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THE IMPACT OF INDOOR $PM_{2.5}$ AND PM_{10} CONCENTRATIONS ON ALLERGY AND ASTHMA IN THE POLISH MOTHER AND CHILD COHORT STUDY (REPRO_PL)

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Highlights
- Twenty-four-hour indoor particulate matter 2.5 ($PM_{2.5}$) and PM_{10} exposure was directly measured.
- Comprehensive assessment included spirometry, fractional exhaled nitric oxide (FeNO) and skin prick testing.
- Atopy was strongly associated with asthma and allergic rhinitis.
- Indoor PM_{10} showed a positive but non-significant association with asthma.

Abstract
Objectives: Particulate matter (PM) is an important component of air pollution and may contribute to the development or exacerbation of allergic diseases. The purpose of this study was to evaluate the associations between 24-hour indoor PM concentrations and the prevalence of asthma, allergic rhinitis/allergic conjunctivitis, and atopic dermatitis among adolescents participating in the Polish Mother and Child Cohort Study (REPRO_PL). **Material and Methods:** Indoor $PM_{2.5}$ and PM_{10} concentrations were measured over a 24-hour period using portable air-sampling pumps. Information on adolescent health was obtained from questionnaires and medical records. Additional assessments included spirometry, fractional exhaled nitric oxide (FeNO) measurement, and skin prick testing. Unadjusted comparisons and multivariable logistic regression analyses were performed for 172 participants with complete data on the analyzed outcome and exposure variables. **Results:** Particulate matter 10 showed a positive but statistically non-significant association with asthma (OR = 2.22, 95% CI: 0.88–5.57, p = 0.09). No statistically significant associations were observed between indoor $PM_{2.5}$ or PM_{10} concentrations and allergic rhinitis/allergic conjunctivitis or atopic dermatitis. **Conclusions:** Further studies involving larger populations and repeated or longer-term air measurements are needed to clarify the relationship between indoor particulate matter exposure and allergic diseases. Int J Occup Med Environ Health. 2026;39(5)

Key words:
adolescent, air pollution, particulate matter, asthma, allergic diseases, REPRO_PL

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INTRODUCTION

Air pollution remains a major environmental health concern and contributes substantially to the global burden of the lungs, heart and brain diseases [1–3]. Reducing ambient air pollution to the levels recommended by the WHO could prevent premature deaths and reduce the associated healthcare burden [4,5].

Particulate matter (PM), including $PM_{2.5}$ and PM_{10}, originates from both natural sources (e.g., wildfires, sea spray) and human activities (e.g., industrial processes, road traffic) [6]. As people spend a substantial proportion of their time indoors, the indoor environment may contribute considerably to their overall exposure to PM. Indoor $PM_{2.5}$ and PM_{10} concentrations may be affected by outdoor air quality, heating method and heating season, and emissions from cooking and tobacco smoke [7,8].

Young people may be particularly vulnerable to PM exposure due to ongoing lung development and behavioral factors that may increase exposure to air pollutants [9,10]. Exposure to air pollution may promote oxidative stress, airway inflammation, epithelial barrier dysfunction, and immune dysregulation, contributing to respiratory and allergic diseases [6,11].

Previous studies, which have largely focused on ambient or long-term particulate matter exposure, have associated $PM_{2.5}$ exposure with reduced lung function and higher fractional exhaled nitric oxide (FeNO) levels in children [12]. Exposure to both $PM_{2.5}$ and PM_{10} has also been associated with an increased risk of asthma and wheezing [13]. However, evidence concerning other allergic outcomes, including allergic rhinitis and atopic dermatitis, remains inconsistent [14].

The aim of this study was to evaluate the associations between measured indoor PM concentrations ($PM_{2.5}$ and PM_{10}) in the home environment and the prevalence of asthma, allergic rhinitis/allergic conjunctivitis, and atopic dermatitis among adolescents participating in the Polish Mother and Child Cohort Study (REPRO_PL).

MATERIAL AND METHODS

Study population and study design

The REPRO_PL is a multicenter prospective birth cohort established in Poland in 2007. The cohort was designed to evaluate the effects of prenatal and postnatal environmental exposures and lifestyle factors on child health and development. A detailed description of the study design and methodology has been published elsewhere [15–18].

Women were recruited during the first trimester of a singleton pregnancy conceived without the use of assisted reproductive technologies and without major pregnancy complications. They were followed throughout pregnancy (phase I). Their children were subsequently assessed at 1 year and 2 years of age (phase II), at 7–9 years of age (phase III), and during adolescence at 12–18 years of age (phase IV).

The present analysis included 181 adolescents who participated in phase IV of the REPRO_PL cohort study. According to the study protocol, the assessment comprised the following elements: collection of questionnaire data, 24-hour $PM_{2.5}$ and PM_{10} exposure measurement, spirometry, skin prick testing, and clinical examination by an allergist.

