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Prenatal and postnatal early life exposure to greenness and particulate matter of different size fractions in relation to childhood rhinitis - A multi-center study in China

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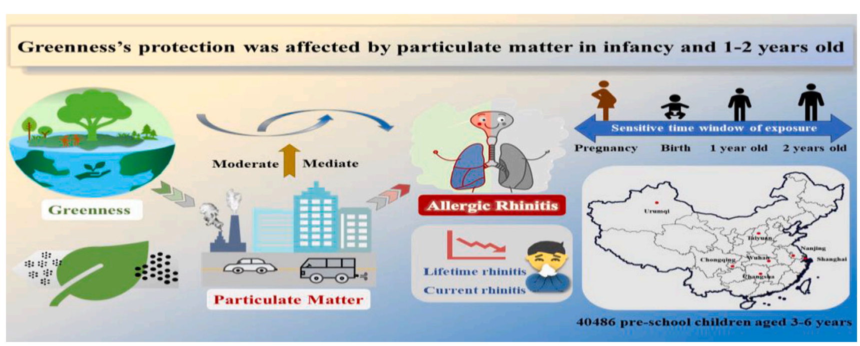
HIGHLIGHTS

- A multi-center study including 40,486 preschool children aged 3–6 years was conducted.
- Prenatal greenness exposure was more consistently associated with lower risk of children's rhinitis.
- Postnatal greenness-rhinitis association was moderated and mediated by ambient PM.

GRAPHICAL ABSTRACT



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ABSTRACT

The impact of early life exposure to residential greenness on childhood rhinitis and its interaction with particulate matter (PM) of different size fractions remain inconsistent. Herein, we recruited 40,486 preschool children from randomly selected daycare centers in 7 cities in China from 2019 to 2020, and estimated exposure to residential greenness by the normalized difference vegetation index (NDVI) with a 500 m buffer. Exposure to ambient PM (PM_1, $PM_{2.5}$, and PM_{10}) was evaluated using a satellite-based prediction model (daily, at a resolution of 1 km × 1 km). By mixed-effect logistic regression, NDVI values during pregnancy, in the first (0–1 year old) and the second (1–2 years old) year of life were negatively associated with lifetime rhinitis (LR) and current rhinitis (CR) ($P < 0.001$). PM in the same time windows was associated with increased risks of LR and CR in children, with smaller size fraction of PM showing greater associations. The negative associations between prenatal and postnatal NDVI and LR and CR in preschool children remained robust after adjusting for concomitant exposure to PM, whereas the associations of postnatal NDVI and rhinitis showed significant interactions with PM. At lower levels of PM, postnatal NDVI remained negatively associated with rhinitis and was partly mediated by PM (10.0–40.9 %), while at higher levels of PM, the negative associations disappeared or even turned positive. The cut-off levels of PM were identified for each size fraction of PM. In conclusion, prenatal exposure to greenness had robust impacts in lowering the risk of childhood rhinitis, while postnatal exposure to greenness depended on the co-exposure levels to PM. This study revealed the complex interplay of greenness and PM on rhinitis in children. The exposure time window in prenatal or postnatal period and postnatal concomitant PM levels played important roles in influencing the associations between greenness, PM and rhinitis.

1. Introduction

Allergic rhinitis (AR) is one of the most common allergic diseases, affecting approximately 10–40 % of the population worldwide (Wang et al., 2016a, 2016b), and it continuously increases particularly in low- and middle-income countries (Asher. I, 2014; Greiner et al., 2011). In China, the self-reported prevalence of AR increased substantially from 2005 and 2011, doubling in Beijing, Shanghai, and Hangzhou (Wang et al., 2016a, 2016b). In Children, a cross-sectional study in Shanghai revealed that the prevalence of AR in preschool children ($n = 13{,}335$; aged 4–6 years) was 12.6 % (Huang et al., 2017). AR can markedly affect the patients' life quality (i.e., poor sleeping, difficulty in breathing, and memory loss) and cause a large economic burden, along with school absenteeism (Blaiss et al., 2018; Linneberg et al., 2016).

Children living in urban areas had higher prevalence of AR, and it has been associated with higher air pollution in urban areas, such as particulate matter (PM) (Burte et al., 2020; Chen et al., 2018; Lin et al., 2021; Savouré et al., 2021; Sugiyama et al., 2020) and traffic-related air pollutants (TRAP) (Lu et al., 2020). As a heterogeneous mixture of solid and liquid particles suspended, PM is typically categorized into PM_1 (aerodynamic diameter PM ≤ 1 μm), $PM_{2.5}$ (aerodynamic diameter PM ≤ 2.5 μm), and PM_{10} (aerodynamic diameter PM ≤ 10 μm). According to an eight-city Chinese study conducted in 2010–2011, preschoolers exposed to high levels of $PM_{2.5}$ during pregnancy were more likely to develop symptoms of rhinitis (Chen et al., 2022; Norbäck et al., 2019). A cohort study from the Childhood Environment and Allergic Diseases Study (CEAS) has reported that increased lifetime exposure to $PM_{2.5}$ was associated with a higher risk of AR among children (Wang et al., 2016a). Till now, accumulated evidence supports the positive association of PM and allergic symptoms since PM comprises immunogenic substances (i.e., fungal spores and pollen) (Guarnieri and Balmes, 2014), and may enhance the allergenicity of airborne allergens (Ghiani et al., 2012; Konishi et al., 2014).

On the other hand, living close to green space, such as parks and forests, as well as street trees, gardens, and numerous other arrangements of vegetation, have been reported on its potential health benefits on AR. For example, a study among 8–12-year-old schoolchildren in Austria and Italy showed the lower prevalence of AR symptoms was associated with normalized difference vegetation index (NDVI) and tree coverage areas (Dzhambov et al., 2021). In the seven birth cohorts study, GINI/LISA North and PIAMA cohorts showed NDVI had protective effects on allergic rhinitis (Fuertes et al., 2016). However, studies on greenness exposure in allergic diseases are generally more inconsistent and even contradictory (Eldeirawi et al., 2019; Hu et al., 2023; Parmes et al., 2019; Yang et al., 2023). For example, a cross-sectional study from Spain failed to detect any association between residing near parks and allergic rhinoconjunctivitis (Dadvand et al., 2014), and a German birth cohort suggested that early life residence with many trees and specifically many allergenic trees might increase prevalence of allergic rhinitis (Markevych et al., 2020). Studies conducted in China also reported inconsistent results. A study in Suzhou observed no association between rhinitis and NDVI or distance to park (Li et al., 2019). Moreover, a study in Taiwan reported that exposure to greenness could increase the risk of AR (Lee et al., 2020). The effects of greenness can vary by the study area, exposure assessment method, exposure windows, definitions of outcomes, covariates, vegetation biodiversity, and environmental microbiome (Fuertes et al., 2016; Rufo et al., 2019). And the interaction between air pollution and greenness which might influence the impact of greenness on AR has been neglected.

In real-world settings, children are simultaneously exposed to both ambient PM and greenness. City greenness areas are usually segregated by high-rise buildings or interlaced with traffic roads especially in populous areas. The effects of greenness exposure are mixed with or even obscured by the adverse effects of co-occurrent ambient air pollution, especially in urban area. Even inside green areas, PM can react with emitted chemical compounds from green areas, and increase certain pollutants which are harmful to respiratory health. However, there is a lack of sufficient evidence on the complex interplay between greenness and PM on rhinitis. To our knowledge, one reported the improvement effects of lung health in children associated with greenness exposure might differ at different air pollution levels (Zhou et al., 2021). More other studies considered this as confounding effect by adjusting for the co-exposed air pollutants in the regression mode. Few considered on the cut-off levels of PM at which the associations of greenness and AR might change, nor on the exposure time window of such interaction effects in early life. Hence, it is important to investigate both on whether exposure to greenness exerts a beneficial impact on AR in children and whether the impact is modified or mediated by co-exposure to PM in certain sensitive exposure windows.

