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Air pollution and respiratory health in Sarajevo Canton: cross-sectional study of children and adults

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Background: Air pollution is a major contributor to respiratory disease across southeast Europe; however, population-level epidemiological evidence linking air pollution exposure to health outcomes remains limited in the highly polluted Western Balkan basin, including Sarajevo Canton, Bosnia and Herzegovina.
Methods: A population-based cross-sectional study of 1800 children (aged 0–18 years) and 883 adults (aged ≥ 19 years) was conducted in six municipalities of Sarajevo Canton. Daily PM10, PM2·5, NO2, and SO2 concentrations were obtained from eight cantonal monitoring stations between Oct 14, 2024, and Jul 11, 2025; clinical visits took place in a winter period (October 2024 to February 2025) and a summer period (May to July 2025). For children, physician-diagnosed asthma, chronic bronchitis, allergic disease, and prolonged cough were recorded, and for adults, asthma, chronic respiratory disease, hypertension, diabetes, and prolonged cough were ascertained at clinical visits. Associations between municipality-level study-period mean pollutant concentrations and outcome prevalence were estimated using multivariable regression models adjusted for relevant covariates.
Results: Daily PM2·5 exceeded the WHO 2021 24-h guideline (15 μg/m^3) on 65–73% of monitored days, NO2 (25 μg/m^3) on 64–93%, and PM10 (45 μg/m^3) on 31–53%. In children, each 10 μg/m^3 increment in study-period mean PM10 was associated with adjusted OR 1·47 (95% CI 1·15–1·88) for asthma; SO2 with 1·50 (1·20–1·88) for asthma; NO2 with 1·45 (1·13–1·87) for chronic bronchitis and 1·55 (1·28–1·88) for prolonged cough. In adults, NO2 was associated with prolonged cough (OR 1·76 [1·37–2·25]); estimates for asthma, chronic respiratory disease, hypertension, and diabetes were imprecise and not statistically significant; with an estimated 35–55% power to detect ORs of 1·10–1·15 per 10 μg/m^3, these results do not rule out modest effects.
Discussion: Study-period mean exposure to PM10, SO2, and NO2 at concentrations routinely exceeding WHO 2021 guidelines was associated with physician-diagnosed respiratory morbidity in children and with prolonged cough in adults in

Sarajevo Canton; the adult cardiometabolic analyses were underpowered and are inconclusive. These findings are consistent with prioritising residential-heating and traffic components of the cantonal Air Quality Plan, and motivate longitudinal follow-up to clarify the underlying associations.

KEYWORDS

air pollution, Bosnia & Herzegovina, children, health effect, Sarajevo

Introduction

Solid-fuel domestic heating, primarily coal and wood combustion, is the dominant source of winter particulate matter and sulphur dioxide in cities across the Western Balkans, Central and Eastern Europe, and large parts of Central Asia, exposing an estimated 150–200 million urban residents to seasonal PM concentrations that routinely exceed WHO 2021 air-quality guidelines by factors of 3 to 10 (1, 2).

Despite this scale, population-based epidemiological evidence from these settings remains sparse relative to the cohort literature generated in Western European cities where natural-gas heating predominates. The large European cohort studies such as ESCAPE and ELAPSE have robustly characterised associations between long-term ambient PM2·5, NO_2, and health outcomes, but their exposure models and reference populations reflect a fundamentally different combustion-fuel mix, in which SO2 is a minor contributor and coal-derived fine particles are rare. Whether the respiratory and cardiometabolic risk estimates from those cohorts are transferable to solid-fuel heating cities remains an open question with direct implications for environmental health policy across a wide arc of low-middle-income urban settings.

Air pollution is the largest environmental contributor to noncommunicable disease mortality worldwide and was estimated to have caused approximately 4.2 million premature deaths in 2019, of which more than 90% occurred in low-and middle-income countries (1, 2). Long-term exposure to fine particulate matter (PM2·5), coarse particulate matter (PM10), nitrogen dioxide (NO2), and sulphur dioxide (SO2) is associated with increased incidence of asthma, chronic obstructive pulmonary disease, lower respiratory tract infection in children, and a growing list of cardiometabolic and neurocognitive outcomes (3–5). In recognition of the increasing evidence of adverse health effects at concentrations well below earlier guideline values, the World Health Organization revised its Air Quality Guidelines in 2021, lowering the recommended 24-h limits to 45 μg/m^3 for PM10, 15 μg/m^3 for PM2·5, 25 μg/m^3 for NO2, and 40 μg/m^3 for SO2, and introduced annual targets that are now exceeded across most of urban Europe (6). The European Environment Agency estimates that exposure to PM2·5 alone is responsible for more than 230,000 premature deaths per year in the EU-27 and that fewer than 5% of the European population currently lives at concentrations below the WHO 2021 annual guideline (7). Within Europe, the urban basins of the Western Balkans rank consistently among the most polluted, driven by an unusual combination of widespread solid-fuel domestic heating, an ageing residential building stock with poor thermal insulation, traffic-derived emissions, and topographically constrained valley locations that promote winter temperature inversions and stagnant air masses (8, 9). Sarajevo Canton, which is the administrative unit comprising the city of Sarajevo and the surrounding municipalities, with population of approximately 413,000 inhabitants, sits at the bottom of basin between 500 and 1,500 metres elevation in central Bosnia and Herzegovina. Sarajevo has been one of the worst polluted cities in the world during the winter season. Moreover, during winter heating seasons over the past decade, daily mean PM2·5 concentrations measured at the cantonal regulatory monitoring stations have exceeded 200 μg/m^3 on multiple days each year, ranking the canton at or near the top of European urban-air-pollution league tables (10, 11). Despite this, the population-level health consequences of chronic exposure have been characterised primarily through ecological modelling and through hospital admissions analyses, rather than through population-based primary epidemiological data linking individually-measured health outcomes and pollutant concentrations (12, 13).

Three specific issues motivated the present study. First, no published cross-sectional study has combined the regulatory monitoring network with primary clinical assessment of respiratory and cardiometabolic outcomes in both children and adults living across Bosnia and Herzegovina. Second, the relative contribution of pollutants (PM10, PM2·5, NO2, and SO2) to the burden of paediatric respiratory disease in this setting has not been quantified previously. Third, no Sarajevo-specific evidence base currently exists to inform the prioritisation of the cantonal Air Quality Plan among the residential-heating, transport, and industrial-emission interventions on offer. Therefore, we designed and conducted a population-based cross-sectional study of 1,800 children and 883 adults living in six municipalities of Sarajevo Canton between October 2024 and July 2025, with the following aims of: (i) to characterise the levels and spatial distribution of PM10, PM2·5, NO2, and SO2 across the cantonal monitoring network during the study period; (ii) to estimate the prevalence of selected respiratory and cardiometabolic outcomes in children and adults across the six municipalities; (iii) to analyse associations between municipality-level study-period mean pollutant concentrations and the prevalence of those outcomes; and (iv) to identify exposure-outcome patterns that may inform the design of future longitudinal studies with individual-level exposure assessment.

Methods

Study design

A population-based, cross-sectional epidemiological study was conducted on air-pollution exposure and respiratory and cardiometabolic health among children and adults living in six municipalities of Sarajevo Canton, Bosnia and Herzegovina. Approval was obtained from the Ethics Committee of Public Health Center of the Sarajevo Canton number 01-06-33-2-1060-2/23 obtained on 02 April 2024. Written informed consent was obtained from all adult participants and from a parent or legal guardian for all paediatric participants. The study was conducted in accordance with the Declaration of Helsinki. Field data collection ran from October, 2024, to July, 2025, and was paired with municipality level air-quality measurements obtained

from the cantonal monitoring network for the period from October, 2024, to July, 2025. The study was designed and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for cross-sectional studies (14).

Setting

Sarajevo Canton has a population of approximately 413,000 inhabitants. It lies in a valley at 500–550 m elevation in central Bosnia and Herzegovina, with a continental climate and frequent winter temperature inversions that trap combustion-derived particulate matter in the lower atmosphere. Solid-fuel domestic heating (firewood and coal) remains widespread, and the Canton has reported the highest annual mean PM10 and PM2·5 concentrations in Europe in recent winters. The six sampled municipalities were Centar, Hadžići, Ilidža, Ilijaš, Novi Grad, and Vogošća. They span the urban core and the surrounding suburbs.

