Published in final edited form as:

Environ Res. 2019 March ; 170: 83–91. doi:10.1016/j.envres.2018.12.012.

Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors

Ehsan Majd¹, Meredith McCormack², Meghan Davis¹, Frank Curriero¹, Jesse Berman³, Faith Connolly⁴, Philip Leaf⁵, Ana Rule¹, Timothy Green¹, Dorothy Clemons-Erby¹, Christine Gummerson², and Kirsten Koehler^{1,*}

¹Johns Hopkins Bloomberg School of Public Health, 615 N Wolfe Street, Baltimore, MD 21205, USA

²Johns Hopkins School of Medicine, Pulmonary and Critical Care Medicine, 1830 East Monument Street, Baltimore, MD 21205, USA

³University of Minnesota, School of Public Health, 420 Delaware St SE, Mayo Mail Code #807, Minneapolis, MN 55455, USA

⁴Johns Hopkins University Baltimore Education Research Consortium, 2701 N. Charles Street, Suite 300, Baltimore, MD 21218, USA

⁵Johns Hopkins Bloomberg School of Public Health, Center for Adolescent Health, 624 N. Broadway, Hampton House 819, Baltimore, MD 21205, USA

Abstract

Indoor concentrations of fine particulate matter (PM_{2.5}), nitrogen dioxide (NO₂), and carbon monoxide (CO) were measured across 16 urban public schools in three different seasons. Exceedance of the WHO guidelines for indoor air was observed, mainly for the hourly average NO₂ concentrations. Seasonal variability was statistically significant for indoor NO₂ and CO concentrations, with higher exposures in fall and winter. An extensive list of potential factors at the outdoor environment, school, and room level that may explain the variability in indoor exposure was examined. Factors with significant contributions to indoor exposure were mostly related to the outdoor pollution sources. This is evidenced by the strong associations between indoor concentration of CO and NO₂ and factors including outdoor PM_{2.5} and NO₂ concentrations, including length of the nearby roads and the number of nearby industrial facilities. Additionally, we found that poor conditions of the buildings (a prevalent phenomenon in the studied urban area), including physical defects and lack of proper ventilation, contributed to poor air quality in schools. The results suggest that improving building conditions and facilities as well as a consideration of the school surroundings may improve indoor air quality in schools.

*Corresponding author: Dr. Kirsten Koehler, Phone: +1 (410) 955-7706, kkoehle1@jhu.edu.

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Keywords

Indoor air quality; school; exposure; building characteristics; environmental factors

1. Introduction

Indoor exposures to air pollutants, including particulate matter, allergens, oxides of nitrogen, endotoxin, and mold, have been associated with impaired health and performance in children and adults (Breyse et al., 2005; Gaffin & Phipatanakul, 2009; Kanchongkittiphon, et al., 2015; McCormack et al., 2009; Niemela et al., 2006). Children are believed to be more susceptible than adults to the adverse health effects of poor indoor air quality (IAQ) because their higher metabolic demands and higher minute ventilation rates increase their exposures (Bluyssen, 2016; Mendell & Heath, 2005). Children spend approximately 65 to 90% of their time in indoor environments, with a large portion at school (Annesi-Maesano et al., 2013). Therefore, characterization of indoor air pollution in school environments is of critical public health concern given the potential long-term adverse consequences from such exposures, such as respiratory and cognitive performance effects (Chatzidiakou et al., 2012).

Sources that contribute to increased indoor air pollution include outdoor air, smoking, gas stoves, cleaning activities, dampness and water damage, pest infestation, and proximity to major roadways and industrial activities (Butz et al., 2011; Hansel et al., 2008; Matsui et al., 2008; Vette et al., 2013). Among the known indoor environmental factors and pollutants, CO₂, a surrogate for the quality of ventilation in an indoor environment, and temperature have been of primary interest in many of the conducted studies in schools (Petersen et al., 2016; Shendell et al., 2004; Toyinbo et al., 2016). A range of other pollutants such as particulate matter, volatile organic compounds, and gaseous species have also been investigated extensively (Annesi-Maesano et al., 2013; Bluyssen, 2016; Chatzidiakou et al., 2012; de Gennaro et al., 2014; Mendell & Heath, 2005). Prior studies have often focused on indoor and sometimes outdoor air pollutants (Buonanno et al., 2013; Crilley et al., 2016; Godwin & Batterman, 2007; Laiman et al., 2014; Mazaheri et al., 2016; Ramachandran et al., 2005; Rivas et al., 2014; Stranger et al., 2008; Zhang & Zhu, 2012) and some studies have linked these to health and student performance outcomes (Sheehan et al., 2017; Simoni et al., 2010; Wallner et al., 2012; Zhao et al., 2008). Studies have examined a range of factors related to school environment including microclimatic parameters (temperature, relative humidity and ventilation) (Reche et al., 2014; Weichenthal et al., 2008), building age (Yang et al., 2015; Yang et al., 2009), occupancy level (Madureira et al., 2016), floor covering (Fromme et al., 2007; Pegas et al., 2011), distance to roads and traffic density (Janssen et al., 2001), concentration of outdoor pollutants (Elbayoumi et al., 2014; Zhang & Zhu, 2012), etc. However, these studies were often limited by the small sample sizes, lack of repeated measurements to account for the possible daily variability and seasonal effects, and short durations of monitoring, sometimes as little as one day per school. Furthermore, due to the limited number of parameters examined, the contributions of environmental factors and building characteristics were not comprehensively addressed in these studies.

