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Long-term exposure to $PM_{2.5}$ and its constituents and visual impairment in schoolchildren: A population-based survey in Guangdong province, China

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ABSTRACT

Background: Exposure to fine particulate matter ($PM_{2.5}$) has been linked to visual impairment. Nevertheless, evidence associating $PM_{2.5}$ constituents with visual impairment in schoolchildren is sparse.

Objectives: To explore the effects of long-term exposure to $PM_{2.5}$ and its constituents on visual impairment.

Methods: We conducted a large cross-sectional population-based study to recruit 59,054 schoolchildren from four cities in Guangdong province, China, and used the ChinaHighAirPollutants (CHAP) dataset to estimate 3-year average concentrations of $PM_{2.5}$ and its constituents (black carbon (BC), organic matter (OM), nitrate (NO_3^-), sulfate (SO_4^{2-}) and ammonium (NH_4^+)) based on individuals' home addresses. Visual acuity was measured with a standardized logarithmic chart, and visual impairment was defined as visual acuity below 4.9 (Snellen 5/6 equivalent) in at least one eye. We utilized generalized linear mixed models and weighted quantile sum regression to assess the association between $PM_{2.5}$ constituents and visual impairment.

Results: The observed associations typically displayed a nonlinear pattern. Compared to the lowest quartile of $PM_{2.5}$ and its constituents, the fourth quartile was associated with higher odds of visual impairment in schoolchildren (e.g., the adjusted odds ratio (OR) was 1.23 (95% CI: 1.13, 1.33) for $PM_{2.5}$, 1.53 (95% CI: 1.40, 1.67) for OM, and 1.35 (95% CI: 1.27, 1.44) for BC), respectively. Similarly, joint exposure to $PM_{2.5}$ constituents was associated with visual impairment (OR = 1.17, 95% CI: 1.13, 1.22), while BC and OM contributed more to the observed associations.

Conclusions: Long-term exposure to $PM_{2.5}$ and its constituents was significantly associated with higher rates of visual impairment in schoolchildren, with combustion-related BC and OM potentially driving the observed associations.

1. Introduction

Visual impairment has become a significant global health concern, affecting 10–30 % of adults in many countries and up to 47 % of children in Asia, with myopia being the primary type of visual impairment among schoolchildren (Baird et al. 2020; Yang et al. 2021b). A recent

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investigation revealed that the estimated number of schoolchildren with visual impairment in China will rise to 180 million by 2030 (Chen et al. 2022). Visual impairment results from a combination of genetic predispositions, environmental influences, and modern factors (Biswas et al. 2024). Compelling evidence from multicenter studies has demonstrated that extended durations of near-work activities are significant determinants of myopia (Pärssinen and Kauppinen, 2019; Wu et al. 2018). Besides, air pollution is also believed to adversely affect visual health. Several studies indicate that prolonged exposure to polluted air, especially high concentrations of fine particulate matter ($PM_{2.5}$), could elevate the risk of eye inflammation and irritation, thereby exacerbating the risk of visual impairment (Han et al., 2024).

Evidence has shown the presence of exogenous atmospheric particulate black carbon on the human ocular surface for the initial time, revealing that exposure to particulate matter (PM) may pose risks to eye health (Liu et al. 2023). Moreover, increasing epidemiological evidence has observed that exposure to $PM_{2.5}$ is related to visual impairment (Chen et al. 2022; Grant et al. 2021; Yang et al. 2021a). The specific impact of $PM_{2.5}$ on visual impairment has varied across studies and may differ by region. The composition of $PM_{2.5}$ varies widely across different areas, containing a complex mix of toxic substances such as heavy metals, organic compounds, and inorganic salts. These components may affect the eyes through distinct mechanisms, potentially leading to varying degrees of visual impairment (Li et al. 2023a; Nassan et al. 2021). Nevertheless, the impact of $PM_{2.5}$ components on visual impairment remains unclear. Until now, a single longitudinal study conducted in Barcelona, Spain, has explored the relationship between black carbon and spectacles use in schoolchildren, suggesting a potential link between black carbon and the development of myopia. Furthermore, since individuals are exposed to a complex and changing combination of pollutants throughout their lives, multi-pollutant models that account for potential synergistic effects, whether linear or nonlinear, among $PM_{2.5}$ constituents are likely more appropriate for investigating the impact of $PM_{2.5}$ constituents on visual impairment (Huang et al. 2023).

The composition of $PM_{2.5}$ varies significantly across different regions, and its unique biological mechanisms may differently impact eye health. Additionally, there is limited research analyzing the long-term effects of $PM_{2.5}$ on children's visual development. Therefore, to explore the single and joint effects of prolonged exposure to $PM_{2.5}$ and its components on visual impairment in schoolchildren, we carried out a large population-based study in Guangdong province, China. Furthermore, we tested whether modifiable factors related to lifestyle among schoolchildren could serve as modifiers of these associations.

