Global Environmental Science
www.sciltp.com/journals/ges

Article

Combined Effects of Parental and Childhood Physical Activity and Air Pollution on Childhood Asthma and Wheezing

Chan Lu [1,2,3,*,†], Yuanqi Li [1,†], Zhangxiong Guo [1,†], Xianglong Xiao [1], Lin Wang [1], Wenying Sun [1] and Zipeng Qiao [1]

[1] Xiangya School of Public Health, Central South University, Changsha 410013, China
[2] Furong Laboratory, Changsha 410078, China
[3] Hunan Provincial Key Laboratory of Low Carbon Healthy Building, Central South University, Changsha 410083, China
* Correspondence: chanlu@csu.edu.cn
† These authors contributed equally to this work.

How To Cite: Lu, C.; Li, Y.; Guo, Z.; et al. Combined Effects of Parental and Childhood Physical Activity and Air Pollution on Childhood Asthma and Wheezing. *Glob. Environ. Sci.* **2026**, *2*(2), 107–127. https://doi.org/10.53941/ges.2026.100009

Publication History

Received: 15 September 2025
Revised: 28 October 2025
Accepted: 11 December 2025
Published: 1 April 2026

Keywords

childhood asthma and wheeze; early-life exposure; physical activity; ambient air pollution; exercise-pollution interaction

Highlights

- Paternal running and ball sports before pregnancy was related with reduced childhood wheeze risk
- Maternal preconceptional nigh walking and exercise were related with reduced childhood asthma risk
- Maternal long duration of meditation in utero was associated with increased childhood wheeze risk
- Childhood exercise in long duration and daytime was negatively related with asthma and wheeze
- Early-life "exercise-pollution interaction" affects children's asthma and wheeze

Abstract: The combined effects of early-life exercise and air pollution on childhood asthma and wheeze remain unclear, particularly during and after the COVID-19 epidemic. We aim to examine the joint impacts of paternal, maternal, and childhood exercise habits and air pollutant exposures on asthma and wheeze in children. We analyzed 20,730 valid questionnaires from five Chinese cities (2022–2023), covering individual characteristics, health outcomes, and household environments. Multilevel (city-family) logistic regression assessed the associations of paternal (preconceptional), maternal (preconceptional and prenatal), and childhood (postnatal) exercise, along with early-life air pollution exposure, with childhood asthma and wheeze. We found that paternal running and ball sports before conception reduced offspring's wheeze risk (OR [95% CI] = 0.70 [0.54–0.91] and 0.47 [0.23–0.97]). Maternal walking before pregnancy was linked to reduced asthma risk (0.37 [0.16–0.85]); however, maternal daytime exercise and prolonged meditation increased asthma/wheeze risk, while exercise during periods typically characterized by lower pollution levels (such as afternoon and nighttime in our study setting) was associated with reduced risk. Childhood exercise decreased asthma and wheeze risk (0.29 [0.14–0.63] and 0.57 [0.36–0.90]), especially when performed longer and during the day. Exposure to $PM_{2.5-10}$ in the first trimester and $PM_{2.5}$ in the second trimester were associated with asthma, while exposure to NO_2 before pregnancy and PM_{10} in the third trimester were associated with wheeze. Particulate matter exposure modified the effects of parental and childhood exercise, suggesting a potential "exercise–pollution interaction". This study indicates that exercise habits across preconceptional, prenatal, and postnatal periods, combined with air pollution exposures, independently and interactively may influence childhood asthma and wheeze.

1. Introduction

Asthma and wheeze are among the most common respiratory conditions in children worldwide, and their rising incidence has become a major public health challenge. Globally, the number of asthma cases increased from 226.9 million in 1990 to 262.4 million in 2019, accompanied by a disease burden of 21.6 million disability-adjusted life years (DALYs) [1,2]. In China, the prevalence of asthma among children aged 3 to 6 years has reached 7.4% [3]. Wheeze, a hallmark clinical manifestation of asthma, is strongly associated with the progression of childhood asthma. Clinical observations suggest that while mild wheezing in infancy often resolves spontaneously, persistent or worsening symptoms markedly increase the risk of developing asthma [4,5]. Identifying risk factors for childhood wheeze and asthma, especially during the COVID-19 epidemic and post-pandemic era, is therefore crucial for early prevention and public health planning.

With rapid urbanization, children face increasing exposure to air pollutants and reduced opportunities for physical activity—both key determinants of respiratory health. Globally, 80–90% of adolescents aged 11–17 years are insufficiently active, and increasing physical activity by 10–25% could prevent 533,000–1.3 million deaths annually. Eliminating physical inactivity could even increase global life expectancy by 0.68 years [6,7]. While exercise is known to improve cardiovascular and pulmonary function and alleviate asthma symptoms, it also increases respiratory ventilation, thereby elevating pollutant inhalation during outdoor activities [8,9]. Some studies indicate that insufficient physical activity increases the risk of new-onset asthma in children [10], whereas others highlight that asthma symptoms, such as exercise-induced bronchoconstriction, may discourage physical activity [11]. Thus, the relationship between physical activity and childhood asthma or wheeze remains complex and poorly understood, particularly in the context of the COVID-19 pandemic and the post-pandemic era.

A wealth of evidence has established that early-life exposure to air pollution contributes to childhood asthma [12–15]. For example, prenatal exposure to $PM_{2.5}$ during mid-pregnancy has been linked to asthma development in boys by age 6 [13]. PM_{10}, a heterogeneous mixture of particulate matter, is known to exacerbate asthma in children [14], while prenatal exposure to ozone (O_3) during early gestation—especially the third month—has been identified as a critical window for asthma risk [15]. Air pollutants, such as NO_2 and SO_2 from traffic and industrial sources, have also been associated with childhood asthma and wheeze [16–18]. However, the impact of preconceptional and prenatal exposures to different pollutants on asthma and wheeze, particularly during the COVID-19 epidemic and post-pandemic era, remains inconclusive.

Although numerous studies have examined the health impacts of outdoor air pollution and physical activity, their combined effects remain unclear. On one hand, exercise during periods of high air pollution may increase pollutant deposition in the lungs due to elevated ventilation [19]. Both acute and chronic exposures to $PM_{2.5}$ and O_3 during exercise have been shown to impair lung function and promote pulmonary inflammation [20]. A U.S. cohort study reported that in communities with high O_3 levels, children engaged in three or more sports had a 3.3-fold increased risk of developing asthma compared to those not participating in sports [21]. On the other hand, other studies have suggested that the protective health effects of exercise are not entirely negated by pollution exposure [22,23]. Whether there is an interaction between early-life physical activity and air pollution on childhood asthma and wheeze remains unknown.

To address this knowledge gap, we conducted a retrospective cohort study of father–mother–child triads in five Chinese cities. We aimed to systematically evaluate the independent and interactive effects of preconceptional, prenatal, and postnatal physical activity of parents and offspring, together with air pollutant exposures, on the occurrence of childhood asthma and wheeze during the COVID-19 epidemic and post-pandemic period.

2. Materials and Methods

2.1. Study Protocol

We conducted a retrospective cohort study of father–mother–child triads during the COVID-19 pandemic and post-pandemic period (2022–2023) in five Chinese cities: Liangshan Autonomous Prefecture (n = 3660), Zhangjiajie (n = 471), Xiangxi Autonomous Prefecture (n = 1584), Changsha (n = 13,656), and Loudi (n = 801) (Figure 1) [24,25]. A large-scale questionnaire survey was administered to 20,730 participants, and written informed consent was obtained from all participating families. Participation was voluntary, and all collected data were anonymized prior to analysis. Ethics approval was granted by the Ethics Committee of Central South University (CSU-IRB No.: XYGW-2022-91; 21 November 2022).

The questionnaire was adapted from the International Study of Asthma and Allergies in Childhood (ISAAC) and the Swedish Buildings and Health (DBH) questionnaire. It collected information on children's health outcomes, exercise habits, personal and household environmental factors, and lifestyle characteristics of the father–mother–child triads and their family members.

 https://doi.org/10.53941/ges.2026.100009

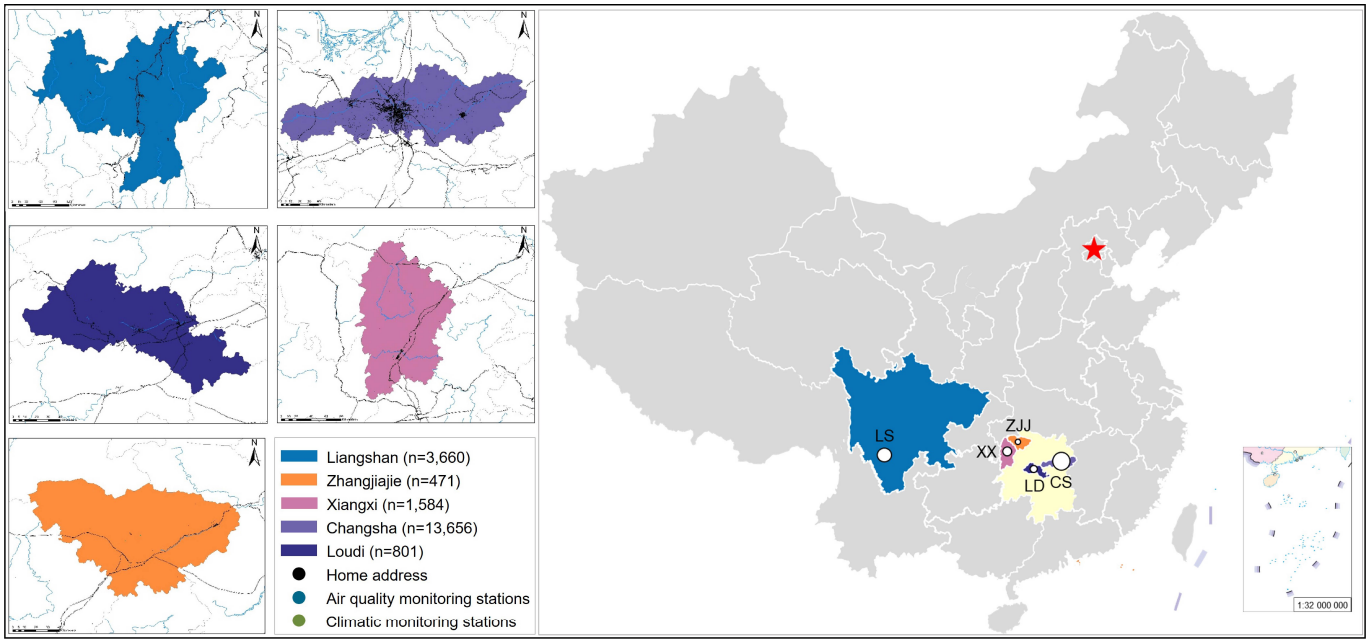


Figure 1. Geographic distribution of 6724 home addresses, 25 ambient air quality monitoring stations (Liangshan: 4, Zhangjiajie: 4, Xiangxi: 3, Changsha: 10, Loudi: 4), and 44 meteorological monitoring stations (Liangshan: 17, Zhangjiajie: 4, Xiangxi: 8, Changsha: 10, Loudi: 5) across five study cities.

To ensure data reliability, we provided systematic training to parents (the primary respondents) before the survey, which consists of three sections of Pre-Organization, Training Sessions including explaining the study purpose, clarifying questionnaire items, and Post-Training Support with questionnaire retrieval. Parents were asked to complete and return the questionnaires within one week. Because asthma and wheeze diagnoses in children are generally reliable after age 3, and the number of children older than 6 years was small, we focused on families with at least one child aged 3–6 years. In order to obtain more reliable data, the relevant information of children aged 3–6 years was filled in by their adult guardians (e.g., their parents, grandparents or nannies). This yielded 20,172 eligible participants (6724 fathers, 6724 mothers, and 6724 children) (Figure 2).

Among the 6724 surveyed families, 6114 (90.9%) had not changed residences for at least one year prior to pregnancy, enabling reliable estimation of long-term air pollution and meteorological exposures. Over 99% of questionnaires (n = 6657) were completed by parents, who are typically more aware of early-life exposures and family behaviors than other guardians, thereby minimizing recall bias. A double-sampling check of 10% of completed questionnaires confirmed >98% completeness and minimal logic errors, indicating high data validity and reliability [26].

2.2. Health Outcomes

The primary study outcomes were defined as follows:

- Physician-diagnosed asthma (PDA): "Has your child been diagnosed with asthma by at least one clinical physician?"
- Physician-diagnosed wheeze (PDW): "Has your child been diagnosed with wheezing symptoms by at least one clinical physician?"

