most metal/metalloid elements, except Cr and Cu, had a relatively high positive correlation with each other. PM$_{2.5}$ was weakly or moderately correlated with WSIs ($0.02 \leq r_s \leq 0.67$) and moderately correlated with BaP ($r_s = 0.65$) and PAHs ($r_s = 0.56$).

Table 3 shows the consistent results from regression models with various levels of adjustment, thus the fully adjusted model was used in the main analyses for PM$_{2.5}$ and its components. Fig. 3 displays the associations between exposure to PM$_{2.5}$ and its constituents and oxidative stress. Exposure to PM$_{2.5}$ was significantly associated with an increase in MDA. For PM$_{2.5}$ constituents, BaP, PAHs, SO$_4^{2-}$, NH$_4^+$, V, Cr, Cu, As, Se, Cd, and Pb were positively associated with an increase in MDA across at least two of the three LMMs; Mn, Fe, Ni, and Zn had a significant positive association only in LMM 1, while NO$_3^-$ exposure showed a negative relationship with MDA in LMMs 1 and 3. Exposure to PM$_{2.5}$ was negatively associated with SOD, and such a significant association was also found in LMM 1 for V, Mn, Fe, Zn, As, and Se.

Fig. 4 illustrates the associations of exposure to PM$_{2.5}$ and its constituents with patients' self-perceived scores of AR symptoms, severity, and quality of life. This suggests that PM$_{2.5}$ and its constituents were not associated with SRS. Consistent with the positive significant association between exposure to PM$_{2.5}$ and VAS, the constituents including Cl$^-$, SO$_4^{2-}$, Cr, Fe, Ni, Zn, and Se were positively associated with VAS by at least two of the three PMMs, while BaP, PAHs, NO$_3^-$, NH$_4^+$, Cu, and Cd tended to be negatively associated with VAS. The effects of PM$_{2.5}$ constituents on RQLQ showed a similar pattern to their effects on VAS, as Cl$^-$, Mn, Fe, Ni, Zn, As, and Se were positively associated with RQLQ in at least two of the three PMMs.

The results of VIFs indicated that the associations of Cl$^-$ exposure with MDA and SOD in both LMM1 and LMM2, as well as the associations of Cl$^-$ exposure with SRS, VAS, and RQLQ in both PMM1 and PMM2, were unreliable (all VIFs > 10). The sensitivity analysis, adjusting for an additional potential ambient allergen score, yielded results that were consistent with the main analysis (**Figs S3 and S4**).

4. Discussion

To our knowledge, this is the first epidemiological study to investigate the short-term effects of exposure to PM$_{2.5}$ constituents on oxidative stress status, subjective symptoms, and quality of life among individuals with AR. We found significant effects of PM$_{2.5}$ and its constituents on oxidative stress and inflammatory responses in AR patients. We found that exposure to PM$_{2.5}$ and its constituents, including BaP, PAHs, SO$_4^{2-}$, NH$_4^+$, V, Cr, Cu, As, Se, Cd, and Pb, was significantly and robustly associated with an increase in the MDA index, and PM$_{2.5}$ and its constituents, including V, Mn, Fe, Zn, As, and Se, were associated with a decline in the SOD index from AR patients' nasal lavage over two lag days (lag 0 to 1). Moreover, exposure to PM$_{2.5}$ and its constituents was also significantly associated with more serious subjective symptoms and lower quality of life in AR patients, as indicated by increased VAS and RQLQ scale assessments, which highlights the adverse effects of exposure to PM$_{2.5}$ and its constituents.

The findings of prior studies on the association between ambient PM$_{2.5}$ exposure and AR were inconsistent. A large French population-based cohort indicated that long-term exposures to PM$_{2.5}$ and black carbon were significantly correlated with increased risks of rhinitis (Savouré et al., 2021), and a study in Norway and Sweden revealed similar adverse effects of ambient PM$_{2.5}$ on rhinitis (Kuiper et al., 2021), while two cohort studies conducted in Europe failed to find a significant correlation between air pollution and rhinitis incidence in adults (Burte et al., 2018). In China, the association between exposure to PM and AR has not yet been thoroughly assessed based on existing published studies with different sources of AR patients (Chu et al., 2019; Li et al., 2020; Wang et al., 2020). Specifically, a study in Nanjing city reported that ambient PM$_{10}$ and PM$_{2.5}$ were related to an elevated risk of AR (Chu et al., 2019), but another Chinese study investigating pollution from 226 bus stations across the nation failed to identify a significant association between exposure to PM$_{2.5}$ and AR (Li et al., 2020). The variations in study design, the spatiotemporal discrepancy of PM$_{2.5}$ compositions, and the specific characteristics of the study population might potentially explain the inconsistent findings among the previous studies. Additionally, we noticed that indoor PM$_{2.5}$ concentrations were also lower than outdoor levels during the heating season. In nonheating seasons, residents open windows for ventilation, but not in heating seasons. The

Table 2

Summary statistics for outcomes and exposures to $PM_{2.5}$ and 17 constituents during 0–1 days before measurement.

