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Greenness and allergic rhinitis in children: the moderating and mediating effects of meteorological factors and air pollution

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Background: Emerging evidence suggests that greenness may be beneficial to human health; however, the relationship between greenness exposure and childhood allergic rhinitis (AR) is inconsistent, and whether and how the link is moderated or mediated by meteorological factors and air pollutants remains unclear.

Methods: We conducted an observational study in Sanya, China. Information on AR and covariates was collected from e-questionnaires. Greenness exposure was assessed using satellite-estimated data based on the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Binomial generalized linear models with a log link were used to evaluate the associations between greenness exposure and childhood AR, presented as prevalence ratio (PR) and 95% confidence interval (CI) per interquartile range (IQR) increase in greenness, adjusting for potential confounders. Stratified analyses and mediation analyses were also performed.

Results: Of the 9,754 children included in the study, the prevalence of ever AR (EAR) and current AR (CAR) was 15.6 and 23.2%, respectively. An IQR increase in greenness was associated with an attenuated PR of childhood AR. The PRs (95% CIs) were 0.95 (0.88–1.02), 0.94 (0.88–1.00), 0.94 (0.89–0.99), and 0.95 (0.90–0.99) for EAR-NDVI, EAR-EVI, CAR-NDVI, and CAR-EVI, respectively. Furthermore, these associations existed only in boys [PRs (95% CIs) were 0.92 (0.85–0.99), 0.92 (0.85–0.98), and 0.93 (0.88–0.99) for EVI-EAR, NDVI-CAR, and EVI-CAR, respectively], and low-temperature groups [PRs (95% CIs) were 0.89 (0.80–0.99), 0.87 (0.78–0.97), 0.91 (0.84–0.98), and 0.92(0.85–0.99) for NDVI-EAR, EVI-EAR, NDVI-CAR, and EVI-CAR, respectively]. Ambient temperature and relative humidity were found to mediate these associations.

Conclusion: Greenness exposure seems to reduce the prevalence ratio of childhood AR. These associations may be more pronounced in boys and in low-temperature groups and were mediated by ambient temperature and relative humidity. These findings offer new perspectives for considering ambient temperature and relative humidity in relation to greenness exposure and children's health.

KEYWORDS

allergic rhinitis, children, enhanced vegetation index, greenness, normalized difference vegetation index

1 Introduction

Allergic rhinitis (AR), along with asthma and atopic dermatitis, is commonly referred to as the "allergic march." These allergic diseases have had—and will continue to have—detrimental health effects on people worldwide, particularly children. AR is a complex condition that arises from the intricate interplay of various genetic and environmental factors (Meng et al., 2019). Nevertheless, the increase in AR prevalence over recent decades could be partially attributed to environmental transformations. Climate change, urbanization, and biodiversity loss have substantial impacts on the sources, emissions, and concentrations of the primary aeroallergens and air pollutants (Tong et al., 2022). These challenges pose significant obstacles to the health and quality of life of allergic patients, including children with AR, both currently and in the future (Tong et al., 2022).

Given the increasing incidence of childhood AR, it is imperative to tackle these concerns with utmost urgency. Huang et al. conducted a large-scale cross-sectional study involving 40,868 children aged 2–17 years in three cities of Northeast China from 2012 to 2013 (Huang et al., 2022). Their findings revealed a prevalence of 9.7% for physician-diagnosed AR in this population, consistent with the reported global AR prevalence range of 10–40% (Jo et al., 2022). Our previous research in 2019 found that the prevalence of ever AR (EAR) among children aged 3–14 years in Shanghai was 28.8% (Chen et al., 2020). These findings highlight the need for proactive measures to mitigate the consequences of climate change, promote sustainable urban growth, and preserve biodiversity, ultimately safeguarding public health and wellbeing (Tong et al., 2022; Cecchi et al., 2018).

The relationship between greenness and human health has gained significant attention in the context of urbanization and biodiversity loss. However, conflicting findings have been reported regarding the association between greenness and AR (Jackson et al., 2023). Multiple studies have reported varying findings regarding the relationship between exposure to green environments and childhood AR. Some scholars have found no significant association between greenness exposure and childhood AR (Gernes et al., 2019; Li et al., 2019; Lin et al., 2022). Conversely, other researchers have observed an inverse association (Dzhambov et al., 2021; Huang et al., 2022; Parmes et al., 2020) or a positive association between greenness and AR in children (Markevych et al., 2020).

Abbreviations: NDVI, Normalized difference vegetation index; AR, Allergic rhinitis; EVI, Enhanced vegetation index; PR, Prevalence ratio; CI, Confidence interval; IQR, Interquartile range; EAR, Ever allergic rhinitis; CAR, Current allergic rhinitis; ISAAC, International Study of Asthma and Allergies in Childhood; MODIS, Moderate Resolution Imaging Spectroradiometer; TAP, tracking air pollution; SD, Standard deviation; GLMs, Generalized linear models; VIF, Variance inflation factor; GLMMs, Generalized linear mixed-effect models.

Therefore, the relationship between greenness exposure and childhood AR remains inconclusive. Moreover, evidence on the potential influence of meteorological factors and air pollutants on the association between greenness and AR is sparse, particularly in the context of global climate change. Given these gaps in knowledge, we conducted a population-based observational study among preschool and school children aged 2–11 years in Sanya, a tropical city in Hainan Province, China. The primary objective of this study was to examine the associations between greenness exposure and childhood AR, as well as to explore the potential moderating and mediating roles of meteorological factors and air pollutants in these associations, to provide evidence for making tailored strategies to better prevent and manage childhood AR.