The study protocol was approved by the Ethical Committee of the Nofer Institute of Occupational Medicine, Łódź, Poland (decision No. 3/2021), and by the Ethical Committee of the Medical University of Lodz, Łódź, Poland (decision No. RNN/258/23/KE).

Written informed consent was obtained from the parents or legal guardians of all participants. Participants <16 years provided assent, whereas participants aged ≥16 years additionally provided their own written informed consent before participation.

Indoor $PM_{2.5}$ and PM_{10} exposure assessment

Air samples to assess indoor air pollution were collected using GilAir 5 personal air sampling pumps (Sensidyne, St. Petersburg, FL, USA) placed in backpacks carried by teenagers during a 24-hour sampling period in

their home environment, as described elsewhere [19]. The 24-hour PM measurements were conducted in December 2022 – January 2026. Across the study period, measurements were performed in all calendar months. For the purposes of the analyses, measurements conducted from October through April were classified as occurring during the heating season. The inlet ports of sampling pumps were connected to sampling heads with plastic tubing. Glass fiber filters were placed inside the sampling heads. The sampler inlets were located outside the backpack, within the teenager's breathing zone. The collected dust samples were analyzed at the Aerosol Laboratory of the Nofer Institute of Occupational Medicine. Filters were placed in individually labeled containers and weighed before and after sampling to determine dust concentration, calculated as the mass of dust retained on the filter divided by the volume of air flowing through the filter. Before weighing, clean filters were conditioned in a silica gel desiccator for at least 20 h. Weighing was performed using a Sartorius R 180 D analytical balance (Sartorius GmbH, Göttingen, Germany) (resolution of 0.01 mg) with a calibration certificate; the balance was checked before each weighing using a calibration weight certified by the Central Office of Measures (Główny Urząd Miar), Warsaw, Poland.

Outcome variables

Information on the children's health was obtained from questionnaires completed by their parents or legal guardians and supplemented with data from medical records. Clinical examination by an allergist was also performed.

Questions concerning allergic diseases diagnosis were developed by an allergologist based on the International Study of Asthma and Allergies in Childhood (ISAAC) methodology [20]. Asthma was diagnosed according to the Global Initiative for Asthma (GINA) guidelines [21]. A physician-confirmed diagnosis was required to classify a participant as having allergic rhinitis/allergic conjunctivitis or/and atopic dermatitis or/and asthma. Lung function was assessed by spirometry performed by trained personnel in accordance with the recommendations of the American Thoracic Society (ATS) and the European Respiratory Society (ERS), and spirometric indices were additionally expressed as Global Lung Function Initiative (GLI) z-scores [22].

Nitric oxide was measured in accordance with ATS/ERS recommendations [23]. Allergic sensitization was assessed by skin prick testing performed in accordance with the recommendations of the European Academy of Allergy and Clinical Immunology [24]. The test panel included the most common inhalant allergens, as described previously [19].

Variables included in the multivariable models

Variables for the multivariable logistic regression models were selected based on the results of univariable analyses, available literature, clinical relevance, and their availability in the REPRO_PL dataset. Separate models were fitted for asthma, atopic dermatitis, and allergic rhinitis/allergic conjunctivitis.

All models included the child's sex and age, measured $PM_{2.5}$ and PM_{10} concentrations, atopy, season of assessment (heating season: October–April; non-heating season: May–September), and parental history of atopy or asthma. Outcome-specific covariates included coexisting allergic diseases, selected spirometric parameters, FeNO, household smoking, and dampness in the home, depending on the outcome analyzed.

Data analysis

Continuous variables were summarized as medians and interquartile ranges (IQRs), whereas categorical variables were presented as numbers and percentages. Descriptive analyses were performed for all 181 participants included in the study cohort. Unadjusted comparisons and multivariable logistic regression analyses were performed in 172 participants with complete data on

the analyzed outcomes and exposure variables. The outcomes were dichotomous and included asthma, allergic rhinitis/allergic conjunctivitis, and atopic dermatitis at 12–18 years of age.

In the unadjusted analyses, participant characteristics were compared according to the presence or absence of each allergic outcome. Categorical variables were compared using appropriate tests for categorical data, i.e., the χ^2 test of independence or Fisher's exact test, whereas continuous variables were compared using the Mann-Whitney U test.

The main analyses were based on multivariable logistic regression models fitted separately for asthma, allergic rhinitis/allergic conjunctivitis, and atopic dermatitis. The associations between measured $PM_{2.5}$ and PM_{10} concentrations and each allergic outcome were assessed after adjustment for selected demographic, clinical, familial, respiratory, allergic sensitization, seasonal, and home-environmental covariates, depending on the outcome analyzed.

Results from the multivariable logistic regression models are presented as odds ratios (ORs) with 95% confidence intervals (95% CIs) and p-values. All statistical tests were 2-sided, and statistical significance was set at $p < 0.05$. The statistical analyses were performed using Stata, release 14.2 (StataCorp LLC, College Station, TX, USA).

