Environmental Pollution 410 (2026) 129064

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Early-life exposure to particulate matter and green spaces: Associations with infant growth

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A R T I C L E I N F O

Keywords:
Air pollution
Vegetation
Body mass index
Head circumference
Length

A B S T R A C T

Early-life exposure to air pollution and green space may influence child growth, but evidence across multiple anthropometric indicators is limited. We examined whether perinatal exposures to particulate matter (PM) and residential green space are associated with longitudinal changes in body mass index (BMI), length, and head circumference (HC). In 119,110 Flemish children, BMI-, length-, and HC-for-age z-scores were derived from well-baby clinic data. Perinatal PM_{10} and $PM_{2.5}$ concentrations were estimated using the RIO detrended-kriging interpolation model. Municipal green space was categorized into low, high, and total vegetation. Mixed-effects models incorporating a 5-degree-of-freedom natural cubic spline for child age, exposure-by-age spline interaction terms, and child-level random intercepts and age slopes were used to assess associations per interquartile-range (IQR) contrast in exposure, adjusting for key covariates and co-exposures. Associations varied nonlinearly across child age and growth outcome.At 12 months, an IQR increase in PM_{10} or $PM_{2.5}$ concentration was associated with lower HC-for-age z-scores (PM_{10}: B = −0.0499; 95% CI: −0.0606; −0.0393; $PM_{2.5}$: B = −0.0645; 95% CI: −0.0771; −0.0518), and inverse associations were observed between 6 and 24 months. Associations of PM with BMI-for-age and length-for-age changed direction across age. Total and high green-space exposures were associated with higher BMI-for-age and length-for-age at several ages, whereas associations with HC were inconsistent across green-space measures and ages. Low green-space exposure was associated with lower HC-for-age and length-for-age at several ages. Estimates were small, and urbanicity did not consistently modify associations. Most nominally significant associations remained significant after false-discovery-rate correction; exceptions were $PM_{2.5}$ exposure at 2 months and high and total green-space exposure at 12 months in relation to length-for-age. Perinatal air pollution and green space exposures showed small, nonuniform associations with early childhood growth that varied across child age and anthropometric outcomes.

1. Introduction

A growing body of research on environmental exposures, including air pollution and the built and natural environment, has identified the first 1000 days of life as a sensitive period for shaping long-term health outcomes (McIntyre et al., 2023). This period, spanning from conception through the second year of life, is marked by rapid physical growth, making it highly responsive to external influences (Shao et al., 2020). Among these, air pollution and exposure to residential green space have attracted attention as key modifiable environmental factors that may impact developmental and health trajectories. Studies have shown that early-life exposure to particulate matter (PM), including PM_{10} and $PM_{2.5}$, defined as particles with aerodynamic diameters ≤ 10 μm and ≤ 2.5 μm, respectively, is associated with adverse outcomes, such as low birth weight, impaired lung function, and increased risk of obesity and cardiometabolic disease (Brauer et al., 2024; Thaichana et al., 2025). Air

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https://doi.org/10.1016/j.envpol.2026.129064
Received 16 December 2025; Received in revised form 24 August 2026; Accepted 28 August 2026
Available online 4 September 2026

pollution can affect children's health in both the short and long term by damaging developing lungs, contributing to respiratory illnesses such as asthma and pneumonia, and potentially impairing cognitive and physical development (Aithal et al., 2023). In Belgium, overweight is common: 34.3% of Flemish adults are overweight, with 16.4% classified as obese (Vancoppenolle et al., 2020; Vlaams Instituut Gezond Leven, 2025), underscoring the relevance of environmental determinants from early life. Importantly, signs of excess weight are already evident in early childhood; the prevalence of overweight in two-year-olds in Flanders increased from 6.7% in 2011 to 11% in 2023 (Eetexpert, 2025).

Early childhood growth indicators, such as body mass index (BMI) and head circumference (HC), are critical for assessing both short- and long-term health. BMI is widely used as a proxy for adiposity, even in early life, and elevated BMI in infancy is associated with higher risk of overweight and metabolic disorders later in childhood (de Bont et al., 2020; Taveras et al., 2009). HC reflects early brain growth and is often used as an indicator of neurodevelopmental status. Length provides a measure of linear growth that may be sensitive to environmental and nutritional influences (Gale et al., 2004; Victora et al., 2010). Monitoring these parameters in the first years of life is therefore essential for identifying deviations from expected growth trajectories and potential underlying risk factors, including environmental exposures.

Several studies have examined how environmental factors influence growth. Particulate matter exposures may influence early childhood growth; however, findings remain mixed and often focus on isolated outcomes. For instance, higher postnatal exposure to PM_{10} has been associated with greater BMI increases during early childhood (de Bont et al., 2020). However, other studies report inconsistent or null associations, with some suggesting that PM exposure may be associated with reduced weight or growth delay, particularly among children with low birth weight or other vulnerabilities (Ji et al., 2023). Thus, the available evidence does not consistently indicate whether particulate-matter exposure is associated with higher or lower early-childhood growth, and relatively few studies have examined several anthropometric indicators simultaneously.