We further categorized types of PDA and PDW in 3–6-year-old children using a modified version of our previously published questionnaire (Table S1) [27]. Parental histories of PDA, allergic rhinitis, and eczema were also recorded.

2.3. Assessment of Exercise

We assessed exercise habits of fathers (during normal days and one year before conception), mothers (during normal days, before, and during pregnancy), and children (during normal days and after birth) via questionnaire (Tables S2–S4). The assessment included three dimensions:

(1) Exercise preference: A four-point scale captured exercise inclination (very dislike, dislike, neutral, like). Types of exercise (e.g., walking, running, ball sports, other) were also recorded.

(2) Exercise habits:

- Weekly frequency: 0–2 days, 3–4 days, or ≥5 days/week.
- Duration per session: <0.5 h, 0.5–1 h, 1-2 h, or ≥2 h.
- Intensity: low, middle, or high.
- Sedentary behavior: <2 h, 2–4 h, 4–6 h, or ≥6 h/day sitting.

(3) Exercise timing: Daytime (06:00–18:00) and nighttime (18:00–06:00) periods were recorded to assess circadian activity patterns.

For analysis, multilevel variables were dichotomized. Exercise preference was grouped as active (neutral/like) versus passive (dislike/very dislike). Key exposure indicators were defined as high frequency (≥3 days/week), long duration (≥1 h/session), moderate-to-high intensity, and sedentary behavior (≥6 h/day).

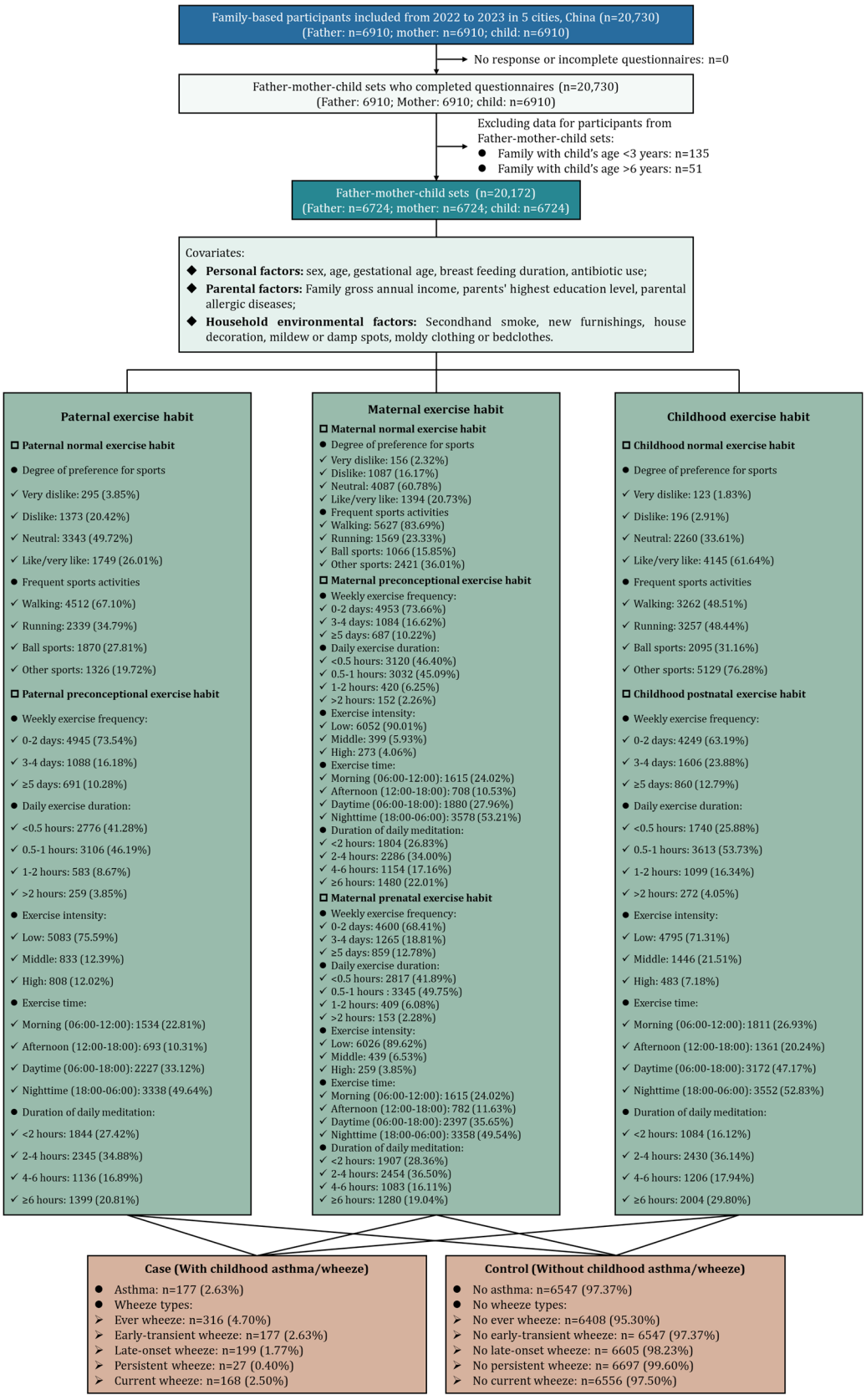


Figure 2. Flowchart of the study protocol, including maternal and childhood intake of nutritional additives across different time windows, and the number and prevalence of various types of childhood food allergies.

2.4. Outdoor Air Pollution and Climatic Exposure

Individual pollutant exposure was estimated using the Inverse Distance Weighting (IDW) method. Home addresses (with ±0.000001° precision) were linked to the four nearest air quality monitoring stations in each city. Using the IDW interpolation algorithm, we derived daily individualized exposures for seven pollutants based on data from 25 stations (June 2010–June 2023): fine particulate matter ($PM_{2.5}$), coarse particulate matter ($PM_{2.5-10}$), inhalable particulate matter (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3). Daily mean temperature (T) and relative humidity (RH) were calculated using data from 44 meteorological stations. For each participant, pollutant and climatic exposures were computed across ten life-course time windows: 4–6 months before conception, 3 months before conception, 1 year prior to conception, 1st, 2nd, and 3rd trimesters in utero, entire pregnancy, 0-1 year after birth, previous year, and entire postnatal period.

2.5. Exposure Time Windows

This study considered ten life-time windows: 4–6 months before pregnancy, 3 months before pregnancy, year before pregnancy, 1st, 2nd, and 3rd trimesters in utero, entire pregnancy, first year after birth, the past year, and the entire postnatal period. Detailed definitions of the ten time windows are provided in Table S5.

2.6. Covariates

Thirteen covariates known to influence asthma and wheeze were included (Table S6) [25,27].

2.7. Statistical Analysis

We evaluated the independent and interactive effects of paternal, maternal, and childhood exercise and air pollutant exposure during preconception, pregnancy, and postnatal periods on children's asthma and wheeze.

- Descriptive statistics: Categorical variables were summarized as frequencies (%) and compared using the Chi-square test (α = 0.05). Continuous variables (e.g., pollutant concentrations) were summarized as mean ± standard deviation (SD) and interquartile range (IQR) and compared using t-tests (α = 0.05).
- Multivariate logistic regression (city-family): The regression model is defined by three hierarchical levels of individual (especially the child), family and city. Odds ratios (ORs) with 95% confidence intervals (CIs) quantified the associations between exercise exposure and outcomes.
- Interaction analysis: Product terms between exercise and pollutant concentrations (α = 0.1) were included to assess effect modification. Subgroup analyses explored sensitivity differences across population groups.
- Software: The initial phase of data management, cleaning, and basic descriptive statistics including Chi-square and t-tests were performed using SPSS 22.0 (IBM), multilevel logistic regression models such as logistic regression (city-family) and other complex analyses were conducted in Stata 18.0 (StataCorp LLC), and atmospheric exposure calculations were performed using Python 3.9 by compiling a program for Inverse Distance Weighting (IDW).

3. Results

3.1. Prevalence of Asthma and Wheeze

Among 6724 families, 177 children (2.63%) were diagnosed with asthma, and 316 (4.70%) with wheeze (Table 1). The highest asthma prevalence was observed in Xiangxi (3.79%), while the lowest was in Loudi (1.50%). Wheeze prevalence was highest in Changsha (5.25%) and lowest in Zhangjiajie (1.91%). No significant variation in wheeze subtypes was found across the cities (Table S7).

Table 1. Demographic characteristics and prevalence of physician-diagnosed asthma and wheezing among children aged 3–6 years (n = 6724).

	Total		Asthma			Wheeze		
	Number (n)	(%)	Case (n)	(%)	*p*-Value	Case (n)	(%)	*p*-Value
Total	6724	(100.00)	177	(2.63)		316	(4.70)	
Sex					**0.030**			**<0.001**
Boys	3525	(52.42)	107	(3.04)		203	(5.76)	
Girls	3199	(47.58)	70	(2.19)		113	(3.53)	
Age (years)					0.119			0.130
3	1755	(26.10)	33	(1.88)		69	(3.93)	
4	2287	(34.01)	70	(3.06)		125	(5.47)	
5	2046	(30.43)	55	(2.69)		91	(4.45)	
6	636	(9.46)	19	(2.99)		31	(4.87)	
Gestational age (weeks)					**0.049**			**0.001**
<37	645	(9.59)	25	(3.88)		48	(7.44)	
≥37	5602	(83.31)	143	(2.55)		252	(4.50)	

Table 1. *Cont.*

	Total		Asthma			Wheeze		
	Number (n)	(%)	Case (n)	(%)	*p*-Value	Case (n)	(%)	*p*-Value
Breast feeding duration (months)					0.113			0.936
0	555	(8.25)	19	(3.42)		26	(4.68)	
<6	1624	(24.15)	51	(3.14)		79	(4.86)	
≥6	4545	(67.59)	107	(2.35)		211	(4.64)	
Antibiotic use					**<0.001**			**<0.001**
No	3483	(51.8)	42	(1.21)		96	(2.76)	
Yes	3241	(48.2)	135	(4.17)		220	(4.17)	
Family gross annual income (CNY)					0.594			**0.028**
<50,000	694	(10.32)	16	(2.31)		26	(3.75)	
50,000-200,000	4335	(64.47)	111	(2.56)		191	(4.41)	
≥200,000	1695	(25.21)	50	(2.95)		99	(5.84)	
Parents' highest educational level					**0.020**			**0.001**
Elementary/middle school	513	(7.63)	8	(1.56)		16	(3.12)	
High school/vocational school	1078	(16.03)	27	(2.50)		45	(4.17)	
Bachelor/associate degree	4573	(68.01)	117	(2.56)		211	(4.61)	
Master/Doctor or above	560	(8.33)	25	(4.46)		44	(7.86)	
Parental allergic diseases					**<0.001**			**<0.001**
No	4960	(73.77)	102	(2.06)		173	(3.49)	
Yes	1764	(26.23)	75	(4.25)		143	(8.11)	
Secondhand smoke					0.909			0.546
No	2404	(35.75)	64	(2.66)		118	(4.91)	
Yes	4320	(64.25)	113	(2.62)		198	(4.58)	
New furnishings					0.989			0.907
No	4448	(66.15)	117	(2.63)		210	(4.72)	
Yes	2276	(33.85)	60	(2.64)		106	(4.66)	
House decoration					0.479			**0.022**
No	5420	(80.61)	139	(2.56)		239	(4.41)	
Yes	1304	(19.39)	38	(2.91)		77	(5.90)	
Mildew or damp spots					0.532			0.086
No	5441	(80.92)	140	(2.57)		244	(4.48)	
Yes	1283	(19.08)	37	(2.88)		72	(5.61)	
Moldy clothing or bedclothes					0.455			0.189
No	5825	(86.63)	150	(2.58)		266	(4.57)	
Yes	899	(13.37)	27	(3.00)		50	(5.56)	

Note: The total number of cases does not sum to 6724 due to missing data. *p*-values less than 0.05 are considered statistically significant and are indicated in bold.

3.2. Sociodemographic and Household Factors

Asthma and wheeze were more prevalent among boys, children born prematurely, those with antibiotic use, and those with parental allergic diseases or higher parental education. Children from families with higher annual income and recent household decoration also showed increased wheeze prevalence. No significant associations were found with age, breastfeeding duration, secondhand smoke exposure, new furnishings, mildew/damp spots, or moldy clothing/bedding.