RESULTS

Characteristics of the study cohort

The characteristics of the study cohort are presented in Table 1. The descriptive analysis included 181 participants, with a median age of 14.7 years; 94 participants (51.9%) were females. Measurements were performed during the heating season (October–April) in 110 participants (60.8%). The monthly distribution of measurements pooled across all study years was as follows: January – 14.9%, February – 9.4%, March – 9.4%, April – 9.4%, May – 6.6%, June – 9.4%, July – 6.6%, August – 8.3%, September – 8.3%, October – 4.4%, November – 5.5%, and December – 7.7%. The median $PM_{2.5}$ and PM_{10} concentrations were 6.9 μg/m³ and 9.3 μg/m³, respectively.

The prevalence of atopic dermatitis, allergic rhinitis/allergic conjunctivitis, and asthma at 12–18 years of age was 26.7%, 15.1%, and 7.6%, respectively. Atopy, as assessed by skin prick testing, was observed in 78 participants (44.8%). The most common sensitizations were to grass pollen, birch pollen, *Dermatophagoides pteronyssinus*, and *Dermatophagoides farinae*. Parental atopy or asthma was reported for 51 participants (29.7%), and dampness in the home was reported for 27 participants (15.7%) (Table 1).

Associations of indoor $PM_{2.5}$ and PM_{10} concentrations with allergy and asthma

Comparisons of PM concentrations according to the presence of asthma, allergic rhinitis/allergic conjunctivitis, and atopic dermatitis are presented in Table 2.

Multivariable logistic regression models were fitted separately for asthma, atopic dermatitis, and allergic rhinitis/allergic conjunctivitis (Table 3).

In the asthma model, PM_{10} showed a positive but statistically non-significant association (OR = 2.22, 95% CI: 0.88–5.57, $p = 0.09$), whereas $PM_{2.5}$ was not significantly associated with asthma (OR = 1.68, 95% CI: 0.88–3.20, $p = 0.1$). Asthma was significantly associated with atopy (OR = 7.56, 95% CI: 2.32–24.66, $p < 0.001$), allergic rhinitis/allergic conjunctivitis (OR = 6.46, 95% CI: 1.50–27.84, $p = 0.01$), lower forced expiratory volume in 1 s (FEV_1)/forced vital capacity (FVC) (OR = 0.87, 95% CI: 0.81–0.93, $p < 0.001$), and higher FeNO levels (OR = 1.02, 95% CI: 1.01–1.03, $p = 0.006$) (Table 3).

In the atopic dermatitis model, neither $PM_{2.5}$ (OR = 1.22, 95% CI: 0.78–1.91, $p = 0.4$) nor PM_{10} (OR = 0.87, 95% CI: 0.55–1.35, $p = 0.5$) was significantly associated with the outcome. Significant associations were observed with allergic rhinitis/allergic conjunctivitis (OR = 6.87, 95% CI: 3.31–14.26, $p < 0.001$) and dampness in the home (OR = 2.91, 95% CI: 1.47–5.75, $p = 0.002$) (Table 3).

Table 1. Baseline characteristics of adolescents participating in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026

Variable	Participants (N = 181) [n (%)]	Me (IQR)
Environmental exposure		
PM concentration in the air [µg/m^3]		
$PM_{2.5}$		6.9 (2.3–13.9)
PM_{10}		9.3 (4.6–18.5)
measurements during the heating season (October–April)	110 (60.77)	
household members smoke	45 (26.16)	
exposure to tobacco smoke during a working day		
never	165 (95.93)	
≥1 h	7 (4.07)	
exposure to tobacco smoke on weekends		
never	161 (93.30)	
≥1 h	11 (6.40)	
dampness at domicile	27 (15.70)	
pets at home	116 (67.44)	
Demographic and socioeconomic characteristics		
children		
sex (female)	94 (51.93)	
age [years]		14.73 (13.05–15.39)
BMI [kg/m^2]		20.79 (18.63–23.38)
body fat mass [kg]		11.20 (7.40–16.20)
household status		
living together with both parents	141 (81.98)	
living with a single parent	31 (18.02)	
maternal age at birth [years]		29.25 (26.50–33.00)
mother's education time		
≤12 years	42 (24.00)	
>12 years	133 (76.00)	
mother's level of education		
secondary or lower	44 (25.14)	
higher	131 (74.86)	
socio-economic status		
very poor/poor	0 (0.00)	
good	124 (72.09)	
very good	48 (27.91)	
place of residence		
urban area	141 (80.57)	
rural area	34 (19.43)	
Perinatal and early-life characteristics		
gestational age [weeks]		39 (38–40)
birth weight [g]		3350 (3050–3650)
maternal pre-pregnancy BMI [kg/m^2]		21.75 (19.88–24.34)
breastfeeding duration [months]		7 (4–9)
Clinical characteristics		
atopic dermatitis at 12–18 years	46 (26.74)	
allergic rhinitis/conjunctivitis	26 (15.12)	
asthma	13 (7.56)	
atopy in skin prick test	78 (44.83)	
parental atopy or asthma	51 (29.65)	
Respiratory assessment		
spirometry		
FEV_1		
l		3.42 (2.96–3.96)
% pred.		107 (99–118)
z-score		0.16 (−0.48–0.91)
FVC		
l		3.83 (3.40–4.54)
% pred.		105 (95–113)
z-score		0.08 (−0.57–0.73)
FEV_1/FVC		
% pred.		105 (99–111)
z-score		0.28 (−0.64–0.99)
FeNO [ppb]		45.90 (37.60–58.10)
Skin prick test	78 (48.45)	
grass pollen	49 (32.89)	

Table 1. Baseline characteristics of adolescents participating in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026 – cont.