Participants

Two distinct cohorts were enrolled. Children (n = 1,800) were recruited from primary-care paediatric clinics and primary schools in the six municipalities (n per municipality: Centar 306, Ilidža 300, Hadžići 299, Ilijaš 306, Novi Grad 293, Vogošća 296). Eligibility required residence at the registered address for ≥ 12 months, age 0–18 years, and written informed consent provided by a parent or legal guardian. Participants were surveyed in two periods matching the air-quality monitoring record: a winter period (October 14, 2024, to February 28, 2025) and a summer period (May 5 to July 11, 2025). At each health centre, the first five consenting patients attending on Mondays were surveyed. Adults (n = 883) were recruited from family-medicine clinics in the same catchment areas, with municipality groupings of Stari Grad/Centar (n = 150), Novi Grad and Novo Sarajevo (n = 149), Ilidža (n = 144), Hadžići (n = 146), Ilijaš (n = 149), and Vogošća (n = 145). Eligibility required age ≥ 19 years, residence at the registered address for ≥ 12 months, and written informed consent. Adults were surveyed in the same winter and summer periods.

Air-quality data

Daily 24-h mean concentrations of PM10, PM2·5, NO2, SO2, CO, and O3 were obtained from the Federal Hydrometeorological Institute and the Cantonal Environmental Protection Department for eight automated monitoring sites (Centar, Ilidža, Stari Grad, Novi Grad, Ilijaš, Vogošća, Hadžići, and Otoka). Six of these stations, one in each study municipality (Centar, Novi Grad, Ilidža, Ilijaš, Vogošća, and Hadžići), were used for exposure assignment; the Stari Grad station is reported descriptively, and the Otoka site measured only O3 and was not used. The stations are part of the regulatory monitoring network of Sarajevo Canton, and participants were recruited at the primary health-care centres in the same municipalities as the stations. Particulate matter was measured gravimetrically and by tapered-element oscillating microbalance (PM10, PM2·5); gaseous pollutants were measured by ultraviolet fluorescence (SO2), chemiluminescence (NO2), non-dispersive infrared (CO), and ultraviolet photometry (O3), in accordance with EU Directive 2008/50/EC reference methods (15). The full record covered October 14, 2024, to July 11, 2025 (4,958 station-days of valid measurements: 1,360 SO2, 1,195 PM10, 828 NO2, 816 PM2·5, 407 CO, and 352 O3 values); NO2 monitoring ended on February 28, 2025, so the NO2 study-period mean at every station covers October 14, 2024, to February 28, 2025 (138 days) and reflects cold-season concentrations only. Daily concentrations are reported in μg/m^3, except CO (mg/m^3). Each participant was assigned the daily concentrations recorded at the monitoring station of their municipality of residence. Adults living in Stari Grad or Centar were assigned the Centar station, and adults living in Novi Grad or Novo Sarajevo were assigned the Novi Grad station. Because each municipality was served by a single station, all participants in a municipality were assigned the same study-period mean, and the exposure contrast in the models is therefore between municipalities. The Hadžići station measures only SO2, and the Ilijaš station does not measure PM2·5; participants from these municipalities contribute only to the models for pollutants measured at their station. Season-specific means (cold season: October–March; warm season: April–September) were also computed to support sensitivity analyses.

Health outcomes

Structured interviewer-led questionnaires adapted from the International Study of Asthma and Allergies in Childhood (ISAAC) for the paediatric cohort (16) and from the European Community Respiratory Health Survey (ECRHS) for the adult cohort were used (17). Children's outcomes comprised physician-diagnosed asthma, chronic bronchitis, allergic rhinitis or conjunctivitis (allergies), and a composite measure of any cough lasting at least 4 weeks in the past 12 months. Adult outcomes included physician-diagnosed asthma, any chronic respiratory disease (asthma, chronic obstructive pulmonary disease, or chronic bronchitis), hypertension, diabetes mellitus, and any cough lasting at least 4 weeks in the past 12 months. Covariates collected at interview included age, sex, household domestic-heating type (clean fuels—central heating, electricity, or natural gas; solid fuels—firewood or coal; mixed), exposure to environmental tobacco smoke, current and former cigarette smoking, pack-years, weekly hours of passive smoke exposure, educational attainment (adults only), and date of visit (used to derive cold/warm season). Heating type was recorded with the same three categories in both cohorts. In the primary models it was entered as a binary indicator of any solid-fuel use (solid fuel only or mixed) vs. clean fuel only, defined identically in both cohorts; the three-category variable was used in sensitivity analyses.

Outcomes

The pre-specified primary outcomes were physician-diagnosed asthma in both cohorts, chronic bronchitis in children, and any chronic respiratory disease in adults. Pre-specified secondary outcomes were allergic rhinitis or conjunctivitis (children), any cough lasting ≥ 4 weeks (both cohorts), and physician-diagnosed hypertension and diabetes mellitus in adults.

Statistical analysis

Pollutant concentrations are summarised as mean (SD), median (IQR), and the proportion of days exceeding the 2021 World Health Organization 24-h air-quality guideline (PM10 45 μg/m^3, PM2·5.15 μg/m^3, NO2 25 μg/m^3, SO2 40 μg/m^3) (6). The association of each pollutant with each binary health outcome was estimated using multivariable logistic regression. Children's models were adjusted for age (years), sex, domestic solid-fuel heating, environmental tobacco-smoke exposure, and season of visit. Adult models were additionally adjusted for

educational attainment, current smoking status, and weekly hours of passive smoke exposure. The primary exposure metric was the study-period mean; the 7-day and 30-day pre-visit means were carried forward into sensitivity analyses (18–20). All analyses were conducted using IBM SPSS v.26. No formal *a priori* sample-size calculation was performed; the analytical sample was determined by the operational capacity of the field teams across the six municipalities. Post-hoc power estimates suggest that the adult sub-sample of 883 participants provided 35–55% power to detect an OR of 1·10–1·15 per 10 μg/m^3 for outcomes with a prevalence of approximately 8%, which should be considered when interpreting null findings in adults. To control for the inflated false-discovery risk arising from the testing of multiple pollutant-outcome combinations, *p*-values were adjusted using the Benjamini-Hochberg procedure (significance threshold $q < 0{\cdot}05$); this correction was applied post-hoc and was not pre-specified in the study protocol (28). FDR-adjusted results should therefore be read as an exploratory guard against chance findings rather than as confirmatory tests against a pre-specified threshold. All models were fitted on complete cases; covariate data were complete for all adults and for 1,798 of 1,800 children (99·9%).

Results

Sample characteristics

Between October 2024 and July 2025, 1,800 children were enrolled across the six paediatric municipalities in Canton Sarajevo, with 293 to 306 participants per municipality (Figure 1; Table 1). Mean age was 7·7 years (SD 4·7); 689 children (38·3%) were of preschool age and 1,111 (61·7%) school-age. 983 children (54·6%) were female. Solid-fuel domestic heating (firewood or coal) was the only source of warmth in 538 households (29·9%), used in combination with clean fuels in 122 households (6·8%), and absent in 1,140 (63·3%). Regular indoor exposure to environmental tobacco smoke was reported for 484 children (26·9%).

In the same periods, 883 adults were enrolled with 144 to 150 participants per municipality. Mean age was 45·3 years (SD 16·9, range 19–92); 479 (54·2%) were female. Education level was primary in 7·0%, secondary in 63·5%, and university in 29·4%. Solid-fuel-only heating was reported by 247 adults (28·0%) and mixed heating by 80 (9·1%). 211 adults (23·9%) were current smokers, 111 (12·6%) former smokers; mean lifetime exposure among ever-smokers was 14·4 pack-years (SD 14·6).