Characteristics	1st measurementˆ Median (IQR)	2nd measurementˆ Median (IQR)	3rd measurementˆ Median (IQR)	4th measurementˆ Median (IQR)	*P* *
Oxidative stress expression of the subjects					
MDA (nmol/mL)	3.69 (3.09–4.30)	3.69 (3.09–4.51)	5.57 (4.36–6.18)	6.24 (5.63–6.84)	<0.001
SOD (U/ml)	105.50 (98.00–127.33)	102.50 (95.00–120.00)	95.00 (89.00–105.50)	96.50 (87.50–102.50)	<0.001
Scores of the three scales					
SRS	1.00 (0.00–4.00)	3.00 (1.00–5.00)	2.00 (1.00–3.00)	2.00 (1.00–3.00)	0.057
VAS	3.00 (0.00–12.00)	8.00 (3.00–16.00)	5.00 (2.00–12.00)	6.00 (2.00–12.00)	0.028
RQLQ	0.00 (0.00–13.00)	13.00 (3.00–22.00)	6.00 (0.00–25.00)	8.00 (0.00–18.00)	0.037
$PM_{2.5}$ and constituents					
$PM_{2.5}$ ($\mu g/m^3$)	21.43 (20.87–28.45)	49.52 (45.12–51.19)	49.27 (40.29–54.36)	65.93 (60.32–70.87)	<0.001
BaP (ng/m^3)	0.15 (0.06–0.15)	0.96 (0.96–1.25)	0.14 (0.13–0.48)	11.22 (7.82–13.63)	<0.001
PAHs (ng/m^3)	2.33 (1.08–2.33)	8.96 (8.96–11.07)	1.63 (1.04–4.35)	89.57 (60.93–108.60)	<0.001
Cl^- ($\mu g/m^3$)	0.68 (0.55–0.68)	0.30 (0.17–0.33)	8.01 (5.96–8.82)	5.69 (4.95–6.50)	<0.001
NO_3^- ($\mu g/m^3$)	6.70 (6.70–7.87)	2.61 (1.76–2.61)	8.10 (6.98–10.85)	7.26 (7.26–8.29)	<0.001
SO_4^{2-} ($\mu g/m^3$)	8.51 (8.51–14.23)	14.05 (13.94–16.34)	6.91 (6.07–10.04)	13.55 (11.84–15.21)	<0.001
NH_4^+ ($\mu g/m^3$)	0.04 (0.04–0.04)	0.04 (0.04–0.04)	0.04 (0.04–2.59)	7.92 (5.87–9.12)	<0.001
V (ng/m^3)	0.02 (0.02–0.11)	0.64 (0.64–0.88)	0.93 (0.33–1.36)	2.11 (1.92–2.11)	<0.001
Cr (ng/m^3)	15.60 (14.74–15.60)	44.88 (13.84–44.88)	14.86 (13.02–15.11)	26.07 (26.07–27.76)	<0.001
Mn (ng/m^3)	28.66 (25.18–28.66)	70.09 (70.09–73.74)	60.57 (54.17–78.21)	104.79 (97.49–105.73)	<0.001
Fe (ng/m^3)	520.51 (520.51–554.93)	1184.63 (1094.19–1320.23)	1007.63 (881.04–1147.54)	1586.15 (1394.66–1586.15)	<0.001
Ni (ng/m^3)	2.10 (2.10–2.33)	25.06 (2.20–25.06)	5.83 (5.46–6.03)	9.73 (9.73–11.36)	<0.001
Cu (ng/m^3)	42.11 (42.11–46.01)	42.47 (42.47–44.08)	31.39 (21.53–32.31)	63.57 (57.37–71.00)	<0.001
Zn (ng/m^3)	40.94 (40.94–42.86)	247.85 (247.85–263.05)	258.07 (190.33–321.35)	481.36 (365.99–515.72)	<0.001
As (ng/m^3)	2.15 (2.15–3.47)	10.10 (9.01–12.11)	10.47 (8.27–11.76)	20.98 (20.98–21.87)	<0.001
Se (ng/m^3)	4.02 (4.02–4.32)	8.73 (8.73–8.92)	7.04 (4.50–8.09)	11.27 (9.85–12.43)	<0.001
Cd (ng/m^3)	0.80 (0.74–0.80)	1.77 (1.77–1.98)	1.53 (1.09–1.84)	5.25 (5.15–5.86)	<0.001
Pb (ng/m^3)	80.68 (37.85–80.68)	111.26 (111.26–115.65)	123.68 (97.46–142.17)	452.51 (240.04–539.47)	<0.001
Temperature (℃)	20.50 (20.50–21.00)	26.50 (26.50–26.50)	-3.00 (-3.00 - -2.50)	-1.50 (-1.50 - -1.00)	<0.001

Note: * *P* value of Kruskal-Wallis test. ˆThe 1st and 2nd samplings were collected during the non-heating seasons; the 3rd and 4th samplings occurred during the heating season.