3.3. Exercise Habits and Associations with Childhood Asthma and Wheeze

Tables S8–S10 summarize paternal, maternal, and childhood exercise habits during normal days, preconceptional, prenatal, and postnatal periods, and their associations with childhood asthma and wheeze. Paternal frequent running and participation in other sports significantly reduced the prevalence of wheeze, whereas prolonged daily sedentary time (≥6 h/day) markedly increased wheeze prevalence (Table S8). Overall, paternal exercise habits were not significantly associated with childhood asthma. Maternal exercise habits had stronger effects: frequent walking and preconceptional nighttime exercise were associated with reduced asthma prevalence, while prolonged sedentary behavior during the preconceptional and prenatal periods increased wheeze risk in offspring (Table S9). Children with a stronger preference for sports had lower rates of both asthma and wheeze (Table S10). In addition, children who exercised for ≥1 h per day had a reduced prevalence of asthma, and those who participated in other sports, exercised at lower intensity, and exercised during daytime—particularly in the afternoon—had a lower probability of developing wheeze compared with those who exercised at night.

 https://doi.org/10.53941/ges.2026.100009

3.4. Individual Exposure to Air Pollutants and Climatic Factors

Table S11 presents individual exposure levels to seven outdoor air pollutants ($PM_{2.5}$, $PM_{2.5–10}$, PM_{10}, SO_2, NO_2, CO, and O_3), as well as atmospheric temperature (T) and relative humidity (RH), across preconceptional, gestational, and postnatal periods. Mean concentrations (±SD) of all pollutants except O_3 decreased from one year before conception to the postnatal period, whereas individual O_3 exposure increased. Temperature exposure showed an upward trend, while RH exposure declined. Children with asthma and wheeze experienced higher exposure levels to several pollutants (especially $PM_{2.5}$, $PM_{2.5–10}$, PM_{10}, and NO_2), as well as higher RH exposure across most time windows, compared with children without asthma or wheeze. Spearman correlation coefficients for air pollutant exposures across different time windows varied widely (0.001–0.945; Table S12). Correlations between T and RH also varied substantially (0.002–0.931; Figure S1). Due to strong collinearity between T and RH during specific periods, these two climatic factors were not included in the same model; temperature was selected as the primary meteorological factor and was adjusted for in all subsequent analyses.

3.5. Associations of Paternal Exercise Habits with Childhood Asthma and Wheeze

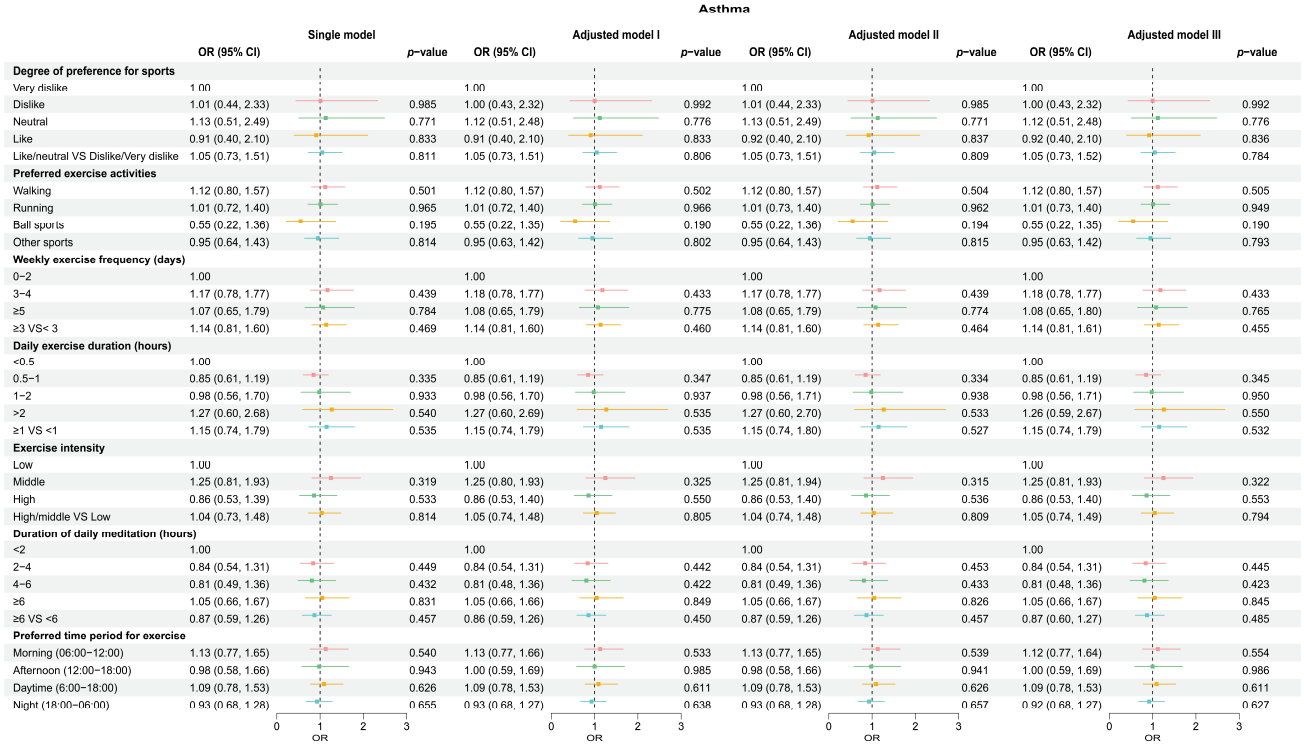
Figure S2a-b illustrates the associations between paternal exercise habits, both during normal days and the preconceptional period, and the risk of asthma and wheeze in children. Similar trends were observed across all analytical models. Paternal running and participation in ball sports before conception were significantly associated with a reduced risk of wheeze in offspring, with adjusted ORs (95% CI) of 0.70 (0.54–0.91) and 0.47 (0.23–0.97), respectively, after accounting for covariates as well as NO_2 and temperature exposures during the year prior to conception. Interestingly, fathers who exercised ≥3 days per week before conception were linked to a higher risk of late-onset and persistent wheeze in their children compared with those who exercised less frequently (<3 days per week) (data not shown). Sensitivity analyses further revealed that premature children were more susceptible to asthma risk associated with paternal high-intensity exercise before conception (Figure S3a–d); Moreover, girls, breastfed children, and those without secondhand smoke or antibiotic exposure were more affected by wheeze risk linked to paternal exercise habits before conception (Figure S4a–d).

3.6. Associations of Maternal Exercise Habits with Childhood Asthma and Wheeze

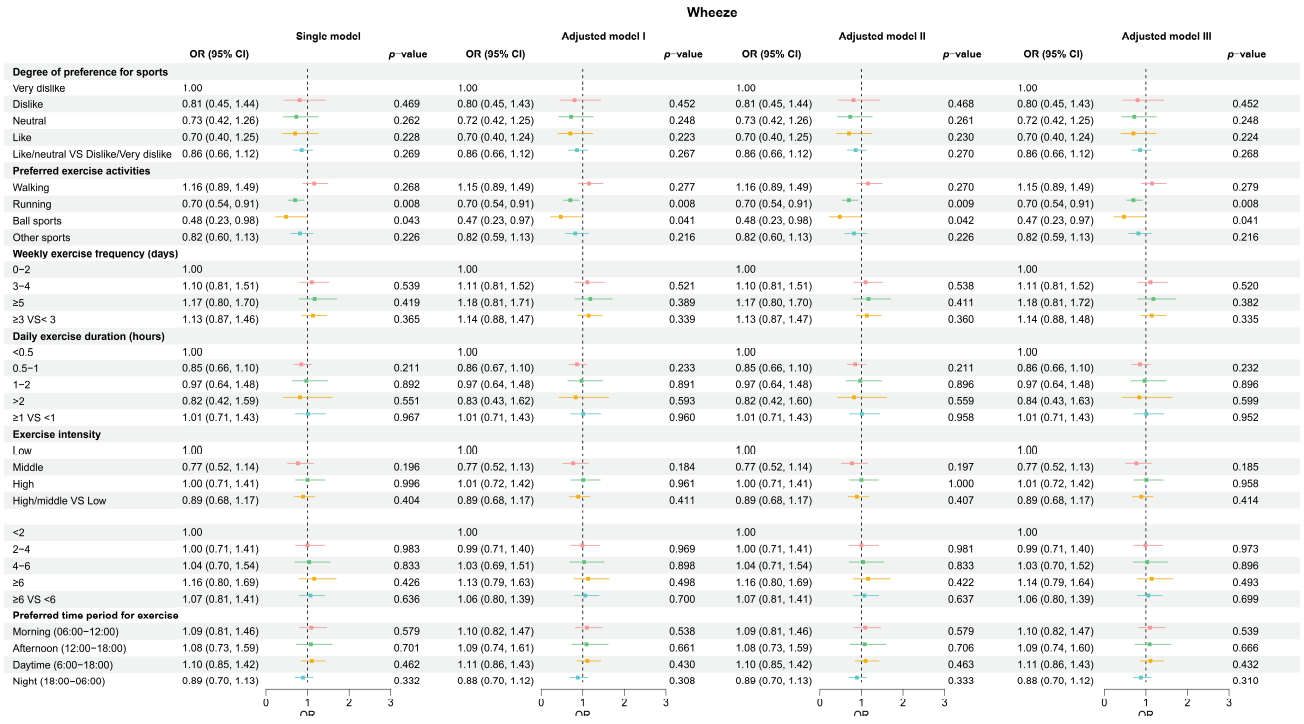
Maternal preference for exercise, particularly walking, was significantly associated with a reduced risk of asthma in offspring, with adjusted ORs (95% CI) of 0.37 (0.16–0.85) and 0.63 (0.43–0.93) (Figure S5a-b). Exercising in the afternoon or at night before pregnancy was also protective, reducing the risk of wheeze and asthma, respectively (ORs [95% CI] = 0.63 [0.39–1.00] and 0.64 [0.47–0.88]). In contrast, maternal exercise during daytime before pregnancy increased the risk of offspring asthma (OR [95% CI] = 1.56 [1.12–2.17]). Prolonged daily sedentary time (≥6 h vs. <6 h) during pregnancy was associated with an elevated risk of wheeze (OR [95% CI] = 1.40 [1.07–1.84]), while maternal daytime exercise during pregnancy increased asthma risk (OR [95% CI] = 1.46 [1.06–2.02]). The protective effects of maternal exercise before pregnancy were particularly pronounced for early-transient wheeze, whereas adverse effects were more evident for late-onset and persistent wheeze (data not shown). Sensitivity analyses indicated that girls, premature children, children aged 4–5 years, and those with parental allergic diseases were more affected by asthma risk associated with maternal exercise habits during pregnancy (Figure S6a–h). Premature children were more susceptible to adverse effects, while non-premature children were more sensitive to protective effects of maternal exercise on wheeze risk (Figure S7a-b); Additionally, younger children, girls, breastfed children, and those with parental allergic diseases or antibiotic use were more affected by wheeze risk associated with maternal exercise habits during pregnancy (Figure S7c-h).

3.7. Associations of Childhood Exercise with Asthma and Wheeze

As shown in Figure 3, children's preference for exercise was negatively associated with both asthma and wheeze, with ORs (95% CI) of 0.29 (0.14–0.63) and 0.57 (0.36–0.90), respectively. Children who exercised for more than 60 min per day had a significantly reduced risk of asthma (OR [95% CI] = 0.55 [0.35–0.86]). Exercising during the daytime, particularly in the afternoon, was associated with lower wheeze risk (ORs [95% CI] = 0.78 [0.62–1.00] and 0.61 [0.43–0.85]), whereas nighttime exercise increased wheeze risk (OR [95% CI] = 1.28 [1.00–1.62]). The protective effects of exercise were more evident for early-transient wheeze, whereas adverse effects were stronger for persistent wheeze (data not shown). Sensitivity analyses further indicated that children aged 4–5 years, those without parental allergic diseases, and those without secondhand smoke exposure were more sensitive to the adverse effects of postnatal exercise on asthma risk (Figure S8a–d). Conversely, younger and breastfed children, those without parental allergic diseases, those without secondhand smoke exposure, and those with antibiotic use were more sensitive to the protective effects of postnatal exercise on wheeze risk (Figure S9a–d).