2 Materials and methods

2.1 Study design and participants

A population-based cross-sectional study from 31 October to 19 December 2022 was performed in Sanya, a picturesque coastal city in the Hainan Province of southernmost China. Sanya City has low latitudes with the coordinates of N 18°09′34″-18°37′27″, accompanied by a tropical oceanic monsoon climate. We randomly selected 20 of 197 kindergartens and 13 of 116 primary schools in four administrative districts. Then, we surveyed all preschoolers in kindergartens and grade 1 to 3 students in primary school. In total, 10,305 participants (response rate: 91.0%) completed the e-questionnaires through their guardians. After eliminating children beyond the age of 11 or with age-filling errors, 9,754 children aged 2 to 11 were involved in the final analysis.

The Ethics Committee of the Institute approved this study (NO. SYFYIRB20220063). All participants provided informed consent prior to data collection.

2.2 Data collection and variable definition

We applied a self-administered e-questionnaire based on the core International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire (Asher et al., 1995) to collect data on health outcomes, socio-demographic characteristics, behaviors, and indoor and outdoor exposures. Our previous research in Shanghai suggested a good quality of the e-questionnaire (Chen et al., 2020; Hu et al., 2023a).

2.2.1 Ascertainment of outcomes

In this study, the primary outcome was AR, which was defined below:

i. Ever AR: Has your child ever been diagnosed with AR by a doctor? Yes or no.

ii. Current AR: In the past 12 months, has your child experienced paroxysmal sneezing, runny nose, stuffy nose, itchy nose, or itchy eyes symptom in the absence of a cold or flu? Yes or no.

2.2.2 Covariates

Socio-demographic characteristics include children's age, sex, ethnicity (Han nationality, Li minority nationality, and others), household income per month, maternal gestational week, delivery mode, history of miscarriage, family history of allergy (such as asthma, allergic rhinitis, atopic dermatitis, food allergy, and drug allergy), prenatal antibiotic use or postnatal antibiotic use (during the first year of the child), and indoor and outdoor exposures, including indoor planting, insecticide use, dampness/mold exposure, traffic conditions within 50 m of the house, and frequency of garden visits during prenatal and early life.

2.2.3 Greenness exposure

Recently, the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) have been commonly used to indicate greenness exposure in epidemiological research (Hartley et al., 2022). The NDVI and EVI from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite were derived to assess greenness exposure around each child's residence, with a buffer area of 500 m (Soltani et al., 2021). As an indicator of greenness exposure, we averaged the NDVI or EVI annual mean values in the area around their present residence from 2020 to 2022, 3 years prior to the 2022 survey. The NDVI and EVI both range from −1 to 1: negative one (water) through zero (rock, sand, or snow) to positive one (dense green vegetation). The higher value (> 0) corresponds to higher greenness.

2.2.4 Meteorological factors and air pollutants

Data on annual average ambient temperature and relative humidity from 2020 to 2022 with 1-km buffers for Sanya were extracted from the National Meteorological Science Data Center (http://data.cma.cn/). Air pollution data for particulate matter with an aerodynamic diameter less than 2.5 µm ($PM_{2.5}$) and ozone during the same period were collected from tracking air pollution (TAP) in China (http://tapdata.org.cn/). Then, all exposures were matched against geocoded participants' current residential addresses. The detailed steps were described in our previous study (Hu et al., 2023a).

2.3 Statistical analyses

We divided all the statistical analysis processes into four steps.

Step I: Descriptive and correlation analyses were performed. Continuous data were presented as the mean (standard deviation, SD), and categorical data were presented as the number (percentage). Then, Spearman's correlation coefficients among variables were calculated to assess the correlations and provide evidence for subsequent model establishment.

Step II: Restricted cubic splines analysis with four knots was conducted to determine the linear or non-linear relationship between greenness exposure and childhood AR (Huang et al., 2022). A directed acyclic graph (Supplementary Figure S1) was constructed to help select confounders, moderators, and mediators on the greenness–AR paths based on comprehensively considering previous literature.

Step III: Based on the former two steps, single-variable and multivariable binomial generalized linear models (GLMs) with a log link (Chen et al., 2020) were used to evaluate the associations of greenness exposure with childhood AR, presenting as the prevalence ratio (PR) and 95% confidence interval (CI) with per interquartile range (IQR) increase of greenness. In the multivariable models, we adjusted for children's age, household income, antibiotic use within the first year, delivery mode, family history of allergy, traffic conditions within 50 meters of the house, indoor planting, and frequency of garden visits. We also calculated the variance inflation factor (VIF) in the adjusted models to avoid collinearity issues (VIF < 5).

Step IV: Subgroup analyses were conducted to explore the potential moderating effects of socio-demographic characteristics, meteorological factors, and air pollutants on greenness–AR associations. Furthermore, mediation analysis was used to elucidate the potential mediating effects of meteorological factors and air pollutants on greenness–AR paths. If mediation existed, we reported the proportion of the relationship mediated through them.

We also conducted several sensitivity analyses. First, we used greenness during 2022 as exposures to repeat all analyses. Second, we performed generalized linear mixed-effect models (GLMMs) with districts as random effects. Third, we applied mediation analysis using the PROCESS () function of the "bruceR" package to compare the results with those from the "mediation" package.

