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To cite this article: Carissa L Lange *et al* 2025 *Environ. Res.: Health* **3** 041002

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ENVIRONMENTAL RESEARCH HEALTH

LETTER

Characterizing air and noise pollution and their determinants in elementary schools in Accra, Ghana

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Keywords: air pollution, environmental noise, noise annoyance, children, elementary schools, Accra, Ghana

Supplementary material for this article is available [online](#)

Abstract

In Sub-Saharan African (SSA) cities, elementary school environments may significantly contribute to children's exposure to environmental pollution, potentially affecting their health, development, and learning. Despite children spending much of their day at school, limited data exists regarding levels, inequalities, and determinants of air and noise pollution in school settings, particularly in rapidly urbanizing regions. As part of the Accra School Health and Environment Study (ASHES), we assessed air and noise pollution in primary schools across the Greater Accra Metropolitan Area, one of SSA's fastest-growing metropolises, and explored determinants of pollution levels around these schools. We conducted weeklong measurements of fine particulate matter (PM_{2.5}), black carbon (BC), and sound pressure levels in 90 schoolyards (74% public, 26% private). We assessed schoolyard characteristics (surface type, greenness, road proximity) and examined their associations with pollutants using generalized additive models. Additionally, we evaluated 1037 child responses to noise annoyance surveys. Annual equivalent PM_{2.5} concentrations exceeded WHO guidelines by 2–13 times (11–65 $\mu\text{g m}^{-3}$). Median noise levels (57 dBA) surpassed Ghana EPA standards at >60% of schools, coinciding with 60% of students reporting high noise annoyance. BC and noise were higher in public and more urban schools. In the most urbanized district, all pollutants were inversely associated with neighborhood socioeconomic status. Lower greenness correlated with higher BC levels; associations with other spatial factors were weak or not statistically significant. These findings underscore the need to reduce air and noise pollution at urban SSA schools and promote healthier, quieter environments that support learning and development.



OPEN ACCESS

RECEIVED

19 August 2025

REVISED

11 November 2025

ACCEPTED FOR PUBLICATION

4 December 2025

PUBLISHED

15 December 2025

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1. Introduction

Like all urban residents, children living in growing sub-Saharan African (SSA) cities benefit from the opportunities urban living offers. For example, urban children have health, developmental, and educational advantages over their rural counterparts [1–3]. However, living in cities also presents unique challenges, including exposure to poor environmental conditions such as air and noise pollution. Ambient air pollution has become a major public health concern in SSA cities as consequence of the ongoing urban and economic growth in the region [4, 5]. Environmental noise may also be a concern but has largely been understudied. Although times spent during daily commute are equally important, children's exposure to air and noise pollution occurs primarily at home and school environments, the two most important places where they spend much of their time. A safe, clean, and quiet school environment may foster physical, cognitive, and social development of children, while promoting general well-being and offering a positive space to learn and play [6]. Yet, little is known about the levels, variations, and determinants of air and noise pollution in schools in rapidly urbanizing SSA cities.

Data from studies, primarily conducted in cities across Western countries with distinct emission profiles, have linked childhood exposure to fine particulate matter (PM_{2.5}) to adverse lung and respiratory, cardiovascular, and metabolic outcomes [7–11]. Additionally, children's exposures to air pollution and transportation noise have been shown to influence sleep, behavior, learning, and cognition [12–20]. Consequently, studies have linked these pollutants to reduced academic performance (e.g. test scores, grade point averages, inattention) and increased school absenteeism, both of which have potential implications for future educational attainment and socioeconomic status (SES) in adulthood [19–25].

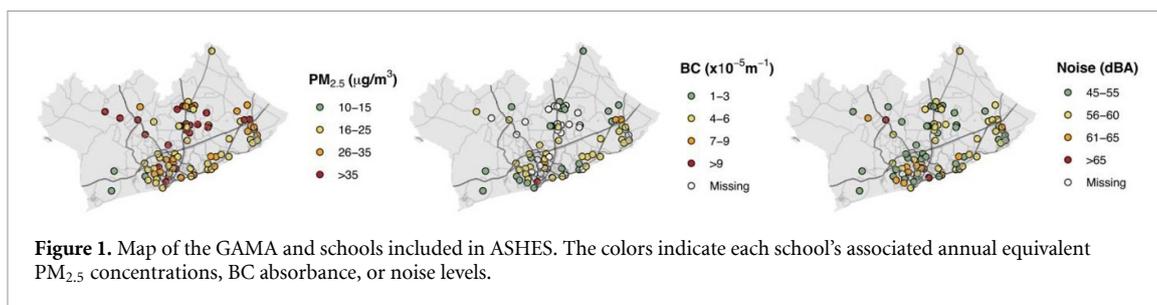
However, due to the complexity of SSA's urban environments, air pollutant emissions and environmental noise have both shared (e.g. road traffic) and distinct (e.g. loud street music from small businesses, household biomass use) local sources. Additionally, exposure patterns and school locations in SSA cities differ from those in high-income countries [26, 27]. A previous study in Accra, Ghana, found that schoolchildren's personal PM_{2.5} exposures were more than double those observed in the US, and factors such as schools' proximity to major roads, community biomass uses near schools, and materials of school ground surfaces all influenced children's personal exposures [28]. Still, it is unknown how much consideration is given to air quality and environmental noise in urban schools in SSA and how much data informs the locations of schools to ensure sufficiently clean and quiet environments conducive to healthy childhood development. Measurement data can motivate policies that specifically address air and noise pollution in existing schools or as new schools are being built, given the ongoing urban population growth and push for universal education in the region.

This paper provides a comprehensive assessment of school-related exposures including air pollution, noise, and green space within the urban environment in a major SSA city. We examined PM_{2.5}, black carbon (BC), and environmental noise pollution in both public and private elementary schools across the Greater Accra Metropolitan Area (GAMA), the most urbanized area of Ghana. We also investigated discordance/concordance, and socioeconomic inequalities, and quantified potential determinants of exposures. This study was part of the Accra School Health and Environment Study (ASHES), which was designed to examine the impact of multiple environmental exposures on key childhood health and developmental outcomes in a major SSA city. To our knowledge, this is the first study to provide a comprehensive assessment of outdoor air and noise pollution across elementary schools in one of SSA's fastest growing metropolises. By characterizing environmental exposure data across a diversity of school settings, our findings aim to inform public health and school-level interventions and urban planning efforts in similar low-resource urban environments.

2. Methods

2.1. Ethical approval

The study was approved by the Institutional Review Boards of the University of Massachusetts Amherst [00003909] and University of Ghana, Legon [ECH 149/ 18–19]. Additional permission to conduct research in schools was secured at the national, regional, and district offices of the Ghana Education Service (GES), along with approval from school head teachers. Written informed consent was obtained from school administrators and parent/guardian(s) as well as assent from the children. The overall research was conducted in accordance with the principles embodied in the Declaration of Helsinki and followed the Ghanaian local statutory requirements.



2.2. Study setting and design

Details of the ASHES design, school selection, and data are described elsewhere [29]. Briefly, our study was conducted in the GAMA, the largest metropolis in Ghana (~ 1500 km²) and home to nearly 6 million residents [30]. Ghana operates a 6-3-3-4 school system (i.e. from elementary to university). Basic education is compulsory and offered by both public and private schools. Public schools are free but are often considered overcrowded and lack resources, whereas private options are fee-paying and often favored by higher income earners for their purported better education. ASHES selected 100 schools from a geocoded list of ~ 700 public and ~ 2000 private primary schools obtained from GES for participation, but ten declined, leaving 90 public (74%) and private (26%) primary schools (figure 1). The schools were from all 13 GAMA districts. Low-income communities and localities in and around the most urbanized Accra (AMA) and Tema (TMA) metropolises have more elementary schools than the other adjoining districts in the GAMA. In these districts, we selected eight or nine public schools and two or three private schools per district, as opposed to four public and one private school in peri-urban districts. Public schools were purposefully over-represented, as that is where many national and local policy interventions are implemented. We recruited 1037 schoolchildren (mainly in grades 4 and 5) aged 8–12 years from the 90 participating schools for assessment of multiple health indicators and outcomes. Specifically, we targeted a total of ten 4th graders from each school with the aim of ensuring equal representation of both genders, and if this target was not met, 5th graders were invited to participate to complete the sample. This age group was chosen in part because they were just old enough to accurately respond to survey questions.