A school renovation program in an urban area provided an ideal opportunity to study school environment. The decision to launch the renovation program was motivated by the aging infrastructure of the city schools portfolio (74% of buildings built between 1946–1985 and 23% built before 1946) and findings of a comprehensive assessment of the condition of the city schools' buildings. The assessment reported significant deficiencies and poor conditions among a vast majority of the examined buildings. According to the conducted analysis, 122 of the total 147 examined schools were rated in 'poor or worse' condition with 40 schools recommended as candidates for replacement (Berman et al., 2018). Some of the identified deficiencies—notably faulty heating/ventilation/air conditioning (HVAC) systems and structural concerns—are likely to contribute to poor indoor air quality in schools. The overarching goal of this work is to inform the implementation of the appropriate intervention strategies at both community and school level to improve the indoor air quality of school children. The aim of this study was to describe indoor air quality over multiple seasons, assess exposure variability, and identify major contributors (structural or contextual) to indoor air pollution among a cohort of schools identified by a city school renovation program as priorities for renovation on the basis of their infrastructure deficits.

2. Methods and Materials

2.1. Air quality monitoring:

Measurements were conducted from December 2015 to May 2017 across 16 schools in a city in the mid-Atlantic region. Indoor air quality was assessed at four locations in each school including two classrooms and two common areas (e.g. cafeteria, gymnasium, library, etc.), at three targeted points in time (fall, winter, and spring; three schools have measurements in all three seasons). Third and 6th grade classrooms were prioritized for monitoring. During each season school visit, sampling was conducted for two weeks as follows: one classroom and one common area (e.g. gymnasium, cafeteria, library, etc.) were monitored during the first week and a second classroom and second common area were monitored in the second week. At each location within the school, sampling was conducted for five consecutive school days (Monday-Friday). Particulate matter less than 2.5 μm in diameter ($\text{PM}_{2.5}$) was measured using a Personal DataRam, model pDR-1200 monitor (Thermo Electron, Franklin, MA, USA) with a 5-min logging resolution and 0.001–400 mg/m^3 concentration measurement range. The pDR was connected to a BGI model 400s personal sampling pump (BGI INC., Waltham, MA, USA) operating at the air flow of 4 L/min, and a BGI model GK 2.05 (Mesa Labs, Butler, NJ, USA) inlet cyclone with a 50% cut point of 2.5 μm . All concentrations from the pDR were corrected for gravimetric time-weighted average (TWA) concentrations using the filter samples collected downstream of the pDR nephelometer. Also, pDR concentrations were humidity-corrected using standard approaches (Soneja et al., 2014). Filter samples were collected on 37-mm, 2.0 μm pore-size PTFE membrane filters. Filters were preconditioned for 24 hours in a temperature- and humidity-controlled room prior to weighing in the same room. NO_2 , CO, CO_2 , temperature, and relative humidity were each measured at 1-min intervals using a direct-reading AdvancedSense Pro indoor air quality meter (GrayWolf Sensing Solutions LLC, Shelton, CT, USA). The IAQ meter has been used in previous studies (Doll et al., 2016). NO_2 and CO were detected using electrochemical sensors while CO_2 was measured via a dual-wave

NDIR IR-Infrared sensor optimized for the indoor concentration range. The IAQ meter was factory-calibrated and quality-control checked according to the manufacturer's instructions using the supplied calibration kit. At each indoor monitoring location, the setup was placed on a table ~1 m above the ground and away from doors, windows, and air vents, as possible.