All analyses were carried out using R language 4.2.2 (R Core Team, https://www.r-project.org/) with "bruceR," "tidiverse," "gtsummary," "forestmodel," "rcssci," "ggplot2," "lme4," and "car" packages. A *p*-value of <0.05 (two-sided) was considered statistically significant.

3 Results

3.1 The basic characteristics

Table 1 shows the basic characteristics of socio-demographic and environmental factors among children with and without AR. Of 9,754 children, 1,526 (15.6%) had ever allergic rhinitis (EAR), and 2,259 (23.2%) had current allergic rhinitis (CAR) symptoms. Overall, the mean (SD) age of children was 6.56 (1.77) years, of whom 5,345 (54.8%) were boys, 6,995 (71.7%) were of Han nationality, and 2,434 (25.0%) were of Li nationality. In addition, the prevalence of AR was significantly higher among children with a history of miscarriage or family history of allergy, those born by cesarean delivery, those who used antibiotics within the first year, and those exposed to traffic within 50 m of the house, insecticide use, dampness/mold, and low frequencies of garden visits, and absence of indoor planting. The overall mean (SD) values of NDVI, EVI, temperature, relative humidity, $PM_{2.5}$, and O_3 were 0.58 (0.15), 0.38 (0.14), 26.04 (0.30)°C, 82.42 (0.45)%, 11.79 (0.86) µg/m^3, and 102.29 (2.20) µg/m^3, respectively.

Supplementary Table S1 shows the distribution of residential exposure to greenness, meteorological factors, and air pollutants from 2020 to 2022 and during 2022. The correlation matrix plot is shown in Supplementary Figure S2. Ambient temperature was moderately to highly inversely correlated with the districts ($r_s = -0.58$, $p < 0.001$). Ozone was also moderately to highly negatively correlated with relative humidity ($r_s = -0.58$, $p < 0.001$). NDVI and EVI were moderately to highly positively correlated with relative humidity

TABLE 1 Basic characteristics of socio-demographic and environmental factors among children with and without allergic rhinitis.

Variables	Overall *N* = 9,754	Ever allergic rhinitis		Current allergic rhinitis	
		No, *N* = 8,228	Yes, *N* = 1,526	No, *N* = 7,495	Yes, *N* = 2,259
Child's age, years, Mean (SD)	6.56 (1.77)	6.52 (1.78)	6.81 (1.65)	6.57 (1.77)	6.52 (1.76)
Sex, *n* (%)					
Boys	5,345 (54.8)	4,408 (53.6)	937 (61.4)	3,996 (53.3)	1,349 (59.7)
Girls	4,409 (45.2)	3,820 (46.4)	589 (38.6)	3,499 (46.7)	910 (40.3)
Ethnicity, *n* (%)					
Han	6,995 (71.7)	5,788 (70.3)	1,207 (79.1)	5,320 (71.0)	1,675 (74.1)
Li	2,434 (25.0)	2,172 (26.4)	262 (17.2)	1923 (25.7)	511 (22.6)
Others	325 (3.3)	268 (3.3)	57 (3.7)	252 (3.4)	73 (3.2)
Household income, RMB, *n* (%)					
<3,000	2,932 (30.1)	2,607 (31.7)	325 (21.3)	2,349 (31.3)	583 (25.8)
3,000–5,999	2,782 (28.5)	2,348 (28.5)	434 (28.4)	2,181 (29.1)	601 (26.6)
6,000–8,999	1,586 (16.3)	1,306 (15.9)	280 (18.3)	1,183 (15.8)	403 (17.8)
9,000–11,999	1,022 (10.5)	824 (10.0)	198 (13.0)	753 (10.0)	269 (11.9)
≥12,000	1,432 (14.7)	1,143 (13.9)	289 (18.9)	1,029 (13.7)	403 (17.8)
Miscarriage, *n* (%)	2,283 (23.4)	1860 (22.6)	423(27.7)	1,589 (21.2)	694 (30.7)
Delivery mode, *n* (%)					
Vaginal delivery	5,967 (61.2)	5,081 (61.8)	886 (58.1)	4,651 (62.1)	1,316 (58.3)
Cesarean delivery	3,787 (38.3)	3,147 (38.2)	640 (41.9)	2,844 (37.9)	943 (41.7)
Prenatal antibiotic use, *n* (%)	193 (2.0)	144 (1.8)	49 (3.2)	114 (1.5)	79 (3.5)
Antibiotic use within the first year, *n* (%)	1,625 (16.7)	1,175 (14.3)	450 (29.5)	969 (12.9)	656 (29.0)
Family history of allergy, *n* (%)	3,079 (31.6)	2,118 (25.7)	961 (63.0)	1811 (24.2)	1,268 (56.1)
Traffic 50 m, *n* (%)					
Much	2,499 (25.6)	2005 (24.4)	494 (32.4)	1735 (23.1)	764 (33.8)
Not much	4,122 (42.3)	3,495 (42.5)	627 (41.1)	3,241 (43.2)	881 (39.0)
Less	3,133 (32.1)	2,728 (33.2)	405 (26.5)	2,519 (33.6)	614 (27.2)
Indoor planting, *n* (%)	4,968 (50.9)	4,276 (52.0)	692 (45.3)	3,914 (52.2)	1,054 (46.7)
Insecticide use, *n* (%)	3,702 (38.0)	3,067 (37.3)	635 (41.6)	2,693 (35.9)	1,009 (44.7)
Dampness/mold, *n* (%)	1,447 (14.8)	1,153 (14.0)	294 (19.3)	947 (12.6)	500 (22.1)
Garden visits, *n* (%)					
≤1time/month	2,272 (23.3)	1883 (22.9)	389 (25.5)	1,693 (22.6)	579 (25.6)
1–2times/week	2,341 (24.0)	1976 (24.0)	365 (23.9)	1833 (24.5)	508 (22.5)
2–3times/month	2,948 (30.2)	2,454 (29.8)	494 (32.4)	2,246 (30.0)	702 (31.1)
3–5times/week	938 (9.6)	825 (10.0)	113 (7.4)	748 (10.0)	190 (8.4)
≥1 time/day	385 (3.9)	327 (4.0)	58 (3.8)	298 (4.0)	87 (3.9)
Unknown	870 (8.9)	763 (9.3)	107 (7.0)	677 (9.0)	193 (8.5)
O_3, μg/m^3, Mean (SD)	102.29 (2.20)	102.25 (2.22)	102.53 (2.08)	102.25 (2.22)	102.42 (2.15)
$PM_{2.5}$, μg/m^3, Mean (SD)	11.79 (0.86)	11.79 (0.86)	11.76 (0.84)	11.80 (0.86)	11.76 (0.84)
Temperature, °C, Mean (SD)	26.04 (0.30)	26.04 (0.32)	26.08 (0.22)	26.04 (0.31)	26.05 (0.27)
Relative humidity, %, Mean (SD)	82.42 (0.45)	82.43 (0.45)	82.37 (0.40)	82.44 (0.45)	82.38 (0.41)
NDVI, Mean (SD)	0.58 (0.15)	0.58 (0.15)	0.56 (0.14)	0.58 (0.15)	0.56 (0.15)
EVI, Mean (SD)	0.38 (0.14)	0.38 (0.15)	0.36 (0.13)	0.38 (0.15)	0.36 (0.14)