In this study, we hypothesized that residential environment with greater greenness would positively impact and even reduce the harmful effects of PM on AR in children. So our aims were to (1) examine the association of AR in preschoolers with early life exposure to residential greenness and ambient PM (before 2 years of age), (2) identify the sensitive exposure time windows of early life greenness exposure on AR and (3) determine the interactions between greenness and PM, as well as the moderation and mediation effects of PM on the relationship between childhood AR and greenness. The current study is a multi-city cross-sectional study conducted in Chinese preschoolers. To our knowledge, this is one of few studies on the associations between greenness, PM and childhood rhinitis. We hope to contribute scientific evidence on the complex interactions between greenness and PM on rhinitis in children.

2. Methods

2.1. Study design and subjects

A cross-sectional study was conducted from 2019 to 2020 in 7 cities in China, including two eastern cities (Shanghai and Nanjing), three south-central cities (Chongqing, Changsha, and Wuhan), and two northern cities (Taiyuan and Urumqi). Participants were recruited using stratified random cluster sampling from each city. All children from selected kindergartens were invited to participate in the study. A questionnaire survey was conducted to collect data on demographics, childhood living environments, and AR symptoms, as described in previously (Chen et al., 2022; Fu et al., 2021; Zhang et al., 2013). The questionnaire was sent to the parents or guardians of children and collected by the teachers (Chen et al., 2022). By standardizing and coding the residential addresses of recruited children in the World Geodetic System-1984 coordinate system, we evaluated exposure to greenness and ambient PM (PM_1, $PM_{2.5}$, and PM_{10}) for each participant in three time windows, prenatally during pregnancy and postnatally during the first (0–1 year old) and the second (1–2 years old) year of life, respectively. Associations between exposure to greenness and PM in three time windows in early life and rhinitis later in preschool were analyzed among 40,486 children.

2.2. Ethic statements

This study was approved by the Institutional Review Board of the School of Public Health, Fudan University (IRB00002408, FWA00002399, IRB#2019-09-0778). The parents or guardians of the children provided informed consent.

2.3. AR and symptoms

We obtained information on AR and its symptoms using core questions from the International Study of Asthma and Allergies in Childhood (ISAAC) (Asher et al., 2006). The ISAAC is a globally recognized study that uses a standard questionnaire to assess asthma, rhinitis, and symptoms in children. It has been validated and widely applied in China (Chan et al., 2001; Lee et al., 2022; Zhao et al., 2000) and Korea (Kim et al., 2018). The rhinitis component of the ISAAC was validated in Brazil and proven to be reproducible, adequate, and able to discriminate between children and adolescents with and without rhinitis (Vanna et al., 2001). The questionnaire used in this study was tested in a pilot study involving 100 children in Chongqing in April 2010 and adapted to improve readability (Zhang et al., 2013). The questionnaire inquired about the three health outcomes of rhinitis using binary questions (yes/no): lifetime rhinitis (LR, ever rhinitis symptoms), current rhinitis (CR, rhinitis symptoms in the last 12 months), and doctor-diagnosed AR. For LR, the question was, “Has the child ever had symptoms of sneezing, a runny or blocked nose without a cold or flu?”. For CR, the question was, “Has the child had symptoms of sneezing, a runny or a blocked nose in the last 12 months without a cold or flu?”. For doctor-diagnosed AR, the question was, “Has the child ever been diagnosed with hay fever or allergic rhinitis by a doctor?”. A positive answer to any of the above questions indicated that the participants had either AR-related symptoms or were diagnosed with AR.

2.4. Exposure assessment

2.4.1. Exposure to residential greenness

Residential greenness was measured using NDVI sourced from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) version 6 Level 3 product data. NDVI is an indicator of green vegetation density ranging from −1 to 1. The higher the NDVI value, the greater the green vegetation density. Negative NDVI values indicate no vegetation (land covered by water or snow), whereas values close to zero refer to bare surfaces or buildings. Original data were generated every 16 days at a spatial resolution of 250 m. We estimated NDVI levels according to the residential address of the mothers during pregnancy and the residential addresses of the children (during the 0–1 and 1–2 years of life). The average NDVI values within a 500-m circular buffer ($NDVI_{500m}$, diameter 1 km) and 1000-m buffer ($NDVI_{1000m}$, diameter 2 km) were calculated, with the level in the 500-m buffer presented as the primary result, and that in the 1000-m buffer as a sensitivity analysis. The average NDVI values were calculated using the R software (version 4.1.2).

2.4.2. Exposure to ambient PM

Exposure to three sizes of ambient PM was evaluated. For PM_1, data were collected from the China Atmosphere Watch Network (CAWNET) of the China Meteorological Administration using a machine learning–based space-time model at a 1 km × 1 km spatial resolution (Wei et al., 2019; Wu et al., 2022). Data regarding $PM_{2.5}$ and PM_{10} exposure were evaluated using validated satellite prediction models at a resolution of 1 km × 1 km following a previously published methodology (Shi et al., 2023). Models for $PM_{2.5}$ and PM_{10} have been applied in several previous studies (Guo et al., 2022; Meng et al., 2022; Niu et al., 2022; Wang et al., 2023). The 10-fold cross-validation R^2 and root mean square error (RMSE) of the prediction models reached 0.81($PM_{2.5}$, 18.50 μg/m^3) and 0.90 (PM_{10}, 18.47 μg/m^3), respectively. The daily PM exposure was averaged over the three time windows: during pregnancy (varying number of exposure days from pregnancy to childbirth), during the first year of life (0–1 year old, the same number of exposure days in an entire year), and during the second year of life (1–2 years old, the same number of exposure days in an entire year).

2.5. Covariates

Covariates were collected using a questionnaire and included demographic characteristics, parental history of allergies, socioeconomic status (SES), home environmental factors, and meteorological factors. SES and meteorological factors were evaluated at the city level, whereas other covariates were evaluated at the individual level. SES is indicated by the average household income per capita for each city from the China Statistical Yearbook (https://www.yearbookchina.com/). Meteorological data (relative humidity and temperature) were obtained from the National Bureau of Statistics and averaged over the three time windows at the city level (http://www.stats.gov.cn). Demographic characteristics included age, sex, single-child status, and duration of breastfeeding (<6 months or >6 months). A parental history of allergies refers to any positive report of a parent's history of asthma, AR, or eczema. Home environmental factors included current residential area (rural/suburban vs. urban), environmental tobacco smoke, home redecoration, and signs of home dampness (any visible damp stain on the floor, walls, or ceiling, damp clothes, and bedding in the child's bedroom). The above variables were adjusted in the regression models after matching to the corresponding exposure windows, i.e., during pregnancy, the first year of life (0–1 year old), or the second year of life (1–2 years old).

2.6. Statistical analysis

Demographics, residential and home environments, and the prevalence of AR outcomes were described for each city in all subjects. Means and variations of NDVI and ambient PM are described in each of the three exposure windows. Kruskal-Wallis and chi-square tests were used to compare the differences between the seven cities for continuous and categorical variables, respectively. Spearman's correlations between PM and NDVI were analyzed.

Considering that the subject sampling was in a hierarchical structure, a mixed-effect logistic regression was applied to evaluate the associations of residential greenness in the three time windows with rhinitis outcomes, with and without adjusting for co-exposure to ambient PM (PM_1, $PM_{2.5}$, and PM_{10}). We controlled for the city by adding it as a random-effects variable, which could improve the reliability of the estimated risks. Age, sex, single-child status, breastfeeding duration, parental history of allergies, and residential area (urban vs. rural/suburban) were adjusted in the regression models for all three exposure time windows. Household income, environmental tobacco smoke, home redecoration, home dampness, temperature, and relative humidity were adjusted by matching exposure time windows. The effect estimates are expressed as odds ratios (ORs) and their 95 % confidence intervals (95 % CI) per 0.1-unit increment of NDVI and 10 μg/m^3 increment of PM, respectively. In addition, we used a multiple informant model with a generalized estimating equation (GEE) approach to compare the associations between residential greenness and rhinitis outcomes among the three exposure time windows (Sánchez et al., 2011).