2. Methods

2.1. Study population

We carried out a cross-sectional study in Guangdong province, China to explore the potential links between environmental exposures and health outcomes, as we previously reported (Wu et al. 2024). Briefly, the study recruited residents from four cities (Shenzhen, Foshan, Maoming, and Zhongshan) in Guangdong province from 2020 to 2021. The selection criteria for participants were students who were studying at the chosen school and residing at their current address for over two years. A total of 69,610 children from the selected schools were invited to participate, and 59,054 returned a completed study questionnaire. Children without exposure measurements (n = 247) or visual acuity data (n = 10,309) were excluded, leaving a final study population of 59,054 for the current analysis (Fig. S1). The study was approved by the Human Studies Committee of Sun Yat-sen University (2019–138).

2.2. Visual acuity measurement and visual impairment

We measured the visual acuity of each eye according to the Standard for Logarithmic Visual Acuity Charts set by the Standardization Administration of China (GB11533-2011). This standard recommends a five-mark record for Chinese schoolchildren, which is equal to five minus the logarithm of the minimum angle of resolution (LogMAR). Visual acuity is quantified on a scale from 4.0 to 5.3, with higher values denoting superior visual acuity. Briefly, in a well-lit room, experienced eye care professionals measured visual acuity for each eye using a retroilluminated logMAR chart with tumbling-E optotypes at a 5-meter distance (Yang et al. 2021b). Children who were unable to read the top line at a 5-meter distance were instructed to approach the visual chart incrementally, moving to distances of 4, 3, 2, or 1 m until they could read it. If the errors counted were fewer than two, the tester continued to examine the next row; otherwise, they re-examined the upper row. The lowest row correctly identified for each eye was recorded as the visual acuity. Prior to the visual acuity test, children were inquired about the use of glasses, contact lenses, or orthokeratology lenses. Children who wore glasses underwent visual acuity assessment initially without correction, followed by a second measurement with optimal correction taken 30 min after the removal of glasses (Bao et al. 2024). Adhering to the guidelines established by the International Council of Ophthalmology in collaboration with the World Health Organization and the International Agency for the Prevention of Blindness (Colenbrander 2002), visual impairment was defined as visual acuity below 4.9 (Snellen 5/6 equivalent) in at least one eye. Both continuous visual acuity levels and dichotomous visual impairment were used as outcome variables.

2.3. Exposure assessment

We collected data on $PM_{2.5}$ mass and its components from ChinaHighAirPollutants (CHAP, https://weijing-rs.github.io/) at a 1 km × 1 km grid resolution across China, including black carbon (BC), organic matter (OM), nitrate (NO_3^-), sulfate (SO_4^{2-}) and ammonium (NH_4^+). The methodology and validation of the models were fully described previously (Wei et al. 2023a; Wei et al. 2023b). Briefly, this data set used a four-dimensional spatiotemporal deep forest (4D-STDF) model to estimate daily $PM_{2.5}$ chemical composition at a spatial resolution of 1 km in China since 2000. The model integrated measurements of $PM_{2.5}$ species from a high-density observation network, satellite $PM_{2.5}$ retrievals, atmospheric reanalyses, and model simulations. We matched the annual average concentrations of $PM_{2.5}$ and its constituents based on students' home addresses. Since ages 3 to 12 are the sensitive period for myopia, and ages 8 to 12 represent the period of high incidence of new myopia (Iribarren 2015), we used the average concentration from the three years prior to the survey (2018–2020) as an indicator of long-term exposure.

We estimated green space surrounding the home of participants using one satellite-based vegetation index: the normalized difference vegetation index (NDVI). The NDVI dataset used in this study covers the annual maximum normalized difference vegetation index (NDVI) with a 30-meter resolution for mainland China from 2000 to 2022. NDVI is a commonly used vegetation index that effectively reflects surface vegetation cover and growth conditions. This dataset is provided by the National Ecosystem Science Data Center, obtained through Landsat 5/7/8/9 remote sensing data, and has been standardized and validated. We used ArcGIS 10.7 (ESRI, Redlands, CA, USA) to predict the level of exposure of NDVI. The value of NDVI ranges from −1 to 1, and a higher value corresponds to a higher density of green space (Tucker 1979).

2.4. Confounders

We utilized a structured questionnaire to gather individuals' information on socio-demographic, behavioral, and living environment factors, mainly including the home address, age (in years), gender (male vs. female), annual household income of the research subjects (≤30,000 vs. 30,000–10,000 vs. >30,000), height (in centimeters), weight (in kilograms), parental education level (defined as the highest education level of either parent, below junior high school/senior high school/ college or above), physical exercise duration (<1.0 h/day vs. ≥1.0 h/ day) (Qu et al. 2020), outdoor activity duration (<2 h/day vs. ≥2 h/day) (Gupta et al. 2021), whether premature birth (yes vs. no), sleep duration (<8 h/day vs. 8–9 h/day vs. >9 h/day) (Huang et al. 2022), interior decoration (yes vs. no), use of kitchen range hood (yes vs. no), duration of electronic product use before bed (<0.5 h vs. ≥0.5 h) (Wang et al. 2020), parents and family members' smoking status (yes vs. no), NDVI and distance from address to main road (≤200 m vs. >200 m). Body mass index (BMI) was calculated as weight (kg) divided by height in meters squared (m^2).