Variable	Participants (N = 181) [n (%)]	Me (IQR)
Skin prick test – cont.		
Dermatophagoides farinae	33 (20.89)	
Dermatophagoides pteronyssinus	37 (23.42)	
cockroach	8 (5.56)	
hazel	23 (21.30)	
birch	39 (25.00)	
mugwort	12 (7.95)	
Cladosporium	8 (5.76)	
Alternaria	11 (15.28)	
dog	9 (11.84)	
cat	25 (16.03)	

BMI – body mass index; FeNO – fractional exhaled nitric oxide; FEV_1 – forced expiratory volume in 1 second; FVC – forced vital capacity; IQR – interquartile range; PM – particulate matter; pred. – predicted; SPT – skin prick test.

In the allergic rhinitis/allergic conjunctivitis model, neither $PM_{2.5}$ (OR = 1.13, 95% CI: 0.45–2.85, p = 0.8) nor PM_{10} (OR = 1.45, 95% CI: 0.55–3.83, p = 0.5) was significantly associated with the outcome. Allergic rhinitis/allergic conjunctivitis was significantly associated with atopy at 12–18 years (OR = 3.60, 95% CI: 1.14–11.32, p = 0.03), asthma (OR = 7.94, 95% CI: 2.40–26.25, p < 0.001), atopic dermatitis (OR = 24.80, 95% CI: 7.77–79.15, p < 0.001), and parental atopy or asthma (OR = 2.97, 95% CI: 1.05–8.38, p = 0.04). Assessment during the heating season (OR = 0.20, 95% CI: 0.06–0.63, p = 0.007) and household smoking (OR = 0.04, 95% CI: 0.01–0.20, p < 0.001) were inversely associated with allergic rhinitis/allergic conjunctivitis in this model (Table 3).

DISCUSSION

In the present study, PM_{10} showed a positive but statistically non-significant association with asthma, whereas $PM_{2.5}$ was not significantly associated with asthma. No statistically significant associations were observed between indoor $PM_{2.5}$ or PM_{10} concentrations and allergic rhinitis/allergic conjunctivitis or atopic dermatitis among adolescents from the REPRO_PL cohort. The lack of a statistically significant association between particulate matter exposure and asthma is consistent with some previous epidemiological findings. In the European Study of Cohorts for Air Pollution Effects (ESCAPE), long-term exposure to $PM_{2.5}$ or PM_{10} was not significantly associated with the prevalence of childhood asthma [25]. A recent systematic review and meta-analysis reported significant positive associations of both $PM_{2.5}$ and PM_{10} exposure with asthma and wheezing in children and adolescents, although substantial heterogeneity was observed across studies [13]. A regional Polish study by Góra et al. [26] reported a higher occurrence of asthma among pupils attending schools in industrial zones. Another Polish study reported positive correlations between PM_{10} concentrations and the incidence of food and skin allergies [27]. Studies using nationwide Polish data from 2018–2024 reported decreases in selected air pollutant concentrations and in the incidence of asthma, food allergies, and skin allergies among children and adolescents [28,29].

In 2021, WHO updated its global air quality guidelines, introducing substantially stricter recommendations for exposure to PM [4]. The revised guidelines set annual average concentration limits of 5 μg/m³ for $PM_{2.5}$ and 15 μg/m³ for PM_{10} in both indoor and outdoor environments. In addition, the recommended 24-hour exposure limits were established at 15 μg/m³ for $PM_{2.5}$ and 45 μg/m³ for PM_{10}. These more stringent standards are based on robust epidemiological findings indicating that fine particulate matter can negatively affect human health even at relatively low concentrations. In the authors' study, the median $PM_{2.5}$ and PM_{10} 24-hour concentrations were 6.9 μg/m³ and 9.3 μg/m³, respectively.