(a)



(b)

Figure 3. (**a**) Associations between childhood exercise after birth and physician-diagnosed asthma in children. (**b**) Associations between childhood exercise after birth and physician-diagnosed wheeze in children. The single model displays odds ratios (ORs) with 95% confidence intervals (CIs) adjusted for the studied covariates. Adjusted Model I further adjusts for individual exposure to ambient temperature during the preconception period. Adjusted Model II includes additional adjustment for individual exposure to ambient nitrogen dioxide (NO_2) during the preconception period. Adjusted Model III accounts for individual exposures to both ambient NO_2 and temperature during the postnatal period along with the studied covariates. A *p*-value of less than 0.05 is considered statistically significant.

3.8. Effects of Air Pollution Exposure on Childhood Outcomes

The relationships between paternal exercise habits before pregnancy and children's asthma and wheeze, stratified by individual air pollution exposure levels, are presented in Figure 4. Consistent trends were observed across different models for specific pollutants. Exposure to $PM_{2.5–10}$ during the first trimester in utero and $PM_{2.5}$ during the second trimester were consistently associated with increased asthma risk in children, with all models showing significant odds ratios. Similarly, NO_2 exposure in the three months before pregnancy and PM_{10} exposure during the third trimester were significantly linked to increased wheeze risk. These associations were particularly significant for early-transient and persistent wheeze but not for late-onset wheeze (data not shown). Sensitivity analyses revealed that children born at term (after 37 gestational weeks), those who were breastfed, children without parental allergic diseases, and those who had not used antibiotics were more vulnerable to the adverse effects of outdoor air pollution exposure on asthma risk (Figure S10a–d). In contrast, children born prematurely (before 37 weeks), younger children, those breastfed for less than six months, children with parental allergic diseases, secondhand smoke exposure, or antibiotic use were more susceptible to wheeze risk from ambient air pollution, particularly $PM_{2.5}$ and NO_2 exposures (Figure S11a–d).

3.9. Interaction Effects of Paternal Exercise and Air Pollution on Childhood Outcomes

Figure S12a-f illustrate the associations between paternal exercise habits before pregnancy and offspring asthma and wheeze, stratified by individual exposure levels to particulate matter ($PM_{2.5}$, $PM_{2.5–10}$, and PM_{10}). The adverse impact of paternal high-frequency weekly exercise (≥3 days per week) before pregnancy on offspring asthma was significantly stronger under conditions of high exposure to $PM_{2.5}$ and PM_{10} (interaction *p*-values: 0.031 and 0.025, respectively). Conversely, the protective effects of paternal longer exercise duration and preference for other sports before pregnancy on offspring wheeze were more pronounced at low exposure levels to $PM_{2.5}$ during the year before pregnancy and $PM_{2.5–10}$ during 4–6 months before pregnancy (interaction *p*-values: 0.017 and 0.052, respectively). In comparison, high exposures to $PM_{2.5}$ and $PM_{2.5–10}$ during 4–6 months before pregnancy, as well as PM_{10} during the three months before pregnancy, amplified the adverse effects of paternal high-frequency weekly exercise before pregnancy on offspring wheeze (interaction *p*-values: 0.014, 0.005, and 0.039). Significant interactions between paternal exercise before pregnancy and low versus high PM exposures on reduced and increased risks of offspring asthma (Figure S13a–c) and wheeze (Figure S14a–c), respectively, were observed.

3.10. Interaction Effects of Maternal Exercise and Air Pollution on Childhood Outcomes

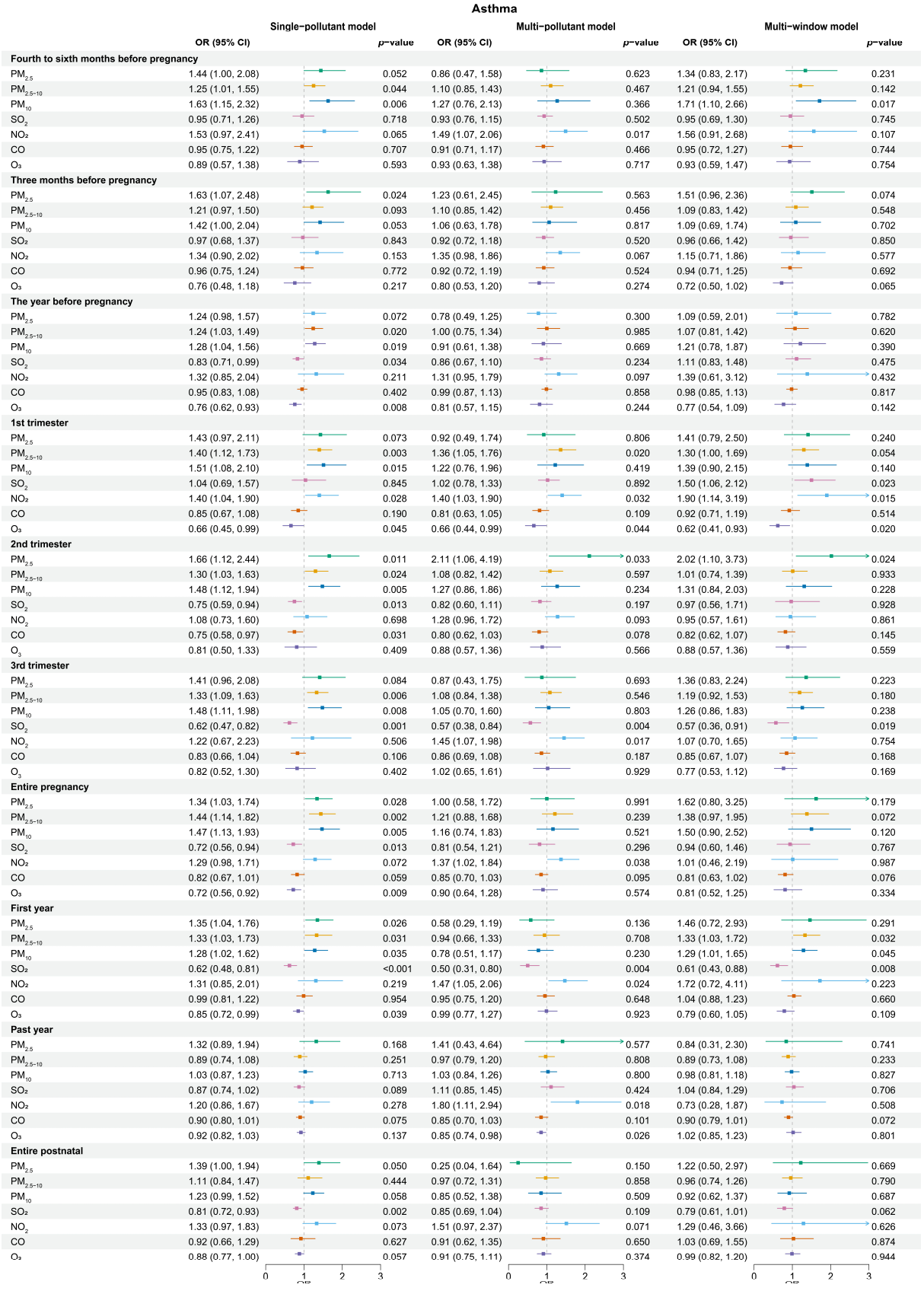
Figure S15a–l show the associations between maternal exercise habits before pregnancy and during pregnancy with offspring asthma and wheeze, stratified by individual exposure levels to particulate matter. The adverse impact of maternal exercise in the afternoon and nighttime before conception on offspring asthma was stronger under high exposures to $PM_{2.5}$ and PM_{10} during the three months before pregnancy (interaction *p*-values: 0.011 and 0.045, respectively) (Figure S16a). In contrast, the protective effect of maternal afternoon exercise before pregnancy on offspring wheeze was more pronounced at low $PM_{2.5}$ exposure during the same period (interaction $p = 0.038$) (Figure S17a). Significant interactions were observed between maternal exercise before conception and high particulate matter exposures on increased risks of offspring asthma (Figure S16a–c) and wheeze (Figure S17a–c).

Additionally, the adverse effects of prolonged maternal exercise during pregnancy on offspring asthma were amplified under high $PM_{2.5–10}$ exposure in the first trimester (interaction $p = 0.023$). High exposures to $PM_{2.5}$, $PM_{2.5–10}$, and PM_{10} during the third trimester further intensified the adverse impact of maternal morning exercise during pregnancy on offspring asthma (interaction *p*-values: 0.005, 0.082, and 0.018). Overall, significant interactions were noted between maternal exercise during pregnancy and low versus high particulate matter exposures on decreased and increased risks of offspring asthma (Figure S18a–d). Conversely, low exposures to these particulate matters across different trimesters and the entire pregnancy period enhanced the protective effects of maternal walking, higher weekly exercise frequency, daytime exercise (particularly afternoon), and stronger preference for sports on offspring wheeze (interaction *p*-values ranging from 0.007 to 0.099). However, high $PM_{2.5}$ and $PM_{2.5–10}$ exposures during pregnancy amplified the adverse effects of longer daily meditation and prolonged exercise duration on offspring wheeze (interaction p-values between 0.013 and 0.083). Overall, significant interactions were noted between maternal exercise during pregnancy and low versus high particulate matter exposures on decreased and increased risks of offspring wheeze (Figure S19a–d), respectively.

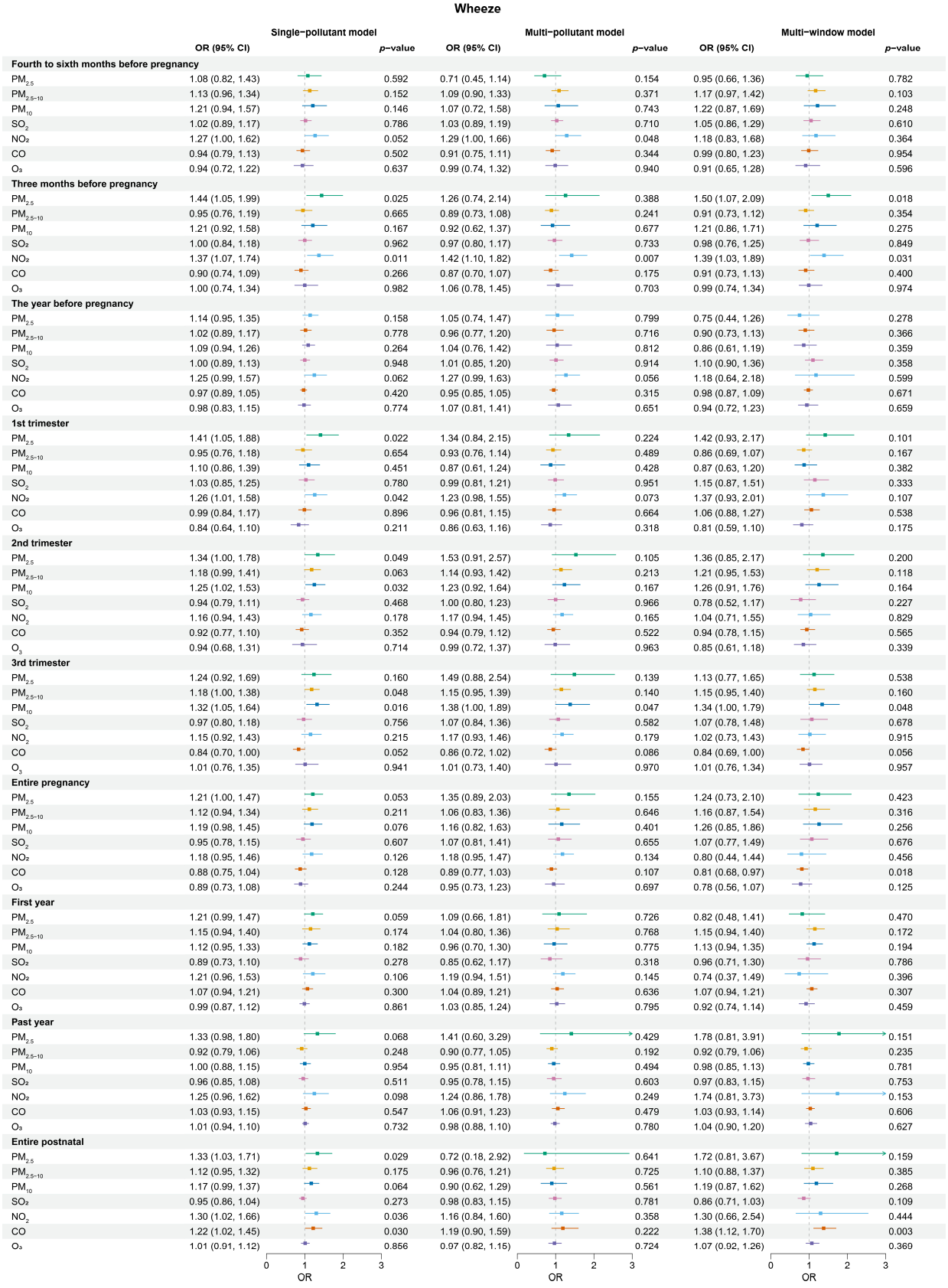
3.11. Interaction Effects of Childhood Exercise and Air Pollution on Childhood Outcomes

The protective effects of longer childhood exercise duration on asthma were more pronounced under conditions of low exposure to $PM_{2.5–10}$ and PM_{10} during the

previous year (interaction *p*-values: 0.030 and 0.070) (Figure 5a) Similarly, the beneficial impact of children engaging in other forms of exercise on wheeze was stronger when $PM_{2.5}$ exposure levels were low during the previous year (interaction p = 0.034) (Figure 5b). Significant interactions were observed between childhood exercise after birth and both low and high particulate matter exposures on the decreased and increased risks of asthma (Figure S20a–c) and wheeze (Figure S21a–c), respectively.