Residential green space has been linked to lower BMI growth over time (de Bont et al., 2020). Research on green space has also reported associations with outcomes beyond weight-related measures, including improved neurodevelopment and reduced risk of stress-related disorders (Dadvand et al., 2019; Markevych et al., 2017). Given that HC has been associated with cognitive development in childhood (Koshy et al., 2021), it may provide additional insight into potential developmental benefits of green-space exposure. However, evidence concerning residential green space and physical growth during infancy remains limited and inconsistent. Most available studies have focused on BMI or developmental outcomes rather than simultaneously examining BMI, HC, and length during infancy. Consequently, associations between residential green space and different dimensions of physical growth during the first years of life remain unclear.

Understanding how early-life exposure to environmental factors, such as air pollution and green space, is associated with physical growth is essential for developing effective prevention strategies targeting childhood overweight and related health risks (Kim et al., 2016). Moreover, much of the available evidence comes from non-Belgian populations, which may differ in terms of exposure levels, environmental policies, urban design, and healthcare access. Relatively few studies have examined particulate matter and residential green space together or evaluated their associations with multiple dimensions of early growth, including BMI, head circumference, and length. Moreover, to our knowledge, these relationships have not previously been examined in a large Flemish infant population. This study addresses these research gaps by using a large, population-based longitudinal dataset from Flanders, including repeated anthropometric measurements during the first three years of life. By linking these health data with modeled environmental exposure estimates, specifically PM_{10}, $PM_{2.5}$, and residential green space, we evaluated both environmental exposures in relation to multiple indicators of early growth. Therefore, our study aims to investigate the associations between perinatal exposure to PM_{10}, $PM_{2.5}$, and green space and repeated measures of BMI, HC, and length in Flemish children from birth to 3 years of age.

2. Methods

2.1. Design and study population

We conducted a longitudinal population study of infants born in Flanders in 2018, 2019, and the first quarter of 2020, using data from the Flemish well-baby clinics (Kind & Gezin [K&G]). K&G provides preventive child healthcare (PCHC) in Flanders for infants up to 3 years of age, including routine growth and development monitoring.

The original dataset included all children born in 2018 (n = 65,079), 2019 (n = 64,485), and Q1 2020 (n = 31,961). Among children with baseline covariate information available, the analytic-eligible dataset included 159,381 children. For this analysis, we applied several exclusion criteria: gestational age < 24 weeks (n = 62), change of municipality of residence since birth during follow-up (n = 32,267), and birth in a small municipality for which the NIS code could not be disclosed for privacy reasons (n = 1180). Infants without any anthropometric measurements were also excluded (n = 6762). The final analytic sample (n = 119,110) was obtained after these exclusions. The participant selection process is shown in Supplementary Fig. S2.

2.2. Physical growth

Physical growth was assessed using three standardized indicators: BMI-for-age z-scores, HC-for-age z-scores, and length-for-age z-scores. BMI was calculated from measured weight and length as weight (kg) divided by squared length (m^2). Age- and sex-standardized z-scores for BMI, HC, and length were derived using the Flemish LMS growth reference (Roelants et al., 2009). Implausible z-scores, defined as values below −5 or above +5, were flagged and excluded unless deemed plausible upon review (e.g., in preterm infants with low but biologically reasonable HC values).

2.3. Particulate matter (PM)

In our study, both PM_{10} and $PM_{2.5}$ were analyzed as environmental risk factors. Their daily mean concentrations (μg/m^3) were obtained from the Interregional Cell for the Environment (IRCEL), which compiles data from 19 monitoring stations across Flanders. Concentrations were estimated on a 4×4 km^2 grid using the RIO interpolation model, a detrended kriging approach that combines monitoring data with land-cover information from the CORINE land-cover dataset (Janssen et al., 2008). In brief, RIO first removes local land-use-related variation from monitoring-site concentrations using a pollutant-specific land-use indicator, interpolates the detrended values using ordinary kriging, and then reintroduces the local component through re-trending. Model performance was evaluated by a leave-one-out cross-validation approach. In previous validation work, cross-validation was performed at the monitoring-station level, and the RIO model explained more than 80% of the overall spatiotemporal variability in PM and 78% of the variability in NO_2 concentrations in Flanders, Belgium (Lefebvre et al., 2011; Maiheu et al., 2013). Due to privacy regulations, exposure estimates were assigned at the municipal level. Although municipality-level exposure assignment is less spatially resolved than individual residential estimates, it is a pragmatic and widely accepted approach for large population-based studies covering the entire Flemish birth cohort, where individual-level exposure assessment is not feasible (Piel et al., 2020). Daily values were then averaged by municipality and calendar quarter to estimate perinatal exposure, and each child was assigned the quarterly average corresponding to their birth quarter. In this study, perinatal exposure was defined as a municipality-level exposure window surrounding birth, including late pregnancy and the early neonatal phase. However, because exposure estimates were available at an aggregated time scale, we were not able to disentangle prenatal from early postnatal exposure.