Between June 2022 and May 2023, we conducted week-long (7 d) measurements of ambient $PM_{2.5}$, BC, and sound pressure levels in the school yards. The monitors were deployed in five schools in each measurement week (e.g. Monday–Monday schedule) during the school months. Trained field assistants completed a structured survey during the deployment to gather information on the built environment of each school, including details of the surfaces of the schoolyard and playground (grass, paved, packed and loose dirt), ventilation (window types), neighborhood type (residential, commercial/business/industrial, background/other), greenness/vegetation, and commercial activity near the school (none, markets, other) (table S4).

We focused our measurements on outdoor schoolyard environments because most schools in Accra rely on natural ventilation, leading to minimal differences in air pollution levels between outdoor and in-classroom settings. In our study, 96% ($n = 86$) of the schools had louver blades, wooden, or hollow block windows that supported natural ventilation; only 4% had glass windows which could support mechanical ventilation, but they also relied on natural ventilation. Our decision to focus on schoolyards was also guided by prior studies in Accra neighborhoods and homes, as well as personal exposure assessments of schoolchildren, which found minimal differences in $PM_{2.5}$ and ultrafine particle levels between indoor and outdoor environments in the absence of direct household biomass burning [28, 31, 32]. Specifically for schoolchildren, factors such as proximity of schools to major roads, materials of schoolyard surfaces, and biomass use in the surrounding areas are known determinants of their personal $PM_{2.5}$ exposure in Accra [28]. These findings suggest that outdoor measurements at schools are a reasonable proxy for estimating schoolchildren's exposure in this context.

2.3. Data collection and analytical methods

2.3.1. $PM_{2.5}$ and BC

We measured both weeklong integrated gravimetric (filter-based) and real-time/continuous (minute-by-minute) $PM_{2.5}$ concentrations using the ultrasonic personal aerosol sampler [33] and the Zefan [34], respectively. $PM_{2.5}$ mass was collected on 37 mm Teflon membrane filters and were weighed pre- and

post-sampling using a MTL AH500 automated robotic scale in a climate-controlled room. Weekly integrated BC concentrations were estimated using the absorption coefficient (light absorbance) of the post-weighed $PM_{2.5}$ filters, which were determined by applying an image-based reflectance method [35]. Filters from 28 samples were excluded from the BC analysis due to filter loss or failure of the sample to meet our pre-specified inclusion requirements that instruments had to (i) operate for $\geq 75\%$ of the measurement period (i.e. at least 5 of 7 d) and (ii) record an average flow rate within 10% of the intended rate (1 l per minute). However, for $PM_{2.5}$, the missing integrated data were replaced with collocated corrected continuous monitor data. Specifically, we applied a correction factor (CF) to the minute-by-minute continuous $PM_{2.5}$ data, consistent with previous studies [36, 37]. CFs were calculated at schools that had both valid integrated and continuous data, such that the average of the continuous $PM_{2.5}$ data was set equal to the integrated sample. On average, the continuous monitors underestimated concentrations during the Harmattan season and overestimated in the non-Harmattan. Consequently, we applied season-specific mean CFs (Harmattan = 1.12; non-Harmattan = 0.83) to adjust continuous data at schools missing integrated samples.

Furthermore, since measurements did not occur simultaneously across all 90 schools to allow for school-to-school comparison, we accounted for the potential influence of time/season by applying a temporal adjustment factor (TAF). TAF was computed separately for each measurement week using data from ten fixed ambient monitoring stations located throughout the GAMA. Details regarding the ambient sites and the adjustment procedure have been previously published elsewhere [38]. In brief, a TAF for each measurement week was calculated as the ratio of the mean $PM_{2.5}$ or BC across all fixed sites during that week to the annual mean $PM_{2.5}$ or BC across those same sites. These weekly TAFs, ranging from 0.39 to 4.67 for $PM_{2.5}$ due to strong temporal variability in air pollution in Accra [36, 37], were then applied to each school's $PM_{2.5}$ (or BC) measurement. This resulted in an annual equivalent mean concentration for each school, enabling school-to-school comparison.

In addition to the annual equivalent mean concentrations, we also derived a unique school pollution metric that reflects exposures during school hours only—defined as 7 am to 3 pm, Monday through Friday (40 h/week total), using the corrected minute-by-minute/continuous data.

2.3.2. Environmental noise

Ambient sound pressure levels were measured in one-minute integrated intervals in A-weighted decibels (dBA) using Convergence Instrument's Noise Sentry sound level meter (SLM) [39]. We collected 445-school days of sound measurements, with one school having lost a full week of data due to equipment theft. We calculated a metric ($L_{\text{day}(\text{school})}$) of equivalent continuous sound levels, integrated across measurements conducted on school days (Monday–Friday) and during typical school hours (7 am–3 pm). The $L_{\text{day}(\text{school})}$ metric excluded data during break periods (i.e. hours when children go out into the schoolyard to play, typically between 9:30 am–10 am and 12 pm–12:30 pm), as we wanted to characterize the environmental noise that children experienced rather than the sound they created themselves (i.e. from laughing/playing/talking) (35 h/week total). The hourly equivalent continuous sound levels during the break periods were on average 0.7 dBA higher than the other school-time hours. Further, we also computed Leq_{wk} , a measure of equivalent continuous sound levels integrated over the entire measurement week. Finally, we calculated the intermittency ratio (IR) which describes the amount of intermittent sound in a specified period [40]. The IR represents the percentage (0%–100%) of sound energy that is created from distinct sound events that surpass a fixed cut-off value above the site and day-specific average equivalent continuous sound level. For this study, we used a threshold of 3 dBA above, in line with previous studies conducted in Accra [41]. Additional details regarding the IR calculation are included in the Supplementary Information.

2.3.3. Assessment of noise annoyance

The children responded to a noise annoyance survey through a set of 5-point verbal and 11-point numeric questions, in line with the 2003 Technical Standard by the International Standards Organization (ISO/TS 15666:2003) [42]. The questions evaluated the students' self-reported annoyance to noise generated by road-traffic, aircraft/planes, industry/factories, business/stores/churches, and neighbors within the past 12 months while in school (table S3). We caution that while these survey questions have been used as a validated instrument in adult populations and household settings for decades, they have not been validated specifically in children [42]. We used the students' responses to calculate three metrics describing the percentage of students 'highly annoyed' (HA) by noise exposure at school, where HA_N refers to numerical values of 8, 9, and 10 from the 11-point numeric questions, and HA_V considers the top two verbal response categories (i.e. very and extremely) to the 5-point verbal questions (Likert scale). The final metric, HA_{VW} , represents the top two verbal response categories to the 5-point verbal questions,

with ‘extremely’ weighted in full and ‘very’ weighted by a factor of 0.4. Because we observed consistency across all three HA metrics (table S1), only HA_N results are reported.

2.3.4. Features of the schools and neighborhood environments

We gathered information on known spatial and meteorological factors that could influence air and noise pollution in Accra school settings. We quantified vegetation greenness (range: 0–1) at each school using the normalized difference vegetation index (NDVI). NDVI values were calculated from spectral bands of green vegetation in Landsat 8 satellite imagery (U.S. Geological Survey) with the least amount of cloud cover (0.02%) using a circular buffer with a radius of 100 m [43]. NDVI values across our schools ranged 0–0.5, thus we further classified each school as either ‘bare soil’ (≤ 0.1) or ‘sparse vegetation’ (0.2–0.5), with none having ‘dense green vegetation’ (0.6–0.9). We computed distance of each school to the nearest major and secondary road using OpenStreetMap road network data. The schools were further categorized as residing within or beyond 500 m of a major road [44]. Meteorological variables, including daily temperature and relative humidity were collected at a fixed peri-urban background location, while rainfall data were obtained from the Ghana Meteorological Agency.

Further, we examined the association between a measure of SES of the neighborhood containing the school and the measured air and noise pollution levels. Indices of neighborhood SES were computed as the median log equivalized household consumption (Ghanaian Cedi (GHC)) of each census enumeration area (EA; the smallest geographic unit for census enumeration), based on household expenditures and rent information collected by the Ghana Living Standards Survey (GLSS) Round 6 [45]. The GLSS data were combined with the 2010 Ghana Population and Housing Census dataset to extrapolate relationships between consumption, area, and a variety of demographic features. We assessed school neighborhood SES on a continuous scale as well as by categorizing each school as below or above the median neighborhood SES.