SD, standard deviation; traffic 50 m: traffic conditions within 50 meters of the house; exposures during 2020 to 2022: O_3, 90% of annual daily maximum 8-h average ozone concentration; $PM_{2.5}$, particulate matter with aerodynamic dimensions less than 2.5 μm; NDVI, normalized difference vegetation index; EVI, enhanced vegetation index.

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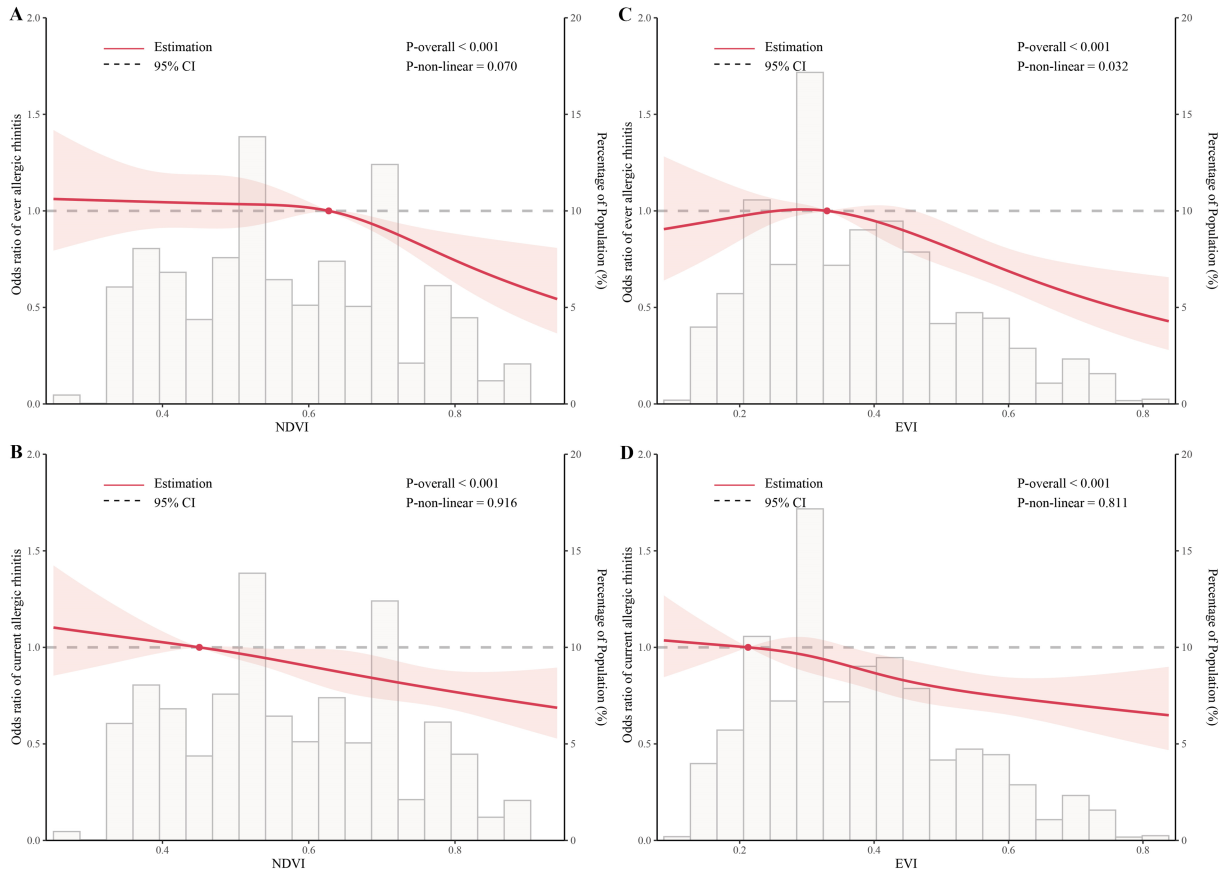