2.4. Green space

Municipal-level green space data were obtained from the 2012 Green Map of Flanders, developed using orthophotos captured during the summer (Agency Digital Flanders, 2012). The map classified the green spaces into four distinct categories: 'High Green', 'Low Green', 'Not Green', and 'Agriculture'. The current analysis focused on 'Low Green', 'High Green', and 'Total Green'. In this classification, 'Low Green' and 'High Green' refer to vegetation structure based on height, rather than to the amount, quality, or accessibility of green space. Following the Green Map of Flanders classification, 'Low Green' refers to vegetation below 3 m in height, 'High Green' refers to vegetation taller than 3 m. 'Total Green' represents the combined extent of both. 'Not Green' was not included because it represents non-vegetated land cover, while agricultural land was excluded because it does not adequately reflect children's beneficial exposure to greenness due to seasonal variability and potential presence of pesticides. In addition, only a very small number of children reside in predominantly agricultural areas. Low, high and total green space were quantified as the percentage of the total surface area of a municipality.

2.5. Covariates

Covariates were included in the analyses, as they were expected to be associated with physical growth and/or the exposures. These included the child's sex ("male" vs "female") (Shah et al., 2020), birth weight, maternal educational background ("low", no secondary school certificate; "middle", completion of secondary education or post-secondary non-tertiary education, and "high", higher education diploma) (Lakshman et al., 2013), gestational age in weeks (Lerbech Vinther et al., 2023), breastfeeding status at 6 months ("exclusive," "partial," "none"), maternal nationality ("Belgian," "Other Northwestern Europe," "Rest of Europe," "Non-western countries") (Sacker & Kelly, 2012; Schembari et al., 2015), and urbanicity ("rural," "semi-urban," "urban") (O'Leary, 2023; Yang et al., 2023). Covariates were collected around childbirth.

2.6. Statistical analyses

Categorical variables were summarized as frequencies and proportions, and continuous variables as mean, median, standard deviation (SD), and interquartile range (IQR). Individual growth profiles were visualized for up to 50 randomly sampled children per calendar year. To assess potential selection bias from excluding children who relocated, baseline characteristics were compared between included and excluded children using chi-square tests for categorical variables and t-tests for continuous variables.

To examine the associations between PM and green space exposures and early childhood growth, linear mixed-effects models with natural cubic splines for age were fitted using PROC GLIMMIX in SAS (version 9.4). A Gaussian distribution with an identity link was specified, and empirical sandwich covariance estimates were used for statistical inference. Models included child-level random intercepts and random slopes for age (months). All primary models were adjusted for year of birth, urbanicity, maternal nationality, maternal education, child sex, birth weight, breastfeeding status at 6 months, gestational age in weeks, and the relevant environmental co-exposure. Specifically, PM models included total green space as the co-exposure, whereas green space models included PM_{10} as the co-exposure; co-exposures were entered as continuous IQR-scaled variables. Total green space was used as the co-exposure in PM models to represent overall municipal vegetation, whereas PM_{10} was used in green-space models as the broader particulate matter indicator. These choices avoided redundancy between total, high, and low green space and overlap between PM_{10} and $PM_{2.5}$. We also conducted a prespecified stratified analysis by urbanicity to explore possible effect modification. In these stratified analyses, urbanicity was not additionally included as a covariate within strata. Child age was modeled using a natural cubic spline to capture potential nonlinear relationships smoothly, without assuming a single linear or low-order polynomial form or prespecifying developmental change points (Durrleman & Simon, 1989; Elhakeem et al., 2022). Candidate age functions comprising a linear specification and natural cubic spline specifications with 3, 4, and 5 degrees of freedom were fitted using maximum likelihood, while retaining the same covariate adjustment and random-effects structure. For each exposure-outcome combination, constant, linear exposure-by-age, and 5-degree-of-freedom spline interaction models were compared using AIC, BIC, and likelihood-ratio tests, with the same age spline, covariate and co-exposure adjustment, analytic sample, and random-effects structure.

Prior to modeling, PM_{10}, $PM_{2.5}$, total green, high green, and low green were scaled by their respective IQR. Consequently, all regression coefficients represent the adjusted difference in the outcome per 1-IQR increase in the exposure. Each final model included the IQR-scaled exposure, the natural cubic spline terms for child age, and interactions between the exposure and all age-spline terms. These interactions allowed the exposure-outcome association to vary nonlinearly across child age. Adjusted age-specific exposure associations and 95% confidence intervals were estimated at birth and at 2, 6, 12, 18, 24, and 36 months. Continuous age-varying association curves and their 95% confidence intervals were also plotted across the full follow-up period from birth to 36 months. Because exposure was assessed once during the perinatal period, these estimates describe how the association with a fixed perinatal exposure differed according to the child's age at outcome assessment. They do not represent distinct exposure windows at the selected ages.

Estimates and 95% confidence intervals (CIs) were reported per IQR increase in PM and green space exposures, and a p-value < 0.05 was considered statistically significant. Model assumptions were assessed by visual inspection of residual and fitted-value plots, and multicollinearity in co-exposure models was evaluated using variance inflation factors. To account for multiple testing, we applied the Benjamini-Hochberg false discovery rate procedure (Benjamini & Hochberg, 1995).

Ethical approval

This study received ethical approval from the Social and Societal Ethics Committee of KU Leuven (G-2022-5246-R2(MAR)). The study was based on secondary data and did not include any identifying information on the children, thereby ensuring participant anonymity and confidentiality.