2.3.5. Descriptive summaries

We reported summary statistics (medians and interquartile ranges (IQRs)) for $PM_{2.5}$, BC, $L_{\text{day(school)}}$, Leq_{wk} , and IR for all schools. We examined potential differences in air and noise pollutants by school type (public vs private), schoolyard surface (paved vs unpaved), and district (comparing the city core Accra Metropolitan Area (AMA), the port and industrial city of Tema (TMA), and all other adjoining peri-urban districts). We also examined the spatial correlation between the air pollutants and environmental noise to understand their degree of concordance. Further, we used Pearson correlation coefficients (r) to examine the associations between the pollutants and various features of the school environment including SES index, distance to nearest major road, and NDVI, with correlations interpreted as weak (< 0.3), moderate (0.3–0.5), or strong (> 0.5). We also specifically examined the pollutants in relation to neighborhood SES for schools residing in the most urbanized AMA. Finally, we described differences between HA_N across districts and estimated a noise annoyance exposure-response curve with focus on noise generated by road-traffic at school. The HA_N to road-traffic noise was calculated within 5 dB bins and the quadratic relationship was investigated.

2.3.6. Determinants of school-level $PM_{2.5}$, BC, and noise pollution

We used generalized additive models to examine the associations of the measured pollutants with their potential determinants. The models were adjusted for district (AMA, TMA, other), distance to major and secondary roads, commercial activity, NDVI score, schoolyard surface, school type (private vs public), and season (Harmattan vs non-Harmattan), using smoothing spline functions of weekly average rainfall, temperature and relative humidity, as these were found to be nonlinearly related to the pollutants. The variables were selected based on existing literature on determinants of air pollution in Accra [28, 45, 46]. The distribution of both $PM_{2.5}$ and BC concentrations were right-skewed, and as such, were log-transformed to achieve normality. These models were used primarily for exploratory analysis.

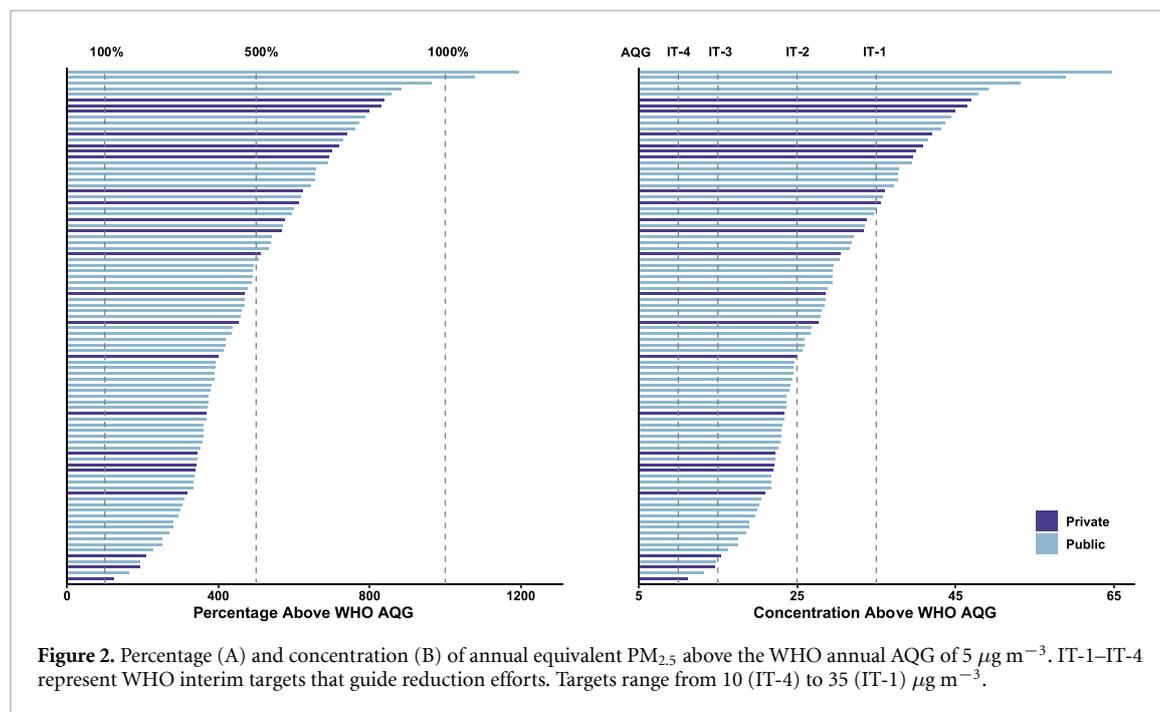
3. Results

3.1. $PM_{2.5}$ and BC concentrations and sound levels

The median (IQR) $PM_{2.5}$ concentration across all 90 schools was 27 (22–36) $\mu\text{g m}^{-3}$, ranging from 11 $\mu\text{g m}^{-3}$ at a private school to 65 $\mu\text{g m}^{-3}$ at a public school ($\sim 600\%$ difference) (table 1). Annual equivalent $PM_{2.5}$ levels in our study schools were 2–13 times higher than the WHO annual guideline of 5 $\mu\text{g m}^{-3}$ (figure 2). The concentrations in more than 55% of the schools were above even the second least stringent interim (IT-2) target of 25 $\mu\text{g m}^{-3}$. This held true even when $PM_{2.5}$ concentrations were

Table 1. Summary statistics of PM_{2.5} and BC concentrations, environmental noise levels and intermittency ratios (IR) across all schoolyards.

	Air pollutants		Noise metrics		
	PM _{2.5} ($\mu\text{g m}^{-3}$)	BC ($1 \times 10^{-5} \text{ m}^{-1}$)	$L_{\text{day(school)}}$ (dBA)	Leq _{wk} (dBA)	IR (%)
Mean (SD)	29.5 (10.4)	4.6 (1.7)	57.1 (4.6)	56.0 (4.5)	52.1 (10.5)
Median (IQR)	27.3 (22.3–35.8)	4.3 (3.6–5.1)	57.2 (52.9–60.1)	55.9 (52.6–58.3)	52.9 (46.2–58.1)
Range	11.2–64.8	1.7–12.0	48.4–69.0	48.5–65.2	12.9–72.6



restricted to only the 7 am–3 pm school period on weekdays (figure 3). The median PM_{2.5} concentrations were higher in private schools, with 61% having levels above the median of all schools, compared to only 46% of public schools (table 1). Similar to PM_{2.5}, BC levels varied widely by more than a factor of six between the least and most polluted schools. However, unlike PM_{2.5}, BC levels were higher in public schools than in private schools (figure 4).

The median (IQR) $L_{\text{day(school)}}$ was 57 (53–60) dBA, with approximately 63% of schools having median levels exceeding 55 dBA, the Ghana EPA's standard for daytime ambient noise at educational facilities. While only 48% of private schools exceeded this standard, 68% of public schools did so (figure 4). Also, 53% (IQR: 46%–58%) of the total noise was found to be created from distinct sound events that was louder than 3 dBA above the school and day-specific $L_{\text{day(school)}}$ (table 1).

3.2. Disparities by spatial and socio-economic factors

By administrative districts, the median BC concentrations were higher at schools in the TMA ($5.9 \times 10^{-5} \text{ m}^{-1}$) and AMA ($4.7 \times 10^{-5} \text{ m}^{-1}$) when compared to schools in other districts ($3.8 \times 10^{-5} \text{ m}^{-1}$). A similar trend was observed for environmental noise, as schools in the TMA and AMA were on average ~ 2 dBA louder. While median PM_{2.5} concentrations were highest among schools in the TMA ($28.5 \mu\text{g m}^{-3}$), the levels were lower in the AMA ($24.5 \mu\text{g m}^{-3}$) when compared to all other GAMA districts ($27.8 \mu\text{g m}^{-3}$). There was a weak spatial correlation between concentrations of air pollutants and environmental noise, as high levels of PM_{2.5} and BC did not always coincide with high levels of noise in the schools, indicating the presence of both shared and distinct sources (figure S3).