FIGURE 1
Restricted cubic spline curves for the odds ratio of allergic rhinitis and greenness exposure. It is ever allergic rhinitis and NDVI **(A)**, current allergic rhinitis and NDVI **(B)**, ever allergic rhinitis and EVI **(C)**, and current allergic rhinitis and EVI **(D)**, respectively. NDVI, normalized difference vegetation index; EVI, enhanced vegetation index.

($r_s = 0.59$ and 0.66, both $p < 0.001$). NDVI was highly positively correlated with EVI ($r_s = 0.97$, $p < 0.001$).

3.2 The linear or non-linear relationships between AR and greenness exposure

Figure 1 depicts the restricted cubic spline curves for AR and greenness exposures. We observed a linear relationship between EAR and NDVI (Figure 1A), CAR and NDVI (Figure 1B), and CAR and EVI (Figure 1D). There is a non-linear relationship between EAR and EVI (Figure 1C). Overall, the patterns showed that higher degrees of greenness were associated with a lower prevalence of childhood AR.

3.3 Associations of greenness exposure with childhood AR

Figure 2 presents the associations between greenness exposure from 2020 to 2022 and the PR of childhood AR. An IQR increase of NDVI or EVI was associated with an attenuated PR of childhood EAR and CAR. In Model I, the crude model, the PR (95% CI) was 0.85 (0.79, 0.92), 0.84 (0.78, 0.90), 0.89 (0.84, 0.94), and 0.89 (0.85, 0.94) for EAR–NDVI, EAR–EVI, CAR–NDVI, and CAR–EVI, respectively. In Model II, after adjusting for the child's age and household income, the corresponding PR (95% CI) was 0.90 (0.84, 0.97), 0.89 (0.83, 0.96), 0.89 (0.84, 0.95), and 0.90 (0.86, 0.95), respectively. In Model III, further adjusting for antibiotic use within the child's first year, delivery mode, and family history of allergy, the corresponding PR (95% CI) was 0.93 (0.87, 0.99), 0.92 (0.87, 0.99), 0.92 (0.87, 0.97), and 0.93 (0.88, 0.98), respectively. In Model IV, additionally adjusting for traffic conditions within 50 m of the house, indoor planting, and garden visits, the corresponding PR (95% CI) was 0.95 (0.88, 1.02), 0.94 (0.88, 1.00), 0.94 (0.89, 0.99), and 0.95 (0.90, 0.99), respectively.

Supplementary Table S2 shows that all VIF values were smaller than 2, indicating that the adjusted models did not exhibit any multicollinearity. Supplementary Figure S3 exhibits the associations between greenness exposure in 2022 and childhood AR, and the results are similar to Figure 2. The results of GLMs presented were robust and reliable compared to those of GLMMs (Supplementary Table S3).

3.4 The moderating effects of demographic and environmental factors on greenness–AR associations

Figure 3 displays the subgroup analyses. Greenness–AR associations were observed only in boys [PR (95% CI) = 0.92 (0.85,