Table 2. Comparison of environmental, demographic and socioeconomic, perinatal and early-life, clinical, respiratory, and skin prick test sensitization characteristics among study participants according to the presence of asthma, allergic rhinitis/allergic conjunctivitis (AR/AC), and atopic dermatitis, in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026

Variable	Participants (N = 172)																	
	asthma						AR/AC						atopic dermatitis					
	with asthma (N = 13)			without asthma (N = 159)			with AR/AC (N= 26)			without AR/AC (N= 146)			with atopic dermatitis (N= 46)			without atopic dermatitis (N= 126)		
	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p
Environmental exposure																		
PM concentration in the air [µg/m^3]																		
$PM_{2.5}$		9.3 (6.9–20.8)	0.2206		6.9 (2.3–13.9)	0.2206		8.1 (2.9–15.6)	0.9463		6.9 (2.3–13.9)	0.9463		9.3 (2.3–17.4)	0.4552		6.9 (2.3–13.9)	0.4552
PM_{10}		13.9 (4.6–25.5)	0.1605		9.3 (4.6–18.5)	0.1605		9.3 (4.6–17.9)	0.8552		9.3 (4.6–18.5)	0.8552		6.9 (2.3–18.5)	0.3731		9.3 (4.6–18.5)	0.3731
household members smoke	4 (30.77)		0.7449	41 (25.79)		0.7449	3 (11.54)		0.0889	42 (28.77)		0.0889	11 (23.91)		0.6850	34 (26.98)		0.6850
exposure to tobacco smoke during a working day																		
never	13 (100.00)		0.5710	152 (95.60)		0.5710	26 (100.00)		0.5964	139 (95.21)		0.5964	45 (97.83)		0.6763	120 (95.24)		0.6763
min. 1 h	0 (0.00)			7 (4.40)			0 (0.00)			7 (4.79)			1 (2.17)			6 (4.76)		
exposure to tobacco smoke on weekends																		
never	12 (92.31)		0.5901	149 (93.71)		0.5901	25 (96.15)		>0.9999	136 (93.15)		>0.9999	44 (95.65)		0.7294	117 (92.86)		0.7294
min. 1 h	1 (7.69)			10 (6.29)			1 (3.85)			10 (6.85)			2 (4.35)			9 (7.14)		
dampness at domicile	1 (7.69)		0.6947	26 (16.35)		0.6947	7 (26.92)		0.0877	20 (13.70)		0.0877	13 (28.26)		0.0062	14 (11.11)		0.0062
pets at home	7 (53.85)		0.2887	109 (68.55)		0.2887	17 (65.38)		0.8080	99 (67.81)		0.8080	33 (71.74)		0.4674	83 (65.87)		0.4674

Table 2. Comparison of environmental, demographic and socioeconomic, perinatal and early-life, clinical, respiratory, and skin prick test sensitization characteristics among study participants according to the presence of asthma, allergic rhinitis/allergic conjunctivitis (AR/AC), and atopic dermatitis, in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026 – cont.

Variable	Participants (N = 172)																	
	asthma						AR/AC						atopic dermatitis					
	with asthma (N = 13)			without asthma (N = 159)			with AR/AC (N= 26)			without AR/AC (N= 146)			with atopic dermatitis (N= 46)			without atopic dermatitis (N= 126)		
	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p
Demographic and socioeconomic characteristics																		
children																		
sex (females)	4 (30.77)		0.1550	84 (52.83)		0.1550	10 (38.46)		0.1596	78 (53.42)		0.1596	21 (45.65)		0.3823	67 (53.17)		0.3823
age [years]		14.97 (13.40–15.25)	0.7281		14.67 (13.01–15.39)	0.7281		14.89 (13.30–15.25)	0.9974		14.65 (13.00–15.39)	0.9974		14.64 (12.86–15.21)	0.3362		14.74 (13.07–15.39)	0.3362
BMI [kg/m^2]		19.49 (18.67–21.46)	0.1175		21.11 (18.76–23.94)	0.1175		19.42 (17.53–22.16)	0.1370		21.19 (19.00–23.95)	0.1370		20.61 (18.63–25.56)	0.9601		21.10 (18.80–23.77)	0.9601
body fat mass [kg]		9.40 (6.80–10.90)	0.0814		11.70 (7.35–16.75)	0.0814		10.40 (5.60–14.50)	0.3830		11.35 (7.40–15.80)	0.3830		12.15 (8.50–16.70)	0.6750		10.90 (7.30–16.20)	0.6750
household status																		
living together with both parents	11 (84.62)		>0.9999	130 (81.76)		>0.9999	20 (76.92)		0.4668	121 (82.88)		0.4668	39 (84.78)		0.5630	102 (80.95)		0.5630
living with a single parent	2 (15.38)			29 (18.24)			6 (23.08)			25 (17.12)			7 (15.22)			24 (19.05)		
maternal age at birth [years]		29.08 (25.58–35.00)	0.7545		29.17 (26.50–33.00)	0.7545		27.61 (25.58–32.33)	0.1178		29.76 (26.83–33.00)	0.1178		29.08 (26.30–33.67)	0.6616		29.33 (26.50–33.00)	0.6616
mother's education time																		
≤12 years	2 (15.38)		0.7371	40 (25.16)		0.7371	4 (15.38)		0.3249	38 (26.03)		0.3249	9 (19.57)		0.3707	33 (26.19)		0.3707
>12 years	11 (84.62)			119 (74.84)			22 (84.62)			108 (73.97)			37 (80.43)			93 (73.81)		
mother's level of education																		