In correlation analysis, distance (meters) of school location to the nearest major road was inversely associated with BC ($r = -0.29$ [95% CI: $-0.51, -0.05$]) and $L_{\text{day(school)}}$ ($r = -0.25$ [95% CI: $-0.44, -0.05$]) but not with PM_{2.5} ($r = 0.04$ [95% CI: $-0.17, 0.25$]). Additionally, schools residing within 500 m of a major road had higher median levels of all pollutants when compared to those located beyond 500 m (figure S1). Schools located near a market ($n = 16$) had PM_{2.5} levels that were, on average, $9 \mu\text{g m}^{-3}$ higher than the other schools. These schools also had median BC and $L_{\text{day(school)}}$ levels that were $2.2 \times 10^{-5} \text{ m}^{-1}$ and 3 dBA higher, respectively. The median PM_{2.5} levels were $2 \mu\text{g m}^{-3}$ lower in

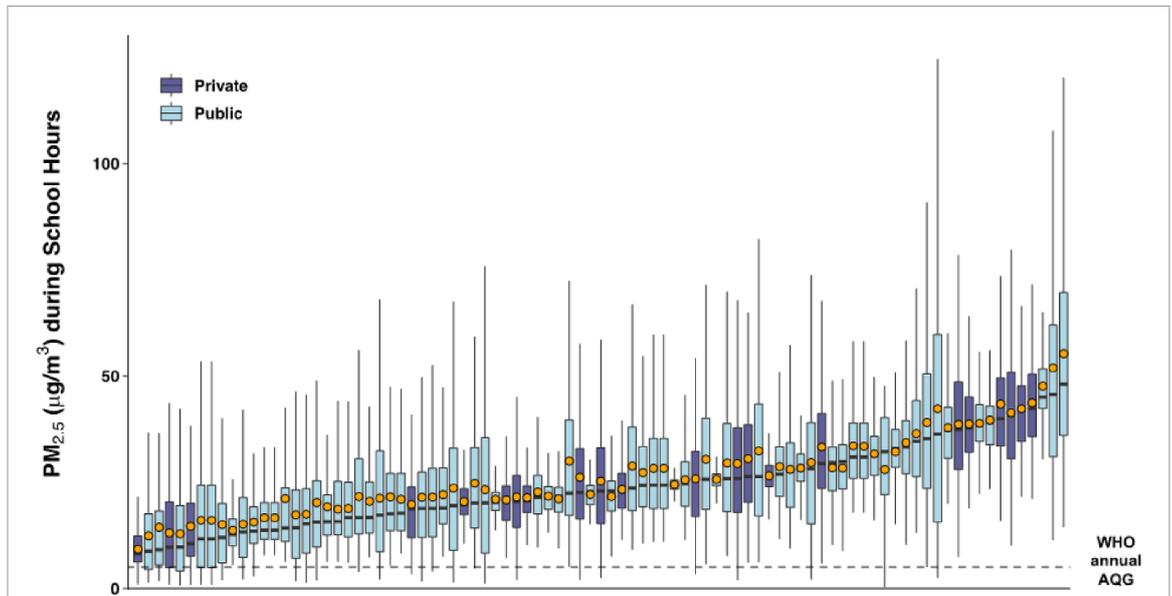


Figure 3. Annual equivalent $PM_{2.5}$ concentrations during school hours (7 am–3 pm) across all schools. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median, and the orange points representing the mean concentrations at each school. The dashed line indicates the WHO’s annual air quality guideline (AQG) of $5 \mu g m^{-3}$.

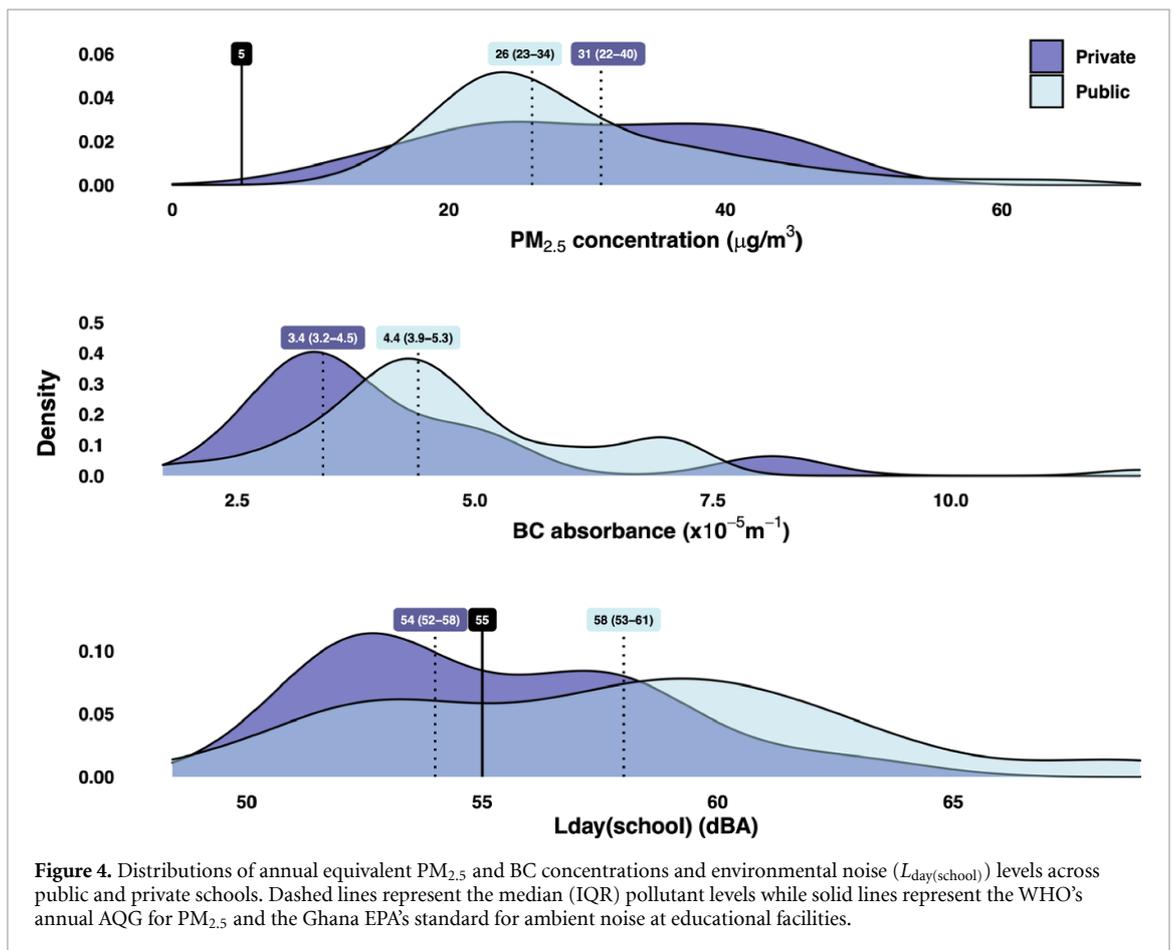


Figure 4. Distributions of annual equivalent $PM_{2.5}$ and BC concentrations and environmental noise ($L_{day(school)}$) levels across public and private schools. Dashed lines represent the median (IQR) pollutant levels while solid lines represent the WHO’s annual AQG for $PM_{2.5}$ and the Ghana EPA’s standard for ambient noise at educational facilities.

schools with paved yard surfaces than those with unpaved (dirt) surfaces. BC was also lower at schools with paved surfaces, but noise levels were unaffected. Furthermore, schoolyard NDVI score was inversely associated with BC ($r = -0.46$ [95% CI: $-0.64, -0.24$]) and $L_{day(school)}$ ($r = -0.23$ [95% CI: $-0.42, -0.02$]), and schools with ‘bare soil’ had higher levels than those that had ‘sparse vegetation’ (figure S2).