Subsequently, we constructed a directed acyclic graph (DAG) (Fig. S2) based on current research and professional expertise, utilizing DAGitty 3.1 software, to identify the minimal necessary adjustment set. The following variables were chosen as confounders based on the DAG: children's age, children's sex, children's body mass index, children's exercise time, children's outdoor activity time, parental education level, annual household income, secondhand smoking, distance from address to main road and NDVI.

2.5. Statistical analysis

Continuous variables were reported as the mean and standard deviation (SD), and the frequencies were calculated for categorical variables. We employed generalized linear models (GLMs) with restricted cubic spline (RCS) functions (knot = 3), selecting the model with the lowest Akaike Information Criterion (AIC) to illustrate the exposure–response curves between $PM_{2.5}$ and its constituents and visual impairment. Given that the relationships in the RCS functions were nonlinear for most pollutants (Fig. S3), we evaluated the odds ratios (ORs) and regression coefficients (βs) with corresponding confidence intervals (CIs) for visual impairment at quartile 2, 3, 4 of air pollutant concentrations against quartile 1 using generalized linear mixed models, with cities as random effects and air pollutant/confounders as fixed effects. Additionally, taking into account the variations in concentration distributions among $PM_{2.5}$ components and the direct impact of exposure levels on the observed associations, as well as the observed linear relationship between the association of SO_4^{2-} and visual impairment, we calculated the odds ratios for both $PM_{2.5}$ and each $PM_{2.5}$ component per interquartile range (IQR) increment and per 1 μg/m^3 increment.

Additionally, we used weighted quantile sum (WQS) regression to explore the joint effect of the five $PM_{2.5}$ components on visual impairment. We computed the WQS index while adjusting for the same confounding variables as in the main model. We presented the estimated odds ratio for visual impairment per quartile increase in the WQS index, along with the weighting of each component in the associations. To identify key constituents with a significant contribution, we applied a threshold of 20.0 % (100 % divided by five constituents) for the average weight of a component.

To verify the robustness of our results, we performed a series of sensitivity analyses. Firstly, we additionally individually adjusted the main models for other potential risk factors of visual impairment (e.g., children's duration of electronic product use before bed, children's sleep duration, and grade level as a proxy for close-up work patterns). Secondly, considering that household decoration and kitchen ventilation may affect the exposure concentration of $PM_{2.5}$ and its constituents, these factors were adjusted separately based on the main model. Thirdly, we excluded premature infants and children in their first year of school from the analysis of the relationship between pollutants and visual impairment. Fourth, we used multi-year mean concentrations of air pollutants, such as four-year averages (2017–2020) and five-year averages (2016–2020), to explore potential changes in exposure over different time periods. Fifth, we used quantile G-computation (QGC) to estimate the joint effect and the weights of individual exposures. Based on the WQS approach, QGC derives causal associations and estimates both positive and negative weights by incorporating additional statistical assumptions(Li et al. 2023b). Finally, we tested for modification of the potential effects of children's age, children's gender, children's outdoor activities, annual household income, parental education level, and NDVI exposure. We incorporated interaction terms between air pollutants and potential modifiers into the adjusted models to assess interactions and subsequently provided stratified interpretations based on subgroups.

R software (version 4.3.1) was used for all analyses. Statistical significance was determined by two-sided $P < 0.05$.

3. Results

3.1. Study population characteristics and air pollutant levels

Table 1 shows the characteristics of participants. A total of 59,054 participants with 31,985 (54.20 %) boys and 27,069 (45.80 %) girls were included in the study. A total of 27,335 (46.29 %) children had visual impairment. The average (SD) age of the participants was 9.91 (2.91) years. Participants with visual impairment were more likely to be older schoolchildren (49.80 % vs 42.40 %), engage in less than 1 h of exercise per day (57.50 % vs 33.50 %), spend less than 2 h on outdoor activities per day (33.50 % vs 31.10 %), and use electronic devices for more than 1 h per day (57.50 % vs 33.50 %).

The distribution of exposure concentrations for $PM_{2.5}$ and its constituents in this study is shown in Table 2. Between 2018 and 2020, the median $PM_{2.5}$ mass concentrations among participants was 25.86 μg/ m^3. The median concentrations of $PM_{2.5}$ constituents were 6.56 μg/m^3 (SO_4^{2-}), 4.02 μg/m^3 (NO_3^-), 3.12 μg/m^3 (NH_4^+), 8.41 μg/m^3 (OM) and 2.47 μg/m^3 (BC). The Spearman correlation coefficients between $PM_{2.5}$ and its five major constituents in the study are shown in Table S1. $PM_{2.5}$ exposure was moderately to highly correlated with SO_4^{2-} NH_4^+, and BC (r_s = 0.44–0.74).