Abbreviations: As, arsenic; BaP, benzopyrene; Cd, cadmium; Cl^-, chloride; Cr, chromium; Cu, copper; Fe, ferrum; MDA, malondialdehyde; Mn, manganese; NH_4^+, ammonium; Ni, nickel; NO_3^-, nitrate; PAHs, polycyclic aromatic hydrocarbons; Pb, lead; $PM_{2.5}$, particulate matter < 2.5 μm in aerodynamic diameter; RQLQ, rhinoconjunctivitis quality of life questionnaire; Se, selenium; SO_4^{2-}, sulfate; SOD, superoxide dismutase; SRS, symptom rating scale; V, vanadium; VAS, visual analog scale; Zn, zinc.

Table 3

Estimated regression coefficients (β) and 95% confidence interval (CI) of $PM_{2.5}$ by single-pollutant models with different adjustment levels.

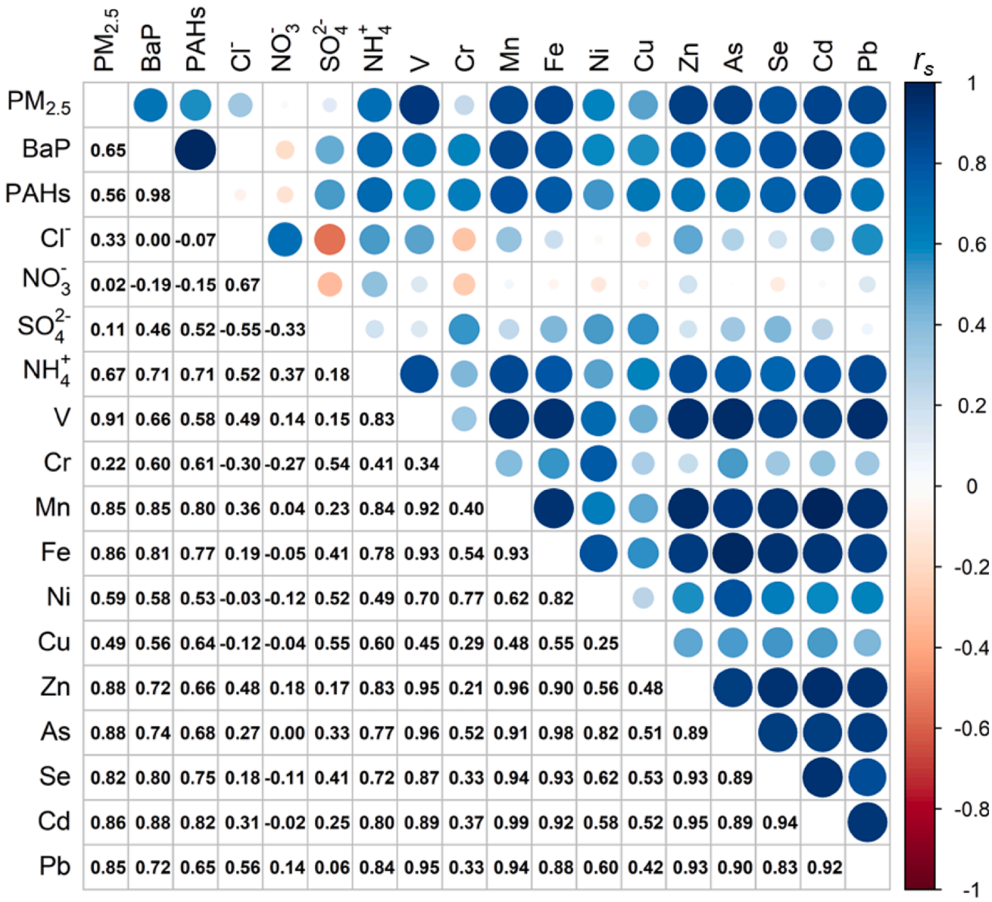
Model	MDA		SOD		SRS		VAS		RQLQ	
	β (95 % CI)	*P*	β (95 % CI)	*P*	β (95 % CI)	*P*	β (95 % CI)	*P*	β (95 % CI)	*P*
Model A	0.83 (0.66, 1.01)	< 0.001	−0.49 (-0.64, −0.34)	< 0.001	0.12 (-0.02, 0.26)	0.092	0.18 (0.11, 0.26)	< 0.001	0.13 (0.07, 0.19)	< 0.001
Model B	0.41 (0.24, 0.57)	< 0.001	−0.25 (-0.41, −0.08)	0.004	0.23 (0.06, 0.39)	0.008	0.32 (0.23, 0.41)	< 0.001	0.15 (0.08, 0.22)	< 0.001
Model C	0.45 (0.28, 0.62)	< 0.001	−0.22 (-0.39, −0.05)	0.011	0.08 (-0.10, 0.26)	0.382	0.14 (0.04, 0.23)	0.006	0.03 (-0.04, 0.10)	0.391
Model D	0.46 (0.29, 0.63)	< 0.001	−0.22 (-0.39, −0.05)	0.011	0.10 (-0.09, 0.29)	0.307	0.15 (0.05, 0.25)	0.004	0.06 (-0.02, 0.14)	0.135