The $PM_{2.5}$ concentrations in schools located in neighborhoods with SES indices below the median value were higher than in schools located in areas with SES indices above the median (29 vs

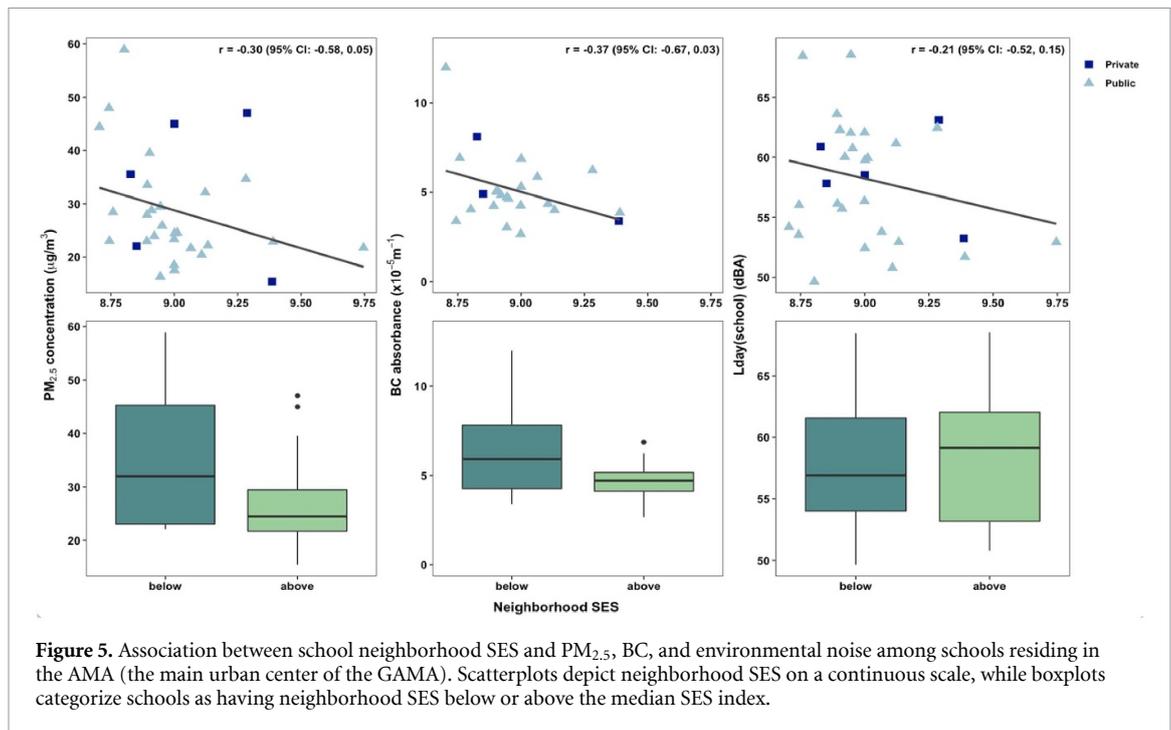


Figure 5. Association between school neighborhood SES and $\text{PM}_{2.5}$, BC, and environmental noise among schools residing in the AMA (the main urban center of the GAMA). Scatterplots depict neighborhood SES on a continuous scale, while boxplots categorize schools as having neighborhood SES below or above the median SES index.

$25 \mu\text{g m}^{-3}$), though no differences were observed for BC or noise. Stronger disparities were observed when considering only those schools located in the AMA ($n = 31$), as levels of $\text{PM}_{2.5}$ and BC were, on average, $7 \mu\text{g m}^{-3}$ and $1.2 \times 10^{-5} \text{ m}^{-1}$ higher for schools below the median SES index. We also found inverse correlations between school neighborhood SES and $\text{PM}_{2.5}$ ($r = -0.30$ [95% CI: $-0.58, 0.05$]), BC ($r = -0.37$ [95% CI: $-0.67, 0.03$]), and environmental noise levels ($r = -0.21$ [95% CI: $-0.52, 0.15$]) among schools within the AMA (figure 5).

In multivariable analyses (table 2), schools located in the AMA and TMA had between 26%–55% higher average $\text{PM}_{2.5}$ and BC concentrations than those outside of these districts. Furthermore, a one unit increase in schoolyard NDVI score was associated with $\sim 93\%$ lower BC concentrations. Both $\text{PM}_{2.5}$ and BC concentrations were $\sim 10\%$ lower in schools with paved schoolyard surface than those with unpaved (dirt) yard surfaces, but the associations were weak. Public schools were ~ 4 dBA (95% CI: 0.52, 7.08) noisier than private schools. In addition, market activity near a school was positively associated with the three pollutants, although not statistically significant. There were minimal associations with other spatial predictors (i.e. distance to major roads, distance to secondary roads, and SES Index) in our models.

3.3. Noise annoyance

The proportion of students highly annoyed (HA_N) by noise from different sources near their schools ranged from as high as 60% due to neighbor noise, 14% due to road-traffic noise, and less than 10% due to noise from businesses/stores/churches, aircraft/planes, and industry/factories (table S1). Differences in responses were observed between districts, with children attending schools in the AMA and TMA generally reporting higher annoyance to noise than those residing in other districts (table S2). For example, approximately 72% of AMA and TMA respondents reported high annoyance to neighbor noise while only 51% of those in other districts did so. An annoyance exposure-response curve that examined the relationship between HA_N to road-traffic noise and the measured school noise levels ($L_{\text{day}(\text{school})}$) showed that schools with higher levels of environmental noise had a higher percentage of students also reporting being HA to road-traffic noise (figure 6).

4. Discussion

To achieve universal primary education in SSA, more children are likely being enrolled in schools and new elementary schools are being built, primarily in rapidly sprawling cities where air and noise pollution present significant health concerns for children. Our study evaluated ambient $\text{PM}_{2.5}$, BC, and noise pollution in 90 public and private primary schools in a major West African city. We found that every school (whether public or private) experienced high levels of air and noise pollution, with a large share

Table 2. Associations of PM_{2.5}, BC, and environmental noise with spatial and meteorological predictors.

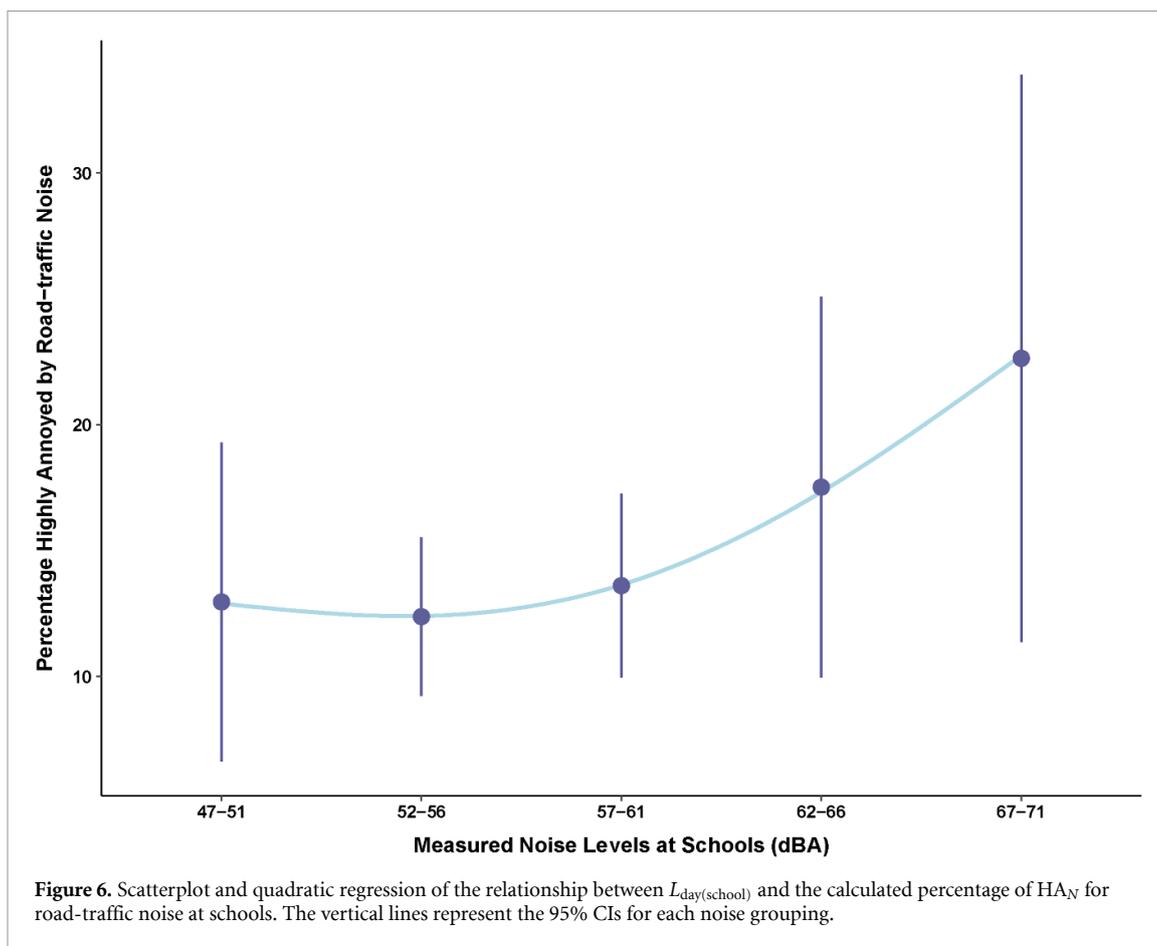
	ln(PM_{2.5}) (Deviance = 84%)	ln(BC) (Deviance = 82%)	Leq_{wk} (Deviance = 42%)
Predictor variables	Coefficient (95% CI)		
District			
<i>Other GAMA districts</i>	—	—	—
<i>TMA</i>	0.52 (0.21, 0.83)	0.23 (−0.05, 0.51)	−3.05 (−6.13, 0.04)
<i>AMA</i>	0.26 (−0.06, 0.59)	0.43 (0.13, 0.74)	−0.05 (−3.09, 3.00)
Distance to major road	< −0.01 (< −0.01, <0.01)	< −0.01 (< −0.01, <0.01)	< −0.01 (< −0.01, <0.01)
Distance to secondary road	< −0.01 (< −0.01, <0.01)	< −0.01 (< −0.01, <0.01)	< 0.01 (< −0.01, <0.01)
Commercial activity			
<i>None</i>	—	—	—
<i>Market</i>	0.09 (−0.21, 0.41)	0.16 (−0.19, 0.52)	2.17 (−1.03, 5.38)
<i>Other</i>	−0.05 (−0.31, 0.19)	< −0.01 (−0.29, 0.29)	0.22 (−2.22, 2.67)
NDVI	1.80 (−0.62, 4.21)	−2.79 (−5.29, −2.92)	−21.44 (−48.90, 6.01)
SES Index	−0.20 (−0.50, 0.10)	0.04 (−0.25, 0.34)	−1.17 (−4.59, 2.26)
Schoolyard surface			
<i>Unpaved</i>	—	—	—
<i>Paved</i>	−0.10 (−0.28, 0.08)	−0.10 (−0.27, 0.08)	2.78 (0.74, 4.83)
School type			
<i>Private</i>	—	—	—
<i>Public</i>	0.05 (−0.28, 0.39)	−0.03 (−0.34, 0.28)	3.80 (0.52, 7.08)
Season			
<i>Non-Harmattan</i>	—	—	—
<i>Harmattan</i>	−0.02 (−0.24, 0.19)	0.22 (0.03, 0.41)	0.17 (−2.16, 2.51)
Predictor variables^a	Effective degrees of freedom (p-value)		
Temperature ^a	5.05 (<0.001)	6.01 (0.001)	1.00 (0.472)
Relative Humidity ^a	1.92 (0.06)	1.00 (0.07)	1.00 (0.053)
Rain ^a	3.71 (<0.001)	3.33 (<0.001)	1.00 (0.059)