We speculated that PM could modify the association between greenness and rhinitis outcomes. Accordingly, we added a multiplicative interaction term to the regression analysis of the greenness exposure. For the significant interaction items, the moderation effects were further analyzed and presented using the Johnson–Neyman plot to explore the PM cut-off values, which distinguished the link between greenness and rhinitis outcomes. Based on the cut-off values, the mediating roles of PM in the relationship between greenness and health outcomes were further analyzed in each stratum.

A sensitivity analysis was performed to test the robustness of the results. First, we replaced the residential greenness in the 500-m buffer with those in the 1000-m buffer and re-performed regression analyses, with and without adjusting for PM. Second, we analyzed the association between the $NDVI_{500m}$ and rhinitis outcomes in children who had never moved homes. Lastly, to exclude the influences of covariates that varied between cities, the heterogeneity of regression results was assessed using meta-analysis and inverse probability weighting (IPW), respectively.

In all analyses, two-tailed *P*-values <0.05 (two-tailed) were considered statistically significant. R version 4.1.2 was used to perform the statistical analyses, with the "glmer" function in the "lme4" package used for mixed-effects logistic regression, and the "bruceR" package used for moderation and mediation analyses.

3. Results

3.1. Demographic characteristics and rhinitis outcomes

The mean age of the recruited children ($n = 40, 486$) was 4.8 years, and 51.9 % were males. Among them, 56.8 % were single children, and 37.3 % had been exclusively breastfed for less than six months. Most of the children lived in urban areas (79.3 %) (Table 1).

The prevalence rates of LR, CR, and doctor-diagnosed AR across the seven cities were 37.9 %, 32.6 %, and 11.9 %, respectively. The highest prevalence of rhinitis was detected in Wuhan (48.7 %, 43.2 %, and 20.4 %, respectively), and the lowest prevalence was recorded in Taiyuan (30.6 %, 25.6 % and 6.4 %, respectively) (Table 1). The proportion of environmental tobacco smoke, home redecoration, and home dampness, as well as the average temperature and relative humidity, varied significantly among the seven cities (Table S1).

3.2. Exposure to residential greenness and ambient PM

Table 2 presents the data regarding the exposure to residential greenness ($NDVI_{500m}$ and $NDVI_{1000m}$) and PM (PM_1, $PM_{2.5}$, and PM_{10}). The mean values of $NDVI_{500m}$ and $NDVI_{1000m}$ increased gradually from pregnancy to those during the first (0–1 year old) and second (1–2 years old) years of life, while PM concentrations decreased gradually. We identified negative correlations between the NDVI values and PM in the three exposure time windows, and the NDVI showed a strong relationship among the three time windows (Fig. S1). Exposure to residential greenness in the east and south was higher than in the west and north of China (Fig. 1). Across the three time windows, 66 % ($n = 26,868$) of children had never moved home since pregnancy. Figs. S2–S4 present the concentration levels of PM of the three sizes based on the home address of children.

3.3. Associations of residential greenness and PM with rhinitis

Regression analyses between early life exposure to $NDVI_{500m}$ in the three time windows and rhinitis outcomes were performed with and

Table 1
Demographic characteristics and prevalence of rhinitis in the total subjects and in each city, respectively.

Variables	Total (N = 40,486)	Wuhan (*N* = 9477)	Shanghai (*N* = 5828)	Nanjing (*N* = 1408)	Changsha (*N* = 8560)	Chongqing (*N* = 3959)	Urumqi (*N* = 6422)	Taiyuan (*N* = 4832)	*P*
Age (years)									<0.001
Mean (SD)	4.8 (1.0)	4.6 (1.0)	4.7 (1.0)	4.5 (1.1)	4.8 (0.9)	4.8 (1.0)	5.0 (0.9)	4.7 (1.0)	
Sex (%)									<0.001
Male	51.9	52.2	52.6	51.8	53.5	50.6	50.5	50.4	
Female	48.1	47.8	47.4	48.2	46.5	49.4	49.5	49.6	
Single child (yes, %)	56.8	66.9	66.3	67.8	43.3	52.5	56.2	50.6	<0.001
Duration of breastfeeding (%)									<0.001
<6 months	37.3	41.6	41.4	34.3	32.1	48.5	35.0	28.1	
≥6 months	62.7	58.4	58.6	65.7	67.9	51.5	65.0	71.9	
Parental history of allergies (%)	38.0	42.3	50.4	41.3	30.7	23.7	43.8	28.9	<0.001
Health outcomes (%)									
Lifetime rhinitis	37.9	48.7	45.8	38.2	31.0	29.6	34.2	30.6	<0.001
Current rhinitis	32.6	43.2	42.0	34.2	25.7	23.4	28.3	25.6	<0.001
Doctor-diagnosed AR	11.9	20.4	15.4	11.0	7.4	9.5	7.6	6.4	<0.001
Current living area (%)									<0.001
Rural/suburban	20.7	3.9	38.2	30.5	29.8	31.4	13.1	15.1	
Urban	79.3	96.1	61.8	69.5	70.2	68.6	86.9	84.9	

P < 0.001: statistically significant difference.
Notes: The number of available observations at baseline may differ from the total number of participants due to missing values. Kruskal-Wallis test and chi-square test were applied to compare the differences between 7 cities for continuous and categorical variables, respectively.

Table 2
Exposure to residential greenness ($NDVI_{500m}$ and $NDVI_{1000m}$) and mass concentrations of PM in 3 sizes in pregnancy, in 0–1 year old and 1–2 years old, respectively.

Variables	Exposure windows	Mean	Min	P_{25}	P_{50}	P_{75}	Max
$NDVI_{500m}$	In pregnancy	0.2311	0.0189	0.1725	0.2208	0.2725	0.7354
	In 0–1 year old	0.2367	0.0333	0.1771	0.2278	0.2793	0.7546
	In 1–2 years old	0.2431	0.0624	0.1840	0.2378	0.2879	0.7175
$NDVI_{1000m}$	In pregnancy	0.2351	0.0136	0.1766	0.2236	0.2757	0.7448
	In 0–1 year old	0.2407	0.0290	0.1794	0.2313	0.2820	0.7539
	In 1–2 years old	0.2464	0.0811	0.1863	0.2410	0.2908	0.7272
PM_1 (μg/m^3)	In pregnancy	36.34	5.82	30.08	35.34	42.38	94.42
	In 0–1 year old	33.45	6.64	28.53	32.21	38.22	79.37
	In 1–2 years old	30.84	8.05	27.02	30.38	34.23	64.56
$PM_{2.5}$ (μg/m^3)	In pregnancy	65.22	19.88	55.68	64.23	72.70	149.65
	In 0–1 year old	59.89	21.21	52.77	59.60	66.40	126.56
	In 1–2 years old	55.75	23.12	50.50	54.00	62.21	104.77
PM_{10} (μg/m^3)	In pregnancy	114.62	36.11	94.28	112.52	132.55	275.89
	In 0–1 year old	104.52	35.62	84.80	101.19	124.10	270.63
	In 1–2 years old	96.81	40.32	81.27	90.21	114.26	264.83

Notes: NDVI, Normalized Difference Vegetation Index; PM_1, particles with an aerodynamic diameter $\leq$ 1 μm; $PM_{2.5}$, particles with an aerodynamic diameter $\leq$ 2.5 μm; PM_{10}, particles with an aerodynamic diameter $\leq$ 10 μm.

without PM adjustment (Fig. 2). Significantly negative associations were identified between NDVI and prevalence of LR (OR: 0.91–0.93, 95 % CI: 0.87–0.97) and CR (OR range 0.90–0.93; 95 % CI: 0.87–0.97) in three exposure time windows. These associations remained robust after adjusting for co-exposure to PM_1, $PM_{2.5}$, and PM_{10}, respectively. The lowest risk was observed during pregnancy. We performed a multiple-informant GEE analysis and confirmed that exposure during pregnancy had the most robust negative association with LR and CR (Table S2). The negative associations between greenness exposure and the first (0–1 year old) and second (1–2 years old) years of life showed a significant interaction with PM_1, $PM_{2.5}$, and PM_{10} ($P < 0.05$).