3. Results

3.1. Baseline characteristics and model selection

We analyzed data from 119,110 unique children aged 0-3 years, contributing a total of 1,051,940 anthropometric measurements during the study period (2018, 2019, and the first quarter of 2020). The majority of children were born at term (92.9%), and 76.1% of mothers were of Belgian nationality. Overall, 51.4% of children lived in semi-urban areas, and 57.2% of mothers had a high level of education (Table 1). Individual BMI z-score, HC z-score, and length-for-age z-score values over time for a random sample of children are shown in Supplementary Fig. S1. These figures illustrate substantial variability in early growth across individuals, especially during the first six months of life. Children excluded due to residential mobility to another municipality during follow-up differed slightly from those included in terms of maternal

Table 1
Baseline characteristics of the study population included in 2018, 2019, and the first quarter of 2020 (N = 119,110).

Characteristic		
Sex (missing: n = 0)		
Males	n (%)	60,739 (51.0)
Females	n (%)	58,371 (49.0)
Gestational age in weeks (missing: n = 521)		
Mean (min, max; SD)		38.9 (24, 44; 1.7)
24-36 weeks	n (%)	8434 (7.1)
≥ 37 weeks	n (%)	110,155 (92.9)
Maternal education level (missing: n = 4612)		
Low[a]	n (%)	14,628 (12.8)
Middle[b]	n (%)	34,396 (30.0)
High[c]	n (%)	65,474 (57.2)
Urbanicity (missing: n = 0)		
Rural	n (%)	15,897 (13.3)
Semi-urban	n (%)	61,210 (51.4)
Urban	n (%)	42,003 (35.3)
Breastfeeding status at 6 months (missing: n = 9872)		
Exclusive	n (%)	12,995 (11.9)
Partial	n (%)	73,402 (67.2)
None	n (%)	22,841 (20.9)
Maternal nationality (missing: n = 9771)		
Belgian	n (%)	83,220 (76.1)
Other Northwestern Europe	n (%)	503 (0.5)
Rest of Europe	n (%)	13,743 (12.6)
Non-western countries	n (%)	11,873 (10.9)
Exposures around birth		
PM_{10} (in µg/m^3) (missing: n = 0) Mean (min, max; IQR)		20.9 (10.6, 28.7; 5.2)
$PM_{2.5}$ (in µg/m^3) (missing: n = 0) Mean (min, max; IQR)		12.5 (4.3, 17.9; 5.4)
Low green (in %) (missing: n = 0) Mean (min, max; IQR)		18.3 (4.8, 33.0; 6.0)
High green (in %) (missing: n = 0) Mean (min, max; IQR)		19.1 (1.3, 64.4; 11.4)
Total green (in %) (missing: n = 0) Mean (min, max; IQR)		37.4 (6.8, 81.0; 13.2)

[a] No secondary school certificate.
[b] Completed secondary education or post-secondary non-tertiary education.
[c] Attainment of a higher education diploma.

education, maternal nationality, urbanicity, gestational age, and birth weight, whereas sex distribution was similar (Supplementary Table S4).

All candidate models converged. The 5-degree-of-freedom natural cubic spline provided the best fit for the main age function across all three growth outcomes (Supplementary Table S5). For the 15 exposure-outcome combinations, the spline interaction model had the lowest AIC for all combinations and the lowest BIC for 13 of the 15 exposure-outcome combinations; likelihood-ratio tests favored the spline over the linear interaction model for all combinations (all $P < 0.0001$). The spline interaction models were therefore used for the primary analyses (Supplementary Table S6).

3.2. BMI z-score over time in relation to particulate matter and green space exposures

Associations between PM exposure and BMI-for-age z-score varied across child age (Supplementary Table S1 and Fig. 1). Higher $PM_{2.5}$ exposure was associated with lower BMI-for-age z-scores at 6 and 12 months, followed by higher z-scores at 18 and 24 months. At 12 months, an IQR increase in $PM_{2.5}$ exposure was associated with a lower BMI-for-age z-score (B = −0.0238; 95% CI: −0.0357; −0.0119), whereas at 18 months it was associated with a higher BMI-for-age z-score (B = 0.0338; 95% CI: 0.0216; 0.0460). Higher PM_{10} exposure was associated with higher BMI-for-age z-scores at birth and 2 months, lower z-scores at 6 and 12 months, and higher z-scores from 18 to 36 months. At 12 months, the estimate was −0.0304 (95% CI: −0.0404; −0.0204), compared with 0.0307 at 36 months (95% CI: 0.0163; 0.0451).

Green-space associations were generally higher after early infancy. Higher total and high green-space exposures were associated with higher BMI-for-age z-scores from 6 to 36 months. Higher low green-space exposure was associated with a lower BMI-for-age z-score at birth but with higher z-scores from 6 to 36 months. At 36 months, the largest green-space estimate was observed for low green space (B = 0.0564; 95% CI: 0.0450; 0.0678). The corresponding estimates were 0.0211 for high green space (95% CI: 0.0117; 0.0305) and 0.0367 for total green space (95% CI: 0.0273; 0.0462).