^a Thin plate regression splines were applied to temperature, relative humidity, and rain, as the relationship between these variables and the pollutants was non-linear.

of the students expressing a high level of noise annoyance. No school was close to meeting the international health-based guideline for ambient PM_{2.5}, and roughly two-thirds of the schools were not meeting the local standard for noise at educational facilities. We also found higher BC and noise levels in public schools compared to private schools, and in schools located in the AMA and TMA when compared to other districts in the GAMA. We further observed higher levels of all three pollutants in schools residing in lower-SES neighborhoods in the AMA.

Like our study, recent work documented mean PM_{2.5} concentrations several times above the WHO AQG [47] in outdoor playgrounds of elementary schools in Kigali, Rwanda. Furthermore, PM_{2.5} concentrations in our study were higher than those reported in elementary schools in the UK (mean: 9.1 $\mu\text{g m}^{-3}$) [48], US (mean: 6.5 $\mu\text{g m}^{-3}$) [49], Italy (mean: 14.2 $\mu\text{g m}^{-3}$) [50] and South Africa (mean: 20.7 $\mu\text{g m}^{-3}$) [51], but lower than those observed at schools in China (mean: 63 $\mu\text{g m}^{-3}$) [52] and India (mean: 135 $\mu\text{g m}^{-3}$) [53]. Environmental noise in schools in Accra was on average 10 dBA lower than those reported at four schools in the Greater Kumasi Metropolis (Ashanti Region), the second largest city in Ghana [54]. However, we observed higher average noise levels compared to schools in European countries such as those in Spain (53.5 dBA) [55], Germany (50.6 dBA) [56] and France (51.5 dBA) [57].

We found associations between the measured pollutants and several spatial factors, including distance to major roads, vegetation/greenness of the schoolyard, schoolyard surface, and commercial activity near the school. These factors have also been identified in previous studies in Accra [45, 46]. Similar to ours, studies from developed countries have also documented the influence of green spaces surrounding schools on pollutant concentrations [27, 58]. In fact, a recent review of the literature showed that installing green infrastructure as a physical barrier can reduce BC concentrations at schools by up to 63% [59]. This suggests that enhancing greenness at schools within the GAMA may be an effective strategy for reducing children's exposure to both air and noise pollution, particularly at schools with the lowest NDVI scores. Furthermore, our finding of inverse associations between neighborhood SES and pollutant levels are consistent with a much wider body of literature on childhood SES and disparities in pollution exposures, emphasizing the need to identify and resolve these exposure disparities in Accra



[48, 60, 61]. Finally, the percentage of children who reported being HA to road traffic noise was comparable to findings from previously published meta-analyses aggregating results from studies amongst adults globally [62]. These findings underscore the importance of reducing road-traffic noise by encouraging local government in Accra to identify and target predominant noise sources (e.g. engines, honking, tire contact, etc.)

Unlike BC and noise, the relationship between $PM_{2.5}$ and the spatial factors was less apparent. As noted in a previous study [37], $PM_{2.5}$ pollution in Accra has become more uniform across communities and not as much affected by local sources as was documented in the past. This could explain the relatively weak association with the spatial factors. In contrast, BC and environmental noise in the schools are better predicted by local pollution sources [63, 64]. While the associations between neighborhood SES and pollutant levels were weak in our multivariate models, the link was stronger in the AMA, the most urbanized part of the GAMA. This could be because SES was shown to vary more widely in the inner-city core than in the neighboring communities [65].

4.1. Strengths and limitations

Our study has several innovations and strengths. To the best of our knowledge, this is the largest air and noise pollution study in schools in a major SSA city, a region where cities are experiencing high levels of environmental pollution but lack measurement data to motivate policy actions. Our design approach allowed for the assessment of multiple air pollutants and indicators of environmental noise pollution in schools across the entire metropolis with varied land use and population features. Additionally, for the first time in SSA, we captured the perception of schoolchildren in terms of their annoyance to environmental noise at schools. While policy interventions are primarily implemented through public schools, we also included a representative sample of private schools for comparison, as they have become a significant part of the educational system in SSA and highlight major inequalities in pollution exposures between fee and non-fee paying schools. With the large sample size, we have identified school- and community-level factors that can be a focus of targeted policy interventions to reduce exposures at school environments.

Our study also has some limitations. Due to logistical difficulties, including a limited number of monitors, the large number of schools involved, and the large study area, we could not conduct measurements in all our study schools simultaneously. However, to allow for comparisons across schools, we adjusted for the effect of season using concurrent measurements at the ten fixed sites located across the city, an approach which has been used in previous studies. For the same reason, we could not conduct in-classroom and personal exposure measurements in the children, which would provide additional information about schoolchildren exposures in Accra. Nevertheless, we captured data on some of the school-level factors (e.g. schoolyard surface, distance of school location to main road) that were found to be determinants of personal exposure among schoolchildren in Accra [28]. Furthermore, the standardized noise annoyance questions used in this research have only been validated for use at homes and among adult populations [42], and not specifically among schoolchildren. However, the proportion of children identified as HA by road traffic noise was similar to findings from previously published studies [62]. Nonetheless, the results should be interpreted with caution. Finally, our measure of neighborhood SES included the 2010 census and 2012 GLSS data. While these were the most recent data available, sociodemographic dynamics have likely shifted since then, with many areas becoming more developed and higher income. As a result, the relationship between SES and pollutant concentrations may be underestimated, as these areas may now experience lower pollution levels than reflected by older SES data.