3.2. Associations between $PM_{2.5}$ and its constituents and visual impairment

We generally found nonlinear dose–response associations between $PM_{2.5}$ and its constituents and visual impairment, except for SO_4^{2-} (Fig. S3). $PM_{2.5}$, OM, and BC had linear dose–response relationships at low exposure levels, but the association diminished at higher concentrations. The combined analysis using both the quartile-based method and the linear method for each IQR increase comprehensively revealed that higher levels of $PM_{2.5}$ and its components were associated with an increased risk of visual impairment. Compared to the lowest quartile (reference), the estimated ORs at the fourth quartile were 1.23 (95% CI: 1.14, 1.33) for $PM_{2.5}$, 1.53 (95% CI: 1.40, 1.67) for OM, 1.34 (95% CI: 1.26, 1.43) for BC, 1.23 (95% CI: 1.05, 1.45) for NO_3^-, and 1.09 (95% CI: 1.00, 1.19) for NH_4^+ (Table 3). Elevated concentrations of $PM_{2.5}$ and its components were linked to reduced levels of visual acuity. For example, at the fourth quartile of $PM_{2.5}$, OM, and BC, left eye visual level was decreased by 0.02 (95% CI: −0.03, −0.01), 0.02 (95% CI: −0.03, −0.01), 0.03 (95% CI: −0.04, −0.03), respectively (Table S2). We also found that per IQR increase in each pollutant, odds ratios of visual impairment were 1.35 (95% CI: 1.31, 1.39) for $PM_{2.5}$ mass, 1.21 (95% CI: 1.12, 1.30) for SO_4^{2-}, 1.20 (95% CI: 1.10, 1.30) for NO_3^-, 1.07 (95% CI: 1.03, 1.12) for NH_4^+, 1.19 (95% CI: 1.15, 1.23) for BC and 1.69 (95% CI: 1.61, 1.77) for OM (Table 3).

In the WQS analyses, we observed that each quartile increase in the WQS index of the five-constituent mixture of $PM_{2.5}$ was associated with higher odds of prevalent visual impairment (OR = 1.17; 95% CI: 1.13–1.22) in a positive direction (Table S4). The weights of the $PM_{2.5}$ constituents in the WQS index are displayed in Fig. 1. We observed that BC and OM contributed more to the increased risk of visual impairment. Specifically, the contribution weights of BC, OM, NO_3^-, NH_4^+ to the prevalence of visual impairment were determined to be 0.5175, 0.4396,

Table 1
Characteristics of the study participants according to visual impairment status.

Characteristics	Study participants (n = 59,054)	Children without visual impairment (n = 31,719)	Children with visual impairment (n = 27,335)	*P* Value
Sex [a]				
Male	31,985 (54.20)	18,275 (57.60)	13,710 (50.20)	<0.001
Female	27,069 (45.80)	13,444 (42.40)	13,625 (49.80)	
Age [b]	9.91 (2.91)	8.85 (2.56)	11.14 (2.79)	<0.001
BMI (kg/m^2) [b]	18.45 (3.83)	18.14 (3.86)	18.82 (3.76)	<0.001
Annual household income [a]				
≤ 30,000	13,910 (23.60)	7,390 (23.30)	6,520 (23.90)	<0.001
30,000–10,000	14,206 (24.10)	7,320 (23.10)	6,886 (25.20)	
> 10,000	30,938 (52.40)	17,009 (53.60)	13,929 (51.00)	
Parental education level [a,*]				
Below junior high school	22,707 (38.50)	11,672 (36.80)	11,035 (40.40)	<0.001
Senior high school	13,533 (22.90)	7,004 (22.10)	6,529 (23.90)	
College or above	22,814 (38.60)	13,043 (41.10)	9,771 (35.70)	
Exercise time [a]				
< 1 h	12,324 (20.90)	5,985 (18.90)	6,339 (23.20)	<0.001
≥ 1 h	46,730 (79.10)	25,734 (81.10)	20,996 (76.80)	
Outdoor activity [a]				
< 2 h	19,041 (32.20)	9,879 (31.10)	9,162 (33.50)	<0.001
≥ 2 h	40,013 (67.80)	21,840 (68.90)	18,173 (66.50)	
Sleep duration [a]				
< 8 h	4,042 (6.80)	1,128 (3.60)	2,914 (10.70)	<0.001
8 ~ 9 h	22,277 (37.70)	9,472 (29.90)	12,805 (46.80)	
> 9 h	32,735 (55.40)	21,119(66.60)	11,616(42.50)	
Electronic product usage time [a,**]				
≤ 1 h	52,117 (88.30)	29,003 (91.40)	23,114(84.60)	<0.001
> 1 h	6,937 (11.70)	2,716 (8.60)	4,221 (15.40)	
Renovation [a]	25,529 (43.20)	13,853 (43.70)	11,676 (42.70)	0.019
Kitchen hoods [a]	53,383 (90.40)	28,544 (90.00)	24,839 (90.90)	<0.001
Secondhand smoke [a]	28,574 (48.40)	15,272 (48.10)	13,302 (48.70)	0.215
Road distance [a,***]				
≤ 200 m	36,407 (61.70)	19,198(60.50)	17,209 (63.00)	<0.001
> 200 m	22,647 (38.30)	12,521 (39.50)	10,126 (37.00)	
Left eye sight [b]	4.87 (0.27)	5.04 (0.08)	4.68 (0.28)	<0.001
Right eye sight [b]	4.87 (0.27)	5.05 (0.08)	4.68 (0.28)	<0.001

Abbreviations: BMI, body mass index;
[*] Parent education level, defined as the highest degree of either parent;
[**] Electronic product usage time, defined as the screen time before bed;
[***] Residential proximity to major roadways;
[a] N (%);
[b] Mean (SD).