Samplers were also placed outside of each school, often on the roof, to assess the contribution of outdoor air to indoor air quality. Outdoor sampling at each school was conducted for the entire two weeks of indoor monitoring in each season (including the weekend between the two indoor sampling periods). A SKC Personal Environmental Monitor (PEM) for PM_{2.5} with the same type of filter used for the pDR, connected to an Allegro model 9805 diaphragm sampling pump (Allegro Industries, Piedmont, SC, USA), operating at the air flow of 4 L/min. An Ogawa passive NO₂ sampler (Ogawa & Company, USA, Inc., Pompano Beach, FL, USA) that contains two gas collection pads specially coated to react with NO₂. A battery-powered iButton data logger (iButtonLink, Whitewater, WI, USA) was used to measure the outdoor temperature and relative humidity at 10-min intervals. CO and CO₂ were not measured outdoors. Following the two-week exposure, the outdoor PM_{2.5} filters were pre-conditioned and weighed as described for the indoor PM_{2.5} filters (above). The NO₂ passive sampler was returned to the laboratory to determine the average NO₂ concentration during the exposure via ion chromatography according to the manufacturer's standard procedure for analysis. At each school, there were only two outdoor samples collected (one for PM_{2.5} and one for NO₂) over the two-week monitoring period.

2.2. School, room, and outdoor environment characteristics:

On their first visit to each school, the study staff performed a walk-through inspection of the school and the selected rooms for air quality monitoring and recorded building and room characteristics. These observations were later used as explanatory variables in the regression analysis. Information on more than 60 parameters were collected at the school level (building type, number of floors, heating and air conditioning, distance to the curb, etc.) and room level (classroom grade, room floor, facing street or playground, sign of water damage, furniture used, number of windows and air vents, floor covering, etc.). The Facility Condition Index (FCI), a national standard for the overall condition of a building, was considered as a separate factor (Center on Reinventing Public Education, 2013).

Monitored schools were assigned an overall score by the renovation program following a thorough inspection of the buildings conducted in 2012. FCI ranges from 0 to 100 and a lower score means a good condition building. Outdoor environment data at school level were also available including: length of all roads or major roads and highways within 100, 200, and 300 meters of schools, number of Toxic Release Inventory (TRI) sites within 1 and 2 km of schools, and the distance to the closest TRI site. TIGER/Line Maryland primary and secondary roads shapefiles from 2013 for Baltimore City were used to assess the roadways around school buildings (U.S. Census Bureau, 2013). Another parameter is the Risk-Screening Environmental Indicator (RSEI) score, calculated and made available by the US Environmental Protection Agency (EPA). This score is based on the amount and relative toxicity of the chemicals released from TRI sites, as well as their fate and transport in the environment and potential human exposure (U.S. Environmental Protection Agency, 2017).

A higher score means a higher hazard level. Wind speed data were obtained from the National Centers for Environmental Information for the monitoring periods in each school. Wind speed was measured at a meteorological station located within ~10 km of all monitored schools.

2.3. Statistical Analysis:

The dataset for analysis was limited to measurements collected during the school hours (8 am to 4 pm). For each monitored location, continuously-measured exposure variables were summarized as daily medians, daily means, and hourly means. Daily medians were used for all the analyses in this paper, except for comparing the indoor exposure levels with the WHO guidelines where daily (for PM_{2.5} and CO) or hourly (for NO₂) means were employed to match corresponding guidelines. Wilcoxon rank sum and Kruskal-Wallis tests were used to examine the statistical significance of variability in measured exposure variables indoors (by season and room type) as well as outdoors (by season). Indoor/Outdoor (I/O) ratios were calculated and the correlations across exposure variables were evaluated using the Spearman rank correlation coefficient. To examine the I/O ratio and correlation between indoor and outdoor PM_{2.5}, the total average of indoor gravimetric concentration was used to match the outdoor gravimetric PM_{2.5} concentration sampled over two weeks at each school in each season. This total average concentration was calculated as the average of all four samples collected at different indoor locations within the school (two samples collected in week 1 and the other two collected in week 2). For NO₂, the total average of all real-time indoor concentrations measured in four different locations within two weeks of monitoring was used to examine the I/O ratio and correlation.

Associations between each indoor exposure variable and both continuous and categorical school and community parameters were individually assessed using bivariate mixed-effect linear regression model with random intercept and a compound symmetry covariance structure with a constant correlation. In each model, the exposure variable was log-transformed due to the skewed concentration data and the approximately normally distributed log-transformed values were used as the outcome. Each continuous and categorical parameter was used as the fixed effect in a separate model. In these models, school was used as the random effect with room considered to be nested within school.