5. Conclusion

Our findings show that children in elementary schools in Accra are learning in polluted air and annoyingly noisy environments, raising concerns about their physical, cognitive, and social well-being. No school (private or public) is close to meeting the international health-based guidelines or local standards for ambient air and environmental noise pollution. Children in public schools, and those attending schools located in the more urbanized areas, are at higher risk of exposure. As SSA works towards its goal of universal primary education, our data highlight an urgent need for policies aimed at reducing children's exposures to air and noise pollution in urban schools. Effective actions could include paving the schoolyards using brick or concrete-based pavement tiles and introducing green spaces on school grounds. Additionally, the planning and construction of new schools should consider proximity to pollution sources. While public schools may warrant particular attention due to existing disparities, broader policy discussions are needed to ensure all GAMA students, regardless of school type, have equitable access to clean and quiet learning environments. Mitigating these exposures is an important step toward supporting the health and academic success of future generations.

Data availability statement

Environmental measurement data is available through the open-source platform, Zenodo. Those interested in accessing the data should direct any questions to Raphael E Arku [rarku@umass.edu].

Supplementary Information available at <https://doi.org/10.1088/2752-5309/ae27eb/data1>

Acknowledgment

The authors would like to thank all parents, children, and elementary school leaders that participated in this study and generously allowed us to install monitors in the school playgrounds. We would also like to thank the staff at the Physics Department, University of Ghana for their support in organizing the laboratory used during this project.

Conflict of interest

The authors declare they have no conflicts of interest related to this work to disclose.

Funding

The ASHES project was in parts supported by the National Geographic Society exploratory grant [NGS-64242R-19], *Pathways to Equitable Healthy Cities* grant (209376/Z/17/Z) and *Climate Change Resilient Equitable Healthy Cities in Africa (CLARITY-Africa)* grant (227779/Z/23/Z) from the Wellcome Trust, and UMass SPHHS Dean's Research Enhancement grant. For the purpose of Open Access, the author has applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

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References

- [1] Mishra A, Zhou B and Rodriguez-Martinez A 2023 Diminishing benefits of urban living for children and adolescents' growth and development *Nature* **615** 874–83
- [2] Fink G, Günther I and Hill K 2014 Slum residence and child health in developing countries *Demography* **51** 1175–97
- [3] Agyekum M W *et al* 2023 Rural-urban differentials in early childhood education and child development: evidence from Multiple Indicator Cluster Survey (MICS) in Ghana *PLoS Glob. Public Health* **3** e0002171
- [4] Katoto P D M C, Byamungu L, Brand A S, Mokaya J, Strijdom H, Goswami N, De Boever P, Nawrot T S and Nemery B 2019 Ambient air pollution and health in Sub-Saharan Africa: current evidence, perspectives and a call to action *Environ. Res.* **173** 174–88
- [5] Fisher S, Bellinger D C, Cropper M L, Kumar P, Binagwaho A, Koudenoukpo J B, Park Y, Taghian G and Landrigan P J 2021 Air pollution and development in Africa: impacts on health, the economy, and human capital *Lancet Planet. Health* **5** e681–e688
- [6] World Health Organization. WHO Information Series on School Health 2003 Creating an environment for emotional and social well-being (available at: <https://iris.who.int/bitstream/handle/10665/42819/9241591048.pdf>) (Accessed 25 November 2024)
- [7] Dominski F H, Lorenzetti Branco J H, Buonanno G, Stabile L, Gameiro da Silva M and Andrade A 2021 Effects of air pollution on health: a mapping review of systematic reviews and meta-analyses *Environ. Res.* **201** 111487
- [8] Khreis H, Kelly C, Tate J, Parslow R, Lucas K and Nieuwenhuijsen M 2017 Exposure to traffic-related air pollution and risk of development of childhood asthma: a systematic review and meta-analysis *Environ Int.* **100** 1–31
- [9] Parasin N, Amnuaylojaroen T and Saokaew S 2021 Effect of air pollution on obesity in children: a systematic review and meta-analysis *Children* **8** 327
- [10] Mozafarian N, Hashemipour M, Yazdi M, Hani Tabaei Zavareh M, Hovsepian S, Heidarpour M and Taheri E 2022 The association between exposure to air pollution and type 1 diabetes mellitus: a systematic review and meta-analysis *Adv. Biomed. Res.* **11** 103
- [11] Huang M, Chen J, Yang Y, Yuan H, Huang Z and Lu Y 2021 Effects of ambient air pollution on blood pressure among children and adolescents: a systematic review and meta-analysis *J. Am. Heart Assoc.* **10** 17734
- [12] Mayne S L, Mitchell J A, Virudachalam S, Fiks A G and Williamson A A 2021 Neighborhood environments and sleep among children and adolescents: a systematic review *Sleep Med. Rev.* **57** 101465
- [13] Basner M and McGuire S 2018 WHO environmental noise guidelines for the European Region: a systematic review on environmental noise and effects on sleep *Int. J. Environ. Res. Public Health* **15** 519
- [14] Thompson R, Smith R B, Karim Y B, Shen C, Drummond K, Teng C and Toledano M B 2023 Air pollution and human cognition: a systematic review and meta-analysis *Sci. Total Environ.* **859** 160234
- [15] Thompson R, Smith R B, Bou Karim Y, Shen C, Drummond K, Teng C and Toledano M B 2022 Noise pollution and human cognition: an updated systematic review and meta-analysis of recent evidence *Environ Int.* **158** 106905
- [16] Zundel C G, Ryan P, Brokamp C, Heeter A, Huang Y, Strawn J R and Marusak H A 2022 Air pollution, depressive and anxiety disorders, and brain effects: a systematic review *Neurotoxicology* **93** 272
- [17] Schubert M, Hegewald J, Freiberg A, Starke K, Augustin F, Riedel-Heller S, Zeeb H and Seidler A 2019 Behavioral and emotional disorders and transportation noise among children and adolescents: a systematic review and meta-analysis *Int. J. Environ. Res. Public Health* **16** 3336