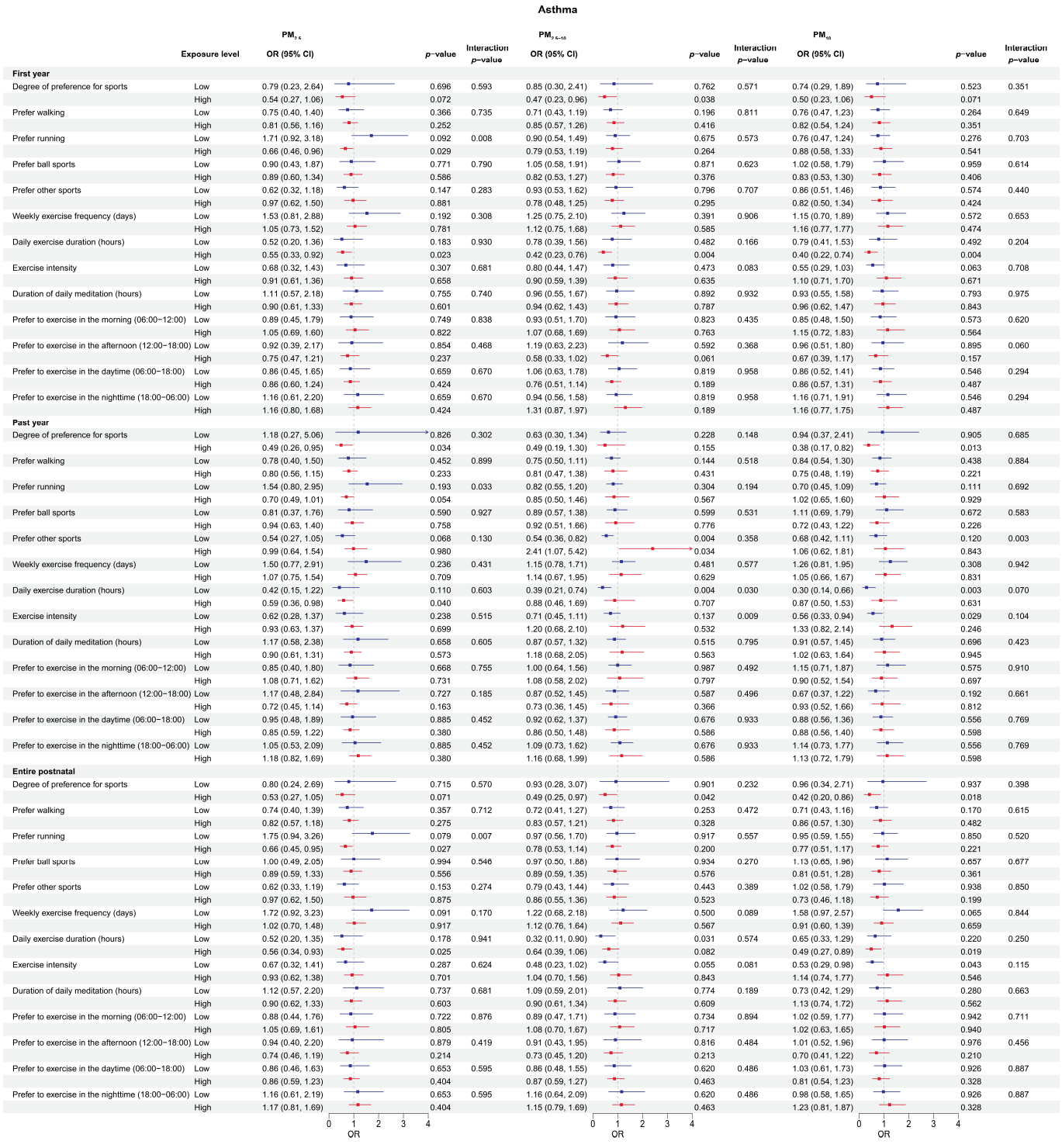
(a)



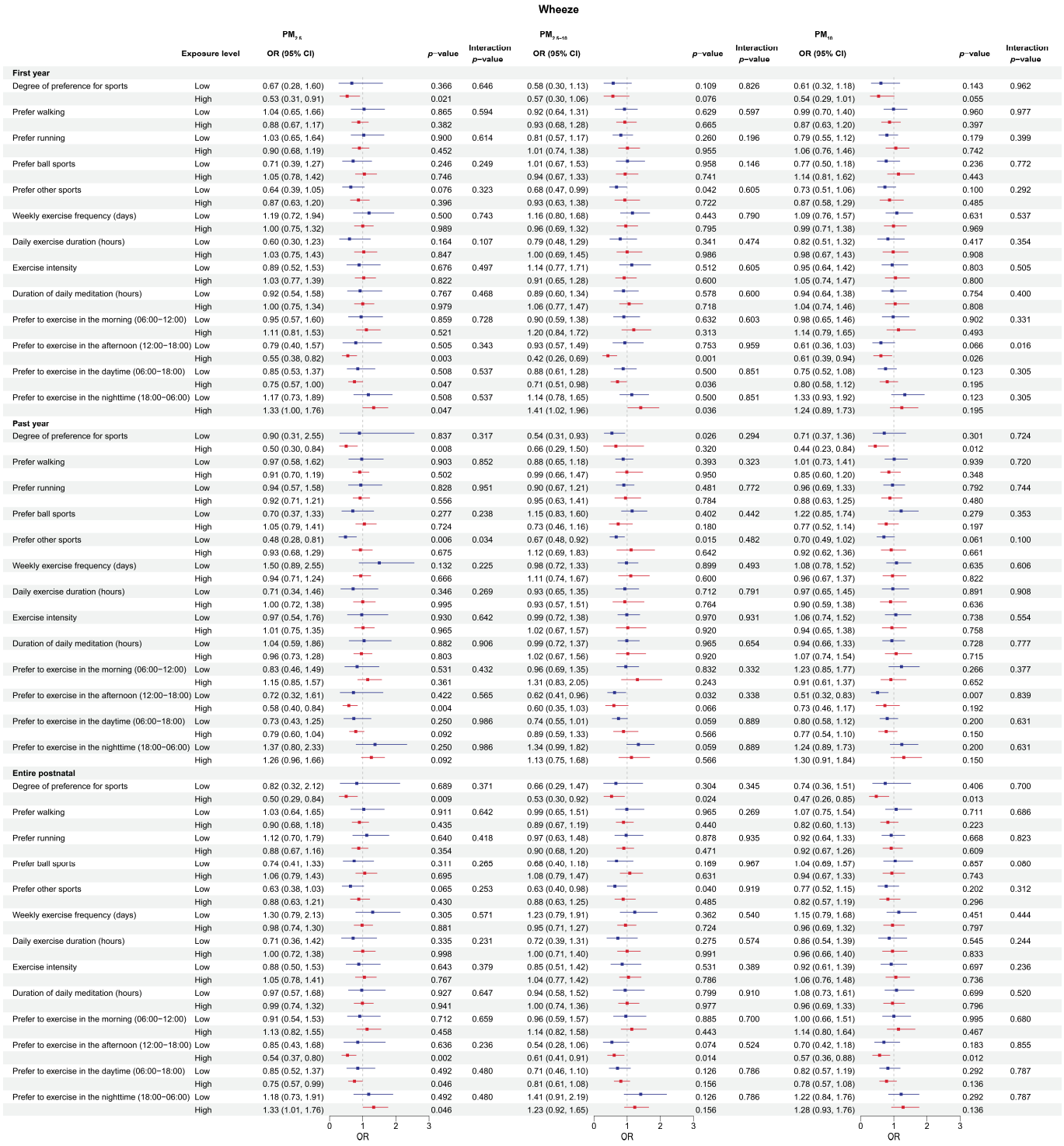
(b)

Figure 4. (**a**) Associations between ambient air pollution exposure during different time windows and physician-diagnosed asthma. (**b**) Associations between ambient air pollution exposure during different time windows and physician-diagnosed wheeze in children. The single-pollutant model shows odds ratios (ORs) with 95% confidence intervals (CIs) adjusted for the studied covariates. The multi-pollution model further adjusts for individual exposure to ambient temperature and concurrent exposures to other pollutants within the same time period, in addition to the studied covariates. The multi-

window model adjusts for the studied covariates, individual exposure to ambient temperature, and exposures to the same pollutant during other time windows. A *p*-value less than 0.05 is considered statistically significant.



(a)



(**b**)

Figure 5. (**a**) Associations between childhood exercise after birth and physician-diagnosed asthma in children, stratified by different exposure levels of particulate matters ($PM_{2.5}$, $PM_{2.5–10}$, PM_{10}) during the postnatal period. Odds ratios (ORs) and 95% confidence intervals (CIs) were adjusted for the studied covariates, along with individual exposure to ambient nitrogen dioxide (NO_2) and temperature within each corresponding time window. Statistical significance is indicated by *p*-values less than 0.05, while interaction effects were considered significant at *p*-values below 0.1. (**b**) Associations between childhood exercise after birth and physician-diagnosed wheeze in children, stratified by varying exposure levels of particulate matters ($PM_{2.5}$, $PM_{2.5–10}$, PM_{10}) during the postnatal period. Odds ratios (ORs) with 95% confidence intervals (CIs) were adjusted for the studied covariates, as well as individual exposure to ambient nitrogen dioxide (NO_2) and temperature within each respective time window. Statistical significance is denoted by *p*-values less than 0.05, and interaction effects are considered statistically significant at *p*-values below 0.1.

4. Discussion

4.1. Key Findings and Interpretation

This retrospective cohort study of father-mother-child triads is the first to systematically investigate the separate and combined effects of parental preconceptional, maternal prenatal, and childhood postnatal exercise habits, ambient air pollutant exposures, and their interactions on asthma and wheeze in children during and after the COVID-19 epidemic. Our findings emphasize several key points. First, paternal exercise habits such as running and ball sports before conception were associated with a reduced risk of wheeze in offspring, although no significant associations were observed with childhood asthma. Second, maternal exercise preferences, particularly walking on normal days and nighttime exercise before pregnancy, were linked to lower asthma risk in offspring, whereas maternal daytime exercise before pregnancy and during pregnancy correlated with increased asthma risk. Maternal afternoon exercise before pregnancy was protective against wheeze, while prolonged daily meditation during pregnancy elevated wheeze risk. Third, childhood exercise preferences, especially longer duration and daytime activity (notably in the afternoon), were associated with decreased risks of both asthma and wheeze, while nighttime exercise increased wheeze risk. Fourth, exposure to particulate matter ($PM_{2.5–10}$ in the first trimester and $PM_{2.5}$ in the second trimester) was consistently associated with increased asthma risk, whereas NO_2 exposure before pregnancy and PM_{10} exposure in the third trimester correlated with wheeze. Lastly, low and high exposures to particulate matter respectively amplified the protective and adverse effects of specific exercise habits among fathers before pregnancy, mothers before and during pregnancy, and children after birth, highlighting a potential "exercise-pollution interaction" at the statistical level. It should be noted that this observed effect modification does not necessarily imply a direct biological causation.