Conversely, exposure to PM was associated with higher risks of LR, CR, and doctor-diagnosed AR (Fig. 3), with an obvious inverse trend with PM size. That is, exposure to the smallest particle PM_1 showed the highest risk of rhinitis, followed by $PM_{2.5}$ and PM_{10}. However, the association between particles and rhinitis was attenuated after adjusting for $NDVI_{500m}$, and the significance disappeared for PM_{10} with LR or CR after adjusting for $NDVI_{500m}$.

3.4. Moderation effects of PM

For LR and CR, NDVI exposure during the first (0–1 year old) and second (1–2 years old) years of life significantly interacted with PM, while NDVI exposure in pregnancy showed no interaction effect with PM (Fig. S5). The moderating effects of PM on the association between NDVI during the first and second year of life and rhinitis outcomes were further explored using Johnson-Neyman plots (Fig. 4).

The negative associations between $NDVI_{500m}$ exposure in the first year of life (0–1 year old) and LR were detected only in the presence of co-exposure to ambient $PM_1 \leq 37$ μg/m^3, $PM_{2.5} \leq 65$ μg/m^3, or $PM_{10} \leq 109$ μg/m^3, respectively. For CR, similar patterns were observed, and the cut-off values were 35 μg/m^3 (PM_1), 62 μg/m^3 ($PM_{2.5}$), and 106 μg/m^3 (PM_{10}), respectively (Fig. 4(a)). Likewise, the negative associations between $NDVI_{500m}$ exposure in the second year of life (1–2 years old) and LR were present only when ambient concentrations of PM_1, $PM_{2.5}$, and PM_{10} were $\leq$30 μg/m^3, $\leq$55 μg/m^3, and $\leq$94 μg/m^3, respectively, and the cut-off values for the association between $NDVI_{500m}$ and CR were 32 μg/m^3 (PM_1), 57 μg/m^3 ($PM_{2.5}$), and 98 μg/m^3 (PM_{10}), respectively (Fig. 4(b)). For LR and CR, the cut-off levels for the same PM size were similar.

However, when the ambient PM was higher than the cut-off values as mentioned above, exposure to greenness during the first year of life (0–1 year old; Fig. 4(a)) and during the second year of life (1–2 years old; Fig. 4(b)) showed no association or even positive associations with LR and CR, respectively. Considering $PM_{2.5}$ as an example, when the ambient $PM_{2.5}$ exposure during the first year of life (0–1 year old) was $\geq$97 μg/m^3, the association between $NDVI_{500m}$ in this time period and CR was significantly positive. Similar moderating effects were observed on LR and CR following PM exposure in the second year of life (1–2 years old).

3.5. Mediation effects of PM

Given that the association between NDVI and rhinitis varied with PM levels, we further tested whether the association between NDVI and rhinitis was mediated by PM and differed by PM levels (Table 3). The results showed that ambient PM mediated the negative association between $NDVI_{500m}$ and rhinitis when the PM level was lower than the cut-off levels, while no mediation effects were detected when PM levels exceeded the cut-off levels. For example, the highest mediation proportion of $PM_{2.5}$ exposure ($\leq$55 μg/m^3) in the second year of life (1–2 years old) accounted for 40.9 % of the negative association between $NDVI_{500m}$ and LR. This proportion was followed by 34.6 % of PM_1 ($\leq$30 μg/m^3) and 30.4 % of PM_{10} ($\leq$94 μg/m^3) in the same exposure window, respectively.

Thus, the negative associations of greenness with rhinitis in preschool children was partly attributed to the lower PM level, and this mediation was present only when the PM level was below a certain level. Accordingly, at higher PM levels, the negative associations between NDVI and rhinitis disappeared, and the mediation effects were no longer present.

3.6. Sensitivity analysis

We performed several sensitivity analyses. First, we replaced $NDVI_{500m}$ with $NDVI_{1000m}$ in the regression analysis of rhinitis outcomes. Similar results were observed for $NDVI_{1000m}$ with and without adjusting for PM exposure (Fig. S6). Second, we restricted the participants to those who had never moved residences (n = 26,868). The greenness and PM results revealed no changes when compared with the primary results (Figs. S7 and S8). Third, considering the potential heterogeneity across the seven cities, we applied IPW to manage heterogeneous variables and performed a regression analysis (n = 35,258) in the same model. The main findings were unaltered (Fig. S9). Finally, we have conducted analyses in a location-wise way and categorized cities by climate zones to compare the association between subgroups (Fig. S10).

4. Discussion

In the current study, we observed a negative relationship between prenatal and postnatal residential greenness exposure (NDVI) and