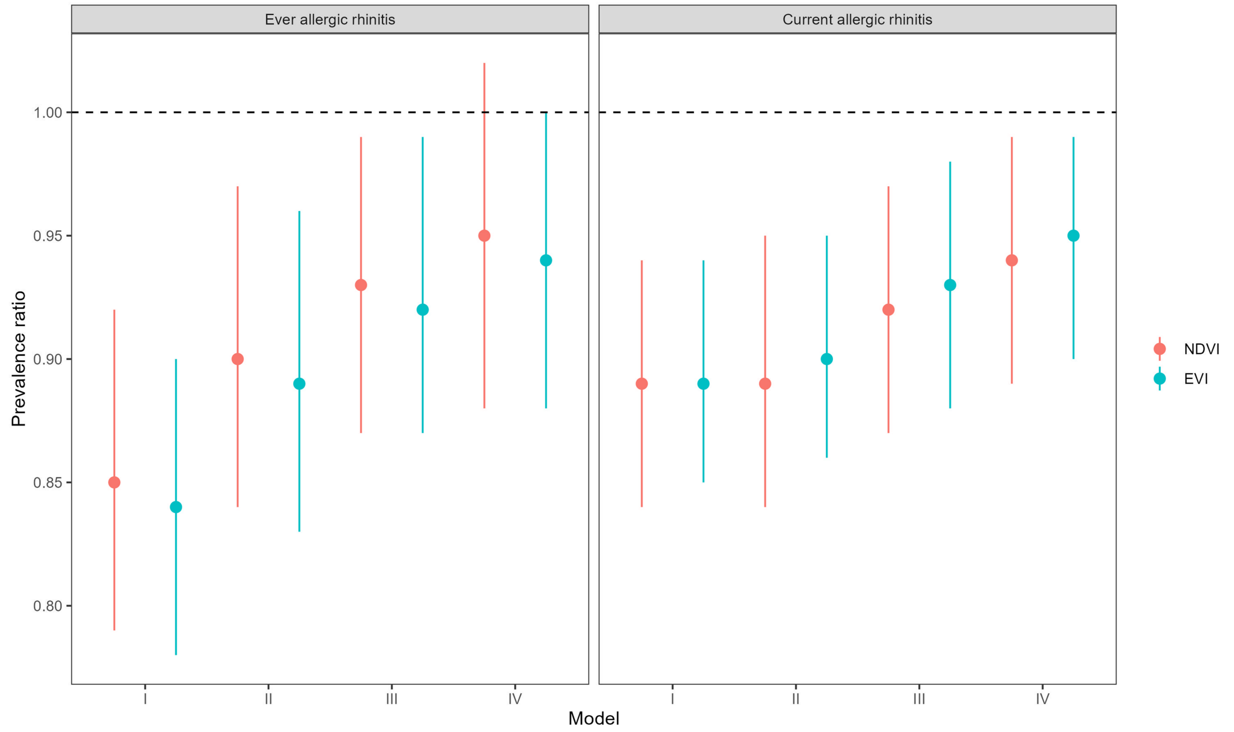

FIGURE 2
Associations of greenness exposure from 2020 to 2022 with childhood allergic rhinitis. Model I: crude model; Model II: adjusting for the child's age, household income; Model III: further adjusting for antibiotic use within the first year, delivery mode, and family history of allergy; and Model IV: additionally adjusting for traffic conditions within 50 m of the house, indoor planting, and garden visits. NDVI, normalized difference vegetation index; EVI, enhanced vegetation index.

0.99) for EVI–EAR, PR (95% CI) = 0.92 (0.85, 0.98) for NDVI–CAR, and PR (95% CI) = 0.93 (0.88, 0.99)] for EVI–CAR, Han nationality [PR (95% CI) = 0.93 (0.88, 0.99) for NDVI–CAR], and low temperature [PR (95% CI) = 0.89 (0.80, 0.99) for NDVI–EAR, PR (95% CI) = 0.87 (0.78, 0.97) for EVI–EAR, PR (95% CI) = 0.91 (0.84, 0.98) for NDVI–CAR, and PR (95% CI) = 0.92(0.85, 0.99) for EVI–CAR]. For ozone subgroups, an IQR increase of EVI was associated with reduced PR (0.88, 95% CI: 0.78, 0.99) of childhood EAR in low levels, but an IQR increase of NDVI was associated with reduced PR (0.93, 95% CI: 0.87, 0.99) of childhood CAR in high levels. Similar results were found for the associations between greenness exposure during 2022 and childhood AR (Supplementary Figure S4).

3.5 The mediating effects of meteorological factors and air pollutants on greenness–AR associations

Table 2 shows the mediating effects of meteorological factors (i.e., temperature and relative humidity) and air pollutants (i.e., ozone) on the associations of greenness exposure with childhood AR. Ambient temperature mediated the NDVI–EAR and EVI–EAR associations, with an indirect effect of −0.005 (95% CI: −0.008, −0.002) and −0.005 (95% CI: −0.009, −0.002) and a mediation proportion of 33.3 and 33.0%. Relative humidity mediated the NDVI–CAR and EVI–CAR associations, with an indirect effect of −0.008 (95% CI: −0.016, −0.001) and −0.010 (95% CI: −0.017, −0.002) and a mediation proportion of 50.9 and 73.5%. Supplementary Table S4 shows similar trends and coefficients using different R packages for the mediation analysis.

4 Discussion

4.1 Principal findings

We found a slightly attenuated prevalence ratio of childhood allergic rhinitis associated with an increase in the interquartile range of greenness exposure. The associations were more pronounced in boys and the low-temperature groups. Furthermore, ambient temperature mediated the greenness–EAR association, and relative humidity mediated the greenness–CAR association.

4.2 Comparison with other studies

Compelling evidence shows the beneficial effects of greenness on human health, while the findings on childhood AR are complicated and inconsistent (Jackson et al., 2023; Gernes et al., 2019; Li et al., 2019; Dzhambov et al., 2021; Parmes et al., 2020; Markevych et al., 2020). Three recent meta-analyses suggested a non-significant association between greenness exposure and childhood AR (Cao et al., 2023; Wu et al., 2022; Ye et al., 2022). One meta-analysis showed that a 10% increase in greenness (via land cover data rather than NDVI) was