4.2. Maternal and Childhood Exercise as Protective Factors

Our results align with previous studies demonstrating the beneficial impact of maternal exercise on offspring respiratory health. For instance, a Finnish birth cohort study reported that engaging in physical activity three or more times per week during pregnancy significantly reduced asthma risk in children [28]. Similarly, research from Shanghai identified maternal inactivity as a risk factor for respiratory allergies in offspring [29]. Furthermore, a Scandinavian study showed that maternal lack of exercise during early pregnancy was associated with reduced lung function in infants at three months of age [30]. These protective effects may be linked to improved placental function and growth [31,32], as well as modulation of maternal and neonatal immune status [33]. Thus, low-intensity maternal exercise during pregnancy may play an important preventive role against childhood asthma and wheezing.

Consistent with our findings, children's own exercise habits have been shown to influence asthma risk. Prior research suggests that physical inactivity increases the likelihood of new-onset asthma in children and adolescents [10]. Our data further indicate that exercising for more than one hour per session confers a protective effect against asthma. However, this contrasts with some reports highlighting increased asthma prevalence among athletes, particularly those engaged in high-intensity endurance sports [34]. High-intensity exercise may trigger bronchoconstriction and wheezing symptoms [35], underscoring the complexity of the relationship between exercise intensity and respiratory health in children.

4.3. Timing of Exercise and Diurnal Pollution Patterns

Our study also revealed a nuanced relationship between the timing of maternal exercise and childhood asthma risk. Specifically, maternal exercise at night before pregnancy was associated with a reduced risk of asthma in offspring, whereas exercise during the day before pregnancy or during pregnancy appeared to increase this risk. This discrepancy may be attributable to diurnal variations in air pollutant emissions and the behavior of particulate matter. For example, particulate matter concentrations tend to peak during morning hours due to increased human activities [35]. In certain regions of China, $PM_{2.5}$ levels are highest in the morning [36], while in New York City, peak pollution levels typically occur between 7 and 9 a.m. during summer weekdays [37]. Additionally, studies have documented that polycyclic aromatic hydrocarbons (PAHs) in $PM_{2.5}$ increase significantly in early morning hours in Shanghai, China [38,39]. At night, lower temperatures, higher relative humidity, and reduced wind speeds contribute to decreased particulate matter concentrations near roadways [40]. Such nocturnal reductions in pollution could explain the protective effect we observed for maternal exercise during nighttime hours, suggesting that the benefits may be linked to exercising during periods of lower ambient pollution rather than the time of day per se.

4.4. Differential Child Susceptibility by Breathing Height

Interestingly, we observed the opposite trend for children: nighttime exercise was associated with an increased risk of wheezing. One potential explanation for this opposite trend may lie in the difference in breathing zone height between adults and children. Children, whose breathing zones are closer to the ground, are more

 https://doi.org/10.53941/ges.2026.100009

vulnerable to pollutant accumulation near the surface. Studies have shown that fine particulate matter concentrations in strollers can be 44% higher than those measured at adult breathing height [41], and urban infants may experience greater exposure to air pollution compared to walking adults [42]. This height-related differential exposure could lead to generally higher $PM_{2.5}$ levels encountered by children relative to adults [43]. Additionally, other factors not measured in our study, such as the specific type and intensity of children's nighttime activities, or differences in the microenvironment where children versus adults tend to exercise at night, might also contribute to the observed association. These findings highlight that parents and children may face different pollutant exposures during outdoor activities, underscoring the need for further research to clarify the mechanisms and for tailored strategies regarding exercise timing and environment to mitigate respiratory risks for both groups.

4.5. Impacts of Early-Life Air Pollution Exposure on Childhood Asthma

Exposure to coarse particulate matter ($PM_{2.5–10}$) prior to pregnancy was found to significantly increase the risk of childhood asthma, a finding that aligns with our previous research [44]. Additionally, exposure to fine particulate matter ($PM_{2.5}$) during mid-pregnancy was also significantly associated with increased asthma risk in children. Numerous studies have consistently demonstrated strong links between early-life exposure to particulate matter and the development of childhood asthma. For instance, one study reported that higher prenatal $PM_{2.5}$ exposure during mid-pregnancy was specifically associated with asthma development in boys by age six [45]. This sensitive exposure window corresponds to the canalicular stage of fetal lung development, a critical period during which key tissues and respiratory functions are established [45]. Other research further suggests that both prenatal and postnatal exposures to $PM_{2.5}$ elevate the risk of childhood asthma, likely through modulation of the developing immune system [46,47]. Animal studies have illustrated that $PM_{2.5}$ exposure can induce inflammatory responses in the placenta, which may be transmitted from mother to fetus, leading to fetal developmental abnormalities [48]. Similarly, evidence indicates that both prenatal and postnatal $PM_{2.5}$ exposures contribute to increased childhood asthma risk [49].

Our study also identified nitrogen dioxide (NO_2) exposure as a significant contributor to childhood asthma and wheezing, with the critical window for asthma risk occurring during pregnancy and for wheezing mainly before pregnancy. NO_2, a key component of industrial and traffic-related pollution, has been extensively linked to childhood asthma. A global burden of disease study estimated that NO_2 exposure contributed to 1.85 million new cases of childhood asthma worldwide in 2019 [50]. Further supporting this, studies by Lu et al. have demonstrated that prenatal NO_2 exposure increases childhood asthma risk [51]. A meta-analysis confirmed a robust association between prenatal NO_2 exposure and childhood wheezing and asthma, with effects persisting into the postnatal period [52].

In summary, different air pollutants appear to impact children's respiratory health differently depending on the timing of exposure. Prenatal exposure to $PM_{2.5}$ may interfere with fetal lung and immune system development, thereby increasing asthma risk, whereas pre-pregnancy NO_2 exposure is more strongly linked to wheezing risk. These findings underscore the time-sensitive nature of air pollution's impact on child respiratory health and highlight pregnancy as a critical window for intervention, emphasizing the urgent need to improve air quality for pregnant women and their developing fetuses.

4.6. Exercise–Pollution Interactions: Parental Pathways

Our study also indicated that the associations between parental exercise habits and childhood asthma and wheezing appeared to be modified by particulate matter ($PM_{2.5}$, $PM_{2.5–10}$, PM_{10}) exposure. Previous research suggests that paternal exercise interventions can induce notable alterations in offspring phenotypes, with different exercise regimens influencing the development of various organs and tissues in the offspring [53]. These effects are thought to involve epigenetic or physiological changes in sperm [54]. Similar patterns were observed for maternal exercise: engaging in exercise during the afternoon, when combined with high $PM_{2.5}$ exposure prior to pregnancy, was associated with an increased risk of childhood asthma. This may be due to increased pollutant inhalation during exercise, as minute ventilation rises, potentially amplifying adverse effects [55,56].

Interestingly, under conditions of high PM_{10} exposure, maternal walking and participation in ball sports appeared to exhibit protective effects. This might be due to the lower intensity of such activities, which may limit pollutant penetration into the respiratory tract compared with high-intensity exercise. Supporting this, a study demonstrated that even in regions with elevated $PM_{2.5}$ levels, prolonged walking (10.5 h per week) was associated with a reduction in all-cause mortality [57]. Moreover, a study involving 1.2 million participants reported that racquet sports, such as badminton and tennis, were associated with a 47% reduction in all-cause mortality [58].

4.7. Exercise Timing, Intensity, and Susceptibility: Maternal and Child Perspectives

We observed differential susceptibility to the timing and intensity of exercise in relation to childhood asthma and wheezing. A nationwide study across 367 Chinese cities found that outdoor exercise performed in the morning leads to higher inhalation of $PM_{2.5}$ [59], suggesting that maternal exercise during this period may increase pollutant exposure. Air pollutants inhaled during pregnancy can cross the placental barrier, directly affecting fetal development [60]. The perinatal period is particularly critical for the maturation of the fetal lungs and immune system [61,62], and maternal exposure to high levels of air pollution during exercise may impair these developmental processes. For instance, a cohort study in the UK reported that PM_{10} exposure during pregnancy was associated with significantly reduced lung function in children at the age of eight [63]. Interestingly, our findings revealed that maternal walking during pregnancy, even under high particulate matter exposure, was associated with a reduced risk of childhood asthma. This suggests that the type and intensity of exercise performed during pregnancy may exert distinct effects on offspring respiratory outcomes, with low-intensity exercise likely being preferable when pollution levels are high.

Postnatally, we observed that children who engage in running during periods of high $PM_{2.5}$ exposure had a lower risk of developing asthma. This aligns with studies showing that physical activities such as running, swimming, and walking can reduce airway inflammation and improve lung function in asthma patients [64]. A Spanish study further demonstrated that even moderate, intermittent exercise in polluted environments may have positive effects on lung function [65]. Supporting evidence also suggests that exercise performed under high-pollution conditions can yield overall health benefits, including anti-inflammatory effects and improved cardiopulmonary function [22,23]. Similarly, paternal exercise has been linked to benefits for offspring metabolic health, including reduced risks of obesity and diabetes [54,66,67].

Our results also suggest that prolonged maternal sedentary behavior during pregnancy, particularly under high $PM_{2.5}$ exposure, increases the risk of wheezing in children. Previous studies have found that extended sedentary time during pregnancy is associated with a higher risk of offspring obesity [68], while reducing sedentary time and increasing physical activity have been shown to improve respiratory outcomes in children [69]. Moreover, under conditions of low particulate matter exposure, maternal exercise preferences—particularly walking, ball sports, and daytime activities—were strongly associated with a reduced risk of wheezing in children. These benefits may be mediated by the ability of regular, moderate exercise to increase maternal plasma volume, enhance cardiac output, and improve placental function [70]. A comprehensive review has provided substantial evidence supporting the positive effects of prenatal exercise on maternal and fetal health [71].

In addition, during the first year of life, we observed that children who enjoy exercise or who exercise in the afternoon, even when exposed to high concentrations of particulate matter, exhibit a reduced risk of wheezing. This is consistent with systematic reviews reporting that exercise training improves wheezing symptoms and enhances lung function in both children and adults with asthma [72]. Our findings indicate a potential exercise-pollution interaction during early-postnatal period, which may provide a better understand in early prevention and effective reduction of childhood asthma and allergies.

4.8. Integrative Interpretation and Preventive Implications

Interaction analyses further revealed the complex interplay between environmental pollution and parental exercise behaviors, particularly during pregnancy. We found that the interaction between exercise patterns and air pollution exposure significantly influences the risk of childhood asthma and wheezing at different developmental stages. During the first and third perinatal periods, both the type and timing of maternal exercise appeared to modulate the impact of air pollution on respiratory outcomes in children. Pregnancy is a critical window for fetal respiratory system development, and the combined effects of maternal physical activity and environmental pollution may influence respiratory health through multiple biological pathways, including altered fetal lung development, immune system maturation, and maternal cardiopulmonary function.

Collectively, our findings suggest that parental exercise behaviors—especially the type, intensity, and timing of maternal exercise in relation to pollution peaks during pregnancy—along with the level of air pollution exposure, play a pivotal role in shaping childhood respiratory health. Under conditions of high air pollution, moderate, low-intensity maternal exercise may exert protective effects, whereas high-intensity exercise or exercise during times of typically high pollution may increase the risk of asthma and wheezing in offspring.

4.9. Strengths and Limitations

Our study has several notable strengths. First, it was conducted across multiple cities and included a large sample size of father-mother-child groups, enhancing the reliability, generalizability, and statistical power of the findings. Second, this is the first study to systematically examine the comprehensive impacts of paternal, maternal, and childhood exercise habits—together with ambient air pollutant exposures during preconceptional, prenatal, and postnatal periods—and their interactions on childhood asthma and wheeze in children aged 3–6

years. Third, we evaluated exercise behaviors from multiple dimensions, including preference, frequency, intensity, timing, and duration, and, for the first time, identified associations between circadian exercise patterns and childhood asthma and allergic outcomes. Fourth, we incorporated data on seven major ambient air pollutants and applied the inverse distance weighting (IDW) method to estimate individual exposures to pollutants, temperature, and relative humidity (RH) based on family residential addresses, ensuring high spatial accuracy and detailed exposure assessment. Finally, our statistical models were carefully adjusted for a wide range of covariates, including individual, parental, and environmental factors, as well as key meteorological variables, thereby improving the robustness of the analysis.