All statistical analyses were conducted in R Statistical Software (version 3.3.3) (R Core Team, 2017). The lmerTest and nlme packages were used to fit the linear mixed-effect models (Kuznetsova et al., 2016; Pinheiro et al., 2017). Since all the fitted models were log-linear (i.e. log-transformed outcome and untransformed explanatory variables), the estimated regression results (coefficients and 95% confidence intervals) were multiplied by 100 and reported as % change in the outcome per unit increase in the continuous explanatory variable. For the categorical explanatory variables, the results were reported as % change in the outcome from the reference level. In some cases, and for easier interpretation, regression results were reported as % change in the outcome per an interquartile range (IQR) increase in the continuous explanatory variable.

3. Results

3.1. School characteristics and general summary of IAQ in schools:

After accounting for missing data, the total number of monitoring days was 291, across three seasons (fall: n=120 days in 9 schools, winter: n=92 days in 8 schools, spring: n=79 days in 6 schools), and two types of rooms in schools (classroom: n=165, common area: n=126). Figure 1 illustrates the distribution of the monitored schools in Baltimore City, as well as the major roads, highways, and TRI sites.

Some of the main characteristics of the 145 monitored locations within these 16 schools are listed in Table 1. None of the monitored schools had a fully-operational central HVAC system. The majority of the monitored locations had old unit ventilators consisting of heating coil, fan assembly, temperature controls, etc. installed for heating. The use of window air conditioning units for cooling was observed in some of the monitored locations. Based on the observation of the study staff, natural ventilation via opening and closing windows and doors was the main method of ventilation in some locations.

Table 2 provides an overview of the indoor exposure levels by season, showing summary statistics including mean and range of the daily median concentrations. The p-value indicates if the seasonal variability in the daily median of the exposure variable is statistically significant. Except for PM_{2.5}, statistically significant seasonal differences were observed in the daily medians of the indoor exposure variables, with highest exposures often occurring in winter.

Some statistically significant differences were also observed between exposure levels in classrooms versus common areas in schools. Average of the daily median of CO₂ concentrations was somewhat higher in classrooms than common areas (948 vs 749 ppm), whereas NO₂ had higher concentrations in common areas compared to classrooms (average of the daily median: 81.7 vs 71.9 ppb). PM_{2.5} and CO concentrations did not show any statistically significant variability by room type (p-value <0.05).

3.2. Comparison of indoor exposure levels with the IAQ guidelines:

Indoor air pollution concentrations were compared to existing indoor air quality guidelines that are available for the daily and hourly (for NO₂) averages. Daily means of PM_{2.5} and CO and hourly means of NO₂ were compared to the corresponding WHO guidelines (World Health Organization (WHO), 2010). Daily means of CO₂ were compared with the 1000-ppm concentration recommended for indoor environment by the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) (ANSI/ASHRAE, 2016). Most exposure levels fell within the limits recommended by the guidelines for indoor air quality, however, exceedances (values outside of established guidelines) were observed on multiple occasions for NO₂ and CO₂. Of the 271 available PM_{2.5} daily averages, 3 (1.1%) that were measured among all 16 schools were above the 25 µg/m³ daily exposure limits recommended by the WHO. For NO₂, 385 hourly measures from the total of 1548 (24.9%) that were measured among 12 of the all 16 schools were above the 200 µg/m³ (~100 ppb at room conditions) limit for hourly average exposure. CO was the only exposure variable that did not exceed the WHO-recommended daily average on any sampling day (Figure 2).

An uneven seasonal distribution of the cases that exceeded the WHO limits was observed, particularly for the hourly average NO₂ exposure, where winter had the highest number of such cases (216), followed by fall (124), and spring (45). The proportions of the out-of-range hourly average NO₂ concentrations and daily average CO₂ concentrations in winter were 41% and 37%, respectively.

Figure 3 shows the distribution of mean indoor exposure variables (daily for PM_{2.5}, CO, and CO₂, and hourly for NO₂) with their corresponding WHO limits (ASHRAE standards for CO₂), compared across two different room types.

All 3 days exceeding the WHO guideline for the daily average indoor PM_{2.5} concentrations were observed in classrooms. Of the 385 observed cases of exceedance of the WHO limit for the hourly average indoor NO₂ concentration, 235 were in classrooms and 150 were in common areas including gymnasiums (58), cafeterias (41), libraries (23), and hallways (28).