Note: Linear mixed-effects model was used for MDA and SOD, Poisson mixed-effects model was used for SRS, VAS, and RQLQ. **Model A** was adjusted for demographic information (gender, age, BMI); **Model B** was additionally adjusted for ambient temperature than Model A; **Model C** was additionally adjusted for lifestyle (smoking status, drinking status, medication, home pets, exercise, and cooking status) than Model B; **Model D** (fully adjusted model) was additionally adjusted for living-environmental status (the duration since last house renovation, status of opening area of bedroom/living room windows number, humidifier usage in the house) than Model C.

Abbreviations: MDA, malondialdehyde; RQLQ, rhinoconjunctivitis quality of life questionnaire; SOD, superoxide dismutase; SRS, symptom rating scale; VAS, visual analog scale.

average I/O ratios of residential and workplaces for different experimental periods applied in this study were crucial for predicting indoor $PM_{2.5}$ concentrations over time.

China is confronting an unprecedented air pollution issue due to rapid industrialization development and urbanization on a large scale. As the capital city of the main industrial province in China, Taiyuan is an industrial base focusing on energy and heavy industry that is rich in both natural resources of coal mines. The main sources of $PM_{2.5}$ in Taiyuan city have been identified as coal combustion, biomass burning, industrial processes, and vehicle emissions (Wang et al., 2017). Specifically, personal exposures to different $PM_{2.5}$ constituents in Taiyuan come from a variety of sources: the predominant sources of $PM_{2.5}$-bound PAHs were coal combustion in industrial processes and residential heating, along with biomass burning and vehicular emissions (Yan et al., 2019); coal coking industries were responsible for high WSI concentrations, except for NO_3^-, which was more closely related to vehicle emissions; and the main sources of heavy metals were coal combustion/industrial emissions, road/soil dust, vehicle emissions in urban areas, and raw coal combustion in rural areas (Liu et al., 2017). Thus, the species of particulate matter in Taiyuan were distinct from those in other places, and



	$PM_{2.5}$	BaP	PAHs	Cl^-	NO_3^-	SO_4^{2-}	NH_4^+	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Se	Cd	Pb
$PM_{2.5}$																		
BaP	0.65																	
PAHs	0.56	0.98																
Cl^-	0.33	0.00	-0.07															
NO_3^-	0.02	-0.19	-0.15	0.67														
SO_4^{2-}	0.11	0.46	0.52	-0.55	-0.33													
NH_4^+	0.67	0.71	0.71	0.52	0.37	0.18												
V	0.91	0.66	0.58	0.49	0.14	0.15	0.83											
Cr	0.22	0.60	0.61	-0.30	-0.27	0.54	0.41	0.34										
Mn	0.85	0.85	0.80	0.36	0.04	0.23	0.84	0.92	0.40									
Fe	0.86	0.81	0.77	0.19	-0.05	0.41	0.78	0.93	0.54	0.93								
Ni	0.59	0.58	0.53	-0.03	-0.12	0.52	0.49	0.70	0.77	0.62	0.82							
Cu	0.49	0.56	0.64	-0.12	-0.04	0.55	0.60	0.45	0.29	0.48	0.55	0.25						
Zn	0.88	0.72	0.66	0.48	0.18	0.17	0.83	0.95	0.21	0.96	0.90	0.56	0.48					
As	0.88	0.74	0.68	0.27	0.00	0.33	0.77	0.96	0.52	0.91	0.98	0.82	0.51	0.89				
Se	0.82	0.80	0.75	0.18	-0.11	0.41	0.72	0.87	0.33	0.94	0.93	0.62	0.53	0.93	0.89			
Cd	0.86	0.88	0.82	0.31	-0.02	0.25	0.80	0.89	0.37	0.99	0.92	0.58	0.52	0.95	0.89	0.94		
Pb	0.85	0.72	0.65	0.56	0.14	0.06	0.84	0.95	0.33	0.94	0.88	0.60	0.42	0.93	0.90	0.83	0.92	

Fig. 2. Spearman's rank correlation coefficients (r_s) among individual exposure to $PM_{2.5}$ and its constituents during 0–1 days before measurements. The color gradient and dot size in the upper triangle represent the correlation coefficient, and the detailed correlation coefficient values are shown in the lower triangle. Abbreviations: As, arsenic; BaP, benzopyrene; Cd, cadmium; Cl^-, chloride; Cr, chromium; Cu, copper; Fe, ferrum; Mn, manganese; NH_4^+, ammonium; Ni, nickel; NO_3^-, nitrate; PAHs, polycyclic aromatic hydrocarbons; Pb, lead; $PM_{2.5}$, particulate matter < 2.5 μm in aerodynamic diameter; Se, selenium; SO_4^{2-}, sulfate; V, vanadium; Zn, zinc.