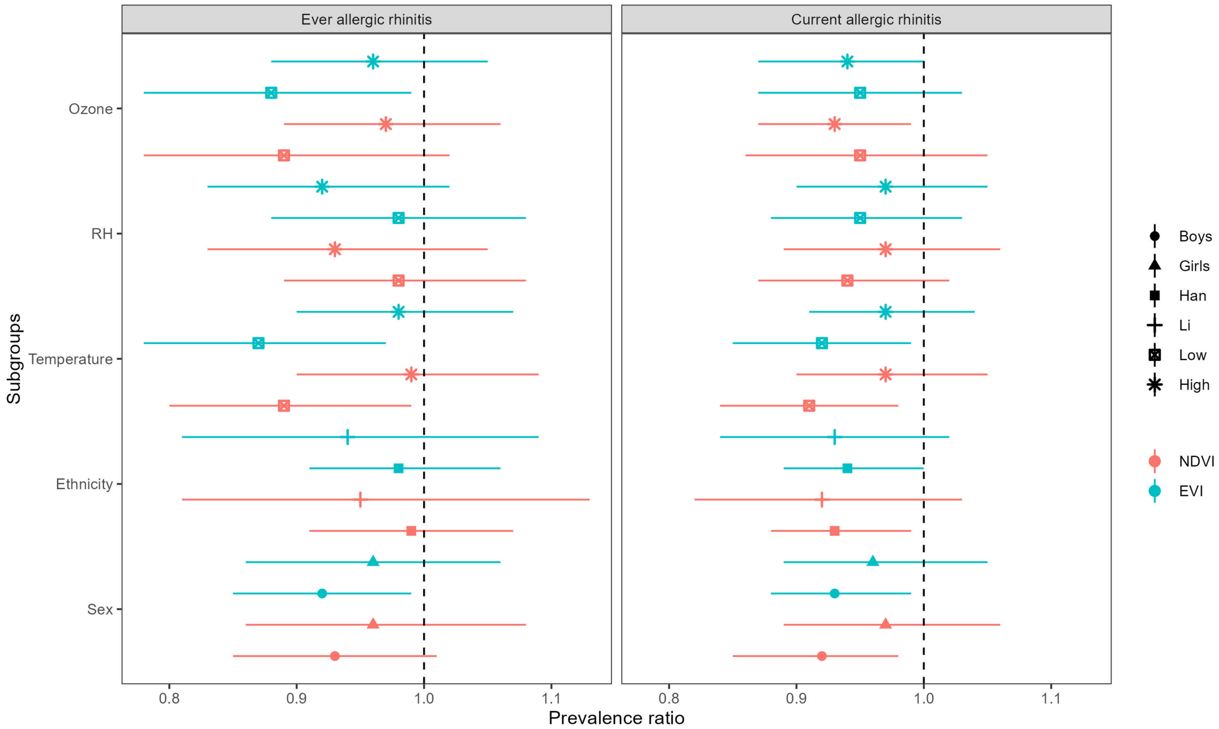

FIGURE 3
Moderating effects of demographic and environmental factors on greenness–allergic rhinitis association. The models were adjusted for the child's age, household income, antibiotic use within the first year, delivery mode, family history of allergy, traffic conditions within 50 meters of the house, indoor planting, and garden visits. RH: relative humidity; NDVI: normalized difference vegetation index; EVI, enhanced vegetation index; low, < the median value; high, ≥ the median value.

TABLE 2 Mediating effects of meteorological factors and air pollutants on greenness–allergic rhinitis associations.

Mediators	Direct effect	Indirect effect	Total effect	*P* for indirect effect	Mediated proportion (%)
NDVI–EAR (X–Y)					
Temperature	−0.008 (−0.022,0.005)	**−0.005 (−0.008,-0.002)**	−0.013 (−0.026,0.001)	**<0.001**	33.3
RH	−0.008 (−0.023,0.006)	−0.003 (−0.009,0.003)	−0.011 (−0.025,0.001)	0.36	23.0
Ozone	−0.009 (−0.024,0.003)	−0.001 (−0.004,0.003)	−0.009 (−0.023,0.001)	0.70	4.2
NDVI–CAR (X–Y)					
Temperature	**−0.017 (−0.033,-0.006)**	0.001 (−0.002,0.004)	**−0.016 (−0.032,-0.004)**	0.44	8.8
RH	−0.009 (−0.027,0.007)	**−0.008 (−0.016,-0.001)**	**−0.017 (−0.032,-0.003)**	**0.04**	50.9
Ozone	**−0.017 (−0.035,-0.001)**	0.002 (−0.003,0.006)	**−0.015 (−0.031,-0.001)**	0.64	11.4
EVI–EAR (X–Y)					
Temperature	−0.010 (−0.0025,0.002)	**−0.005 (−0.009,-0.002)**	**−0.015 (−0.030,-0.003)**	**<0.001**	33.0
RH	−0.009 (−0.019,0.004)	−0.002 (−0.008,0.003)	**−0.011 (−0.021,-0.001)**	0.42	21.0
Ozone	−0.010 (−0.022,0.001)	−0.001 (−0.005,0.005)	−0.011 (−0.022,0.001)	0.76	5.1
EVI–CAR (X–Y)					
Temperature	**−0.014 (−0.027,-0.004)**	0.002 (−0.002,0.006)	**−0.013 (−0.023,-0.003)**	0.36	10.9
RH	−0.004 (−0.018,0.009)	**−0.010 (−0.017,-0.002)**	**−0.013 (−0.025,-0.003)**	**<0.001**	73.5
Ozone	−0.013 (−0.028,0.002)	0.001 (−0.003,0.006)	−0.012 (−0.027,0.002)	0.70	6.2

Bold values indicate that the *p*-value was smaller than 0.05. The models were adjusted for the child's age, household income, antibiotic use within the first year, delivery mode, family history of allergy, traffic conditions within 50 meters of the house, indoor planting, and garden visits. NDVI, normalized difference vegetation index; EVI, enhanced vegetation index; EAR, ever allergic rhinitis; CAR, current allergic rhinitis; RH, relative humidity.

associated with elevated odds of AR (Parmes et al., 2020). Another meta-analysis reported that exposure to greenness could reduce the risk of childhood AR (Wang et al., 2023). Although Ye et al. found no association between greenness and childhood AR (Ye et al., 2022), they indicated that greenness could influence children's lung function (Ye et al., 2023). Queiroz Almeida et al. supported the finding that increasing residential $NDVI_{-100}$ exposure was associated with higher levels of FEV1 (L) and FEF25-75% (L/s) [β (95% CI) = 0.01 (0.0002, 0.03) and β (95% CI) = 0.02 (0.001, 0.05)] (Queiroz Almeida et al., 2022). Our previous findings in Shanghai showed a beneficial influence of higher greenness exposure on childhood asthma (Hu et al., 2023a, 2023b). These mixed findings could be due to various study designs, exposure measurements, greenness types, geographical regions, and ascertainment of outcomes (Wu et al., 2022). Our findings provide additional evidence supporting the benefits of greenness exposure to childhood AR.