0.0276, 0.0153, respectively.

3.3. Stratified analyses

The subgroup-specific ORs in single-constituent models are shown in Tables S5–S10. We found that in subgroups with household income ≤ 30,000, parents' education level below high school, and NDVI exposure level ≤ 0.4, the effect estimates for $PM_{2.5}$ and its constituents showed consistent directions. Specifically, compared to the lowest quartile, we observed that the effect estimates of $PM_{2.5}$, SO_4^{2-} and OM on visual impairment tended to be higher in male individuals and older schoolchildren in the highest quartile. Children from families earning below 30,000 yuan annually had a higher risk of visual impairment with $PM_{2.5}$ and OM. Significant effect modification by parental education level was detected for $PM_{2.5}$ and its components, with children of parents with lower education levels being more likely to have visual impairment. Furthermore, we observed that $PM_{2.5}$ and its five components were more strongly linked to visual impairment in individuals with lower NDVI exposure.

3.4. Sensitivity analysis

The robustness of our findings was confirmed through a series of sensitivity analyses. Firstly, considering that indoor air pollution will affect the exposure of $PM_{2.5}$ and its components, after additionally adjusting for indoor decoration and range hood use in the main model, the results were found to be consistent with the main model (Tables S11 and S12). In addition, we individually adjusted the primary models for additional risk factors associated with visual impairment (sleep duration, electronic product usage time, and grade level). We observed no substantive changes in the results (Tables S13–S15). Secondly, results from analyses excluding children born prematurely or in first grade were consistent to the main analysis (Tables S16 and S17). Thirdly, the findings were similar to the main models when utilizing the 4- and 5-year average concentrations of $PM_{2.5}$ and its components (Tables S18 and S19). Finally, QGC estimated both positive and negative weights (Fig. S4), with OM and BC showing the most significant positive weights. Joint exposure to $PM_{2.5}$ components was positively associated with visual impairment (OR= 1.14, 95% CI: 1.11–1.17) by using the QGC method (Table S20). The statistical methods used in the sensitivity analysis yielded similar conclusions to those in the main text, consistently suggesting that OM and BC may contribute more to the relationship between $PM_{2.5}$ components and visual impairment.

4. Discussion

In this large cross-sectional study, we observed that elevated levels of $PM_{2.5}$ and its components were linked to a higher risk of visual impairment and a corresponding decrease in average visual acuity. Specifically, exposure to BC and OM appeared to be the main contributors to the observed association. In addition, the association between $PM_{2.5}$ and its constituents with visual impairment was more significant among schoolchildren with lower household income, parental education level below high school, and lower NDVI exposure. To our knowledge, this is the first study to investigate the relationship between $PM_{2.5}$ constituents and visual impairment in developing countries.

To date, previous studies have found a positive correlation between $PM_{2.5}$ and visual impairment. Consistent with our findings, a large cross-sectional study conducted in 2013, involving 61,995 children from seven provinces/municipalities across China, has observed that an IQR increase in the 3-year averaged $PM_{2.5}$ concentration (an average level of 60.09 μg/m^3) was linked to an increased likelihood of visual impairment

Table 2
The concentrations of $PM_{2.5}$ and its constituents in present study.

Air pollutant[a,*]	Mean	Minimum	25th	Median	75th	Maximum	IQR
$PM_{2.5}$	25.83	19.88	24.68	25.86	26.22	31.82	1.54
SO_4^{2-}	6.49	5.69	6.06	6.56	6.78	7.76	0.72
NO_3^-	4.29	3.18	3.76	4.02	4.61	6.70	0.86
NH_4^+	3.22	2.69	3.04	3.12	3.35	4.69	0.31
OM	8.37	3.44	7.70	8.41	9.23	10.69	1.53
BC	2.54	1.56	2.37	2.47	2.78	3.31	0.41

Abbreviations: $PM_{2.5}$, particles with aerodynamic diameter ≤ 2.5 μm; SO_4^{2-}, sulfate; NO_3^-, nitrate; NH_4^+, ammonium; OM, organic matter; BC, black carbon; IQR, interquartile range;

[*] (μg/m^3);

[a] Three-year (2018–2020) average concentrations of air pollutants;

(OR = 1.267, 95% CI, 1.082–1.484), with stronger associations in boys, older individuals, and those living in rural areas (Yang et al. 2021a). Similarly, a retrospective cohort study in Taiwan with 97,306 children revealed that the fourth quartile of $PM_{2.5}$ (> 41.2 μg/m^3) was linked to increased risk of myopia (hazard ratio = 1.76, 95% CI, 1.68–1.83) compared with the lowest quartile of $PM_{2.5}$ (< 29.5 μg/m^3) (Wei et al. 2019). Only one study has reported the associations between the use of spectacles and $PM_{2.5}$ components like BC in schoolchildren. Specifically, this cohort study involving 2,727 schoolchildren in Barcelona, Spain, found that per IQR increment in $PM_{2.5}$ absorbance (median: 2.3 × 10^{-5}/m^3, OR = 1.23, 95% CI, 1.03–1.46) and BC (median: 1.4 μg/m^3, OR = 1.23, 95% CI, 1.03–1.46) were associated with an increased use of spectacles (Dadvand et al. 2017). In line with this study, our findings also revealed an association between exposure to $PM_{2.5}$ and BC and a higher risk of visual impairment in China. Although the Spanish study exhibited strengths in terms of utilization of a cohort design, this study only focused on the effect of BC on spectacle use (an alternative test for myopia), which would lead to misclassification of the results. Notably, our large-scale study used precise home addresses to estimate concentrations of $PM_{2.5}$ components, uncovering the associations between long-term exposure to five $PM_{2.5}$ components and visual impairment.