Examining the correlations between the daily medians of the IAQ variables showed that NO₂ exposure was inversely correlated with relative humidity and temperature. However, the inverse correlation between NO₂ and temperature was not consistently significant when stratified by season or room type (Table S1). PM_{2.5} showed a consistent but weak positive relationship with relative humidity. The positive correlation between PM_{2.5} and CO was also weak but not consistent across all seasons.

3.3. Outdoor concentrations and relationship with indoor levels:

Table 3 contains descriptive statistics of the outdoor data. Seasonal differences were shown to be statistically significant for all variables with the exception of the relative humidity. Similar to the indoor values, the concentrations of PM_{2.5} and NO₂ were higher outdoors in winter.

Figure 4 shows the comparison of the indoor concentrations of PM_{2.5} and NO₂ in the schools monitored in 2016 with the ambient data obtained from Maryland Department of Environment's (MDE) air monitoring site located in downtown Baltimore. As shown in Figure 4, the majority of the daily means of indoor PM_{2.5} were smaller than the outdoor levels, whereas the daily maximum values of the hourly means for indoor NO₂ were mostly greater than the outdoor levels. While Figure 4 does not suggest the existence of a clear seasonal trend in indoor PM_{2.5} concentrations, NO₂ was shown to be higher in heating seasons (also suggested by Table 2).

We examined the correlations between indoor and outdoor exposure levels and found that total average indoor PM_{2.5} concentrations, gravimetrically measured for two weeks at each school in each season, and the corresponding outdoor PM_{2.5} concentration had a weak positive relationship (spearman $r=0.37$, marginally significant, $p\text{-value}=0.08$). There was a moderate positive relationship between the two-week average indoor concentration of NO₂ measured in real-time and the average outdoor concentration obtained from the passive sampler ($r=0.62$, $p\text{-value}<0.05$). These relationships did not change markedly when stratified by room type. However, they varied significantly by season with the correlation coefficient ranging from 0.08 to 0.56 for PM_{2.5} and from 0.49 to 0.81 for NO₂. PM_{2.5} I/O

ratio ranged from 0.1 to 1.2 with the mean of 0.6. For NO₂, the I/O ratio varied over a wider range, from 0.5 to 3.1 with the mean of 0.8.

3.4. Bivariate regression analysis:

Table 4 summarizes the results of the bivariate linear regression analysis as the estimated coefficient and 95% confidence interval of the statistically-significant explanatory variables. It also contains standard deviations of the random intercepts in each pollutant's null model (the model with only the nested random structure and no explanatory variable).

To assess the significance of the effect of repeated measurements in each location within school, sensitivity analysis was performed by adding the first-order autoregressive error structure to each model. There was no statistically significant relationship between exposure measured on different days in each location within school. In other words, the results showed a strong within-location, day-to-day variability of indoor exposure. The full results of bivariate regression analysis are provided in Tables S2 and S3 for categorical and continuous explanatory variables, respectively.

Indoor exposure to all three examined pollutants were found to be associated with different characteristics at school, room, and outdoor environment levels. PM_{2.5} concentrations in schools showed significant positive associations with indoor temperature and relative humidity as well as outdoor temperature. Wind speed was the only continuous explanatory variable to have an inverse association with indoor PM_{2.5} daily median exposure (−4% per 1 km/h increase). Among school building characteristics, rooms located on higher floors appeared to have higher concentrations of PM_{2.5}. Classrooms with younger children showed higher PM_{2.5} concentrations.

We found that indoor NO₂ exposure was influenced by several factors. Schools in temporary buildings showed higher indoor NO₂ exposure than those in permanent buildings. Physical defects in the school building, such as cracks and holes in the walls, broken windows and peeling wallpaper or paint, were significantly associated with higher indoor NO₂ concentrations. At the room level, rooms with air conditioning had up to 60% lower daily median NO₂ concentrations. There were significantly higher indoor NO₂ exposures in winter (by 97%) compared to the reference level (fall), whereas the difference between exposure in spring and fall was found to be insignificant. Temperature and relative humidity both indoors and outdoors were inversely associated with indoor NO₂ exposure, while outdoor PM_{2.5} and NO₂ concentrations showed significant positive associations (12.8% and 11.4% rise in the daily median of indoor NO₂ exposure per unit increase in outdoor PM_{2.5} and NO₂ concentrations, respectively). Finally, a significant 66% rise in the indoor NO₂ exposure was observed per IQR increase in the length of all roads within 100 meters of schools.