≤secondary	2 (15.38)		0.5193	42 (26.42)		0.5193	4 (15.38)		0.2313	40 (27.40)		0.2313	9 (19.57)		0.2746	35 (27.78)		0.2746
higher	11 (84.62)			117 (73.58)			22 (84.62)			106 (72.60)			37 (80.43)			91 (72.22)		
socio-economic status																		
very poor/poor	0 (0.00)			0 (0.00)			0 (0.00)			0 (0.00)			0 (0.00)			0 (0.00)		
good	9 (69.23)		0.7574	115 (72.33)		0.7574	19 (73.08)		0.9034	105 (71.92)		0.9034	32 (69.57)		0.6552	92 (73.02)		0.6552
very good	4 (30.77)			44 (27.67)			7 (26.92)			41 (28.08)			14 (30.43)			34 (26.98)		
place of residence																		
urban area	11 (84.62)		>0.9999	127 (79.87)		>0.9999	22 (84.62)		0.7893	116 (79.45)		0.7893	37 (80.43)		0.9679	101 (80.16)		0.9679
rural area	2 (15.38)			32 (20.13)			4 (15.38)			30 (20.55)			9 (19.57)			25 (19.84)		
Perinatal and early-life characteristics																		
gestational age [weeks]		39 (38–40)	0.3420		40 (39–40)	0.3420		39 (38–40)	0.5665		40 (38–40)	0.5665		39 (38–40)	0.2025		40 (39–40)	0.2025
birth weight [g]		3340 (3150–3500)	0.5713		3350 (3050–3650)	0.5713		3295 (3000–3475)	0.4430		3350 (3050–3650)	0.4430		3375 (3060–3700)	0.8420		3350 (3025–3600)	0.8420
maternal pre-pregnancy BMI [kg/m^2]		21.83 (20.24–21.97)	0.4958		21.56 (19.77–24.44)	0.4958		21.47 (20.08–22.72)	0.6831		21.69 (19.71–24.66)	0.6831		21.97 (20.58–24.66)	0.3781		21.36 (19.71–24.25)	0.3781
breastfeeding duration [months]		7 (4–8)	0.9949		7 (4–9)	0.9949		5 (3–7)	0.1623		7 (4–10)	0.1623		6 (3–8)	0.1928		7 (4–10)	0.1928
Clinical characteristics																		
atopic dermatitis	8 (61.54)		0.0060	38 (23.90)		0.0060	19 (73.08)		<0.0001	27 (18.49)		<0.0001	n/a		n/a	n/a		n/a
allergic rhinitis/allergic conjunctivitis	7 (53.85)		0.0006	19 (11.95)		0.0006	n/a		n/a	n/a		n/a	19 (41.30)		<0.0001	7 (5.56)		<0.0001
asthma	n/a		n/a	n/a		n/a	7 (26.92)		<0.0001	6 (4.11)		<0.0001	8 (17.39)		0.0032	5 (3.97)		0.0032
parental atopy or asthma	8 (61.54)		0.0130	43 (27.04)		0.0130	17 (65.38)		<0.0001	34 (23.29)		<0.0001	22 (47.83)		0.0016	29 (23.02)		0.0016

Table 2. Comparison of environmental, demographic and socioeconomic, perinatal and early-life, clinical, respiratory, and skin prick test sensitization characteristics among study participants (N = 172) according to the presence of asthma, allergic rhinitis/allergic conjunctivitis (AR/AC), and atopic dermatitis, in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026 – cont.

Variable	Participants (N = 172																	
	asthma						AR/AC						atopic dermatitis					
	with asthma (N = 13)			without asthma (N = 159)			with AR/AC (N= 26)			without AR/AC (N= 146)			with atopic dermatitis (N= 46)			without atopic dermatitis (N= 126)		
	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p	n (%)	Me (IQR)	p
Respiratory assessment																		
spirometry																		
FEV_1																		
l		3.20 (2.96–3.79)	0.6946		3.45 (2.96–3.96)	0.6946		3.37 (2.89–3.79)	0.3770		3.46 (2.96–3.97)	0.3770		3.42 (3.04–3.87)	0.9961		3.45 (2.94–3.97)	0.9961
% pred.		99 (93–110)	0.0016		108 (100–119)	0.0016		104 (93–110)	0.0120		109 (99–120)	0.0120		107 (97–118)	0.4953		108 (99–118)	0.4953
FVC																		
l		3.97 (3.82–4.91)	0.2890		3.83 (3.39–4.54)	0.2890		3.83 (3.36–4.31)	0.6396		3.83 (3.40–4.58)	0.6396		3.83 (3.49–4.71)	0.8518		3.84 (3.40–4.50)	0.8518
% pred.		105 (94–113)	0.5046		105 (95–112)	0.5046		97 (90–109)	0.0289		106 (96–113)	0.0289		102 (94–110)	0.3870		106 (95–114)	0.3870
FEV_1/FVC																		
% pred.		99 (95–100)	<0.0001		107 (99–112)	<0.0001		106 (97–110)	0.5195		105 (99–112)	0.5195		105 (99–110)	0.8550		106 (99–111)	0.8550
FeNO [ppb]		57.10 (52.50–73.30)	0.0110		45.10 (37.20–57.60)	0.0110		62.10 (45.90–78.60)	0.0063		44.55 (37.20–54.80)	0.0063		46.30 (38.90–66.80)	0.1265		45.30 (37.10–55.75)	0.1265
Skin prick test	11 (91.67)		0.0020	66 (45.21)		0.0020	19 (86.36)		0.0001	58 (42.65)		0.0001	27 (64.29)		0.0186	50 (43.10)		0.0186
grass pollen	10 (90.91)		<0.0001	39 (28.89)		<0.0001	18 (81.82)		<0.0001	31 (25.00)		<0.0001	21 (52.50)		0.0029	28 (26.42)		0.0029
Dermatophagoides farinae	7 (58.33)		0.0033	26 (18.18)		0.0033	9 (42.86)		0.0094	24 (17.91)		0.0094	15 (37.50)		0.0036	18 (15.65)		0.0036
Dermatophagoides pteronyssinus	6 (50.00)		0.0400	31 (21.68)		0.0400	9 (42.86)		0.0282	28 (20.90)		0.0282	16 (40.00)		0.0055	21 (18.26)		0.0055
cockroach	1 (8.33)		0.5149	7 (5.43)		0.5149	2 (10.00)		0.3168	6 (4.96)		0.3168	3 (8.33)		0.4208	5 (4.76)		0.4208