Between October 14, 2024, and July 11, 2025, 4,958 valid station-day measurements were obtained from the eight monitoring stations in Canton Sarajevo (Figure 1; Table 2). PM10 concentrations exceeded the WHO 2021 24-h air-quality guideline of 45 μg/m^3 on 31% of monitored days at Centar (64/206), 32% at Ilidža (66/206), 38% at Vogošća (79/206), 47% at Novi Grad (92/197), and 53% at Ilijaš (103/194); the daily mean range across all stations was 6·0–303·2 μg/m^3. PM2·5 was even more pervasively elevated, with 65–73% of monitored days exceeding the 15 μg/m^3 guideline at the four stations measuring it (133/206 at Centar, 144/206 at Ilidža, 141/206 at Vogošća, and 141/198 at Novi Grad), and a maximum daily mean of 290·7 μg/m^3 at Novi Grad. Daily NO2 exceeded the 25 μg/m^3 guideline on 70% of monitored days at Centar, 76% at Ilidža, 64% at Vogošća, and 93% at Novi Grad. SO2 daily means exceeded the 40 μg/m^3 guideline on 22–30% of days at the central-valley stations and on 4% at Stari Grad. The seasonal distribution of daily concentrations at each station showed that cold season medians substantially exceeded warm-season medians for PM10, PM2·5, and SO2, with cold-season interquartile ranges reaching 50–120 μg/m^3 for PM10 across the central-valley stations (Figure 2).

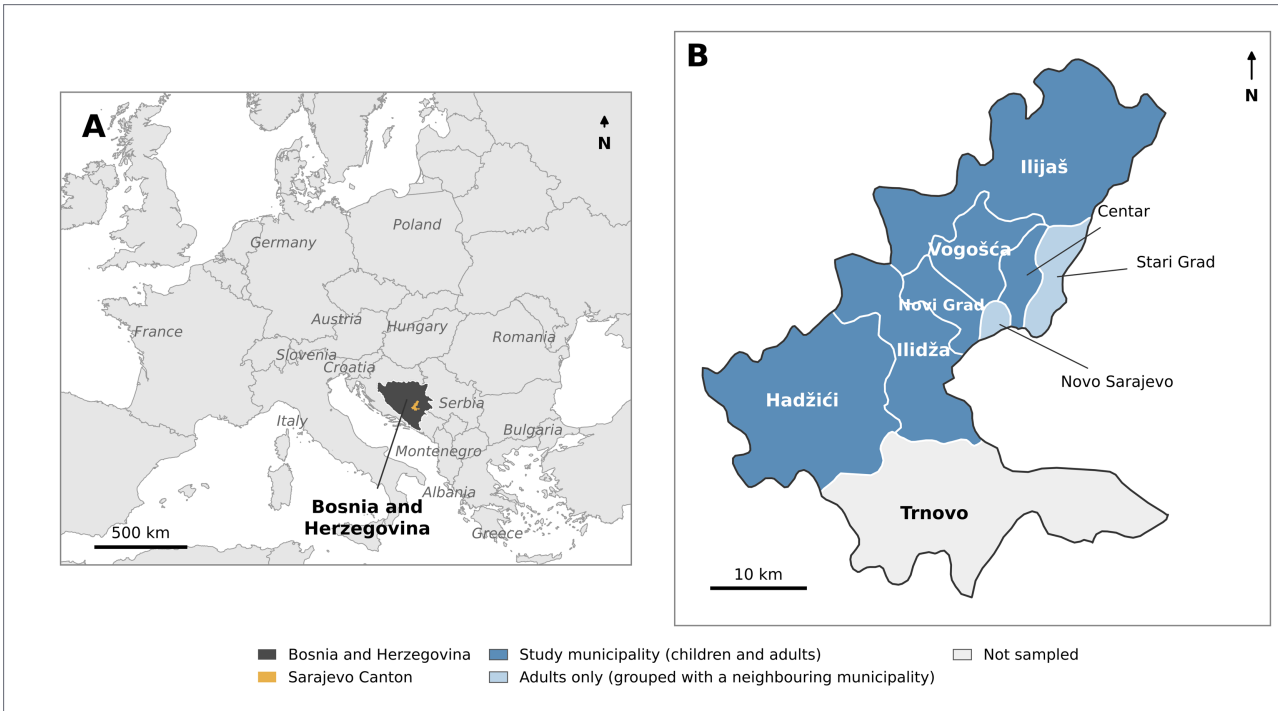


FIGURE 1
Study area and air quality monitoring locations. **(A)** Location of Bosnia and Herzegovina within Europe. **(B)** Municipalities of Sarajevo Canton and air quality monitoring stations included in the study. Blue shading denotes Sarajevo Canton; blue points denote monitoring stations.

TABLE 1 Sample characteristics by cohort.

Characteristic	Children (*n* = 1,800)	%	Adults (*n* = 883)	%
Age, mean (SD), years	7.73 (4.73)		45.3 (16.9)	
Age range	0–18		19–92	
• Children: Preschool	689	38.3%	-	-
• Children: School-age	1,111	61.7%	-	-
• Adults: 20–24	-	-	102	11.6%
• Adults: 25–34	-	-	201	22.8%
• Adults: 35–44	-	-	144	16.3%
• Adults: 45–64	-	-	278	31.5%
• Adults: 65 and older	-	-	158	17.9%
Sex				
• Female	983	54.6%	479	54.2%
• Male	817	45.4%	404	45.8%
Education (adults)	-	-		
• Primary	-	-	62	7.0%
• Secondary	-	-	561	63.5%
• Higher / postgraduate	-	-	260	29.4%
Municipality				
• Centar	306	17.0%		
• Ilidža	300	16.7%	144	16.3%
• Ilijaš	306	17.0%	149	16.9%
• Hadžići	299	16.6%	146	16.5%
• Vogošća	296	16.4%	145	16.4%
• Novi Grad	293	16.3%		
• Stari Grad / Centar (adults)	-	-	150	17.0%
• Novi Grad i Novo Sarajevo (adults)	-	-	149	16.9%
Season of visit				
• Winter	1,200	66.7%	590	66.8%
• Summer	600	33.3%	293	33.2%
Heating type				
• Clean fuel (central / electric / gas)	1,140	63.3%	556	63.0%
• Mixed	122	6.8%	80	9.1%
• Solid fuel only (wood / pellet / coal)	538	29.9%	247	28.0%
Smoking status (adults)	-	-		
• Never	-	-	561	63.5%
• Former	-	-	111	12.6%
• Current	-	-	211	23.9%
Pack-years, mean (SD)—ever-smokers	-	-	14.4 (14.6)	
Passive smoke total hrs/day, mean (SD)	-	-	3.0 (4.2)	
Tobacco-smoke exposure (children, regular)	484	26.9%	-	-
Exhaust-gas exposure (regular)	572	31.8%	354	40.1%

SD, standard deviation.

Study outcomes

Among the children, 133 (7·4%) had a physician diagnosis of asthma, 213 (11·8%) of chronic bronchitis, and 385 (21·4%) of an allergic disease; 457 (25·4%) reported a cough lasting at least 4 weeks in the preceding year (Table 3, Panel A). Asthma was more prevalent in winter visits than in summer (8·3% vs. 5·5%, $p = 0·038$), and prevalences varied significantly by municipality for asthma (5·4% in Vogošća to 11·8% in Ilijaš, $p = 0·038$), chronic bronchitis (5·6% in Ilijaš to 18·0% in Ilidža, $p < 0·001$), allergic disease (17·3% in Ilijaš to 29·0% in Ilidža, $p = 0·003$),

TABLE 2 Pollutant concentrations by monitoring station, study period (October, 2024–July, 2025).