3.3. Head circumference z-score over time in relation to particulate matter and green space exposures

Associations between PM exposure and HC z-score also varied across child age (Supplementary Table S1 and Fig. 2). Higher $PM_{2.5}$ exposure was associated with lower HC z-scores from 6 to 24 months. The largest difference was observed at 12 months, when an IQR increase in $PM_{2.5}$ exposure was associated with a lower HC z-score (B = −0.0645; 95% CI: −0.0771; −0.0518). Higher PM_{10} exposure was associated with higher HC z-scores at birth and 2 months, followed by lower z-scores from 6 to 24 months. At 12 months, the estimate was −0.0499 (95% CI: −0.0606; −0.0393).

Green-space associations with head circumference were smaller than

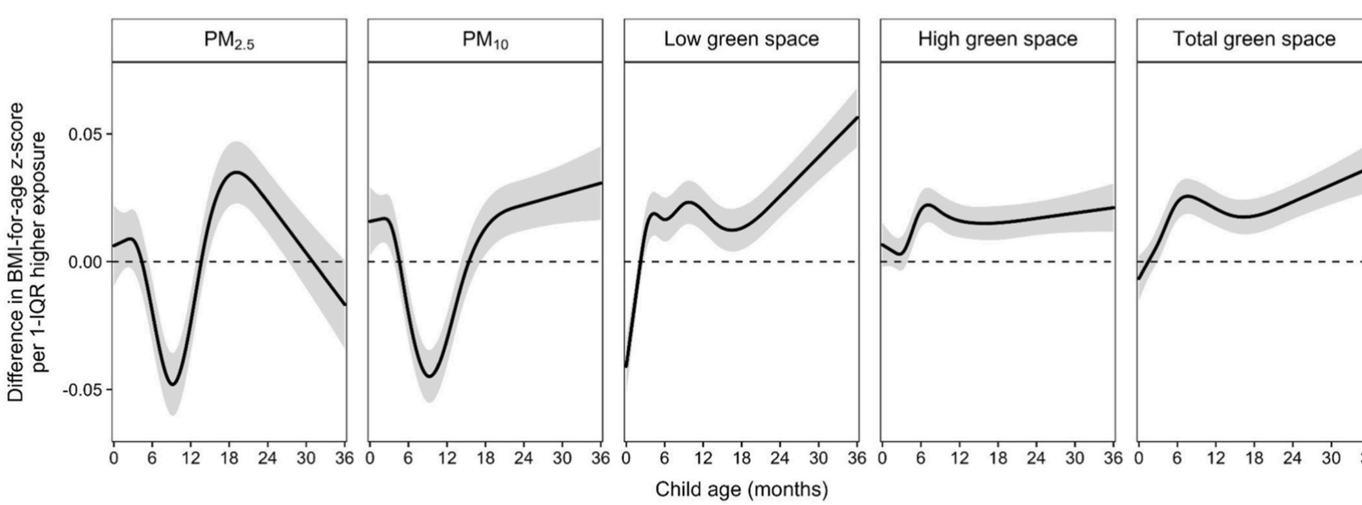

Fig. 1. Associations of perinatal particulate matter and green-space exposures with BMI-for-age z-score across child age. Solid lines show adjusted estimates, shaded areas show 95% confidence intervals.

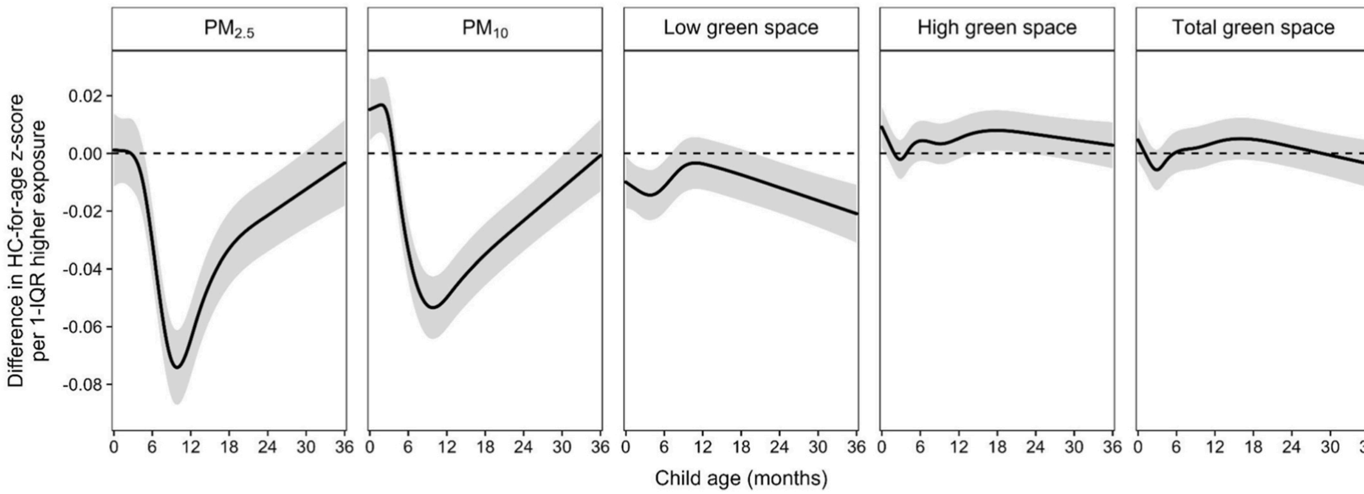

Fig. 2. Associations of perinatal particulate matter and green-space exposures with head-circumference-for-age z-score across child age. Solid lines show adjusted estimates, shaded areas show 95% confidence intervals.

those observed for particulate matter. Higher high green-space exposure was associated with slightly higher HC z-scores at birth and 18 months. Higher low green-space exposure was associated with lower z-scores at birth, 2, 6, 24, and 36 months. At 36 months, the estimate for low green space was −0.0209 (95% CI: −0.0309; −0.0109). There was no clear evidence of an association between total green space and HC z-score at the selected ages.