Identifying key harmful $PM_{2.5}$ components is crucial to implement air pollution management initiatives. In our study, all five major components of $PM_{2.5}$ (SO_4^{2-}, NO_3^-, NH_4^+, BC, and OM) demonstrated statistically significant associations with visual impairment, with BC and OM having stronger effects. Significantly, the mixture of five $PM_{2.5}$ components was associated with visual impairment, with BC contributing more to this association. Based on these findings, we suggest that BC and OM may be crucial contributors to $PM_{2.5}$-associated visual impairment. Similarly, various studies have shown the negative impact of different $PM_{2.5}$ constituents on different health outcomes. For example, a recent systematic review of $PM_{2.5}$ constituents revealed that the most robust and consistent associations with all-cause and cardiovascular mortality and morbidity were seen with BC and organic carbon (OC) exposure (Yang et al. 2019). Likewise, a cohort study in the U.S.A. reported that prolonged exposure to $PM_{2.5}$ constituents was linked to dementia, and SO_4^{2-}, BC, and OM may drive the observed associations (Shi et al. 2023). Despite discrepancies in demographic factors, $PM_{2.5}$ levels, sources, composition, exposure periods, and the methods used to assess exposure, it is crucial to highlight that all studies concluded that $PM_{2.5}$ constituents contribute to adverse health effects. Hence, identifying key $PM_{2.5}$ components contributing to visual impairment may be crucial for policymakers to implement effective exposure reduction measures in society.

The potential biological mechanisms linking $PM_{2.5}$ constituents to visual impairment remain unclear. Recently, a study reported that $PM_{2.5}$ activated NLRP3 inflammasome and inflammatory substances and induced oxidative stress in human trabecular meshwork cells, which may directly damage intraocular tissues, thereby contributing to the development and progression of ocular hypertension and glaucoma (Li et al. 2021). A key finding from our study is that BC and OM contributed more to the observed association than the other three constituents. BC primarily originates from incomplete combustion processes such as traffic emissions, industrial activities, biomass burning, fires, household heating and cooking, waste incineration, and agricultural burning (Long et al. 2013). Importantly, a recent study found that environmental exposure to BC may contribute to an increased risk of elevated intraocular pressure, potentially acting through oxidative stress mechanisms associated with glaucoma and intraocular pressure (Nwanaji-Enwerem et al. 2019). Moreover, an animal study found that exposure to BC on the ocular surface decreased tear film stability and tear secretion, induced inflammatory cell infiltration, and altered the corneal structure in corneal and conjunctival tissues of male BALB/C mice (Jiao et al. 2023). Furthermore, exposure to BC particles induced cell apoptosis, activated the NLRP3 inflammasome, and increased the protein levels of inflammatory mediators (e.g., IL-1β, NLRP3, caspase-1, and ASC) in human corneal epithelial cells (Long et al. 2020). These findings suggest that BC exposure may not only affect intraocular pressure but also exacerbate the inflammatory and oxidative damage in ocular tissues, potentially leading to visual impairment. Overall, these findings provide important clues to the potential mechanisms of BC-related visual impairment.

Generally, OM accounts for a significant portion of $PM_{2.5}$ mass. Primary OM is emitted from combustion sources and other origins, while secondary OM is generated by the oxidation of gas-phase compounds in the atmosphere (Gawhane et al. 2017; Li et al. 2022). Notably, OM includes various organic species such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and polychlorinated biphenyls (PCBs), which contributes a substantial part of aerosol oxidative potential (Santiago-De La Rosa et al. 2022). Previously, an experimental study found that exposure to organic extracts of particles induced cytotoxicity, ROS generation, oxidative damage, upregulation of inflammatory genes (*IL-6*, *IL-8*, and *IL-1β*), and AhR inducible genes (*CYP1A1* and *CYP1B1*) in human corneal epithelial cells (Xiang et al. 2016). Importantly, experimental evidence from different OM species-induced visual impairment may offer crucial insights into the mechanisms of visual impairment. For example, exposure to PAHs decreased the expression levels of vision-specific genes (e.g., *Arr3b*, *Crx*, *Gnat2*, *Opn1mw*, *Pde6c*, *Pde6h*, *Rho*, and *Sws1*) in embryonic zebrafish (Magnuson et al. 2020). Similarly, exposure to PCBs in zebrafish embryos delayed the development of retinal layers, impaired the shape of photoreceptor cells, inhibited the growth of the photoreceptor outer segment, and further induced developmental deficits in the retinas of zebrafish (Wang et al. 2012). The complexity and diversity of OM compounds may explain its higher contribution to oxidative stress, inflammatory responses, and tissue damage compared to other components of $PM_{2.5}$. Although these findings indicate potential mechanisms of OM-related visual impairment, more experimental research employing OM at doses comparable to human exposure levels is necessary to elucidate the potential mechanisms of visual impairment.