Station	Pollutant	Mean (SD)	Median	Range (min-max)	WHO 24-h AQG	Days exceeding AQG
Centar	PM10	46.9 (50.4)	30.6	6.3–298.9	45 μg/m³	64/206
Centar	PM2.5	41.0 (49.4)	23.6	3.7–286.4	15 μg/m³	133/206
Centar	NO2	36.4 (21.0)	30.7	4.5–106.4	25 μg/m³	97/138
Centar	SO2	31.9 (23.2)	27.1	1.9–149.8	40 μg/m³	53/205
Ilidža	PM10	48.0 (44.5)	30.9	6.0–252.3	45 μg/m³	66/206
Ilidža	PM2.5	43.1 (44.2)	27.4	4.1–243.6	15 μg/m³	144/206
Ilidža	NO2	36.4 (15.1)	32.9	10.2–106.9	25 μg/m³	105/138
Ilidža	SO2	27.7 (27.9)	18.6	1.8–173.5	40 μg/m³	45/201
Ilijaš	PM10	63.7 (47.9)	49.6	9.3–296.2	45 μg/m³	103/194
Ilijaš	PM2.5	-	-	-	15 μg/m³	-
Ilijaš	NO2	25.7 (11.9)	23.3	6.7–73.5	25 μg/m³	62/138
Ilijaš	SO2	42.1 (56.5)	27.1	1.1–358.5	40 μg/m³	55/185
Hadžići	PM10	-	-	-	45 μg/m³	-
Hadžići	PM2.5	-	-	-	15 μg/m³	-
Hadžići	NO2	-	-	-	25 μg/m³	-
Hadžići	SO2	23.9 (22.9)	18.2	1.1–117.7	40 μg/m³	30/205
Vogošća	PM10	49.5 (46.7)	34.8	6.6–248.8	45 μg/m³	79/206
Vogošća	PM2.5	43.1 (46.2)	28.1	3.4–237.3	15 μg/m³	141/206
Vogošća	NO2	32.2 (13.8)	28.3	11.5–83.9	25 μg/m³	88/138
Vogošća	SO2	20.2 (25.8)	12.6	1.0–159.0	40 μg/m³	20/173
Novi Grad	PM10	64.6 (60.7)	41.9	6.7–303.2	45 μg/m³	92/197
Novi Grad	PM2.5	56.1 (59.7)	34.0	2.3–290.7	15 μg/m³	141/198
Novi Grad	NO2	45.6 (19.0)	40.7	11.1–133.3	25 μg/m³	128/138
Novi Grad	SO2	17.5 (17.5)	13.0	1.9–112.5	40 μg/m³	15/196
Stari Grad	PM10	31.7 (28.9)	23.3	7.8–164.8	45 μg/m³	29/186
Stari Grad	PM2.5	-	-	-	15 μg/m³	-

(Continued)

TABLE 2 (Continued)

Station	Pollutant	Mean (SD)	Median	Range (min-max)	WHO 24-h AQG	Days exceeding AQG
Stari Grad	NO2	30.5 (16.9)	26.2	6.3–94.0	25 μg/m³	75/138
Stari Grad	SO2	11.4 (12.4)	8.8	0.4–96.9	40 μg/m³	7/195

SD, standard deviation. WHO 24-h AQG, World Health Organization 2021 24-h Air Quality Guideline. "Days exceeding" counts station-days with daily mean above the AQG. Hadžići station measures only SO2; Stari Grad and Ilijaš lack PM2.5; Otoka station (O3 only) is not used in the main analysis.

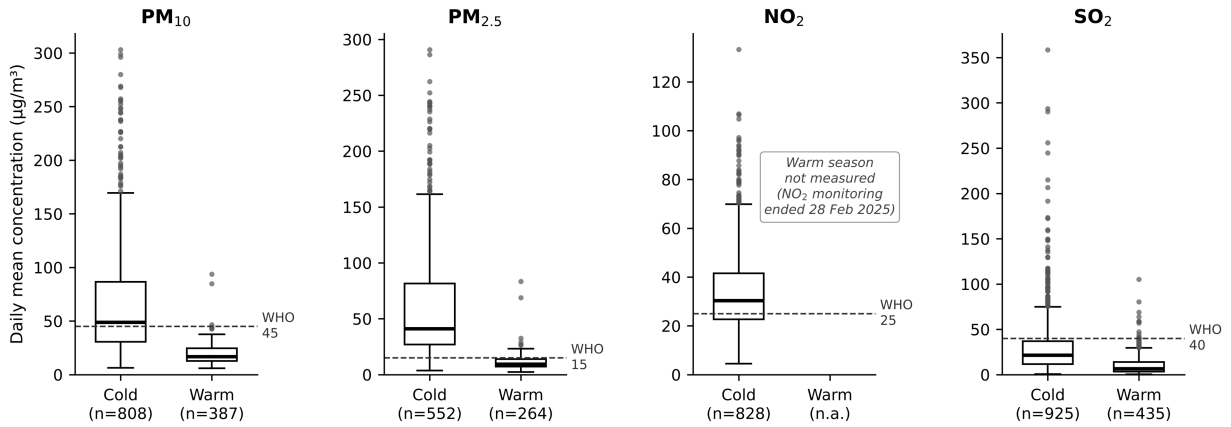


FIGURE 2
Seasonal distribution of daily 24-h mean pollutant concentrations across the eight cantonal monitoring stations, Sarajevo Canton, October, 2024 to July, 2025. Box plots show daily 24-h mean concentrations of PM10, PM2·5, NO_2, and SO_2 measured at the eight automated monitoring stations of the Federal Hydrometeorological Institute and Cantonal Environmental Protection Department network (Centar, Ilidža, Stari Grad, Novi Grad, Ilijaš, Vogošća, Hadžići, and Otoka), pooled across stations and stratified by cold season (October–March; n = 808 station-days for PM10, 552 for PM2·5, 828 for NO_2, 925 for SO_2) and warm season (April–September; n = 387 for PM10, 264 for PM2·5, 435 for SO_2). PM10, particulate matter ≤ 10 μm aerodynamic diameter; PM2·5, particulate matter ≤ 2·5 μm aerodynamic diameter; NO_2, nitrogen dioxide; SO_2, sulphur dioxide.

and any cough (7·5% in Ilijaš to 36·8% in Vogošća, $p < 0·001$; Table 3, Panels B–D). Among the adults, 67 (7·6%) reported physician-diagnosed asthma, 76 (8·6%) any chronic respiratory disease, 229 (25·9%) hypertension, 138 (15·6%) diabetes, and 341 (38·6%) any cough lasting ≥ 4 weeks. Asthma, chronic respiratory disease, hypertension, and diabetes prevalence did not differ significantly between municipalities (all $p > 0·05$); any cough showed marked between-municipality variation (15·4% in Ilijaš to 54·0% in Stari Grad/Centar, $p < 0·001$) and was more prevalent in summer than winter (46·4% vs. 34·7%, $p = 0·001$).

Outcomes in paediatric cohort

Three of the four primary children outcomes showed statistically significant associations with at least one pollutant after a 10-μg/m³ increment in the study-period mean (Table 4).

Asthma. Each 10-μg/m³ increment in study-period mean PM10 was associated with an adjusted OR of 1·47 (95% CI 1·15–1·88; $p = 0·002$), and each 10-μg/m³ increment in SO2 with an aOR of 1·50 (1·20–1·88; $p < 0·001$). The association with NO2 ran in the opposite direction (aOR 0·59, 0·42–0·82; $p = 0·002$), most plausibly reflecting between-municipality confounding by the spatial structure of NO2 (highest in the dense urban core of Novi Grad, where asthma prevalence was 7·5%, lower than in the lower-NO2 municipality of Ilijaš at 11·8%) rather than a true protective effect of NO2; this directional inversion is examined in the two-pollutant analyses below. PM2·5 was not significantly associated with asthma (aOR 1·13, 0·78–1·65).

Chronic bronchitis. NO2 was positively associated (aOR 1·45, 1·13–1·87; $p = 0·004$), whereas PM10 showed a paradoxical inverse association (0·73, 0·59–0·91; $p = 0·004$). PM2·5 (0·90, 0·67–1·20) and SO2 (0·88, 0·73–1·07) were null.

Allergic disease. No pollutant was significantly associated with allergic-disease prevalence (PM10 aOR 1.01, 0.86–1.18; PM2·51.06, 0.84–1.34; NO2 1.06, 0.86–1.30; SO2 0.99, 0.85–1.15).