However, our study also has several limitations. First, due to its retrospective cohort design, causal relationships between exercise habits, air pollutant exposures, and childhood asthma or wheeze cannot be definitively established. Second, physician-diagnosed asthma and wheeze were reported based on parental recall and survey responses, which may have introduced recall bias. We attempted to mitigate this by controlling for the timing of survey completion and conducting rigorous data logic checks. Third, exercise behaviors (e.g., frequency, intensity, duration, and timing) were self-reported rather than objectively measured, which may have led to some degree of misclassification. Fourth, although we collected data on air conditioning temperature settings during winter and summer, we did not directly measure indoor temperature or RH, which may have introduced residual confounding. Nevertheless, because of the high frequency of window opening in these households—indicating good natural ventilation—we assume that indoor and outdoor pollutant concentrations were largely comparable, thereby minimizing potential bias. Last, though it is widely considered that there is a close relationship between exercise and meditation, we still suspect that some participants may confuse the meaning of "meditation", or consider it too widely, which might slightly reduce the reliability of our conclusion about the relation between meditation and offspring's wheeze.

5. Conclusions

This multicenter father-mother-child retrospective study is, to our knowledge, the first to systematically examine the effects of exercise habits—among fathers during the preconceptional period, mothers during preconception and pregnancy, and children after birth—alongside preconceptional, prenatal, and postnatal ambient air pollutant exposures and their interactions on childhood asthma and wheeze during and after the COVID-19 epidemic. Our findings highlight that paternal exercise before conception, maternal exercise both before and during pregnancy, and childhood exercise all play crucial roles in shaping the risk of asthma and wheeze. Parents who engage in regular physical activity, prefer low-intensity activities such as walking, exercise during nighttime, and encourage appropriately timed and moderate-intensity physical activity in early childhood can significantly lower the risk of childhood asthma and allergy. In contrast, high-intensity or daytime exercise may increase risk, particularly in polluted environments.

We also observed that preconceptional and prenatal exposures to particulate matter (PMs) and NO_2 substantially increased the risk of asthma and wheeze. Importantly, we found significant interactions between exercise habits and ambient PM exposure across both parental and childhood periods, supporting a potential "(Pre-) Fetal origins of childhood asthma and wheeze" hypothesis mediated by exercise-pollution interactions. These findings, while requiring further confirmation, highlight the potential importance of cross-generational strategies, integrating both physical activity guidance and air pollution control, for the early prevention and management of childhood asthma and allergy in the COVID-19 epidemic and post-pandemic era.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2512121514416979/Checked-Revised-Supplementary-Materials-449M-clean-version.pdf. Figure S1: Pearson correlation coefficients between individual exposure to outdoor temperature and relative humidity across different time windows. Figure S2a-b: Associations between paternal exercise prior to conception and children's physician-diagnosed asthma and wheeze. The single model presents odds ratios (ORs) and 95% confidence intervals (CIs) adjusted for the studied covariates. Figure S3a-d: Odds ratio (95% CI) of children's physician-diagnosed asthma for paternal exercise during normal days and before pregnancy, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S4a-d: Odds ratio (95% CI) of children's physician-diagnosed wheeze for paternal exercise during normal days and before pregnancy, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S5a-b: Associations between maternal exercise during normal days, the year prior to pregnancy and pregnancy and physician-diagnosed asthma and wheeze in children. Figure S6a-f: Odds ratio (95% CI) of children's physician-diagnosed asthma for maternal exercise during normal days, the year prior to pregnancy and pregnancy, stratified by gender and premature, age., secondhand smoke and antibiotic use. Figure S7a-h: Odds ratio (95% CI) of children's physician-diagnosed wheeze for maternal exercise during normal days, the year prior to pregnancy and in utero, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S8a-d: Odds ratio (95% CI) of children's physician-

diagnosed asthma for childhood exercise after birth, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S9a-d: Odds ratio (95% CI) of children's physician-diagnosed wheeze for childhood exercise after birth, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S10a-d: Odds ratio (95% CI) of children's physician-diagnosed asthma for outdoor air pollution exposure during different time windows, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S11a-d: Odds ratio (95% CI) of children's physician-diagnosed wheeze for outdoor air pollution exposure during different time windows, stratified by gender and premature, age, breastfeeding and parental allergic diseases, secondhand smoke and antibiotic use. Figure S12a-f: Associations between paternal exercise prior to conception and physician-diagnosed asthma and wheeze in children, stratified by different exposure levels of particulate matter ($PM_{2.5}$, $PM_{2.5-10}$, PM_{10}) during the preconceptional period and the same prenatal timeframe. Figure S13a-c: Interaction (OR [95% CI]) of paternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during the 4-6 months, 3 months, and one year before pregnancy on childhood physician-diagnosed asthma. Figure S14a-c: Interaction (OR [95% CI]) of paternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during the 4-6 months, 3 months, and one year before pregnancy on childhood physician-diagnosed wheeze. Figure S15a-l: Associations between maternal exercise prior to conception and physician-diagnosed asthma and wheeze in children, stratified by different exposure levels of particulate matter ($PM_{2.5}$, $PM_{2.5-10}$, PM_{10}) during the preconceptional period and the same prenatal timeframe. Figure S16a-c: Interaction (OR [95% CI]) of maternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5-10}$ and PM_{10}) during the 4-6 months, 3 months and one year before pregnancy on childhood physician-diagnosed asthma. Figure S17a-c: Interaction (OR [95% CI]) of maternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during the 4-6 months, 3 months and one year before pregnancy on childhood physician-diagnosed wheeze. Figure S18a-d: Interaction (OR [95% CI]) of maternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during the first, second and third trimester of pregnancy and entire pregnancy on childhood physician-diagnosed asthma. Figure S19a-d: Interaction (OR [95% CI]) of maternal exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during first, second and third trimester of pregnancy and entire pregnancy on childhood physician-diagnosed wheeze. Figure S20a: Interaction (OR [95% CI]) of childhood exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during first year of life, past year and entire postnatal period on childhood physician-diagnosed asthma. Figure S21a-c: Interaction (OR [95% CI]) of childhood exercise and individual exposure to particulate matters ($PM_{2.5}$, $PM_{2.5–10}$ and PM_{10}) during first year of life, past year and entire postnatal period on childhood physician-diagnosed wheeze. Table S1: Childhood doctor-diagnosed asthma and wheeze, questions and answer options set in the questionnaire. Table S2: Descriptions, questions and answer options for paternal exercise during normal days and before pregnancy. Table S3: Descriptions, questions and answer options for maternal exercise before and during pregnancy. Table S4: Descriptions, questions and answer options for childhood exercise after birth. Table S5: Definitions of time windows for individual exposure to outdoor air pollution and climatic factors. Table S6: Covariates and their corresponding questions and answer options set in the questionnaire. Table S7: Statistics of the number and prevalence of childhood asthma and wheeze in different cities. Table S8: Statistics on paternal exercise habits during normal days and preconceptional period as well as their relationships with childhood doctor-diagnosed asthma and wheeze. Table S9: Statistics on maternal exercise habits during normal days, preconceptional, and prenatal period as well as their relationships with childhood doctor-diagnosed asthma and wheeze. Table S10: Statistics on childhood exercise habits during normal days and preconceptional period as well as their relationships with childhood doctor-diagnosed asthma and wheeze. Table S11: Statistical description of individual exposures to outdoor air pollution, temperature and relative humidity (RH) as well as the differences in exposure level between cases and controls for childhood asthma and wheeze. Table S12: Pearson correlation between individual exposures to outdoor air pollution during different time widows.

Author Contributions

C.L. conducted the study, conceptualized, designed, performed the study, collected the data, analysed the data, supervised the data analysis, draw the figures, drafted the initial manuscript and revised the manuscript. Y.L. and Z.G. collected the data, analysed the data, draw the figures and drafted the manuscript. X.X. collected the data and helped to draw the figures. L.W. collected and analysed the data. W.S. and Z.Q. revised the manuscript. All authors have reviewed and approved the final manuscript.

Funding

This study was supported by the National Natural Science Foundation of China (No. 42277432; 42007391), the Excellent Youth Foundation of Hunan Province (No. 2025JJ20037), and the Natural Science Foundation of Hunan Province (No. 2021JJ30813).

Institutional Review Board Statement

This work has received approval for research from Central South University (CSU) and the proof/certificate of approvals from CSU (CSU-IRB No.: XYGW-2022-91; 21 November 2022) is available upon request.

Informed Consent Statement

Written informed consent was obtained from all the surveyed families, parents or guardians for all individual participants included in the study.

Data Availability Statement

Data and material are available when request to the authors.

Acknowledgments

We appreciate all surveyed family participants for their time and enthusiastic participation. We also sincerely thank the participated teachers and students for their contribution and worked to this study.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Wang, Z.; Li, Y.; Gao, Y.; et al. Global, regional, and national burden of asthma and its attributable risk factors from 1990 to 2019: A systematic analysis for the Global Burden of Disease Study 2019. *Respir. Res.* **2023**, *24*, 169.
2. Momtazmanesh, S. Global burden of chronic respiratory diseases and risk factors, 1990–2019: An update from the Global Burden of Disease Study 2019. *EClinicalMedicine* **2023**, *59*, 101936.
3. Norbäck, D.; Lu, C.; Zhang, Y.; et al. Sources of indoor particulate matter (PM) and outdoor air pollution in China in relation to asthma, wheeze, rhinitis and eczema among pre-school children: Synergistic effects between antibiotics use and PM_{10} and second hand smoke. *Environ. Int.* **2019**, *125*, 252–260.
4. Stern, D.A.; Morgan, W.J.; Halonen, M.; et al. Wheezing and bronchial hyper-responsiveness in early childhood as predictors of newly diagnosed asthma in early adulthood: A longitudinal birth-cohort study. *Lancet* **2008**, *372*, 1058–1064.
5. Ly, N.P.; Gold, D.R.; Weiss, S.T.; et al. Recurrent wheeze in early childhood and asthma among children at risk for atopy. *Pediatrics* **2006**, *117*, e1132–e1138.
6. Guthold, R.; Stevens, G.A.; Riley, L.M.; et al. Global trends in insufficient physical activity among adolescents: A pooled analysis of 298 population-based surveys with 1.6 million participants. Lancet Child Adolesc. *Health* **2020**, *4*, 23–35.
7. Lee, I.M.; Shiroma, E.J.; Lobelo, F.; et al. Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *Lancet* **2012**, *380*, 219–229.
8. Carson, K.V.; Chandratilleke, M.G.; Picot, J.; et al. Physical training for asthma. *Cochrane Database Syst. Rev.* **2013**, *9*, CD001116.
9. Kawahara, J.; Tanaka, S.; Tanaka, C.; et al. Daily inhalation rate and time-activity/location pattern in Japanese preschool children. *Risk Anal.* **2012**, *32*, 1595–1604.
10. Lochte, L.; Nielsen, K.G.; Petersen, P.E.; et al. Childhood asthma and physical activity: A systematic review with meta-analysis and Graphic Appraisal Tool for Epidemiology assessment. *BMC Pediatr.* **2016**, *16*, 50.
11. Mancuso, C.A.; Sayles, W.; Robbins, L.; et al. Barriers and facilitators to healthy physical activity in asthma patients. *J. Asthma* **2006**, *43*, 137–143.
12. Feng, G.; Xia, J.; Wang, X.; et al. Assessing the disease burden of air pollution on children and adolescents in China from 1990 to 2019. *Innov. Med.* **2024**, *2*, 100057.
13. Leon Hsu, H.H.; Mathilda Chiu, Y.H.; Coull, B.A.; et al. Prenatal particulate air pollution and asthma onset in urban children. Identifying sensitive windows and sex differences. *Am. J. Respir. Crit. Care Med.* **2015**, *192*, 1052–1059.
14. Weinmayr, G.; Romeo, E.; De Sario, M.; et al. Short-term effects of PM_{10} and NO_2 on respiratory health among children with asthma or asthma-like symptoms: A systematic review and meta-analysis. *Environ. Health Perspect.* **2010**, *118*, 449–457.
15. Liu, X.; Fu, L.; Yang, X.; et al. Exposure to O_3 during pregnancy and offspring asthma induced by OVA: Sensitive window identification. *Environ. Pollut.* **2021**, *270*, 116297.
16. Carthy, P.; Ó Domhnaill, A.; O'Mahony, M.; et al. Local NO_2 concentrations and asthma among over-50s in Ireland: A microdata analysis. *Int. J. Epidemiol.* **2021**, *49*, 1899–1908.
17. Bowatte, G.; Lodge, C.J.; Knibbs, L.D.; et al. Traffic-related air pollution exposure is associated with allergic sensitization, asthma, and poor lung function in middle age. *J. Allergy Clin. Immunol.* **2017**, *139*, 122–129.
18. Mendola, P.; Wallace, M.; Liu, D.; et al. Air pollution exposure and preeclampsia among US women with and without asthma. *Environ. Res.* **2016**, *148*, 248–255.
19. Bigazzi, A.Y.; Figliozzi, M.A. Review of urban bicyclists' intake and uptake of traffic-related air pollution. *Transp. Rev.* **2014**, *34*, 221–245.
20. Giles, L.V.; Koehle, M.S. The health effects of exercising in air pollution. *Sports Med.* **2014**, *44*, 223–249.
21. McConnell, R.; Berhane, K.; Gilliland, F.; et al. Asthma in exercising children exposed to ozone: A cohort study. *Lancet* **2002**, *359*, 386–391.
22. Andersen, Z.J.; de Nazelle, A.; Mendez, M.A.; et al. A study of the combined effects of physical activity and air pollution on mortality in elderly urban residents: The Danish Diet, Cancer, and Health Cohort. *Environ. Health Perspect.* **2015**, *123*, 557–563.
23. Fisher, J.E.; Loft, S.; Ulrik, C.S.; et al. Physical activity, air pollution, and the risk of asthma and chronic obstructive pulmonary disease. *Am. J. Respir. Crit. Care Med.* **2016**, *194*, 855–865.
24. Lu, C.; Deng, W.; Qiao, Z.; et al. Effects of early-life air pollution exposure on childhood COVID-19 infection and sequelae in China. *J. Hazard. Mater.* **2025**, *491*, 137940.