3.4. Length-for-age z-score over time in relation to particulate matter and green space exposures

Associations between PM exposure and length-for-age z-score changed in magnitude and direction across child age (Supplementary Table S1 and Fig. 3). Higher $PM_{2.5}$ exposure was associated with a lower length-for-age z-score at birth, higher z-scores at 2 and 6 months, lower z-scores at 12 and 18 months, and higher z-scores at 24 and 36 months. At 12 months, the estimate was −0.0762 (95% CI: −0.0885; −0.0639), compared with 0.1229 at 36 months (95% CI: 0.1068; 0.1391). Higher PM_{10} exposure was associated with higher length-for-age z-scores from birth to 6 months, a lower z-score at 12 months, and higher z-scores at 24 and 36 months. At 12 months, the estimate was −0.0507 (95% CI: −0.0611; −0.0403), whereas at 36 months the estimate was 0.0927 (95% CI: 0.0790; 0.1064).

Higher low green-space exposure was generally associated with lower length-for-age z-scores, with lower estimates observed at birth, 2, 6, 18, 24, and 36 months. The largest lower estimate was observed at 36 months (B = −0.0631; 95% CI: −0.0740; −0.0523). Higher high and total green-space exposure showed smaller and less consistent associations. High green space was associated with higher length-for-age z-scores at birth, 2, 12, 18, and 24 months. Total green space was associated with higher z-scores at birth, 12, and 18 months, but with a lower z-score at 36 months (B = −0.0135; 95% CI: −0.0224; −0.0045).

3.5. Stratified analyses

Stratification by urbanicity showed some variation in age-specific estimates across rural, semi-urban, and urban strata, including differences in magnitude and occasionally direction. However, no consistent pattern of effect modification was observed across exposures, growth outcomes, or child's age; detailed results are provided in Supplementary Table S2.

3.6. Multiple testing correction

Following Benjamini-Hochberg correction of the age-specific estimates from the spline model, most of the stronger associations remained statistically significant. Three associations with length-for-age z-score no longer met the corrected significance threshold: $PM_{2.5}$ exposure at 2 months, high green-space exposure at 12 months, and total green-space exposure at 12 months. All nominally significant age-specific associations with BMI-for-age and head-circumference-for-age z-scores remained significant after correction. The corrected p-values are presented in Supplementary Table S3.

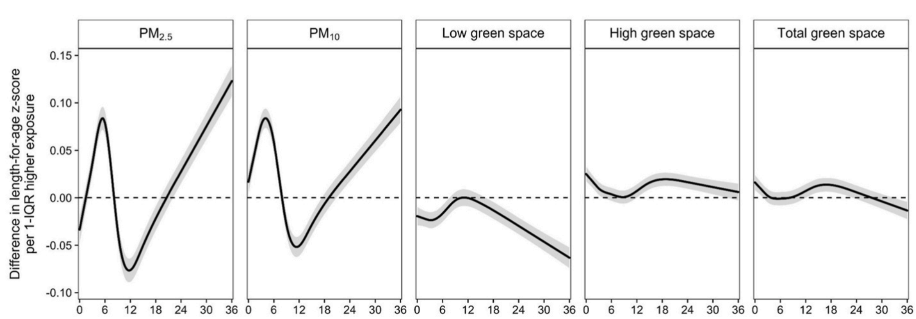

Fig. 3. Associations of perinatal particulate matter and green-space exposures with length-for-age z-score across child age. Solid lines show adjusted estimates, shaded areas show 95% confidence intervals.

4. Discussion

In this large longitudinal cohort, perinatal PM and green-space exposures showed small, nonlinear associations with child growth that varied across child age and anthropometric outcome. Higher PM_{10} and $PM_{2.5}$ exposures were most consistently associated with lower HC-for-age z-scores from 6 to 24 months, whereas associations with BMI-for-age and length-for-age changed direction across follow-up. Total and high green-space exposures were generally associated with slightly higher BMI-for-age and length-for-age z-scores at several ages, while associations with HC were mostly null. Stratification by urbanicity did not reveal a consistent pattern of effect modification. Although many age-specific associations remained after correction for multiple testing, the estimated differences were small, and their clinical relevance is uncertain. Nevertheless, small differences that occur systematically across large populations may, under some circumstances, have population-level relevance (Matthay et al., 2021; Rose & Day, 1990).

The unexpected positive associations between green-space exposure and BMI warrant cautious interpretation. Stratified analyses by urbanicity did not reveal a clear pattern that could account for these findings. These patterns were broadly similar across rural, semi-urban, and urban strata, providing little evidence that the positive associations between green-space exposure and BMI were explained solely by differences in urbanicity.