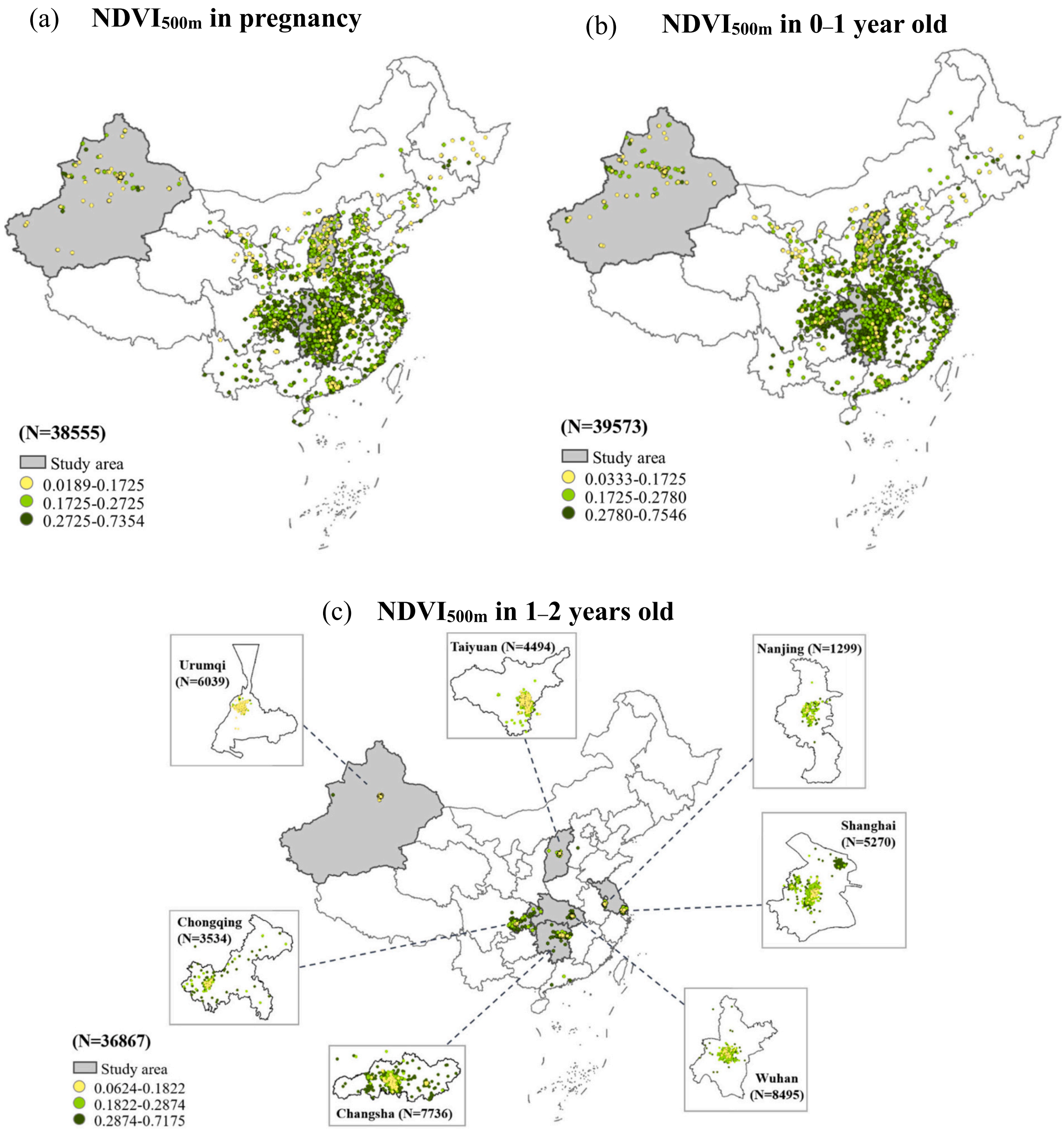

Fig. 1. Spatial distribution and estimated $NDVI_{500m}$ in 3 exposure time windows surrounding children's home addresses. (a) In pregnancy; (b) In 0–1 year old; (c) In 1–2 years old. There was some missing sample size in each period because some participants did not provide the exact address information. The residential address of children for 1–2 years old has a higher density.
Notes: $NDVI_{500m}$ was stratified into 3 levels by the P_{25} and P_{75} values, indicated by yellow, light green and dark green colors; Dots refer to the participants involved in the study. 66 % of participating children never moved homes during 3 time windows.

rhinitis in preschool children. The most robust negative association was prenatal greenness exposure in pregnancy, whereas postnatal greenness exposure in infancy (0–1 year old) and in 1–2 years old was conditional, depending on the ambient levels of PM. When ambient PM levels were below the cut-off levels, the association of greenness and rhinitis remained negative and was significantly mediated by PM. When ambient PM levels were higher than the cut-off levels, there were no significant or even positive associations with rhinitis. These findings were robust in multiple sensitivity analyses.

To date, the association between greenness and AR in children has been inconsistent and even controversial. In seven birth cohorts from Canada, the Netherlands, Australia, Germany, and Sweden, the BAMSE and GINI/LISA South cohorts revealed that greenness increased the risk of AR, while the GINI/LISA North and PIAMA cohorts showed that greenness reduced the risk of AR, and the CAPPS and SAGE cohorts showed no significant effects (Fuertes et al., 2016). There is a lack of conclusive interpretations of the effects of greenness on allergic diseases (Ferrante et al., 2020). To the best of our knowledge, our study is one of few studies to investigate the associations and interactions between residential greenness, PM and childhood AR. Our findings added evidence into the current knowledge by suggesting that, PM played both moderation and mediation roles in the impact of greenness on childhood AR symptoms, in which the roles differed depending on exposure windows and co-exposed ambient PM levels.

AR is characterized by nasal itching, sneezing, rhinorrhea, or nasal blockage without a cold or flu and is closely related to the living

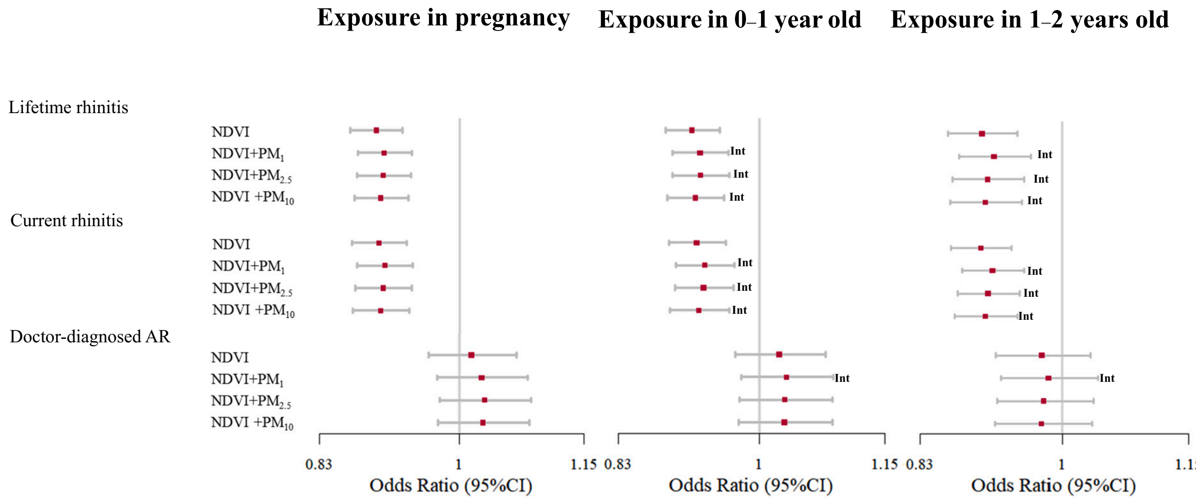

Fig. 2. Association of $NDVI_{500m}$ in 3 exposure time windows with rhinitis in preschool children.
Int: the multiplicative interaction between $NDVI_{500m}$ and particulate matter is significant ($P < 0.05$). NDVI, Normalized Difference Vegetation Index; PM_1, particles with an aerodynamic diameter ≤1 μm; $PM_{2.5}$, particles with an aerodynamic diameter below ≤2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤10 μm. Models were adjusted for age, sex, breastfeeding time lengths, household income, residency area, single-child, home redecoration, home dampness, environmental tobacco smoke, parental history of allergies, temperature and relative humidity. The descriptions on home environmental factors are in Table S1 in the Supplement Materials.

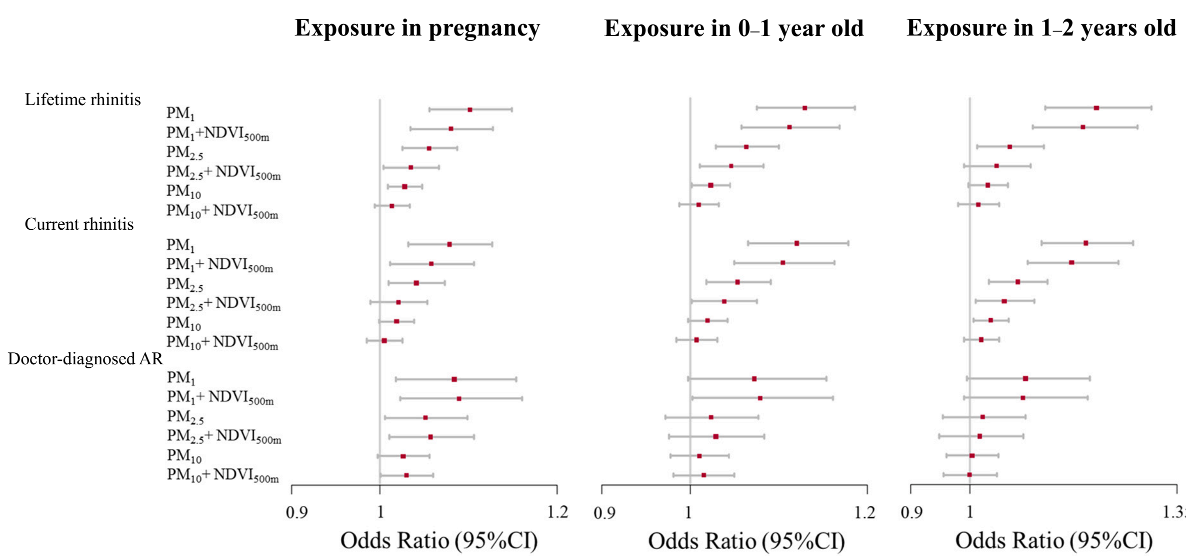

Fig. 3. Association of particulate matter (per 1 $\mu g/m^3$) in 3 exposure time windows with rhinitis in preschool children.
NDVI, Normalized Difference Vegetation Index; PM_1, particles with an aerodynamic diameter ≤1 μm; $PM_{2.5}$, particles with an aerodynamic diameter ≤2.5 μm; PM_{10}, particles with an aerodynamic diameter ≤10 μm. Models were adjusted for age, sex, breastfeeding time lengths, household income, residency area, single-child, home redecoration, home dampness, environmental tobacco smoke, parental history of allergies, temperature and relative humidity. The descriptions on home environmental factors are in the Supplement Materials.

environment (Bousquet et al., 2008). The information regarding rhinitis was obtained using the ISAAC questionnaire which has been validated in previous studies (Lee et al., 2022; Vanna et al., 2001; Zhang et al., 2013). According to the ISAAC questionnaire applied in Korean, the sensitivity and specificity of "AR symptoms, ever" were 57.5 % and 58.4 %, respectively (Kim et al., 2018). In an American birth cohort study, the sensitivity and specificity of the ISAAC core questions regarding current AR symptoms were 67 % and 63 %, respectively (Kim et al., 2012). This suggested symptom-based questions were effective in assessing the prevalence of AR symptoms. In addition, questionnaires could help specify and identify AR in children at earlier time points. Therefore, we believed using questionnaire was applicable for such a large-scale survey.