coal combustion contributes to a larger effect on the chemical composition of $PM_{2.5}$ pollution (Cao et al., 2014). An experimental study also indicated that $PM_{2.5}$ from Taiyuan showed more serious toxicity on cells than that from Guangzhou (Song et al., 2020). In addition, the levels of $PM_{2.5}$ and its chemical constituents in Taiyuan observed in this study were higher than those in most Chinese megacities (e.g., Guangzhou, Shenzhen, Chengdu) (Wu et al., 2021, He et al., 2017a, Song et al., 2020) and developed countries (Bell et al., 2014, Basagaña et al., 2015).

Additionally, the results of our tests of the two main inflammatory indexes in the nasal lavage samples of AR patients highlight the adverse consequences of $PM_{2.5}$ and constituent exposure. Specifically, our findings regarding the oxidative stress status in AR patients suggest a link between ambient pollutant exposure and strengthened oxidative stress reactions. The underlying mechanisms by which ambient air pollution and AR are correlated are still not fully understood. Inflammation aggravation, oxidative stress promotion, signal transduction interference, enzyme inhibition, autophagy, DNA damage, immune suppression, and epigenetic dysregulation are the primary routes that have been suggested for apoptosis (Feng et al., 2016, Li et al., 2022b, Huang et al., 2015). As a cause of a variety of physiological and pathological conditions, oxidative stress could disturb the antioxidant system and induce adverse health impacts, such as respiratory tract inflammatory diseases, that could deteriorate the daily function and quality of life of AR patients (Han and Lee, 2021). Previous toxicological research has explored the diverse underlying potential mechanisms and molecular pathways for $PM_{2.5}$ exposure and the inflammatory response through allergic rhinitis mouse models, including that $PM_{2.5}$ could exacerbate oxidative stress reactions and interfere with the content of SOD and MDA (Piao et al., 2021; Wang et al., 2020a). However, evidence of toxic constituents adhering to ambient $PM_{2.5}$ and the oxidative stress response in patients with allergic problems is still limited.

Our novel findings suggested that exposure to $PM_{2.5}$ was significantly associated with increased MDA but decreased SOD. Consistent with the findings in this study, several experimental studies also suggested a positive association between $PM_{2.5}$ and MDA and a negative association between $PM_{2.5}$ and SOD (Piao et al., 2021; Wang et al., 2020a). Generally, MDA is the product of lipid peroxidation caused by the attack of oxygen-free radicals on biofilms, which indirectly reflects the damage degree of cells subjected to attacks from oxygen-free radicals; SOD removes superoxide anions and protects cells, so the level of SOD activity indirectly reflects the ability of the body to remove oxygen-free radicals. Reportedly, high concentrations of metal cations and PAHs in PM could aggravate Th2-dominant allergic inflammation in AR mice and cause redox imbalance, along with nasal epithelial cell stripping and eosinophil infiltration (Wang et al., 2020a), which might be the potential mechanisms of the reactions we observed in AR patients.

In this study, we found that BaP, PAHs, SO_4^{2-}, NH_4^+, V, Cr, Cu, As, Se, Cd, and Pb were stably linked to an increase in MDA in at least two of the three LMMs, and some metal cations, including V, Mn, Fe, Zn, As, and Se, correlated with a decrease in SOD in LMM 1. This potentially indicates that inflammatory responses and oxidative stress might play an essential role in the symptoms and quality of life of AR patients. A previous study demonstrated that PAHs could participate in cellular redox reactions that promote the formation of reactive oxygen species