The PM findings were only partly consistent with previous literature, which has also reported mixed results. A recent systematic review and meta-analysis involving over 101,000 children and adolescents aged 0-19 years reported that higher exposure to PM_{10} and $PM_{2.5}$ was associated with a 6% and 7% increased risk of overweight or obesity, respectively (Parasin et al., 2021). Another meta-analysis of 27 studies including participants aged $\leq$ 19 years found consistent positive associations between air pollution and weight-related outcomes. Stronger effects were observed in adolescents (10-19 years) compared to younger children ($\leq$10 years) for $PM_{2.5}$, while PM_{10} effects were slightly more pronounced in early childhood (Zheng et al., 2024). However, these pooled estimates are not directly comparable with our age-specific findings because of differences in age, exposure period, outcome definition, and analytical approach. In our study, the associations between PM exposure and BMI-for-age changed direction across child age rather than showing a consistently higher or lower BMI-for-age pattern. Other studies have reported no significant associations between prenatal or early-life exposure to PM_{10} or $PM_{2.5}$ and repeated BMI measures in childhood (Fleisch et al., 2019). Differences across studies may reflect variation in exposure levels, timing, participant age, confounder adjustment, outcome assessment, and exposure-estimation methods.

Additionally, several studies have reported inverse associations between prenatal exposure to PM_{10} and $PM_{2.5}$ and newborn HC. In European cohorts, increased exposure to PM_{10} during the third trimester was associated with reduced fetal head size (Pedersen et al., 2016). Ultrasound-based studies have also observed smaller HC in relation to mid-to late-pregnancy PM_{10} exposure (Smarr et al., 2013; Zhao et al., 2018). A Chinese study similarly found that PM_{10} and $PM_{2.5}$ exposure during pregnancy was associated with smaller neonatal HC (Hu et al., 2023). These findings are broadly consistent with our inverse associations of PM_{10} and $PM_{2.5}$ with HC-for-age, which were most evident between 6 and 24 months.

Studies examining the effects on length have reported similar associations. A Chinese study of children under 5 years reported that higher exposure to PM_{10} and $PM_{2.5}$ was associated with lower length-for-age z-scores and increased risk of stunting (X. Li et al., 2023). Studies in Poland (Klis & Wronka, 2020) and a large birth cohort in Hong Kong (Huang et al., 2018) also reported shorter attained height following higher early-life or childhood PM_{10} exposure. Our length-for-age findings were less consistent with this predominantly inverse literature. Associations with both PM_{10} and $PM_{2.5}$ changed direction across child age, and did not indicate a uniform association between higher PM exposure and slower linear growth. Differences between our findings and those of previous studies may reflect variation in exposure timing and levels, participant age, particle composition, outcome assessment, confounder adjustment, and exposure-estimation methods.

Several studies have reported associations between residential green space and indicators of fetal or child development, including fetal growth, bone mineral density, and brain development (Q. Li et al., 2025; Sleurs et al., 2024; Torres Toda et al., 2022). Several pathways have been proposed in the literature to explain these associations. Green space may reduce exposure to air pollution, environmental noise, and heat, while supporting stress reduction, social interaction, and physical activity (Markevych et al., 2017). Reduced exposure to air pollution may lessen oxidative stress, systemic inflammation, and vascular dysfunction, supporting placental function and fetal growth (Fussell et al., 2024). Reduced psychosocial stress may also influence neuroendocrine regulation, with potential consequences for fetal development and childhood metabolic processes (O'Donnell et al., 2009; Pervanidou & Chrousos, 2011). Greater opportunities for physical activity may additionally influence energy balance and weight-related development during childhood (Jia et al., 2021).

Our findings were partially consistent with previous evidence concerning green space and physical growth. Higher total and high green-space exposures were associated with slightly higher length-for-age z-scores at several ages, suggesting a modest positive association with linear growth. However, associations with HC-for-age were generally small and mostly null, although some age-specific associations were observed for high and low green-space exposure.

In contrast, our study found that greater exposure to high and total green space was associated with higher BMI at several ages. This unexpected finding should be interpreted with caution, as our green space exposure metric was relatively coarse. It was based on municipality-level percentage cover derived from the 2012 Green Map of Flanders and therefore may not fully reflect contemporaneous, individual-level exposure, accessibility, quality, or actual use (Frank et al., 2007). This contrasts with much of the existing literature, which generally reports that green space is associated with a lower risk of obesity in older children (Dadvand et al., 2019; de Bont et al., 2020; Markevych et al., 2017), while evidence in younger age groups remains limited. In Flanders, urban planning is often fragmented, with green areas that are discontinuous, poorly equipped, or lacking safe, child-friendly infrastructure (Verbeek & Tempels, 2016). Some types of green space captured by municipality-level vegetation measures, such as private gardens or wooded areas, may not be accessible or suitable for infants. Moreover, infants may have limited direct interaction with surrounding vegetation, and greener suburban environments may also coincide with greater car dependency or lower walkability, potentially attenuating expected benefits (Wilhelmsen et al., 2017). Finally, BMI does not distinguish between fat and fat-free mass; in young children, a higher BMI may partially reflect greater muscle or bone mass, particularly if green space promotes physically engaging play (Collings et al., 2013). These findings underscore the need to consider both the quantity and quality of green space when evaluating its potential benefits for early physical development.