School proximity to toxic release sites was significantly associated with indoor CO levels; each additional TRI site within 2km of the school was associated with a 2.7% increase in CO concentrations. A ~7.5 m (25 ft) distance between the school building entrance and the street curb was associated with 58% lower indoor CO levels. A 3.5% decrease in median indoor CO concentration was observed per 1 km/h increase in outdoor wind speed. The

pattern of seasonal variability for CO was similar to NO₂ with lower concentrations in winter (by 23%) and higher concentrations (by 34%) in spring compared to fall, which was used the reference season. The variability in indoor CO exposure between winter and fall was smaller than of the observed variability in NO₂ exposure between the same seasons. Unlike NO₂, the difference between indoor CO exposure in spring versus fall was found to be statistically significant. Building and room-levels characteristics also contributed to the indoor CO exposure. Similar to indoor NO₂, physical defects in the building were associated with higher concentrations of CO. At the room level, a strong positive relationship was observed between the number of open windows in the room and CO exposure with an 8.2% increase in the daily median of CO concentration for each additional open window. Indoor and outdoor relative humidity also showed statistically significant yet weak positive associations with CO exposure.

4. Discussion

To our knowledge, this is the first study that investigates the association of infrastructural and contextual conditions with indoor air quality in a major Mid-Atlantic U.S. city with a dominant African-American population. We observed higher NO₂ exposure than the previously reported levels. Seasonality and microclimatic parameters (temperature, relative humidity and ventilation) were important factors with significant impacts on indoor exposure levels. Other factors that were important, particularly in NO₂ and CO exposures, related to the building characteristics such as physical defects, as well as potential outdoor sources of pollution, mainly vehicle emissions and industrial facilities. PM_{2.5} did not exceed the limits recommended by the indoor air quality guidelines frequently and its likely determinants also included outdoor sources, building characteristics and possibly the activity level in the room.

While PM_{2.5} and CO levels were generally lower in this work compared to the reported results in the literature, we observed typically higher NO₂ exposures than prior studies. Seasonality was shown to be associated with the indoor concentrations of all examined pollutants. Higher concentrations were observed in winter, which is consistent with the findings of the previous work (Blondeau et al., 2005; Fromme et al., 2007; Goyal & Khare, 2009). This seasonal pattern may be tied to inadequate ventilation as evidenced by higher CO₂ levels (also shown in the present work) in winter. Furthermore, higher levels of outdoor pollutants are expected in the cold season in the United States, which is mainly due to the increased combustion from heating and decreased mixing in the atmosphere (Yanosky et al., 2014), and may also contribute to the increased indoor concentrations.

Low I/O ratios for PM_{2.5} suggest the lack of major indoor sources of PM_{2.5} in the monitored schools. This observation was in agreement with those of the previous IAQ assessment studies (Chithra & Shiva Nagendra, 2012; Blondeau et al., 2005). However, compared to the results reported in other IAQ assessment studies in schools (Blondeau et al., 2005; Stranger et al., 2008), we observed relatively high I/O ratios for NO₂, suggesting a considerable influence of indoor sources on NO₂ exposure, particularly in heating seasons (as further evidenced by the results presented in Table 2, and Figures 2 and 4).

Our results showed strong positive association of temperature with indoor PM_{2.5} concentrations. Relative humidity was another microclimatic parameter showing positive relationships with indoor PM_{2.5} and CO levels. The effect was more pronounced for PM_{2.5} with a 3.1% increase in the indoor exposure for every 1% rise in indoor relative humidity. These results are in line with findings of some previous works (Braniš et al., 2005; Goyal & Khare, 2009). Another outdoor meteorological factor that was significantly associated with two of the examined outcome variables was the wind speed. It showed inverse associations with indoor PM_{2.5} and CO concentrations, which are known to originate mostly from outdoor sources in the absence of major indoor sources such as cooking and smoking. It is believed that the inverse associations between wind speed and the indoor exposure of such pollutants is due to their dispersion and thereby diminished contribution to the indoor air.

Occupancy is known as a factor that can impact PM levels in classrooms (especially the coarse fraction, PM₁₀) due to the re-suspension of the deposited particles. This effect has been reported to be more significant in classrooms with younger children (Fromme et al., 2007). The results obtained in this work suggested that the indoor concentration of smaller particles may also be associated with the activity level of the students according to the significantly higher PM_{2.5} exposure observed in classrooms with younger children.