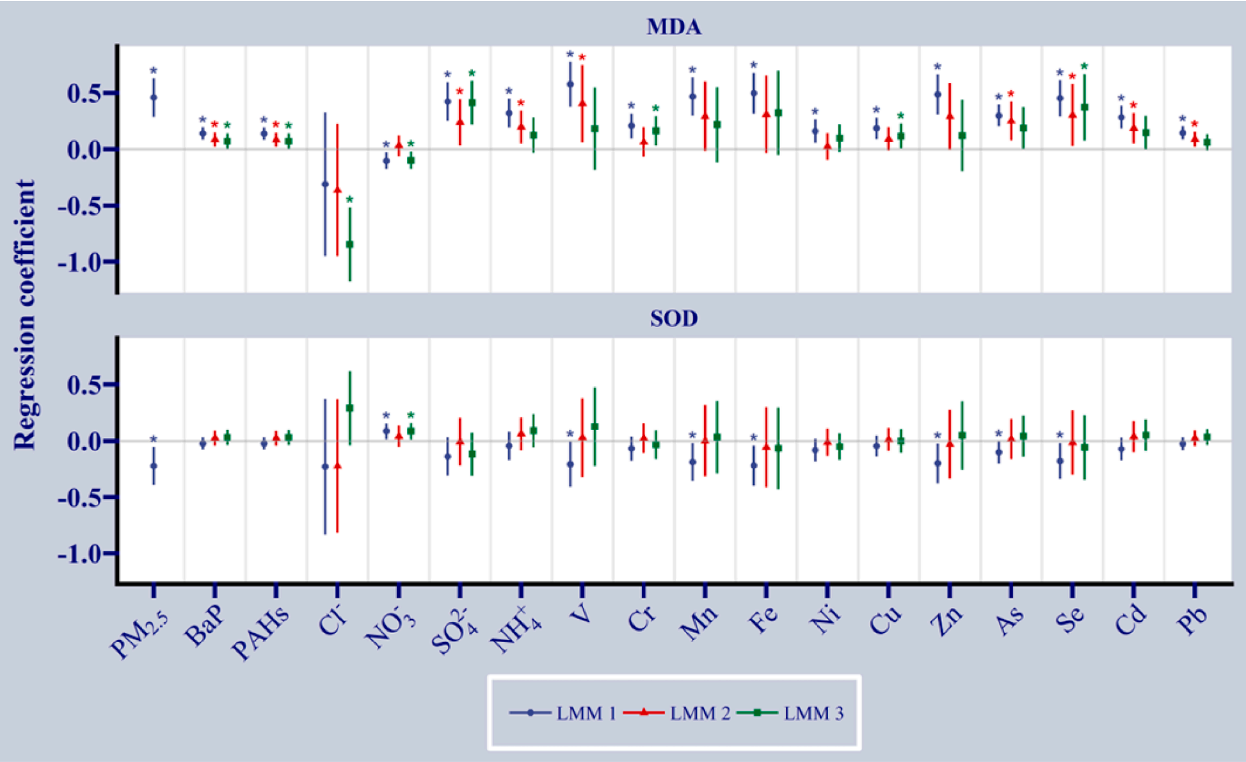


Fig. 3. Estimated regression coefficients and 95 % confidence intervals (CIs) by oxidative stress indicators associated with an interquartile range (IQR) increase in lag$_{0-1}$ exposure to $PM_{2.5}$ and constituent by linear mixed models (LMMs), adjusting for demographic information (gender, age, BMI), lifestyle (smoking status, drinking status, medication, home pets, exercise, and cooking status), living-environmental status (the duration since last house renovation, status of opening area of bedroom/living room windows number, humidifier usage in the house), and ambient temperature. Three different LMMs were used to associate $PM_{2.5}$ constituent exposure with oxidative stress indicators. LMM 1 included a single component without adjusting for $PM_{2.5}$ concentration; LMM 2 included a single component with adjusting for $PM_{2.5}$ concentration; LMM 3 included a single component residual calculated by establishing a simple linear regression model with component exposure as the dependent variable and $PM_{2.5}$ concentration as the independent variable. The symbol * indicates $P < 0.05$. Abbreviations: As, arsenic; BaP, benzopyrene; Cd, cadmium; Cl^-, chloride; Cr, chromium; Cu, copper; Fe, ferrum; MDA, malondialdehyde; Mn, manganese; NH_4^+, ammonium; Ni, nickel; NO_3^-, nitrate; PAHs, polycyclic aromatic hydrocarbons; Pb, lead; $PM_{2.5}$, particulate matter < 2.5 μm in aerodynamic diameter; Se, selenium; SO_4^{2-}, sulfate; SOD, superoxide dismutase; Zn, zinc.

(ROS), thus producing more free radicals (Song et al., 2020). NH_4^+ can cause irritation of the upper respiratory tract and alter mucosal ciliary function (Koenig, 1988). *In vitro* cell experiments indicated that specific transition metals, including Fe, Mn, and Cu, were positively associated with ROS formation (Xu et al., 2020), as soluble transition metals can generate ROS by the Fenton reaction (Sørensen et al., 2005). Additionally, ambient $PM_{2.5}$ with higher transition metals (such as Zn, Cu, K) could enhance higher ROS reactions and the severity of allergic symptoms using a mouse AR model (Gavett et al., 2003). While it remains far from fully understanding the interference of $PM_{2.5}$ and constituents with allergic reactions on deeper mechanisms, this study may provide stronger evidence of the inflammatory symptoms and quality of life in AR patients with continuing $PM_{2.5}$ exposure and thereby warrants further investigation and interventions.