Any cough lasting ≥ 4 weeks. NO2 was strongly positively associated with cough (aOR 1.55, 1.28–1.88; $p < 0.001$). PM10 (0.67, 0.57–0.79; $p < 0.001$) and SO2 (0.65, 0.56–0.75; $p < 0.001$) showed inverse associations of similar magnitude, again concentrated in the spatial gradient between the cough-poor municipality of Ilijaš and the cough-rich central-valley stations.

The four associations in children retained after post-hoc FDR correction, namely PM10 and SO2 with asthma, and NO2 with chronic bronchitis and prolonged cough, are visualised in Figure 3, which plots the multivariable-adjusted predicted prevalence as a function of pollutant concentration over the observed exposure range, with observed municipality-level prevalence overlaid; predicted curves are monotonically increasing across all four panels, with the steepest slope for the NO2-cough association.

Outcomes in adult cohort

Neither asthma, chronic respiratory disease, hypertension, nor diabetes showed a statistically significant association with any pollutant at any exposure window (Table 5; all $p \geq 0·05$ and adjusted for age, sex, education, solid-fuel heating, current smoking, weekly hours of passive smoke, and season). The one significant signal among the adults was for any cough lasting ≥ 4 weeks: each 10-μg/m³ increment

TABLE 3 Outcome prevalences by cohort, municipality, and season.

Panel A. Overall prevalence		
Outcome	Children n (%)	Adults n (%)
Allergies	385 (21.4%)	-
Any chronic respiratory disease	-	76 (8.6%)
Any cough attacks in last year	457 (25.4%)	341 (38.6%)
Cardiac arrhythmia	43 (2.4%)	49 (5.5%)
Diabetes	56 (3.1%)	138 (15.6%)
Doctor-diagnosed asthma	133 (7.4%)	67 (7.6%)
Doctor-diagnosed chronic bronchitis	213 (11.8%)	-
Dyslipidaemia	-	191 (21.6%)
Hypertension	20 (1.1%)	229 (25.9%)
Recurrent laryngitis	369 (20.5%)	-

Panel B. Children—outcome prevalence by municipality							
Outcome	Centar	Ilidža	Ilijaš	Hadžići	Vogošća	Novi Grad	p (χ^2)
Asthma, n (%)	18 (5.9%)	22 (7.3%)	36 (11.8%)	19 (6.4%)	16 (5.4%)	22 (7.5%)	0.038
Chronic bronchitis, n (%)	48 (15.7%)	54 (18.0%)	17 (5.6%)	23 (7.7%)	34 (11.5%)	37 (12.6%)	<0.001
Allergies, n (%)	60 (19.6%)	87 (29.0%)	53 (17.3%)	52 (17.4%)	63 (21.3%)	70 (23.9%)	0.003
Any cough last year, n (%)	111 (36.3%)	66 (22.0%)	23 (7.5%)	64 (21.4%)	109 (36.8%)	84 (28.7%)	<0.001

Panel C. Adults—outcome prevalence by municipality							
Outcome	Stari Grad/ Centar	Ilidža	Ilijaš	Hadžići	Vogošća	Novi Grad i Novo S.	p (χ^2)
Asthma, n (%)	16 (10.7%)	11 (7.6%)	11 (7.4%)	10 (6.8%)	7 (4.8%)	12 (8.1%)	0.583
Chronic respiratory, n (%)	16 (10.7%)	20 (13.9%)	12 (8.1%)	7 (4.8%)	13 (9.0%)	8 (5.4%)	0.058
Hypertension, n (%)	38 (25.3%)	45 (31.2%)	40 (26.8%)	41 (28.1%)	36 (24.8%)	29 (19.5%)	0.316
Diabetes, n (%)	23 (15.3%)	25 (17.4%)	22 (14.8%)	23 (15.8%)	26 (17.9%)	19 (12.8%)	0.857
Any cough last year, n (%)	81 (54.0%)	51 (35.4%)	23 (15.4%)	41 (28.1%)	74 (51.0%)	71 (47.7%)	<0.001

(Continued)

TABLE 3 (Continued)

Panel D. Outcome prevalence by season						
Outcome	Children Winter	Children Summer	Children *p*	Adults Winter	Adults Summer	Adults *p*
Asthma, n (%)	100 (8.3%)	33 (5.5%)	0.038	43 (7.3%)	24 (8.2%)	0.732
Any cough last year, n (%)	315 (26.2%)	142 (23.7%)	0.259	205 (34.7%)	136 (46.4%)	0.001
Chronic respiratory, n (%) (adults only)				49 (8.3%)	27 (9.2%)	0.744

in study-period mean NO2 was associated with an aOR of 1·76 (95% CI 1·37–2·25; $p < 0·001$), in PM10 with 0·69 (0·57–0·84; $p < 0·001$), and in SO2 with 0·63 (0·53–0·76; $p < 0·001$). When the season-mean exposure window was substituted for the study-period mean, the directions and statistical significance were preserved but magnitudes attenuated for PM10 (0·78, 0·63–0·95; $p = 0·016$) and SO2 (0·77, 0·65–0·90; $p = 0·001$); the season-mean NO2 model could not be fit because NO2 was not measured during the summer period (Table 5).

Sensitivity analyses

Restricting the children sample to school-age participants reproduced the primary asthma findings for PM10 (aOR 1·49, 1·14–1·95; $p = 0·004$) and NO2 (0·67, 0·46–0·98; $p = 0·038$; Table 6). Replacing the binary solid-fuel-heating covariate with the three-category clean/mixed/solid-fuel coding produced near-identical estimates for PM10 (1·49, 1·16–1·90; $p = 0·002$) in children and for adult asthma (aOR 0·87, 0·61–1·23 vs. 0·91, 0·64–1·29 in the primary model). Restricting adults to long-term residents (≥ 15 years at the registered address) attenuated but did not reverse the chronic-respiratory-disease estimates for PM10 and PM2·5 (aOR 0·70, 0·49–1·01; $p = 0·054$ and 0·56, 0·30–1·05; $p = 0·07$).

Two-pollutant models. Co-pollutant adjustment generally preserved or strengthened the children PM10 and SO2 effects on asthma (e.g., children PM10-asthma aOR after NO2 adjustment 1·55, 1·20–1·99; SO2-asthma after NO2 adjustment 1·36, 0·95–1·95) and the children NO2-chronic-bronchitis effect (aOR 1·71, 1·26–2·32 after PM10 adjustment). Models entering PM10 and PM2·5 jointly produced implausibly wide confidence intervals (e.g., children PM10-cough aOR 257, 27–2,457 after PM2·5 adjustment), indicating extreme collinearity between the two particulate-matter fractions across the six municipalities; these estimates are uninformative and are reported only to document the limits of multi-pollutant modelling in this six-location spatial design. No sensitivity specification, including the two-pollutant models, resolved the collinearity underlying the inverse associations of PM10 with chronic bronchitis and cough and of SO2 with cough in children; these estimates reflect between-municipality confounding, are uninformative about causal effects, and are not interpreted further.

Discussion

In this population-based cross-sectional study of 1,800 children and 883 adults living in six municipalities of Sarajevo Canton during the 2024–25 heating season, particulate and gaseous air pollution routinely exceeded WHO 2021 24-h air-quality guidelines: PM2·5 was above the 15 μg/m^3 guideline on roughly two-thirds of monitored days at every station that measured it, PM10 above 45 μg/m^3 on 31% to 53% of days, and NO2 above 25 μg/m^3 on 64% to 93% of days, with single-day PM2·5 maxima approaching 290 μg/m^3. Against this background of severe and persistent population-wide exposure, our analysis identified three pollutant-outcome associations in children: each 10 μg/m^3 increment in study-period mean PM10 and SO2 was associated with higher odds of physician-diagnosed asthma (aOR 1·47, 95% CI 1·15–1·88; and aOR 1·50, 1·20–1·88, respectively), and each 10 μg/m^3 increment in NO2 was associated with higher odds of physician-diagnosed chronic bronchitis (aOR 1·45, 1·13–1·87) and of any cough lasting at least 4 weeks in the past year (aOR 1·55, 1·28–1·88).