Water-soluble ions, such as NO_3^-, SO_4^{2-}, and NH_4^+, collectively constitute over 50 % of $PM_{2.5}$ concentrations, rendering them significant contributors to severe air pollution (Wu et al. 2017). They are secondary aerosols formed by chemical reactions in the atmosphere, mainly from industrial emissions, traffic exhaust, agricultural activities, and natural

Table 3
Associations between air pollutants and prevalent visual impairment [a].

Air pollutants	Quartile 1	Quartile 2	Quartile 3	Quartile 4
$PM_{2.5}$				
Concentration (μg/m^3)	≤ 24.68	24.68 – 25.86	25.86 – 26.22	> 26.22
Adjusted model OR (95% CI) [b]	Ref	1.03(0.97, 1.08)	0.97(0.91, 1.03)	1.23(1.14, 1.33)
Per IQR increase OR (95% CI) [c]	1.35(1.31, 1.39)	–	–	–
SO_4^{2-}				
Concentration (μg/m^3)	≤ 6.06	6.06 – 6.56	6.56 – 6.78	> 6.78
Adjusted model OR (95% CI) [b]	Ref	0.91(0.84, 0.99)	0.90(0.82, 0.99)	0.93(0.84, 1.04)
Per IQR increase OR (95% CI) [c]	1.21(1.12, 1.30)	–	–	–
NO_3^-				
Concentration (μg/m^3)	≤ 3.76	3.76 – 4.02	4.02 – 4.61	> 4.61
Adjusted model OR (95% CI) [b]	Ref	0.95(0.90, 1.00)	1.24(1.14, 1.34)	1.23(1.05, 1.45)
Per IQR increase OR (95% CI) [c]	1.20(1.10, 1.30)	–	–	–
NH_4^+				
Concentration (μg/m^3)	≤ 3.04	3.04 – 3.12	3.12 – 3.35	> 3.35
Adjusted model OR (95% CI) [b]	Ref	1.28(1.21, 1.35)	1.09(1.03, 1.15)	1.09(1.00, 1.19)
Per IQR increase OR (95% CI) [c]	1.07(1.03, 1.12)	–	–	–
OM				
Concentration (μg/m^3)	≤ 7.70	7.70 – 8.41	8.41 – 9.23	> 9.23
Adjusted model OR (95% CI) [b]	Ref	1.36(1.29, 1.43)	1.57(1.45, 1.70)	1.53(1.40, 1.67)
Per IQR increase OR (95% CI) [c]	1.69(1.61, 1.77)	–	–	–
BC				
Concentration (μg/m^3)	≤ 2.37	2.37 – 2.47	2.47 – 2.78	> 2.78
Adjusted model OR (95% CI) [b]	Ref	1.26(1.20, 1.33)	1.28(1.22, 1.35)	1.34(1.26, 1.43)
Per IQR increase OR (95% CI) [c]	1.19(1.15, 1.23)	–	–	–

Abbreviations: OR, odds ratio; β, regression coefficient; CI, confidence interval; $PM_{2.5}$, particles with aerodynamic diameter ≤ 2.5 μm; SO_4^{2-}, sulfate; NO_3^-, nitrate; NH_4^+, ammonium; OM, organic matter; BC, black carbon; IQR, interquartile range;

[a] Three-year (2018–2020) average concentrations of air pollutants were used.

[b] Adjusted for sex, age, BMI, annual household income, exercise time, parental education level, outdoor activity, residential proximity to major roadways, secondhand smoking, and NDVI.

[c] Adjusted for sex, age, BMI, annual household income, exercise time, parental education level, outdoor activity, residential proximity to major roadways, secondhand smoking, and NDVI.

sources. Possible explanations for visual impairment caused by secondary aerosols include: they may induce oxidative stress and systemic inflammation (Maciejczyk et al. 2021; Wu et al. 2016), leading to ocular diseases such as conjunctivitis and keratitis. In addition, these water-soluble ions may accumulate in ocular tissues, interfering with normal physiological functions, causing cell damage and dysfunction (Guzman 2021). In this study, we observed that the health effects of NO_3^- and NH_4^+ are more indirect compared to BC and OM. This may be related to the relatively small variation in the concentrations of NO_3^- and NH_4^+ across