hazel	4 (80.00)	0.0066	18 (18.00)	0.0066	9 (75.00)	<0.0001	13 (13.98)	<0.0001	11 (40.74)	0.0034	11 (14.10)	0.0034	
birch	8 (72.73)	0.0009	31 (21.83)	0.0009	13 (65.00)	<0.0001	26 (19.55)	<0.0001	19 (47.50)	0.0002	20 (17.70)	0.0002	
mugwort	2 (18.18)	0.2196	10 (7.30)	0.2196	5 (23.81)	0.0044	7 (5.51)	0.0044	5 (12.82)	0.2091	7 (6.42)	0.2091	
Cladosporium	0 (0.00)	0.2380	8 (6.40)	0.2380	1 (5.56)	>0.9999	7 (5.93)	>0.9999	1 (2.94)	0.6790	7 (6.86)	0.6790	
Alternaria	2 (28.57)	0.2892	9 (13.85)	0.2892	4 (30.77)	0.1030	7 (11.86)	0.1030	5 (23.81)	0.1967	6 (11.76)	0.1967	
dog	4 (57.14)	0.0029	5 (7.25)	0.0029	4 (36.36)	0.0215	5 (7.69)	0.0215	5 (23.81)	0.0460	4 (7.27)	0.0460	
cat	6 (50.00)	0.0043	19 (13.48)	0.0043	9 (40.91)	0.0008	16 (12.21)	0.0008	14 (35.00)	0.0002	11 (9.73)	0.0002	

Abbreviations as in Table 1.
Continuous variables were compared using the Mann–Whitney U test and categorical variables using the χ^2 test or Fisher's exact test, as appropriate.

Studies assessing indoor concentrations and personal exposure provide a more direct context for interpreting the present findings. In a study based on 24-hour measurements in residential buildings, Ścibor et al. [8] reported that indoor $PM_{2.5}$ and PM_{10} concentrations were strongly correlated with outdoor concentrations, while heating season, heating method, and housing characteristics were identified as important predictors of indoor particulate matter concentrations. In a Seattle panel study, Trenga et al. [30] reported that higher indoor and personal $PM_{2.5}$ exposure was associated with short-term reductions in selected lung function parameters among children with asthma.

Differences in exposure assessment, pollution levels, the timing and duration of exposure, age at outcome assessment, outcome definitions, and population characteristics may partly explain the inconsistent findings across studies [13,14]. In studies of indoor PM, additional variability may result from differences in housing characteristics, indoor emission sources, heating methods, season, and occupants' activity patterns [7,8].

The absence of statistically significant associations in this cohort does not exclude a potential biological role of PM in asthma and other allergic outcomes. Particulate matter may promote oxidative stress, airway inflammation, epithelial barrier dysfunction, and immune dysregulation [6,11,31]. Therefore, the present findings may reflect limited statistical power and the limited ability of a single 24-hour measurement to represent long-term exposure rather than the absence of a biological effect.