In adults, the only pollutant-outcome association was for any cough lasting at least 4 weeks: each 10 μg/m^3 increment in NO2 was associated with an aOR of 1·76 (1·37–2·25). Asthma, chronic respiratory disease, hypertension, and diabetes in adults were not significantly associated with any pollutant; given the limited power, these results are inconclusive rather than evidence of no effect. Additionally, three pollutant-outcome combinations in children (PM10 with chronic bronchitis and with cough, and SO2 with cough) yielded statistically significant inverse adjusted odds ratios; we interpret these as artefacts of between-municipality spatial confounding rather than evidence of a protective effect of pollution. Consistent with the exploratory and hypothesis-generating character of the adult cardiometabolic component of this study (aim ii), the absence of significant associations for hypertension and diabetes should not be read as evidence against an effect, but as a reflection of limited statistical power and the ecological nature of the exposure assignment; these outcomes warrant dedicated, adequately powered investigation rather than further interpretation here.

The positive association between study-period mean PM10 exposure and physician-diagnosed asthma in children is consistent in direction and magnitude with the meta-analytic estimate from the Global Burden of Disease air-pollution working group (2, 3) and with the Western European pooled estimates from the ESCAPE consortium (21) (noting that those cohort studies used multi-year exposure metrics, whereas our estimate is based on a single heating season). The strength of the SO2-asthma association we report (aOR 1·50 per 10 μg/m^3) is somewhat larger than the central estimates from urban European cohorts but consistent with studies conducted in Central and South-Eastern European cities where solid-fuel domestic heating dominates the residential emissions inventory and SO2 is a more sensitive marker of combustion-derived fine particulate exposure than in cities heated by natural gas (8). The association between study-period

TABLE 4 Adjusted odds ratios (per 10 μg/m³) for the association between study-period mean air-pollution exposure and children's respiratory and allergic outcomes in Sarajevo Canton, 2024–25.

Outcome	Pollutant	Exposure window	n cases / N total	Adj. OR per 10 μg/m³	Lower 95% CI	Upper 95% CI	*p*-value	OR (95% CI)
Asthma	PM10	Study-period mean	114/1,499	**1.47**	**1.15**	**1.88**	**0.002**	**1.47 (1.15–1.88)**
	PM2·5	Study-period mean	78/1,193	1.13	0.78	1.65	0.519	1.13 (0.78–1.65)
	NO_2	Study-period mean	114/1,499	**0.59**	**0.42**	**0.82**	**0.002**	**0.59 (0.42–0.82)**
	SO_2	Study-period mean	133/1798	**1.50**	**1.20**	**1.88**	**<0.001**	**1.50 (1.20–1.88)**
Chronic bronchitis	PM10	Study-period mean	189/1,499	**0.73**	**0.59**	**0.91**	**0.004**	**0.73 (0.59–0.91)**
	PM2·5	Study-period mean	172/1,193	0.90	0.67	1.20	0.462	0.90 (0.67–1.20)
	NO_2	Study-period mean	189/1,499	**1.45**	**1.13**	**1.87**	**0.004**	**1.45 (1.13–1.87)**
	SO_2	Study-period mean	212/1798	0.88	0.73	1.07	0.208	0.88 (0.73–1.07)
Allergic disease	PM10	Study-period mean	332/1,499	1.01	0.86	1.18	0.949	1.01 (0.86–1.18)
	PM2·5	Study-period mean	279/1,193	1.06	0.84	1.34	0.609	1.06 (0.84–1.34)
	NO_2	Study-period mean	332/1,499	1.06	0.86	1.30	0.585	1.06 (0.86–1.30)
	SO_2	Study-period mean	384/1798	0.99	0.85	1.15	0.895	0.99 (0.85–1.15)
Any cough ≥ 4 weeks	PM10	Study-period mean	392/1,499	**0.67**	**0.57**	**0.79**	**<0.001**	**0.67 (0.57–0.79)**
	PM2·5	Study-period mean	369/1,193	0.90	0.72	1.11	0.308	0.90 (0.72–1.11)
	NO_2	Study-period mean	392/1,499	**1.55**	**1.28**	**1.88**	**<0.001**	**1.55 (1.28–1.88)**
	SO_2	Study-period mean	456/1798	**0.65**	**0.56**	**0.75**	**<0.001**	**0.65 (0.56–0.75)**

[a]Associations with an OR < 1·00 for PM10 (chronic bronchitis, cough) and SO2 (cough) are indicated in the table. Adjusted odds ratios (aOR) per 10 μg/m³ from binary logistic regression, adjusted for age (years), sex, household solid-fuel heating (yes/no), regular environmental tobacco-smoke exposure (yes/no), and season of visit. Bolded cells indicate raw $p < 0{\cdot}05$; FDR-robust associations (Benjamini–Hochberg $q < 0{\cdot}05$ within the children's primary tier of 4 outcomes × 4 pollutants) are PM10 and SO_2 with asthma, NO_2 with chronic bronchitis, and NO_2 with any cough ≥ 4 weeks. Pre-specified 7-day and 30-day pre-visit exposure windows are not reported: cantonal air-quality monitoring records had a complete measurement gap from 1 March 2025 to 30 April 2025, and visit dates fell either within or after this gap, so no child's pre-visit lookback window was covered by observed daily concentrations. NO_2 monitoring additionally ended 28 February 2025. aOR, adjusted odds ratio. CI, confidence interval. FDR, false-discovery rate. NO_2, nitrogen dioxide. PM10, particulate matter ≤ 10 μm aerodynamic diameter. PM2·5, particulate matter ≤ 2·5 μm aerodynamic diameter. SO_2, sulfur dioxide. Bolded numbers are statistically significant.

mean NO2 and chronic bronchitis (aOR 1·45) and any cough (aOR 1·55) in children is consistent in both magnitude and direction with the pooled estimates from the ESCAPE childhood respiratory work (22) and with the recent meta-analyses on traffic-related air pollution and childhood respiratory symptoms (23). NO2 at the concentrations we observed in the urban core of Sarajevo Canton (median 30·7–40·7 μg/m³) has been linked to chronic airway inflammation through oxidative-stress and innate-immunity pathways in controlled-exposure studies (4, 24), offering biological plausibility for the association observed here. Short-term exposure studies in comparable urban settings are consistent with these mechanisms: in a cross-sectional study of 326 healthy non-smoking adults in Turkey, higher same-day and 5-day mean air-quality index values were associated with lower leukocyte, lymphocyte, and platelet counts and with reduced FEV1/FVC and mid-expiratory flows (25). The adult NO2-cough association (aOR 1·76 per 10 μg/m³) is also consistent in