Several factors may influence the relationship between rhinitis and greenness. According to a study from Taiwan, greenness increased the risk of AR in children, owing to increased pollen emissions from green spaces (Lee et al., 2020). Noteworthily, in green spaces, pollens may come from a variety of plant species, and whether nearby residential green spaces emit specific allergenic pollens requires further monitoring and measurements (Macfaden et al., 2013). Second, the type of green vegetation could influence this relationship. Reports from European cohorts have revealed that children living close to coniferous forests had an increased risk of AR (Parmes et al., 2019), whereas agricultural spaces might exert protective effects against allergic and respiratory diseases in children. However, a recent study in China using the same database found that, exposure to forests (forest aggregation index, mean

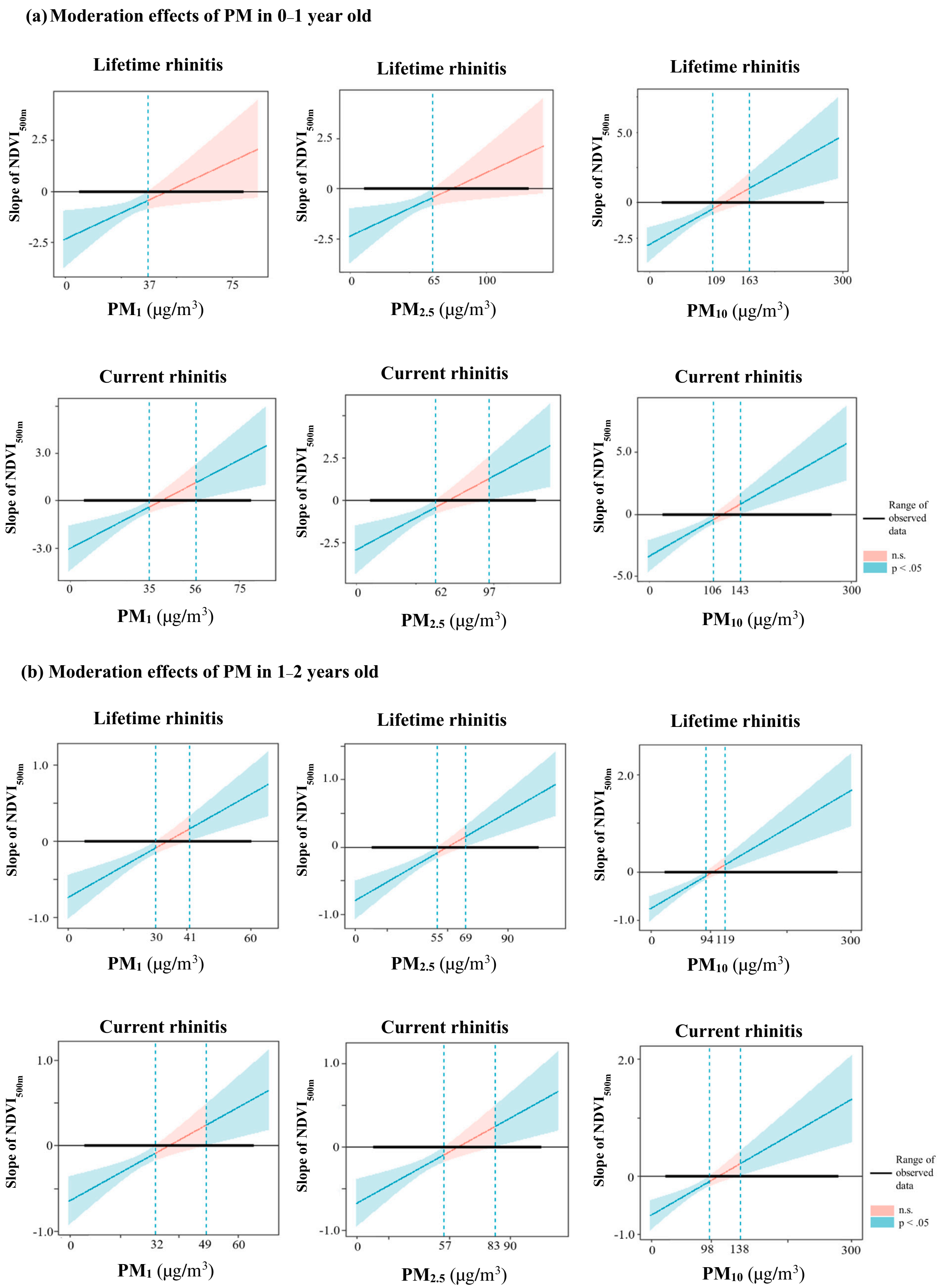

Fig. 4. Johnson-Neyman plots of the associations between $NDVI_{500m}$ and rhinitis outcomes moderated by PM exposure. (a) In 0–1 year old; (b) Between 1 and 2 years old.

Notes: NDVI, Normalized Difference Vegetation Index; PM_1, particles with an aerodynamic diameter ≤1 μm; $PM_{2.5}$, particles with an aerodynamic diameter ≤2.5 μm; PM_{10}, Particles with an aerodynamic diameter ≤10 μm. Regression models were adjusted for age, sex, breastfeeding time lengths, household income, residency area, single-child, home redecoration, home dampness, environmental tobacco smoke, parental history of allergies, temperature and relative humidity.

Table 3
Mediation effects of PM on the associations between $NDVI_{500m}$ and rhinitis outcomes in 0–1 year old and 1–2 years old, respectively.