5. Strengths and limitations

A key strength of this study is its large sample size, which provided high statistical precision. The longitudinal design and repeated anthropometric measurements also enabled evaluation of associations across child age for three growth outcomes. However, several limitations should be acknowledged. First, the observational design precludes causal inference. Information on maternal smoking, maternal BMI, second-hand smoke, indoor environmental factors, outdoor time and sunlight-related factors, breastfeeding duration and complementary feeding practices, daycare attendance, and physical activity level was unavailable; therefore, residual confounding cannot be excluded. Some of these factors, including smoking, are associated with education level (Nakamura et al., 2020), which was included in the analyses.

Second, green space exposure data were from 2012, whereas PM exposure was derived from interpolated 4 × 4 km grids. These exposure metrics may not have fully captured individual- or neighborhood-level variation, potentially causing non-differential exposure misclassification. Privacy regulations precluded finer-scale exposure assessment or sensitivity analyses using residential buffers.

Additionally, actual use of green space by children and caregivers was unknown; recent evidence suggests that children are spending increasing amounts of time indoors, potentially limiting their interaction with natural environments (Nguyen et al., 2021).

Finally, exposures were assessed in a perinatal window spanning late pregnancy and the early postnatal period, precluding separation of prenatal and early-postnatal contributions and potentially obscuring time-specific associations. This assessment also did not capture variation across the full first 1000 days, a critical period for child development (Shao et al., 2020). Excluding children who relocated likely reduced exposure variability and may have introduced selection bias because excluded children differed slightly in maternal education, maternal nationality, and urbanicity (Supplementary Table S4). The direction and magnitude of this bias remain uncertain.

6. Implications for policy and research

Despite their modest magnitude, the observed associations may warrant population-health consideration given the widespread nature of PM and green-space exposures. The clearest unfavorable pattern in our study was observed for PM_{10} and $PM_{2.5}$ in relation to HC-for-age during infancy. This supports continued efforts to reduce childhood exposure to particulate matter, although associations with BMI-for-age and length-for-age were not consistently unfavorable. Increasing both the availability and accessibility of child-friendly green spaces remains an important urban-health objective; however, our mixed findings suggest that vegetation amount alone may be insufficient to support healthier growth. Green-space quality, accessibility, intended use, and broader residential characteristics should also be considered. Integrating environmental health considerations into urban design, transport planning, and childcare infrastructure, particularly in areas with high pollution or limited green space, may support healthier early-life environments and reduce unequal environmental exposures. For Flanders, the findings support evaluating air pollution and green space jointly rather than assuming that greener municipalities necessarily provide more beneficial environments for infant growth.

7. Conclusion

Our study observed small associations between PM (PM_{10} and $PM_{2.5}$) and green space exposure and early-life physical growth indicators, including BMI, HC, and length-for-age z-scores, among children living in Flanders, Belgium. The associations varied across child age and growth outcome, and some changed direction over follow-up. PM exposure showed the clearest inverse associations with HC during infancy, whereas associations with BMI-for-age and length-for-age varied in direction. Green-space associations were mixed across exposure measures, ages, and growth outcomes. These mixed findings for green space may reflect differences in its quality, accessibility, and actual use, which were not captured in the present study, despite distinguishing between low and high vegetation types at the municipal level. Overall, this study provides evidence from a large longitudinal cohort of children in Flanders that associations of perinatal PM and municipal green-space exposure with early childhood growth are nonlinear and differ across child age and anthropometric outcome. Early-life growth patterns have been associated with later childhood overweight, but the implications of the small exposure-related differences observed in this study for later health remain uncertain (Jones-Smith et al., 2013). Further research using more precise, time-resolved, and time-varying exposure assessments, as well as improved characterization of green space environments, is warranted to inform effective, targeted strategies that support optimal physical development in early childhood.

CRediT authorship contribution statement

Jackline Vicent Mbishi: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Lisa Schellemans:** Writing – review & editing, Conceptualization. **Tim S. Nawrot:** Writing – review & editing. **Esmee Bijnens:** Writing – review & editing. **Mathieu Roelants:** Writing – review & editing, Data curation. **Gunnar Naulaers:** Writing – review & editing. **Els Ortibus:** Writing – review & editing. **Marlou L.A. de Kroon:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. This study was approved by the Social and Societal Ethics Committee of KU Leuven. (Approval No. G-2022-5246-R2(MAR))

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used ChatGPT to improve grammar, clarity, and sentence structure. The authors subsequently reviewed and edited all content as needed and take full responsibility for the content of the published article.

Funding

This study was supported by Katholieke Universiteit Leuven (KU Leuven) under grant number ZKE1687-PS-AP.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project, conducted as a part of a PhD study, would not have been successful without the invaluable support of Opgroeien, a public agency in Flanders, Belgium, responsible for coordinating services related to child and family welfare. We would like to extend our deepest gratitude to them for their continued assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.129064.

Data availability

The data that has been used is confidential.

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