We also found that the greenness–AR association was more evident in boys and low-temperature groups. Huang et al. observed that greenness exposure might be associated with attenuated risks of childhood AR, and such associations were more apparent in low $PM_{2.5}$ areas (Huang et al., 2022). In our study, the $PM_{2.5}$ levels were relatively low in Sanya City, where the greenness–AR association was not modified by $PM_{2.5}$. In addition, we found that ambient temperature mediated the greenness–EAR association, and relative humidity mediated the greenness–CAR association. These findings suggest that comprehensively considering ambient temperature and relative humidity is necessary when evaluating the effects of greenness on children's health, such as AR.

In this study, we also observed several potential risk factors for childhood AR, similar to previous findings, such as being born by cesarean delivery (Mitselou et al., 2020), household mold/dampness exposure (Cai et al., 2019; Cai et al., 2020; Norbäck et al., 2018; Norbäck et al., 2021), and living close to the main traffic road (Norbäck et al., 2018; Liu et al., 2020). These findings further support the role of early-life microbial exposure (e.g., the "hygiene hypothesis" in cesarean-born infants), indoor environmental quality, and traffic-related air pollution in childhood AR development. The persistence of these associations for children underscores the need for targeted interventions, such as improving indoor air quality and urban planning strategies to reduce childhood AR risk.

4.3 Potential mechanisms

The potential mechanisms linking greenness exposure and childhood AR may involve improved air quality (Sprague et al., 2022), increased outdoor physical activities, thereby offering exposure to protective microorganisms (Sun et al., 2022), and decreased oxidative stress (Squillacioti et al., 2022). However, this relationship exhibits dual effects—while green spaces confer benefits, they may simultaneously increase exposure to aeroallergens (particularly pollen), potentially exacerbating AR symptoms (Sprague et al., 2022; Zhao et al., 2023).

Notably, local climatic conditions may mediate the association between greenness and childhood AR through several pathways. First, higher greenness levels directly mitigate urban heat island effects through evapotranspiration and shade provision, resulting in optimal ambient temperatures. This thermal regulation could protect against AR by reducing heat stress-induced airway inflammation and decreasing pollen allergenicity. Second, vegetation modulates relative humidity via moisture flux regulation. While moderate humidity in green spaces may suppress particulate allergens (e.g., dust mites and fungal spores), excessive humidity from dense greenery could conversely promote microbial growth.

4.4 Strengths and limitations

Our study has two main advantages. First, we had a large sample size and high response rate, which ensured sufficient statistical power to assess the link. Second, we used satellite-derived data on greenness exposure ($NDVI_{500}$ and EVI_{500}) to determine individual exposure as accurately as possible.

Five major limitations must also be acknowledged. First, due to the cross-sectional design, we cannot establish causation. To determine the relationship between greenness exposure and childhood AR, we relied on the average greenness of 3 years prior to the survey. Second, since the information on AR in children was collected via e-questionnaires without confirmation from actual medical records, there is a possibility of information bias, which may have led to overestimation or underestimation of effects. Third, despite satellite-derived data on residential greenness exposure, there might still be misclassification of individual exposure. Fourth, although NDVI and EVI were standardized measures for assessing greenness, they do not reflect the height of plants or differentiate between different types of plants. Finally, while we adjusted for many confounders in the study, certain confounders, such as pollen exposure, were not available. Children with AR who are exposed to pollen have the possibility of worsening their symptoms. Future studies should incorporate comprehensive environmental assessments, including pollen monitoring, while also accounting for broader ecological factors such as biodiversity loss, air pollution, and climate change, all of which are increasingly recognized as key contributors to the rising prevalence of allergic conditions.

5 Conclusion

Exposure to higher greenness may be modestly associated with a reduced prevalence ratio of childhood allergic rhinitis. Such associations might be more pronounced in boys and in low-temperature groups and could be mediated by ambient temperature and relative humidity. These findings could offer new perspectives on the importance of fully considering ambient temperature and relative humidity in relation to greenness exposure and children's health, including AR.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by the Medical Ethics Committee of Hainan Branch, Shanghai Children's Medical Center, School of Medicine, Shanghai Jiao Tong University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

YH: Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Methodology, Visualization, Software. GY: Data curation, Investigation, Validation, Writing – review & editing. DW: Conceptualization, Methodology, Supervision, Writing – review & editing, Validation. WG: Data curation, Investigation, Methodology, Writing – review & editing, Validation. QL: Data curation, Investigation, Methodology, Validation, Writing – review & editing. LX: Data curation, Investigation, Methodology, Validation, Writing – review & editing. JT: Data curation, Investigation, Methodology, Validation, Writing – review & editing. HW: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. ST: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing. ZL: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing. SL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1539217/full#supplementary-material

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