Time windows	Outcomes	PM (μg/m^3)	N	Indirect effect	Direct effect	Total effect	Mediation proportion
0–1 year old	Lifetime rhinitis	**PM_1**		**−0.02 (−0.04, −0.01)**	**−0.14 (−0.22, −0.07)**	**−0.16 (−0.25, −0.09)**	**12.5 %**
		≤37	28,080	**−0.05 (−0.07, −0.03)**	**−0.13 (−0.22, −0.05)**	**−0.17 (−0.27, −0.09)**	**29.4 %**
		>37	11,338	−0.00 (−0.01, 0.01)	−0.05 (−0.21, 0.11)	−0.05 (−0.21, 0.11)	–
		$PM_{2.5}$		**−0.02 (−0.04, −0.00)**	**−0.14 (−0.22, −0.07)**	**−0.16 (−0.24, −0.09)**	**12.5 %**
		≤65	27,173	**−0.03 (−0.05, −0.00)**	**−0.13 (−0.22, −0.05)**	**−0.15 (−0.25, −0.07)**	**20.0 %**
		>65	12,401	0.00 (−0.00, 0.01)	−0.13 (−0.26, 0.02)	−0.12 (−0.26, 0.03)	–
		PM_{10}		−0.01 (−0.03, 0.01)	−0.15 (−0.23, −0.08)	−0.16 (−0.24, −0.09)	–
		≤109	23,630	**−0.04 (−0.07, −0.01)**	**−0.16 (−0.27, −0.07)**	**−0.19 (−0.31, −0.09)**	**21.1 %**
		109–163	15,877	0.01 (−0.02, 0.03)	−0.05 (−0.20, 0.10)	−0.05 (−0.19, 0.11)	–
		≥163	67	0.03 (−0.14, 0.27)	0.28 (−0.50, 0.93)	0.32 (−0.47, 0.94)	–
	Current rhinitis	**PM_1**		**−0.02 (−0.03, −0.01)**	**−0.12 (−0.20, −0.06)**	**−0.14 (−0.22, −0.08)**	**14.3 %**
		≤35	25,607	**−0.06 (−0.08, −0.03)**	**−0.11 (−0.20, −0.04)**	**−0.17 (−0.26, −0.09)**	**35.3 %**
		35–56	13,496	−0.01 (−0.02, 0.00)	−0.06 (−0.19, 0.08)	−0.06 (−0.20, 0.07)	–
		≥56	315	−0.05 (−0.20, 0.05)	0.68 (−0.09, 0.94)	0.63 (−0.18, 0.92)	–
		$PM_{2.5}$		**−0.02 (−0.03, −0.00)**	**−0.13 (−0.20, −0.06)**	**−0.14 (−0.22, −0.08)**	**14.3 %**
		≤62	22,659	**−0.03 (−0.06, −0.00)**	**−0.11 (−0.22, −0.03)**	**−0.14 (−0.25, −0.06)**	**21.4 %**
		62–97	16,897	0.00 (−0.01, 0.01)	−0.10 (−0.22, 0.03)	−0.10 (−0.22, 0.03)	–
		≥97[a]	18	–	–	–	–
		PM_{10}		−0.01 (−0.03, 0.01)	−0.14 (−0.22, −0.07)	−0.143 (−0.22, −0.08)	–
		≤106	22,074	**−0.04 (−0.08, −0.02)**	**−0.14 (−0.25, −0.05)**	**−0.18 (−0.30, −0.08)**	**22.2 %**
		106–143	15,078	0.01 (−0.02, 0.03)	−0.10 (−0.22, 0.04)	−0.09 (−0.22, 0.05)	–
		≥143	2422	−0.06 (−0.12, 0.00)	0.184 (−0.21, 0.58)	0.13 (−0.25, 0.54)	–
1–2 years old	Lifetime rhinitis	**PM_1**		**−0.03 (−0.05, −0.02)**	**−0.14 (−0.22, −0.06)**	**−0.17 (−0.25, −0.09)**	**17.6 %**
		≤30	18,849	**−0.09 (−0.12, −0.06)**	**−0.17 (−0.27, −0.07)**	**−0.26 (−0.35, −0.16)**	**34.6 %**
		30–41	18,329	0.00 (−0.00, 0.01)	−0.00 (−0.15, 0.14)	0.00 (−0.15, 0.15)	–
		≥41	2641	−0.00 (−0.02, 0.01)	0.07 (−0.35, 0.49)	0.07 (−0.36, 0.48)	–
		$PM_{2.5}$		**−0.02 (−0.03, −0.00)**	**−0.15 (−0.24, −0.08)**	**−0.17 (−0.25, −0.09)**	**11.8 %**
		≤55	21,934	**−0.09 (−0.12, −0.06)**	**−0.14 (−0.24, −0.04)**	**−0.22 (−0.32, −0.13)**	**40.9 %**
		55–69	14,117	0.01 (−0.01, 0.02)	−0.06 (−0.23, 0.10)	−0.06 (−0.22, 0.11)	–
		≥69	3924	−0.02 (−0.05, 0.00)	0.09 (−0.25, 0.42)	0.07 (−0.28, 0.41)	–
		PM_{10}		−0.00 (−0.02, 0.02)	−0.14 (−0.25, −0.05)	−0.14 (−0.25, −0.06)	–
		≤94	23,257	**−0.07 (−0.10, −0.05)**	**−0.16 (−0.26, −0.06)**	**−0.23 (−0.32, −0.14)**	**30.4 %**
		94–119	8079	0.00 (−0.02, 0.02)	0.02 (−0.21, 0.24)	0.02 (−0.20, 0.24)	–
		≥119	8639	0.01 (−0.04, 0.06)	−0.03 (−0.30, 0.23)	0.02 (−0.28, 0.23)	–
	Current rhinitis	**PM_1**		**−0.03 (−0.05, −0.02)**	**−0.16 (−0.24, −0.09)**	**−0.20 (−0.27, −0.12)**	**15.0 %**
		≤32	24,381	**−0.08 (−0.10, −0.05)**	**−0.16 (−0.25, −0.07)**	**−0.24 (−0.32, −0.15)**	**33.3 %**
		32–49	15,417	−0.00 (−0.00, 0.00)	−0.07 (−0.24, 0.09)	−0.07 (−0.24, 0.10)	–
		≥49[b]	21	–	–	–	–
		$PM_{2.5}$		**−0.02 (−0.04, −0.00)**	**−0.18 (−0.26, −0.10)**	**−0.20 (−0.27, −0.12)**	**10.0 %**
		≤57	24,407	**−0.07 (−0.10, −0.04)**	**−0.17 (−0.26, −0.07)**	**−0.24 (−0.33, −0.15)**	**29.2 %**
		57–83	15,545	−0.00 (−0.02, 0.02)	−0.09 (−0.26, 0.08)	−0.09 (−0.25, 0.08)	–
		≥83[c]	23	–	–	–	–
		PM_{10}		−0.01 (−0.03, 0.01)	−0.18 (−0.26, −0.11)	−0.20 (−0.27, −0.12)	
		≤98	24,731	**−0.06 (−0.09, −0.03)**	**−0.18 (−0.28, −0.09)**	**−0.25 (−0.33, −0.16)**	**24.0 %**
		98–138	14,475	0.01 (−0.03, 0.05)	−0.06 (−0.24, 0.12)	−0.05 (−0.23, 0.12)	–
		≥138	769	−0.03 (−0.11, 0.02)	0.62 (−0.20, 1.45)	0.59 (−0.23, 1.42)	–

Notes: Part of the results were not obtained due to small sample size. NDVI, Normalized Difference Vegetation Index; PM_1, Particles with an aerodynamic diameter below 1 μm; $PM_{2.5}$, Particles with an aerodynamic diameter below 2.5 μm; PM_{10}, Particles with an aerodynamic diameter below 10 μm. Models were adjusted for age, sex, breastfeeding time lengths, household income, residency area, single-child, home redecoration, home dampness, environmental tobacco smoke, parental history of allergies, temperature and relative humidity. Significant associations ($p < 0.05$) are marked in bold.

[a] $n = 18$.
[b] $n = 21$.
[c] $n = 23$.

patch area and shape complexity), instead of grass or shrubs, had the most significant negative associations with AR in preschoolers, and PM partially mediated such associations (Chen et al., 2024). Third, the study design and data analysis methods could influence the conclusions. For example, whether studies focusing on one or more exposure time windows, whether adjusting for co-exposure to air pollutants or not, which climatic regions the study was in, how the subjects' accessibility to green areas, or whether applying different regression models, could all produce different conclusions. These further suggested that greenness exposure should be further explored for more precise and quantitative assessment at individual levels, and to exclude the potential influences of co-exposed factors for more clarified relationship with AR.

In our study, 3 size fractions of ambient PM were considered as the main co-exposure factors with greenness. According to a review and meta-analysis study, the high prevalence of AR in children correlated with $PM_{2.5}$ and PM_{10} levels (Chen et al., 2022; Lin et al., 2021). In children and adolescents, $PM_{2.5}$ and PM_{10} levels were strongly correlated with rhinitis (OR 1.11, 95 % CI 1.06–1.16 and OR 1.12, 95 % CI 1.06–1.19) but not in adults (OR 1.40, 95 % CI 0.77–2.56 and OR 1.45, 95 % CI 0.94–2.24) (Li et al., 2022). In our study, we observed robust positive associations between 3 size fractions of PM and rhinitis after adjusting for NDVI. Smaller PM sizes have exerted more detrimental health effects. Fine particles have been reported on their adverse impact on the human nasal ciliary function (Jia et al., 2019), and on the nasal mucociliary system which further increased the susceptibility of the upper respiratory tract to an inflammatory response, leading to rhinitis symptoms (Ratajczak et al., 2021).