Moreover, previous epidemiological evidence revealed that AR can have a detrimental effect on patients' quality of life (Blaiss et al., 2018). The four typical symptoms of AR are nasal congestion, runny nose, paroxysmal sneezing, and nasal itching, which are frequently accompanied by ocular symptoms such as itching, tearing, red eyes, and a burning sensation. Bousquet et al. reported that ocular symptoms, nasal obstruction, and pruritus had significant impacts on the quality of life among AR patients (Bousquet et al., 2013). In this context, it has attracted increasing attention to explore the quality of life of AR patients and environmental exposure. A recent study focusing on preschool children in China demonstrated that ambient $PM_{2.5}$ exposure aggravated subjective symptoms in children diagnosed with AR (He et al., 2017b), which was consistent with our findings. Another study from Iran also indicated that $PM_{2.5}$ exposure increases the risk of nonaccidental years of life lost (YLL), which was associated with life expectancy (Yin et al., 2022). Additionally, a large-scale population-based CONSTANCE cohort study demonstrated that long-term $PM_{2.5}$ exposure was associated with an increased prevalence of current rhinitis in French adults (Savouré et al., 2021). To date, however, no research has investigated whether the severe symptoms and diminished quality of life of AR patients are associated with short-term exposure to $PM_{2.5}$ constituents. $PM_{2.5}$ and its constituents can penetrate deeply into the nose and lungs, irritate, and corrode the alveolar wall, consequently impairing respiratory function. Multiple-city studies indicated correlations between PM exposure and variations in health indicators, with this variance partially attributable to changes in chemical constituent compositions (Bell et al., 2007, Kim et al., 2022, Qiao et al., 2014). A *meta*-analysis that included 59 epidemiological studies with 22 cities in mainland China, Hong Kong, and Taiwan illustrated that evidence of constituent-associated short-term and long-term health effects was still insufficient (Lu et al., 2015). Considering that it remains unclear whether exposure to particular PM constituents poses a greater risk to public health (Yang et al., 2018), both the National Academy of Sciences (NAS) and the United States Environmental Protection Agency (EPA) have emphasized the need to understand the chemical constituents and physical properties of PM that contribute to their toxicity (Wyzga and Rohr, 2015, Council. 2004).

Thus, our findings first identified harmful $PM_{2.5}$ constituents, including Cl^-, Fe, Ni, Zn, and Se, which were consistently associated with increased VAS (i.e., more serious subjective symptoms) and increased RQLQ (i.e., lower quality of life). The good consistency between the RQLQ and VAS in identifying harmful constituents indirectly demonstrated the reliability of the effects estimates in our study, as previous

Fig. 4. Estimated regression coefficients and 95 % confidence intervals (CIs) by life quality-related indicators associated with an interquartile range (IQR) increase in $lag_{0\text{-}1}$ exposure to $PM_{2.5}$ and constituent by Poisson mixed models (PMMs), adjusting for demographic information (gender, age, BMI), lifestyle (smoking status, drinking status, medication, home pets, exercise, and cooking status), living-environmental status (the duration since last house renovation, status of opening area of bedroom/living room windows number, humidifier usage in the house), and ambient temperature. Three different PMMs were used to associate $PM_{2.5}$ constituent exposure with quality-related indicators. PMM 1 included a single component without adjusting for $PM_{2.5}$ concentration; PMM 2 included a single component with adjusting for $PM_{2.5}$ concentration; PMM 3 included a single component residual calculated by establishing a simple linear regression model with component exposure as the dependent variable and $PM_{2.5}$ concentration as the independent variable. The symbol * indicates $P < 0.05$. Abbreviations: As, arsenic; BaP, benzopyrene; Cd, cadmium; Cl^-, chloride; Cr, chromium; Cu, copper; Fe, ferrum; Mn, manganese; NH_4^+, ammonium; Ni, nickel; NO_3^-, nitrate; PAHs, polycyclic aromatic hydrocarbons; Pb, lead; $PM_{2.5}$, particulate matter < 2.5 μm in aerodynamic diameter; RQLQ, rhinoconjunctivitis quality of life questionnaire; Se, selenium; SO_4^{2-}, sulfate; SRS, symptom rating scale; V, vanadium; VAS, visual analog scale; Zn, zinc.

evidence has proven the high correlation between VAS and RQLQ (Bousquet et al., 2013, Valls-Mateus et al. 2017). Additionally, some $PM_{2.5}$ constituents were observed to be negatively correlated with VAS and RQLQ in this study, and we found that BaP, PAHs, NO_3^-, and Cu tended to be negatively associated with VAS and RQLQ. Considering the combined roles, potential synergetic interactions, and transformation of chemicals via complicated cellular mechanisms of individual chemical constituents (Park et al., 2018), further toxicological and epidemiological investigations and tests of the adverse health effects triggered by potential and more complete chemical constituents are still needed. Moreover, gene-environment interactions are also known to be involved in the context of diverse health impacts from air pollution exposure, although the evidence regarding the specific causal effects of exposure and allergic status remains insufficient. Carlsten et al. demonstrated that coexposure to other allergens and genetic or epigenetic variants might also modify the adverse effects of PM exposure (Carlsten and Melén, 2012). Therefore, if PM air pollution could be controlled to a lower level, the symptoms of AR patients might be relieved, and the quality of life and expectancy of AR patients may be extended. It would be feasible to target control legislation more effectively and reduce the disease burden to a lower cost by identifying the PM constituents that are most toxic to public health.