- [18] Gupta A, Gupta A, Jain K and Gupta S 2018 Noise pollution and impact on children health *Indian J. Pediatr.* **85** 300–6
- [19] Shield B M and Dockrell J E 2008 The effects of environmental and classroom noise on the academic attainments of primary school children *J. Acoust. Soc. Am.* **123** 133–44
- [20] Xie H, Kang J and Tompsett R 2011 The impacts of environmental noise on the academic achievements of secondary school students in Greater London *Appl. Acoust.* **72** 551–5
- [21] Orellano P, Reynoso J and Quaranta N 2023 Effects of air pollution on restricted activity days: systematic review and meta-analysis *Environ. Health* **22** 1–16
- [22] Gartland N, Aljofi H E, Dienes K, Munford L A, Theakston A L and van Tongeren M 2022 The effects of traffic air pollution in and around schools on executive function and academic performance in children: a rapid review *Int. J. Environ. Res. Public Health* **19** 749
- [23] Grineski S E, Collins T W and Adkins D E 2020 Hazardous air pollutants are associated with worse performance in reading, math, and science among US primary schoolchildren *Environ. Res.* **181** 108925
- [24] Clark C, Martin R, Van Kempen E, Alfred T, Head J, Davies H W, Haines M M, Barrio I L, Matheson M and Stansfeld S A 2006 Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension: the RANCH project *Am. J. Epidemiol.* **163** 27–37
- [25] Stenson C, Wheeler A J, Carver A, Donaire-Gonzalez D, Alvarado-Molina M, Nieuwenhuijsen M and Tham R 2021 The impact of traffic-related air pollution on child and adolescent academic performance: a systematic review *Environ. Int.* **155** 106696
- [26] Fernandes A, Ubalde-López M, Yang T C, McEachan R R C, Rashid R, Maitre L, Nieuwenhuijsen M J and Vrijheid M 2023 School-based interventions to support healthy indoor and outdoor environments for children: a systematic review *Int. J. Environ. Res. Public Health* **20** 1746
- [27] Osborne S, Uche O, Mitsakou C, Exley K and Dimitroulopoulou S 2021 Air quality around schools: part I—A comprehensive literature review across high-income countries *Environ. Res.* **196** 110817
- [28] Arku R E, Dionisio K L, Hughes A F, Vallarino J, Spengler J D, Castro M C, Agyei-Mensah S and Ezzati M 2014 Personal particulate matter exposures and locations of students in four neighborhoods in Accra, Ghana *J. Expo. Sci. Environ. Epidemiol.* **25** 557–66
- [29] Lange C L, Alli A S and Kyeremateng K A The Accra School Health and Environment Study (ASHES): a study of the urban environment and child health and development in Accra *medRxiv* (<https://doi.org/10.1101/2025.07.11.25331353>)
- [30] Ghana Statistical Service 2012 2010 population and housing census final results (available at: www.ghanahero.com/ARCHIVE_1/Mission-Ghana-Planning-Inventory/2010_POPULATION_AND_HOUSING_CENSUS_FINAL_RESULTS.pdf) (Accessed 29 May 2024)
- [31] Nyarku M, Buonanno G, Ofosu F, Jayaratne R, Mazaheri M and Morawska L 2019 Schoolchildren’s personal exposure to ultrafine particles in and near Accra, Ghana *Environ. Int.* **133** 105223
- [32] Zhou Z, Dionisio K L, Arku R E, Quaye A, Hughes A F, Vallarino J, Spengler J D, Hill A, Agyei-Mensah S and Ezzati M 2011 Household and community poverty, biomass use, and air pollution in Accra, Ghana *Proc. Natl Acad. Sci. USA* **108** 11028–33
- [33] Volckens J, Quinn C, Leith D, Mehaffy J, Henry C S and Miller-Lionberg D 2017 Development and evaluation of an ultrasonic personal aerosol sampler *Indoor Air* **27** 409–16
- [34] Zefan Inc (available at: www.tjzfsk.com/) (Accessed 30 July 2023)
- [35] Jeronimo M, Stewart Q, Weakley A T, Giacomo J, Zhang X, Hyslop N, Dillner A M, Shupler M and Brauer M 2020 Analysis of black carbon on filters by image-based reflectance *Atmos. Environ.* **223** 117300
- [36] Dionisio K L, Arku R E, Hughes A F, Vallarino J, Carmichael H, Spengler J D, Agyei-Mensah S and Ezzati M 2010 Air pollution in Accra neighborhoods: spatial, socioeconomic, and temporal patterns *Environ. Sci. Technol.* **44** 2270–6
- [37] Alli A S *et al* 2021 Spatial-temporal patterns of ambient fine particulate matter (PM_{2.5}) and black carbon (BC) pollution in Accra *Environ. Res. Lett.* **16** 074013
- [38] Clark S N *et al* 2020 High-resolution spatiotemporal measurement of air and environmental noise pollution in Sub-Saharan African cities: pathways to equitable health cities study protocol for Accra, Ghana *BMJ Open* **10** 35798
- [39] NSRT_mk4 (Sound Level Meter Data Logger with type 1 microphone) n.d. Convergence Instruments (available at: <https://convergenceinstruments.com/>) (Accessed 22 January 2024)
- [40] Wunderli J M, Pieren R, Habermacher M, Vienneau D, Cajochen C, Probst-Hensch N, Rösli M and Brink M 2015 Intermittency ratio: a metric reflecting short-term temporal variations of transportation noise exposure *J. Expo. Sci. Environ. Epidemiol.* **26** 575–85
- [41] Clark S N, Alli A S and Nathvani R 2021 Space-time characterization of community noise and sound sources in Accra, Ghana *Sci. Rep.* **11** 1–14
- [42] Clark C, Gjestland T, Lavia L, Notley H, Michaud D and Morinaga M 2021 Assessing community noise annoyance: a review of two decades of the international technical specification ISO/TS 15666:2003 *J. Acoust. Soc. Am.* **150** 3362–73
- [43] United States Geological Survey Landsat products 2023 (available at: www.usgs.gov/landsat-missions) (Accessed 29 May 2024)
- [44] OpenStreetMap Contributors Planet dump 2023 (available at: <https://planet.openstreetmap.org/>) (Accessed 29 May 2024)
- [45] Clark S N *et al* 2022 Spatial modelling and inequalities of environmental noise in Accra, Ghana *Environ. Res.* **214** 113932
- [46] Alli A S *et al* 2023 High-resolution patterns and inequalities in ambient fine particle mass (PM_{2.5}) and black carbon (BC) in the Greater Accra Metropolis, Ghana *Sci. Total Environ.* **875** 162582
- [47] Kalisa E, Kuire V and Adams M 2023 Children’s exposure to indoor and outdoor black carbon and particulate matter air pollution at school in Rwanda, Central-East Africa *Environ. Adv.* **11** 100334
- [48] Osborne S, Uche O, Mitsakou C, Exley K and Dimitroulopoulou S 2021 Air quality around schools: part II—mapping PM_{2.5} concentrations and inequality analysis *Environ. Res.* **197** 111038
- [49] Carrion-Matta A, Kang C-M, Gaffin J M, Hauptman M, Phipatanakul W, Koutrakis P and Gold D R 2019 Classroom indoor PM_{2.5} sources and exposures in inner-city schools *Environ. Int.* **131** 104968
- [50] Conte Keivabu R 2023 Spatial and temporal disparities in air pollution exposure at Italian schools *Genus* **79** 1–27
- [51] Kalisa E, Clark M L, Ntakirutimana T, Amani M and Volckens J 2023 Exposure to indoor and outdoor air pollution in schools in Africa: current status, knowledge gaps, and a call to action *Heliyon* **9** e18450
- [52] Wang X, Zou Z, Dong B, Dong Y, Ma Y, Gao D, Yang Z, Wu S and Ma J 2019 Association of school residential PM_{2.5} with childhood high blood pressure: results from an observational study in 6 cities in China *Int. J. Environ. Res. Public Health* **16** 2515
- [53] Jan R, Roy R, Yadav S and Satsangi P G 2017 Exposure assessment of children to particulate matter and gaseous species in school environments of Pune, India *Build. Environ.* **111** 207–17
- [54] Quartey Lois N K, Amos-Abanyie S and Afram S O 2021 Noise exposure levels in basic school environments in a city in Ghana *Open J. Civ. Eng.* **11** 81–95

- [55] Foraster M, Esnaola M, López-Vicente M, Rivas I, Álvarez-Pedrerol M, Persavento C, Sebastian-Galles N, Pujol J, Davdand P and Sunyer J 2022 Exposure to road traffic noise and cognitive development in schoolchildren in Barcelona, Spain: a population-based cohort study *PLoS Med.* **19** e1004001
- [56] Klatté M, Spilski J, Mayerl J, Möhler U, Lachmann T and Bergström K 2017 Effects of aircraft noise on reading and quality of life in primary school children in Germany: results from the NORAH study *Environ. Behav.* **49** 390–424
- [57] Pujol S, Levain J-P, Houot H, Petit R, Berthillier M, Defrance J, Lardies J, Masselot C and Mauny F 2013 Association between ambient noise exposure and school performance of children living in an urban area: a cross-sectional population-based study *J. Urban Health* **91** 256
- [58] Markevych I *et al* 2017 Exploring pathways linking greenspace to health: theoretical and methodological guidance *Environ. Res.* **158** 301–17
- [59] Rawat N and Kumar P 2023 Interventions for improving indoor and outdoor air quality in and around schools *Sci. Total Environ.* **858** 159813
- [60] Chakraborty J and Aun J J 2023 Social inequities in exposure to traffic-related air and noise pollution at public schools in Texas *Int. J. Environ. Res. Public Health* **20** 5308
- [61] Collins T W, Grineski S E and Nadybal S 2019 Social disparities in exposure to noise at public schools in the contiguous United States *Environ. Res.* **175** 257–65
- [62] Fenech B, Clark S and Rodgers G 2022 An update to the WHO 2018 environmental noise guidelines exposure response relationships for annoyance from road and railway noise *Internoise 2022–51st International Congress and Exposition on Noise Control Engineering* (Institute of Noise Control Engineering) (https://doi.org/10.3397/IN_2022_0244)
- [63] de Paiva Vianna K, Rodrigues R M and Alves Cardoso R M C 2015 Noise pollution and annoyance: an urban soundscapes study *Noise Health* **17** 125
- [64] Sugrue R A, Preble C V, Butler J D A, Redon-Gabel A J, Marconi P, Shetty K D, Hill L A L, Amezcua-Smith A M, Lukanov B R and Kirchstetter T W 2024 The value of adding black carbon to community monitoring of particulate matter *Atmos. Environ.* **325** 120434
- [65] Cavanaugh A C *et al* 2023 Strangers in a strange land: mapping household and neighbourhood associations with improved well-being outcomes in Accra, Ghana *Cities* **143** 104584