Exposure to green space during pregnancy showed robust protective effects against rhinitis symptoms in preschoolers, even after adjusting for PM. This was further confirmed by multiple-informant GEE analysis by comparing the associations among three exposure windows (Table S2). It suggested the possibility of epigenetic mechanisms as the potential link between environmental exposure and allergic diseases, through which environmental exposure during pregnancy could permanently alter the expression of fetal genes and susceptibility to allergic airway disease (Martino and Prescott, 2011). A recent epigenetic analysis confirmed that greenness is associated with allergy-related DNA methylation (Jeong et al., 2022), indicating that exposure to greenness during pregnancy activated or silenced related genes and altered the vulnerability of children to allergic diseases. This change was also likely due to exposure to diverse vegetative and environmental microbiota in green areas, which moderated the gut microbiome and facilitated the development of the immune system (Haahtela, 2019; Peters et al., 2022). Therefore, exposure to greenness during pregnancy is an exposure time window of significance that it can influence the development of AR in children and is of worth for further deep investigation.

The association of NDVI in 0–1 and 1–2 years old (i.e., the first and second years of life) showed significant interactions with PM in terms of the association with rhinitis symptoms. Residential greenness was beneficial in reducing rhinitis symptoms only at lower PM mass concentration levels, in which PM partly mediated the associations (Fig. 3 and Table 3). Such negative associations and mediations could occur through the following 3 pathways: (1) Ambient PM was reduced in green areas by the deposition effects of vegetation leaves (Laurent et al., 2019); (2) greenness could alter the trajectory and velocity of ambient PM dispersions (Wu et al., 2023); (3) greenness might contribute to microbiological modification, given that urban greenspace could alter the proportion of bacteria and fungi (Delgado-Baquerizo et al., 2021; Mhuireach et al., 2016) and shape or maintain the homeostasis of air microbiomes (Li et al., 2021). However, when PM concentrations at higher levels exceeded the cut-off levels, the protection of greenness and the mediation effects of PM disappeared. At higher levels, the adverse effects of PM could not be counteracted or weakened by greenness, suggesting that greenspaces had a limited ability to remove or reduce ambient PM. High levels of PM can aggravate allergic diseases by strengthening the allergenicity of aerosols and airborne pollens (Ghiani et al., 2012). A study conducted in Tokyo reported that the highest cumulative effect of pollen occurred at high $PM_{2.5}$ concentrations (Konishi et al., 2014). Pollutants or their transformations can provide a more suitable growing environment for certain allergenic plants to promote allergenic pollen productivity. Greenspaces could also be the source of both volatile organic compounds and pollens, through which PM may combine and produce more secondary pollutants with adverse respiratory health effects. The overall mediating effects of PM on the association between greenness and health have been well-documented in other studies (Laurent et al., 2019; Yang et al., 2023; Zhang et al., 2022). In the current study, we reported not only the presence of overall mediating effects of PM, but also the conditional mediation effects only at lower concomitant PM levels. This study provided a new perspective for understanding the complex relationship between greenness, PM, and childhood rhinitis.

In the analyses in a location-wise way by climate zones, we found cities in the subtropical monsoon climate had significantly inverse associations with children's AR, but not in the temperate continental climate cities. The heterogeneity might be attributed to the discrepant sample size across subgroups, as suggested in a previous study that larger sample sizes could provide stronger statistical power to reveal the associations between greenness and health outcomes (Wang and Tassinary, 2024). Besides, vegetation types and greenness configuration were different between cities, greenness connections and complex-shaped greenness have also been linked to this heterogeneity. For example, fragmentation and spatial aggregation of greenness will affect the biodiversity and thus affect health (Walz, 2011). A study suggested that small lawn parcels may not be as beneficial as relatively large park (Sugiyama et al., 2010), because larger green space could increase the accessibility of the greenness and therefore beneficial to health. Furthermore, the study mentioned that possibility contamination in exposure to greenness should be considered (Carrus et al., 2015). Otherwise, the differences between cities in terms of infrastructure, economic activity, lifestyle, etc. that might influence the effects and heterogeneity, so in our study we chose to present the results of mixed-effect logistic regression models among participants and IPW analysis and identified the rationality of the covariate adjustment to remove the bias of heterogeneity.

Our study has several strengths. First, our study explored on greenness, PM and their interactions in early life to obtain a more comprehensive understanding on the greenness exposure and AR. Both greenness (NDVI), 3 size fractions of PM and their interactions were explored in each time window focusing on their associations with AR in preschoolers. The cut-off lines of PM were further identified to more precisely illustrate the association of greenness and AR varied by PM. Also, a long time span covering 3 exposure windows from pregnancy to 2 years old was investigated in this study. Second, the findings on the moderating and mediating effects of PM on the relationship between greenness and rhinitis depending on PM levels provided new evidence in understanding the previously inconsistent findings regarding greenness and rhinitis. Third, this was a large-scale, multi-city study which could be better represent and provide robust evidence on the association between early exposure to greenness in young children and rhinitis. Fourth, the estimated exposure to greenness and PM was at a high spatiotemporal resolution, which largely reduced misclassification, in comparison with traditionally data from fixed-site monitoring stations.

Our study has some limitations. First, health information was collected using a questionnaire. Although it has been validated both internationally and nationally, it cannot completely eliminate health uncertainty. In addition, questions on covariates need to be added to ask for more precise information in each time window to obtain more rigorous and accurate results. Second, we only used NDVI to describe residential greenness, which did not represent a full spectrum of greenness exposure characteristics (Cai et al., 2021; Chen et al., 2020; Fuertes and Jarvis, 2021; Zeng et al., 2020). Greenness vegetation types, shapes, collisions, and the dispersion of greenness areas could provide new perspectives in characterizing greenness exposure. Third, the heterogeneity between cities could bring some bias in the results. However, we performed an IPW analysis and identified the rationality of the covariate adjustment to remove the bias of heterogeneity. Fourth, the cut-off levels reported in our study might differ from those in other regions or countries since the PM pollution sources and levels and greenness levels vary between regions. Further validation and investigations of more generalized cut-off levels are required. Finally, we used the NDVI data every 16 days at a spatial resolution of 250 m. In future studies, we plan to explore the effects of NDVI and vegetation type on rhinitis with higher temporal and spatial resolutions to verify the robustness of the results.

5. Conclusions

In conclusion, prenatal exposure to greenness during pregnancy was beneficial for AR symptoms in preschool children, while postnatal exposure to greenness depended on the ambient PM levels. This study provides a new perspective in illuminating the previously inconsistent findings on greenness and rhinitis in children. It is of significance for urban planners to promote the increasement of green areas proportions which is beneficial for children's AR from a public health perspective. It is also suggestive for parents, children and schools to choose appropriate places or time at lower PM levels to be exposed to greenness. Further studies are needed to characterize greenness exposure and rhinitis from novel perspectives to deepen our understanding of their relationship with AR in children.

CRediT authorship contribution statement

Liu Yang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Han**

Chen: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Huiyu Gao:** Investigation, Data curation. **Ying Wang:** Investigation, Data curation. **Tianyi Chen:** Writing – review & editing, Investigation, Data curation. **Magnus Svartengren:** Writing – review & editing. **Dan Norbäck:** Writing – review & editing. **Jing Wei:** Methodology. **Xiaohong Zheng:** Project administration, Investigation. **Chan Lu:** Project administration, Investigation. **Wei Yu:** Project administration, Investigation. **Tingting Wang:** Project administration, Investigation. **John S. Ji:** Writing – review & editing. **Xia Meng:** Writing – review & editing, Methodology, Data curation. **Zhuohui Zhao:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Xin Zhang:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

None of the authors declares any conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173402.

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