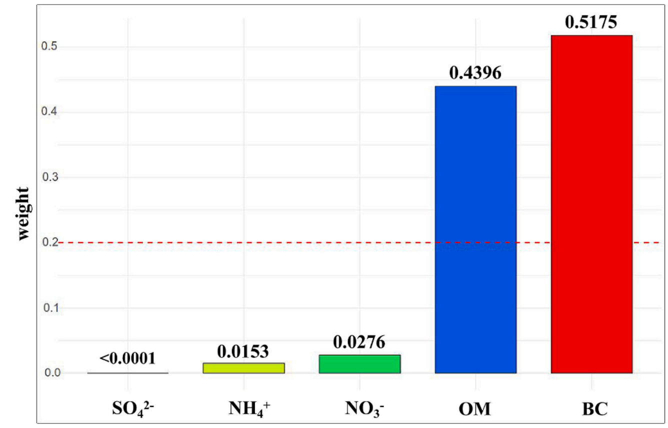

Fig. 1. Association between five major $PM_{2.5}$ components and visual impairment based on WQS regression analysis (The red dashed line indicates the suggested threshold for the most influential components). Abbreviations: SO_4^{2-}, sulfate; NO_3^-, nitrate; NH_4^+, ammonium; OM, organic matter; BC, black carbon; Note: Adjusted for sex, age, BMI, annual household income, exercise time, parental education level, outdoor activity, residential proximity to major roadways, secondhand smoking and NDVI.

different regions and their strong correlation with other pollutants, which could mask their health effects. Therefore, future studies should further investigate the long-term effects of these water-soluble ions on eye health, as well as the cumulative health impact of their joint exposure with other pollutants. In summary, our observations of the relationship between $PM_{2.5}$ and its components and visual impairment are in line with the proposed biological mechanisms.

Although numerous studies have shown that outdoor activities have a significant positive impact on children's visual health, it is important to recognize that this benefit comes with the risk of exposure to air pollution (Zhu et al. 2023). In areas with severe air pollution, children engaging in outdoor activities may be exposed to higher concentrations of $PM_{2.5}$ components, which can pose various health risks. Due to the immaturity of children's immune systems and eye development, they are more vulnerable to environmental pollutants, and exposure to high concentrations of $PM_{2.5}$ may have long-term negative effects on their visual health (Johnson et al. 2021). Therefore, reasonable environmental planning, air quality monitoring, and health education are key measures to maximize the benefits of outdoor activities while minimizing the health risks of $PM_{2.5}$ exposure. For example, establishing real-time air quality monitoring systems, especially in schools and children's activity areas, can ensure that parents and schools are promptly informed about air quality. Increasing urban green spaces, parks, and greenery around school campuses can provide a healthier and safer environment for children during outdoor activities. Additionally, conducting educational programs on eye health and $PM_{2.5}$ protection in schools will help raise awareness among parents and children about the relationship between outdoor activities and environmental pollution.

In interpreting our results, we concede that our study has some limitations. Firstly, the cross-sectional nature of our study does not allow for the identification of a causal link between air pollution and visual impairment. Secondly, despite controlling for significant confounders, residual confounders due to unmeasured variables such as parental myopia history and close-up work hours cannot be completely ruled out because we were unable to obtain data on these factors for analysis. Additionally, although we used grade level status as a proxy for close-up work patterns, this approach may introduce some limitations. Thirdly, we matched the exposure levels of $PM_{2.5}$ and its components, as well as NDVI, based on the students' home addresses, which precluded individual-based exposure measurements. Moreover, this approach may not have captured the exposure levels around schools or during the commute to school, potentially leading to misclassification of exposure levels. Fourth, Bayesian Kernel Machine Regression (BKMR) analysis could not be performed due to computational constraints associated with the large sample size. Finally, the concentrations of $PM_{2.5}$ and its constituents in Guangdong Province are relatively low, and the broader applicability of our findings to other regions of China requires further validation. Future research could consider conducting similar analyses in areas with varying levels of air pollution to validate and extend the findings of this study.

Nonetheless, our study also has several strengths. First, in contrast to most studies that focus on the total mass of $PM_{2.5}$, our study conducted a comprehensive evaluation of the vision-impairing effects of five key components of $PM_{2.5}$, which have not been explored in earlier studies. Second, our study includes a large, representative sample of schoolchildren with a high response rate, which enhances the representativeness and reliability of the study results. Accordingly, the associations we identified may shed light on the health impacts of $PM_{2.5}$ components at elevated concentrations. Third, we conducted a series of sensitivity analyses and showed that our findings were consistent and reliable.

5. Conclusions

In conclusion, long-term exposure to $PM_{2.5}$ and its constituents (NO_3^-, NH_4^+, SO_4^{2-}, OM, and BC) was associated with a higher risk of visual impairment, with BC and OM having stronger associations. Our findings suggest that policies aimed at reducing emissions of combustion-related $PM_{2.5}$ constituents could help lessen the societal burden of $PM_{2.5}$-associated visual impairment.

CRediT authorship contribution statement

Jia-Hui Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hui-Xian Zeng:** Writing – review & editing, Data curation, Conceptualization. **Jing Wei:** Validation, Software, Methodology, Data curation. **Qi-Zhen Wu:** Writing – review & editing, Methodology, Formal analysis. **Shuang-Jian Qin:** Writing – review & editing, Visualization, Conceptualization. **Qing-Guo Zeng:** Writing – review & editing, Investigation. **Bin Zhao:** Writing – review & editing. **Guang-Hui Dong:** Writing – review & editing. **Ji-Chuan Shen:** Writing – review & editing, Supervision, Resources, Project administration. **Xiao-Wen Zeng:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109270.

Data availability

Data will be made available on request.

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