School building and room characteristics were extensively investigated and several significant associations with indoor air quality were identified. Higher room floor level was positively associated with PM_{2.5} concentrations. Our findings were in agreement with some previous studies (Hitchins et al., 2002; Jung et al., 2011), however, the reported results in the literature are not conclusive. This may be related to the fact that the vertical profile of PM_{2.5} concentration depends on several parameters other than the building height including the geometry of the surrounding buildings as well as local meteorological conditions. We also observed that the number of open windows in a room may have an increasing effect on indoor exposure levels due to the penetration of pollutants into the room, especially those that are known to have vehicular sources such as CO. The observed lower concentrations of NO₂ in the air-conditioned rooms are likely due to the reduced need to open the windows and therefore lower penetration of NO₂ from outdoor sources into the rooms.

Higher concentrations of NO₂ and CO were observed in buildings with physical defects including damaged walls and broken windows. Higher air pollution in such locations may be explained by the flow of the outdoor pollutants into the building through the broken windows, cracks in the walls, etc. The same explanation could also apply to the higher NO₂ exposure concentrations in schools with temporary buildings as they may be less effective than the permanent buildings to shield against the penetration of the outdoor air pollutants into the building.

Characteristics related to the school surroundings such as proximity to roads and traffic density are known to have impacts on indoor air quality (Janssen et al., 2001; Patel et al., 2009; Yang et al., 2015). The number of TRI sites within 2 km of schools was associated with a higher CO daily median exposure. Both the total traffic volume nearby schools and the distance between school and sources of traffic emissions were each associated with CO and NO₂ concentrations. An increase in the length of the roads within 100 meters of schools,

which may also be interpreted as the total nearby traffic volume, was positively associated with the indoor NO₂ exposure. Furthermore, the distance between school building and surrounding streets showed inverse associations with indoor exposures (58% lower indoor CO levels in schools where the distance between the building entrance and street curb was greater than ~7.5 m). These findings suggest that this could be a potential target for intervention, but more controlled studies would be needed to determine if this relationship is causal.

5. Conclusions

In a study of city schools in the Mid-Atlantic region, we found that indoor air quality was within the recommended ranges the majority of the time but did exceed showed exceedance of the WHO indoor air quality guidelines (1% of daily averages for PM_{2.5} and 25% of hourly averages for NO₂). We found significant seasonal variability in the studied pollutants. A broad range of contributors at outdoor environment, school, and room level were examined and several factors were found to contribute significantly to indoor pollutant concentration. Most of these factors pointed to the role of the outdoor sources of pollutants either directly (e.g. number of TRI sites, length of the nearby roads, wind speed) or indirectly and through some of the building-level factors such as building type and physical defects. The demonstrated negative impact of poor building conditions on IAQ in schools is of particular concern in areas where school buildings with poor and extremely poor conditions are prevalent. This work contributes to the existing literature by extensively examining the potential predictors and identifying the significant contributors to the indoor air quality in schools. A major implication of our findings is that improving school conditions, from building characteristics to room heating/cooling, as well as choosing the locations for new schools (or if possible, moving the existing ones to locations far from major roads and industrial facilities) may result in significantly improved air quality and healthier environments in schools.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgement

The authors wish to thank Baltimore City Public Schools for their kind contributions. This article was developed under Assistance Agreements No. EPA-G2013-STAR-H1 and No. 83615201 awarded by the U.S. Environmental Protection Agency to Dr. Meredith C. McCormack, and Dr. Nadia N. Hansel, respectively. It has not been formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication. This research was also supported by the National Institute of Environmental Health Sciences of the National Institutes of Health under award number P50ES018176. Dr. Meghan Davis was supported by NIH ORIP grant 1K01OD019918.

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Highlights:

- 25% of the NO₂ hourly averages exceeded the WHO indoor air quality (IAQ) guideline
- Significant seasonal variability for indoor NO₂ and CO; higher levels in cold seasons
- Poor IAQ in schools mostly due to the outdoor pollution sources
- Physical conditions of the buildings contributed to IAQ in schools
- Poor IAQ in schools with poor conditions is a concern where such schools are prevalent

Figure 1.
Spatial distribution of the monitored schools in Baltimore City with major roads and highways, and toxic release inventory (TRI) sites

Figure 2. Distribution of IAQ parameters in schools in different seasons; (a) Daily average $PM_{2.5}$, (b) Hourly average NO_2 , (c) Daily average CO, (d) Daily average CO_2 . Corresponding indoor WHO guidelines shown by the dashed red lines are: 25 $\mu g/m^3$ for $PM_{2.5}$, 200 $\mu g/m^3$ (~ 100 ppb at room conditions) for NO_2 , and 7 mg/m^3 (~ 6.1 ppm at 25 °C) for CO. For CO_2 , the dashed line represents the indoor concentration of 1000 ppm recommended by ASHRAE.