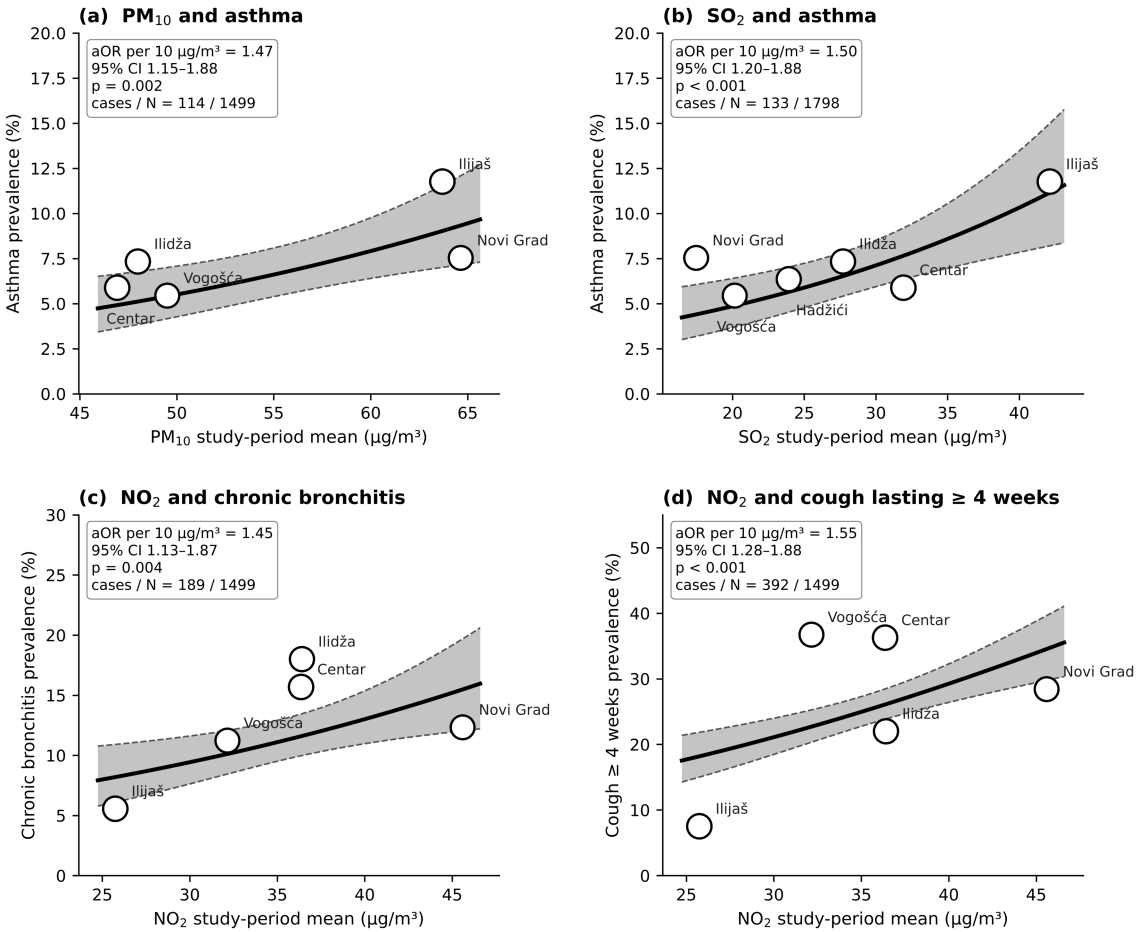


FIGURE 3
Adjusted exposure-response curves for the four pollutant-outcome associations in children, Sarajevo Canton, 2024–25. Each panel shows the model-predicted prevalence of the outcome (solid black line) as a continuous function of the corresponding pollutant's study-period mean concentration over the observed exposure range, with the 95% confidence interval on the predicted prevalence shown as the shaded grey band. Predictions are derived from the multivariable logistic regression reported in Table 4, holding age, sex, household solid-fuel heating, environmental tobacco-smoke exposure, and season of visit at their population means or empirical proportions; confidence intervals are computed by the delta method. Open circles mark the observed crude prevalence in each of the six paediatric catchment municipalities (Centar, Hadžići, Ilidža, Ilijaš, Novi Grad, and Vogošća), with the symbol area scaled to the analytic sample size in that municipality. Panels: **(a)** PM_{10} and physician-diagnosed asthma (adjusted *OR* per 10 µg/m^3 1·47, 95% CI 1·15–1·88; p = 0·002; n = 114/1,499); **(b)** SO_2 and physician-diagnosed asthma (1·50, 1·20–1·88; p < 0·001; 133/1798); **(c)** NO_2 and physician-diagnosed chronic bronchitis (1·45, 1·13–1·87; p = 0·004; 189/1,499); **(d)** NO_2 and any cough lasting at least 4 weeks in the past 12 months (1·55, 1·28–1·88; p < 0·001; 392/1,499). aOR, adjusted odds ratio. CI, confidence interval. FDR, false-discovery rate. NO_2, nitrogen dioxide. PM_{10}, particulate matter ≤ 10 µm aerodynamic diameter. SO_2, sulfur dioxide.

direction with the European Community Respiratory Health Survey findings on NO2 and chronic respiratory symptoms in adults (26). The absence of any robust signal for adult asthma, chronic respiratory disease, hypertension, or diabetes in our sample of 883 participants contrasts with the positive findings reported in much larger ESCAPE/ELAPSE-pooled cohorts (5); this most likely reflects power constraints rather than an absence of effect—for an outcome with prevalence around 8% (asthma, chronic respiratory disease) and a true OR per 10 µg/m^3 of 1·10–1·15, our sample provided only 35–55% power, and the observed CIs are wide enough to be consistent with that range of effects.

This study has several strengths. To our knowledge it is the first population-based study to combine direct field measurement of physician-diagnosed respiratory and cardiometabolic outcomes with the cantonal regulatory monitoring network in Sarajevo, which is one of the most polluted urban environments in Europe. The municipality-stratified sampling design produced near-equal recruitment across the six paediatric and six adult catchments, and primary-care recruitment minimised the selection bias toward clinically severe cases that often shapes hospital-based studies.

Several limitations are present. First, exposure was assigned from a single regulatory station per municipality, so all participants in a municipality share one exposure value and the exposure contrast rests on five or six municipalities. This introduces three kinds of error. (i) Individual exposure varies around the municipal value because of traffic-corridor proximity, household-emission microenvironments, and time-activity patterns; this is mainly Berkson-type error, which widens confidence intervals but introduces little bias (27). (ii) The station value may differ from the true municipal average, for example if a station is sited close to a local source. Because exposure was taken from monitors rather than reported by participants, this error is unrelated to outcome status (non-differential) and in single-pollutant models would usually bias estimates toward the null. (iii) Sarajevo's topography adds a structured component: cold-air pooling concentrates pollution on the valley floor, so residents of higher-lying areas may be assigned higher exposure than

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TABLE 5 Adjusted odds ratios (per 10 μg/m³) for respiratory and cardiometabolic outcomes for adults (*n* = 883).

Outcome	Pollutant	Exposure window	n cases / N total	Adj. OR per 10 μg/m³	95% CI Lower	95% CI Upper	*p*-value
Asthma	PM10	Study-period mean	57/737	0.91	0.64	1.29	0.589
	PM10	Season mean	57/737	1.00	0.71	1.42	0.994
	PM2.5	Study-period mean	46/588	0.83	0.50	1.40	0.488
	PM2.5	Season mean	46/588	1.02	0.64	1.60	0.944
	NO2	Study-period mean	57/737	1.04	0.68	1.60	0.858
	NO2	Season mean	40/493	-	-	-	-
	SO2	Study-period mean	67/883	1.09	0.81	1.48	0.565
	SO2	Season mean	67/883	1.08	0.83	1.41	0.582
Chronic respiratory	PM10	Study-period mean	69/737	0.74	0.53	1.05	0.090
	PM10	Season mean	69/737	0.72	0.50	1.03	0.074
	PM2.5	Study-period mean	57/588	0.64	0.37	1.12	0.119
	PM2.5	Season mean	57/588	0.58	0.32	1.05	0.073
	NO2	Study-period mean	69/737	0.94	0.62	1.41	0.759
	NO2	Season mean	47/493	-	-	-	-
	SO2	Study-period mean	76/883	1.16	0.87	1.55	0.310
	SO2	Season mean	76/883	1.14	0.89	1.47	0.288
Hypertension	PM10	Study-period mean	188/737	0.90	0.70	1.16	0.424
	PM10	Season mean	188/737	0.87	0.67	1.12	0.277
	PM2.5	Study-period mean	148/588	0.88	0.60	1.30	0.535
	PM2.5	Season mean	148/588	0.85	0.59	1.22	0.373
	NO2	Study-period mean	188/737	1.01	0.73	1.39	0.963
	NO2	Season mean	141/493	-	-	-	-
	SO2	Study-period mean	229/883	1.09	0.87	1.36	0.463
	SO2	Season mean	229/883	1.03	0.85	1.24	0.784
Diabetes	PM10	Study-period mean	115/737	0.94	0.71	1.23	0.635
	PM10	Season mean	115/737	0.95	0.72	1.26	0.726
	PM2.5	Study-period mean	93/588	0.97	0.64	1.48	0.891
	PM2.5	Season mean	93/588	0.98	0.66	1.45	0.917
	NO2	Study-period mean	115/737	1.04	0.74	1.46	0.812
	NO2	Season mean	82/493	-	-	-	-
	SO2	Study-period mean	138/883	0.98	0.77	1.24	0.840
	SO2	Season mean	138/883	1.01	0.83	1.24	0.910
Any cough last year	PM10	Study-period mean	300/737	0.69	0.57	0.84	<0.001
	PM10	Season mean	300/737	0.78	0.63	0.95	0.016
	PM2.5	Study-period mean	277/588	0.97	0.73	1.28	0.806
	PM2.5	Season mean	277/588	1.11	0.85	1.45	0.434
	NO2	Study-period mean	300/737	1.76	1.37	2.25	<0.001
	NO2	Season mean	185/493	-	-	-	-
	SO2	Study-period mean	341/883	0.63	0.53	0.76	<0.001
	SO2	Season mean	341/883	0.77	0.65	0.90	0.001

[a]Inverse associations for PM10 and SO2 with cough in adults are interpreted as artefacts of between-municipality spatial confounding, consistent with the pattern observed in the paediatric cohort (see Discussion). aOR, adjusted odds ratio; CI, confidence interval; FDR, false-discovery rate.