The observed associations among asthma, allergic rhinitis/allergic conjunctivitis, atopy, FeNO, and FEV_1/FVC are consistent with an atopic asthma phenotype. The associations of asthma with higher FeNO levels and lower FEV_1/FVC values may reflect eosinophilic airway inflammation and airflow limitation, respectively [21,32]. The associations of atopy with asthma and allergic rhi-

Table 3. Multivariable logistic regression analysis of demographic, clinical, environmental, and respiratory factors associated with asthma, allergic rhinitis/allergic conjunctivitis and atopic dermatitis among study participants (N = 172) in phase IV of the Polish Mother and Child Cohort Study (REPRO_PL), Poland, 2022–2026

Variable	Asthma		Allergic rhinitis/allergic conjunctivitis		Atopic dermatitis	
	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p
Demographic characteristics						
Children						
sex (female)	1.52 (0.45–5.12)	0.5059	2.60 (0.59–11.45)	0.2063	1.02 (0.58–1.79)	0.9530
age	0.71 (0.46–1.10)	0.1240	1.36 (0.81–2.30)	0.2453	0.82 (0.64–1.06)	0.1325
Clinical characteristics						
atopic dermatitis	1.85 (0.35–9.37)	0.3898	24.80 (7.77–79.15)	<0.0001		
asthma			7.94 (2.40–26.25)	0.0004	2.49 (0.55–11.31)	0.2380
allergic rhinitis/allergic conjunctivitis	6.46 (1.50–27.84)	0.0123			6.87 (3.31–14.26)	<0.0001
atopy	7.56 (2.32–24.66)	0.0008	3.60 (1.14–11.32)	0.0284	1.34 (0.74–2.43)	0.3380
parental atopy or asthma	0.56 (0.11–2.87)	0.4894	2.97 (1.05–8.38)	0.0394	1.75 (0.97–3.17)	0.0627
Environmental exposure						
assessment during the heating season (October–April)	2.96 (0.73–11.96)	0.1285	0.20 (0.06–0.63)	0.0068	0.72 (0.40–1.30)	0.2816
PM exposure						
$PM_{2.5}$	1.68 (0.88–3.20)	0.1155	1.13 (0.45–2.85)	0.7890	1.22 (0.78–1.91)	0.3792
PM_{10}	2.22 (0.88–5.57)	0.0901	1.45 (0.55–3.83)	0.4502	0.87 (0.55–1.35)	0.5285
dampness at domicile					2.91 (1.47–5.75)	0.0021
household members smoke			0.04 (0.01–0.20)	0.0002		
Respiratory assessment						
Spirometry						
FEV_1 (% pred.)	1.04 (0.99–1.09)	0.0830	0.94 (0.86–1.02)	0.1567		
FVC (% pred.)			1.01 (0.92–1.11)	0.8283		
FEV_1/FVC (% pred.)	0.87 (0.81–0.93)	0.0002				
FeNO	1.02 (1.01–1.03)	0.0061	0.99 (0.97–1.03)	0.8603		

Abbreviations as in Table 1.
For season of assessment, the reference category was assessment outside the heating season (May–September); the heating season was defined as October–April.

nitis/allergic conjunctivitis further support the clinical relevance of allergic sensitization and are consistent with the frequent coexistence of atopic conditions [33,34].

Atopic dermatitis was associated with allergic rhinitis/allergic conjunctivitis and dampness in the home. Because household dampness was self-reported in the questionnaire, it may represent a broader marker of complex moisture-related indoor exposures rather than a single causative factor [35].

Household smoking was not significantly associated with asthma or atopic dermatitis; however, in the multivariable model, it was associated with lower odds of allergic rhinitis/allergic conjunctivitis. Similarly, assessment during the heating season was not significantly associated with

asthma or atopic dermatitis but was associated with lower odds of allergic rhinitis/allergic conjunctivitis. These inverse associations should not be interpreted as protective effects. They may reflect the seasonality of symptoms, the small number of cases, misclassification of household smoking, or the tendency of families of children with allergies to avoid smoking at home.

Several limitations should be considered. First, the number of asthma cases was small, which limited statistical power and contributed to imprecise estimates in the regression models. Second, a single 24-hour measurement may not represent the participants' usual exposure. Measurements were conducted across different months and years, and changes in temperature and humidity may have affected indoor PM concentrations. Third, residual confounding cannot be excluded despite adjustment for several demographic, familial, clinical, seasonal, and environmental covariates. Finally, the cross-sectional nature of the analyses precludes any conclusions regarding causality or the direction of observed associations. Therefore, these results should be interpreted with caution.

The main strengths of this study include the direct 24-hour measurement of indoor $PM_{2.5}$ and PM_{10} concentrations in the participants' home environment and the availability of standardized assessments, including spirometry, FeNO measurement, and skin prick testing. The study also included information on allergic comorbidities, atopy, season of assessment, and selected home-environmental factors, allowing a broader characterization of allergic phenotypes in adolescence. The combination of direct exposure monitoring and objective respiratory and allergy assessments represents an important methodological strength.

CONCLUSIONS

In this study, indoor PM_{10} measured during a single 24-hour period in the home environment showed a positive but statistically non-significant association with asthma among adolescents from the REPRO_PL cohort. The findings mainly indicate clustering of allergic diseases within an atopic phenotype, with atopy associated with asthma and allergic rhinitis/allergic conjunctivitis. Further studies involving larger populations and repeated and/or longer-term indoor air measurements are needed to clarify the relationship between indoor particulate matter exposure and allergic diseases.

AUTHOR CONTRIBUTIONS

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