25. Wang, F.; Wang, L.; Jiang, Y.; et al. Early-life exposure to outdoor temperature and the risk of childhood allergic diseases: A multicentre retrospective cohort study. *Build. Environ.* **2025**, *267*, 112317.
26. Lu, C.; Jing, Y.; Deng, W.; et al. Early-life nutritional additives, household environment, and air pollution in relation to childhood food allergies: A multi-city mother-child study in China. *Environ. Int.* **2025**, *203*, 109774.
27. Lu, C.; Liu, Z.; Yang, W.; et al. Early life exposure to outdoor air pollution and indoor environmental factors on the development of childhood allergy from early symptoms to diseases. *Environ. Res.* **2023**, *216*, 114538.
28. Musakka, E.R.; Ylilauri, M.P.T.; Jalanka, J.; et al. Maternal exercise during pregnancy is associated with reduced risk of asthma in the child: A prospective birth cohort study. *Med* **2024**, *6*, 100514.
29. Chen, Y.; Lyu, J.; Xia, Y.; et al. Effect of maternal sleep, physical activity and screen time during pregnancy on the risk of childhood respiratory allergies: A sex-specific study. *Respir. Res.* **2020**, *21*, 230.
30. Gudmundsdóttir, H.K.; Carlsen, O.C.L.; Bains, K.E.S.; et al. Infant lung function and maternal physical activity in the first half of pregnancy. *ERJ Open Res.* **2022**, *8*, 00172–02022.
31. Clapp, J.F., III; Kim, H.; Burciu, B.; et al. Beginning regular exercise in early pregnancy: Effect on fetoplacental growth. *Am. J. Obstet. Gynecol.* **2000**, *183*, 1484–1488.
32. Chae, S.A.; Son, J.S.; Du, M. Prenatal exercise in fetal development: A placental perspective. *FEBS J.* **2022**, *289*, 3058–3071.
33. Acosta-Manzano, P.; Coll-Risco, I.; Van Poppel, M.N.; et al. Influence of a concurrent exercise training intervention during pregnancy on maternal and arterial and venous cord serum cytokines: The GESTAFIT project. *J. Clin. Med.* **2019**, *8*, 1862.
34. Del Giacco, S.R.; Firinu, D.; Bjermer, L.; et al. Exercise and asthma: An overview. *Eur. Clin. Respir. J.* **2015**, *2*, 27984.
35. Ownby, D.R.; Peterson, E.L.; Nelson, D.; et al. The relationship of physical activity and percentage of body fat to the risk of asthma in 8 to 10 year-old children. *J. Asthma* **2007**, *44*, 885–889.
36. Guo, J.; Xia, F.; Zhang, Y.; et al. Impact of diurnal variability and meteorological factors on the $PM_{2.5}$-AOD relationship: Implications for $PM_{2.5}$ remote sensing. *Environ. Pollut.* **2017**, *221*, 94–104.
37. DeGaetano, A.T.; Doherty, O.M. Temporal, spatial and meteorological variations in hourly $PM_{2.5}$ concentration extremes in New York City. *Atmos. Environ.* **2004**, *38*, 1547–1558.
38. Liu, J.; Wang, S.; Zhu, K.; et al. Spatial patterns of the diurnal variations of $PM_{2.5}$ and their influencing factors across China. *Atmos. Environ.* **2024**, *318*, 120215.
39. Gu, Z.; Feng, J.; Han, W.; et al. Diurnal variations of polycyclic aromatic hydrocarbons associated with $PM_{2.5}$ in Shanghai, China. *J. Environ. Sci.* **2010**, *22*, 389–396.
40. Zhu, Y.; Kuhn, T.; Mayo, P.; et al. Comparison of daytime and nighttime concentration profiles and size distributions of ultrafine particles near a major highway. *Environ. Sci. Technol.* **2006**, *40*, 2531–2536.
41. Sharma, A.; Kumar, P. Quantification of air pollution exposure to in-pram babies and mitigation strategies. *Environ. Int.* **2020**, *139*, 105671.
42. Garcia-Algar, O.; Canchucaja, L.; D'Orazzio, V.; et al. Different exposure of infants and adults to ultrafine particles in the urban area of Barcelona. *Environ. Monit. Assess.* **2015**, *187*, 4196.
43. Harr, L.; Sinsel, T.; Simon, H.; et al. $PM_{2.5}$ exposure differences between children and adults. *Urban Clim.* **2022**, *44*, 101198.
44. Lu, C.; Wang, L.; Liao, H.; et al. Impacts of intrauterine and postnatal exposure to air pollution on preschool children's asthma: A key role in cumulative exposure. *Build. Environ.* **2023**, *245*, 110874.
45. Kajekar, R. Environmental factors and developmental outcomes in the lung. *Pharmacol. Ther.* **2007**, *114*, 129–145.
46. Jung, C.R.; Chen, W.T.; Tang, Y.H.; et al. Fine particulate matter exposure during pregnancy and infancy and incident asthma. *J. Allergy Clin. Immunol.* **2019**, *143*, 2254–2262.
47. Pedersen, C.E.; Eliasen, A.U.; Ketzel, M.; et al. Prenatal exposure to ambient air pollution is associated with early life immune perturbations. *J. Allergy Clin. Immunol.* **2023**, *151*, 212–221.
48. Yue, H.; Ji, X.; Li, G.; et al. Maternal exposure to $PM_{2.5}$ affects fetal lung development at sensitive windows. *Environ. Sci. Technol.* **2019**, *54*, 316–324.
49. Yang, M.; Chu, C.; Bloom, M.S.; et al. Is smaller worse? New insights about associations of PM(1) and respiratory health in children and adolescents. *Environ. Int.* **2018**, *120*, 516–524.
50. Anenberg, S.C.; Mohegh, A.; Goldberg, D.L.; et al. Long-term trends in urban NO_2 concentrations and associated paediatric asthma incidence: Estimates from global datasets. *Lancet Planet. Health* **2022**, *6*, e49–e58.
51. Deng, Q.; Lu, C.; Norbäck, D.; et al. Early life exposure to ambient air pollution and childhood asthma in China. *Environ. Res.* **2015**, *143*, 83–92.
52. Hehua, Z.; Qing, C.; Shanyan, G.; et al. The impact of prenatal exposure to air pollution on childhood wheezing and asthma: A systematic review. *Environ. Res.* **2017**, *159*, 519–530.
53. Vieira de Sousa Neto, I.; Fontes, W.; Prestes, J.; et al. Impact of paternal exercise on physiological systems in the offspring. *Acta Physiol.* **2021**, *231*, e13620.
54. Kusuyama, J.; Alves-Wagner, A.B.; Makarewicz, N.S.; et al. Effects of maternal and paternal exercise on offspring metabolism. *Nat. Metab.* **2020**, *2*, 858–872.
55. Marmett, B.; Pires Dorneles, G.; Böek Carvalho, R.; et al. Air pollution concentration and period of the day modulates

inhalation of $PM_{2.5}$ during moderate- and high-intensity interval exercise. *Environ. Res.* **2021**, *194*, 110528.
56. Daigle, C.C.; Chalupa, D.C.; Gibb, F.R.; et al. Ultrafine particle deposition in humans during rest and exercise. *Inhal. Toxicol.* **2003**, *15*, 539–552.
57. Tainio, M.; de Nazelle, A.J.; Götschi, T.; et al. Can air pollution negate the health benefits of cycling and walking? *Prev. Med.* **2016**, *87*, 233–236.
58. Chekroud, S.R.; Gueorguieva, R.; Zheutlin, A.B.; et al. Association between physical exercise and mental health in 1·2 million individuals in the USA between 2011 and 2015: A cross-sectional study. *Lancet Psychiat.* **2018**, *5*, 739–746.
59. Ni, X.F.; Peng, S.C.; Wang, J.Z. Is morning or evening better for outdoor exercise? An evaluation based on nationwide $PM_{2.5}$ data in China. *Aerosol Air Qual. Res.* **2019**, *19*, 2093–2099.
60. Bové, H.; Bongaerts, E.; Slenders, E.; et al. Ambient black carbon particles reach the fetal side of human placenta. *Nat. Commun.* **2019**, *10*, 3866.
61. Bhattacharya, S.; Mariani, T.J. Systems biology approaches to identify developmental bases for lung diseases. *Pediatr. Res.* **2013**, *73*, 514–522.
62. Donald, K.; Finlay, B.B. Early-life interactions between the microbiota and immune system: Impact on immune system development and atopic disease. *Nat. Rev. Immunol.* **2023**, *23*, 735–748.
63. Cai, Y.; Hansell, A.L.; Granell, R.; et al. Prenatal, early-life, and childhood exposure to air pollution and lung function: The ALSPAC cohort. *Am. J. Respir. Crit. Care Med.* **2020**, *202*, 112–123.
64. Pakhale, S.; Luks, V.; Burkett, A.; et al. Effect of physical training on airway inflammation in bronchial asthma: A systematic review. *BMC Pulm. Med.* **2013**, *13*, 38.
65. Kubesch, N.J.; de Nazelle, A.; Westerdahl, D.; et al. Respiratory and inflammatory responses to short-term exposure to traffic-related air pollution with and without moderate physical activity. *Occup. Environ. Med.* **2015**, *72*, 284–293.
66. Stanford, K.I.; Rasmussen, M.; Baer, L.A.; et al. Paternal exercise improves glucose metabolism in adult offspring. *Diabetes* **2018**, *67*, 2530–2540.
67. McPherson, N.O.; Owens, J.A.; Fullston, T.; et al. Preconception diet or exercise intervention in obese fathers normalizes sperm microRNA profile and metabolic syndrome in female offspring. *Am. J. Physiol. Endocrinol. Metab.* **2015**, *308*, E805–E821.
68. Dieberger, A.M.; Obermayer-Pietsch, B.; Harreiter, J.; et al. Physical activity and sedentary time across pregnancy and associations with neonatal weight, adiposity and cord blood parameters: A secondary analysis of the DALI study. *Int. J. Obes.* **2023**, *47*, 873–881.
69. Ferrante, G.; Mollicone, D.; Cazzato, S.; et al. COVID-19 pandemic and reduced physical activity: Is there an impact on healthy and asthmatic children? *Front. Pediatr.* **2021**, *9*, 695703.
70. Clapp, J.F. III. The effects of maternal exercise on fetal oxygenation and feto-placental growth. *Eur. J. Obstet. Gynecol. Reprod. Biol.* **2003**, *110*, S80–S85.
71. Prather, H.; Spitznagle, T.; Hunt, D. Benefits of exercise during pregnancy. *PM&R* **2012**, *4*, 845–850.
72. Eichenberger, P.A.; Diener, S.N.; Kofmehl, R.; et al. Effects of exercise training on airway hyperreactivity in asthma: A systematic review and meta-analysis. *Sports Med.* **2013**, *43*, 1157–1170.