TABLE 6 Sensitivity analyses: adjusted odds ratios (per 10 μg/m³).

Cohort / subset	Outcome	Pollutant	n cases / N	Adj. OR per 10 μg/m³	95% CI Lower	95% CI Upper	*p*-value
Children—School-age only	Asthma	PM10 study mean	94/880	1.49	1.14	1.95	0.004
	Asthma	PM2.5 study mean	69/733	1.27	0.85	1.90	0.236
	Asthma	NO2 study mean	94/880	0.67	0.46	0.98	0.038
Children—Heating 3-cat (clean = ref)	Asthma	PM10 study mean	114/1.499	1.49	1.16	1.90	0.002
Children—Winter only	Any cough last year	PM10 30-day	28/123	2.64	0.21	34.00	0.456
Adults—Long-term residents (≥15 y)	Chronic respiratory	PM10 study mean	65/655	0.70	0.49	1.01	0.054
	Chronic respiratory	PM2.5 study mean	53/512	0.56	0.30	1.05	0.070
	Chronic respiratory	NO2 study mean	65/655	0.90	0.59	1.38	0.640
Adults—Never-smokers only	Chronic respiratory	PM10 study mean	43/486	0.74	0.48	1.13	0.166
	Chronic respiratory	PM2.5 study mean	35/381	0.65	0.32	1.32	0.231
	Chronic respiratory	NO2 study mean	43/486	0.92	0.56	1.53	0.759
Adults—Heating 3-cat (clean = ref)	Asthma	PM10 study mean	57/737	0.87	0.61	1.23	0.429

aOR, adjusted odds ratio; CI, confidence interval; PM10, particulate matter ≤ 10 μm aerodynamic diameter; PM2·5, particulate matter ≤ 2·5 μm aerodynamic diameter; NO_2, nitrogen dioxide.

they experience. Because the share of hillside residents differs between municipalities, this error is not random between municipalities, even though it is unrelated to individual outcome status. With few municipalities, errors of types (ii) and (iii) do not average out, and the bias in any given estimate may run toward or away from the null; for example, the inverse associations of PM10 and SO2 with chronic bronchitis and cough are driven largely by Ilijaš, which has the highest PM10 and SO2 concentrations but the lowest reported prevalence of these outcomes. In addition, adults in the combined Stari Grad/Centar group were assigned the Centar station, although most of them live in Stari Grad, which has its own station with lower PM10 and SO2 concentrations; when these participants were instead assigned the Stari Grad station, the adult NO2-cough association was attenuated but remained positive. Address-level exposure models (land-use regression or dispersion modelling) are needed to resolve this limitation. Second, the cross-sectional spatial-contrast design with only six municipalities provides limited statistical leverage to separate the effect of air pollution from the effect of unmeasured municipality-level determinants of respiratory health (housing-stock age, neighbourhood socio-economic gradients, primary-care diagnostic intensity, and patient health-seeking behaviour). Also, several outcomes (asthma, chronic respiratory disease, hypertension, diabetes) had insufficient adult cases to detect the modest effect sizes typical of air pollution, as discussed above. Furthermore, our exposure assignment relied on the residential address at the time of the visit and did not incorporate occupational or commuting microenvironments. In addition, NO2 monitoring ended on February 28, 2025, so the NO2 exposure for all participants is the station mean for October 14, 2024, to February 28, 2025, a cold-season-only value. Because the study-period mean is a fixed station value, this does not create different errors for winter and summer visits, but it has two consequences for the NO2 associations, including the adult NO2-cough finding. First, winter means exceed annual means; if the winter-to-annual ratio is similar across stations, municipalities keep the same ranking and the per-10 μg/m³ OR is, if anything, smaller than it would be on an annual scale, biasing the estimate toward the null. Second, if the ratio differs between stations, for example where traffic contributes more to NO2 than heating, the ranking of municipalities could change and the direction of bias is unpredictable. The cough outcome covers the previous 12 months, which includes the 2024–25 heating season for every participant, so the NO2 exposure window and the symptom recall period largely overlap. The Benjamini-Hochberg correction for multiple testing was applied post-hoc rather than prespecified, which should be considered when interpreting the strength of evidence for individual associations. Finally, the six-municipality design produced substantial collinearity between co-located pollutants, as illustrated by the markedly unstable two-pollutant PM10-PM2·5 estimates (see Results); this limits our ability to attribute observed associations to a single pollutant rather than to the broader regional pollution mixture.

Finally, the cross-sectional design precludes any inference about temporal causality.

Despite these limitations, the consistency of the children's PM10-asthma, SO2-asthma, NO2-chronic bronchitis, and NO2-cough associations provide population-level epidemiological evidence that air pollution during the heating season is associated with clinically meaningful respiratory morbidity in children. These results may imply consequences at the individual-clinical level, where primary-care paediatricians in Sarajevo Canton should consider chronic exposure when evaluating children with recurrent lower-airway symptoms, and should counsel families on within-household mitigation (clean-fuel heating where economically feasible, indoor air-purification, behavioural reduction of outdoor exposure on high-pollution days). At the public-health-policy level, these findings are consistent with prioritising the residential-heating component of the cantonal Air Quality Plan (subsidised replacement of solid-fuel stoves, incentives for connection to district heating, and stricter enforcement of low-emission-zone provisions in the central-valley municipalities), which would be

expected to reduce population PM10, PM2·5, and SO2 concentrations; whether this would translate into a measurable reduction in paediatric respiratory morbidity cannot be established from a cross-sectional design and would require prospective evaluation. An extension of the present cohort with repeated symptom assessment, indoor-air sampling, and personal-monitor sub-studies would substantially strengthen causal inference. Also, increasing the number of adult participants at a sample size of 3,000 would also be required to detect the smaller effect sizes expected for adult cardiometabolic and chronic respiratory outcomes.

Conclusion

In Sarajevo Canton, PM10, PM2·5, NO2, and SO2 routinely and substantially exceed WHO 2021 24-h air-quality guidelines during the heating season. After multivariable adjustment, control of the false-discovery rate, and a comprehensive sensitivity programme, exposure to PM10 and SO2 was associated with higher odds of physician-diagnosed asthma in children, and exposure to NO2 was associated with higher odds of physician-diagnosed chronic bronchitis and prolonged cough in children and of prolonged cough in adults. These findings are consistent with prioritising mitigation of residential and traffic-related air pollution as a public-health target in this basin, and motivate longitudinal and multilevel follow-up to clarify the underlying associations.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of Public Health Center of the Sarajevo Canton number 01-06-33-2-1060-2/23 obtained on 02 April 2024. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

SM-D: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AiP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AK-K: Methodology, Project administration, Writing – original draft, Writing – review & editing. NF: Methodology, Supervision, Writing – original draft, Writing – review & editing. MH: Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. DB: Writing – original draft, Writing – review & editing. EH: Writing – original draft, Writing – review & editing. AŠ: Writing – original draft, Writing – review & editing. ArP: Conceptualization, Investigation, Software, Writing – original draft, Writing – review & editing. LS: Writing – original draft, Writing – review & editing. AJ: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. SŠ: Data curation, Writing – original draft, Writing – review & editing.

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Supplementary material

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