The primary strength of this study was the adoption of a panel study methodology to assess the underlying short-term effects of exposure to ambient $PM_{2.5}$ constituents on oxidative stress, subjective symptoms, and quality of life in AR patients from the main industrial capital city (Taiyuan) in China. Second, the time-microenvironment-activity pattern was applied to estimate the individual exposure of research participants to $PM_{2.5}$, which could significantly reduce the exposure error. Third, three exposure–response analysis models were applied for individual $PM_{2.5}$ constituents and distinct outcome assessments, considering the confounding effects of $PM_{2.5}$ mass. We found that the highest levels of exposure to $PM_{2.5}$ and its constituents were observed at the 4th measurement time point (January 2018), which was mainly attributed to more coal combustion for power and indoor heating activities (He et al., 2017a). Based on the study area of Taiyuan, our study fills the gap of the impact of $PM_{2.5}$ and its constituents on the oxidative stress, subjective symptoms, and quality of life of AR patients by utilizing a fixed group tracking study design with 4 repeated measurements on the participants who were screened. The effects of $PM_{2.5}$ and constituent exposure in AR patients from Taiyuan city would be more accurately estimated by combining city ambient pollution monitoring data, sampling testing of residences and workplaces, outdoor fixed-point monitoring and sampling, and biological samples as well as assessments of subjective symptoms and quality of life in AR patients.

Our study has a few limitations. First, $PM_{2.5}$ constituent exposure was based on monitoring data from three fixed stations, which might not fully account for spatial and geographic variation in individual exposure assessment, potentially resulting in misclassification errors. Considering that all the participants lived in urban Taiyuan city, the variation in $PM_{2.5}$ concentration and the proportion of each constituent were less likely to fluctuate significantly (Huang et al., 2019). Second, allergic rhinitis can sometimes manifest quickly with symptoms that also dissipate swiftly, and 24-hour (daily) exposure might not capture some acute effects as effectively as a shorter time window (e.g., 12 h). The limitation in the data collection, which included only the recording of the collection date of nasal lavage fluid samples and conducted in-person interviews without specifying the exact hour of each measurement, constrained our ability to apply a shorter time window in this study. Nevertheless, using the 24-hour exposure window for assessing acute effects on AR onset aligns with findings from previous studies (Annesi-Maesano et al., 2012, Chen et al., 2023). Third, despite adjusting for important variables such as temperature, medical history, dwelling environment, allergens, etc., unmeasured or residual confounders may not be completely excluded. Fourth, the limited number of AR patients could potentially give a low power to the study; thus, it is hard to rule out the chance that small effects were not detected due to the reduced sample size. Fifth, the specific allergy profiles of AR patients were not available in this study; thus, it was difficult for us to provide detailed information regarding sensitizations to the allergens of the study participants. Nevertheless, the regression models also accounted for the confounding effects of potential allergenic sources, including pets, cooking status, house renovation, and ambient allergens. Notably, the sensitivity analysis indicated that our results were not altered when additionally adjusting for the main ambient allergens (dust mites, artemisia, and pollen) (Gao et al., 2019, Li et al., 2009). Sixth, as possible confounders, additional ambient pollutants such as nitrogen dioxide, sulfur dioxide, ozone, and carbon monoxide were not controlled in regression models to minimize collinearity on effect estimates. Last, due to difficulties and the enormous expense of follow-up in the panel study, the sample size and the number of measurements of this investigation were relatively small, hence limiting the potential generalizability and external validity of the findings. Further studies are warranted to expand the study with more participants to provide more compelling evidence.

5. Conclusion

This panel investigation revealed that exposure to $PM_{2.5}$ and its specific constituents might considerably exacerbate inflammatory symptoms and reduce the quality of life of AR patients in Taiyuan, China. Importantly, moving averages of two lag days (lag 0 to 1) of $PM_{2.5}$ and certain hazardous constituent exposure were associated with inflammatory symptom scale scores and a life quality assessment among AR patients. These findings contribute to a better understanding of the health and life effects of air pollution in AR patients, highlight the priority of air quality improvement in cities with heavy industrialization, such as Taiyuan, and emphasize the need for specialized management to improve the quality of life of AR patients with chronic symptoms. It would be desirable to target control legislation, reduce such environmental exposures, identify the most toxic PM and constituents, better protect vulnerable populations, and reduce the health and economic burden on public health.

Funding

This study was supported by the National Natural Science Foundation in 2023 (82260485); the Shanxi Province Science Foundation for Youths (2015021182); and the Basic Research Project of Science & Technology Department of Yunnan Province in 2020 (202001AT070056).

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108319.

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