Figure 3. Distribution of indoor exposures in schools in different room types; (a) Daily average PM_{2.5}, (b) Hourly average NO₂, (c) Daily average CO, (d) Daily average CO₂. Corresponding indoor WHO guidelines shown by the dashed red lines are 25 µg/m³ for PM_{2.5}, 200 µg/m³ (~100 ppb at room conditions) for NO₂, and 7 mg/m³ (~6.1 ppm at 25 °C) for CO. For CO₂, the dashed line represents the indoor concentration of 1000 ppm recommended by ASHRAE.

Figure 4. Indoor concentrations vs outdoor levels obtained from the MDE site; NO_2 : daily maximum of the hourly means, $\text{PM}_{2.5}$: daily means (Note: the summer data shown in this figure was not used in the analysis)

Table 1.

Information about: a) type b) heating, ventilation and air conditioning (HVAC), and c) presence of physical defects in the monitored locations within schools

Characteristics		N (%)
Room type	<i>classroom</i>	71 (49)
	<i>gymnasium</i>	12 (8)
	<i>cafeteria</i>	38 (26)
	<i>other</i>	24 (17)
HVAC	<i>presence of window air conditioning unit</i>	27 (19)
	<i>presence of unit ventilator for heating</i>	137 (95)
	<i>presence of electric heater</i>	8 (5)
	<i>observed open windows at inspection</i>	27 (19)
	<i>presence of air vents</i>	109 (75)
Physical defects	<i>presence of leaking roof</i>	17 (12)
	<i>presence of broken windows</i>	37 (26)
	<i>presence of cracks/holes in walls</i>	113 (78)
	<i>presence of water damage</i>	56 (39)

Table 2.

Characteristics of indoor air pollutants in schools (daily medians, data was limited to and averaged over school hours 8am-4pm)

Variable Measured	Season	N	Median (P25-P75) ^a	Mean (SD) ^b	Range	p-value ^c
PM _{2.5} (µg/m ³)	Fall	84	5.2 (2.8–8.9)	6.9 (5.5)	0.9–24.3	0.35
	Winter	59	4.7 (3.3–9.6)	7.4 (5.9)	1.1–30.1	
	Spring	74	6.2 (4.0–8.9)	7.3 (5.0)	1.0–28.4	
NO ₂ (ppb)	Fall	80	12.6 (10.8–18.0)	14.4 (5.4)	1.8–32.4	< 0.01
	Winter	76	16.2 (12.6–23.4)	18.0 (7.2)	5.4–34.2	
	Spring	69	10.8 (7.2–14.4)	12.6 (7.2)	1.8–45	
CO (ppm)	Fall	85	0.5 (0.4–0.8)	0.7 (0.5)	0.1–2.4	< 0.01
	Winter	59	0.6 (0.4–0.8)	0.6 (0.4)	0.1–2.0	
	Spring	32	0.4 (0.3–0.5)	0.4 (0.1)	0.1–0.7	
CO ₂ (ppm)	Fall	80	750 (625–1045)	851 (317)	80–1750	< 0.01
	Winter	92	823 (628–1297)	998 (465)	92–2318	
	Spring	79	665 (554–947)	845 (467)	79–2279	

^a25th and 75th percentiles

^bStandard deviation

^cKruskal-Wallis p-value; Bold font denotes significance at 0.05 level

Table 3.

Characteristics of outdoor air in schools (PM_{2.5} and NO₂ –measured over two weeks; daily means of temperature, relative humidity and wind speed)

Variable Measured	Season	N	Median (P25-P75) ^a	Mean (SD)	Range	p-value ^b
PM _{2.5} (µg/m ³)	Fall	9	7.8 (7.2–8.2)	10.0 (6.9)	6.8–28.4	< 0.01
	Winter	14	12.7 (10.4–15.7)	16.0 (12.5)	6.6–56.1	
	Spring	6	7.7 (7.3–8.9)	8.8 (2.7)	6.9–14.1	
NO ₂ (ppb)	Fall	8	11.1 (9.9–13.6)	12.3 (4.4)	6.5–19.7	< 0.01
	Winter	5	18.8 (15.2–19.2)	17.4 (2.6)	14.0–19.7	
	Spring	5	7.9 (7.3–8.2)	7.8 (1.1)	6.3–9.2	
T (°C)	Fall	115	18.9 (15.4–22.0)	18.9 (5.3)	6.1–30.1	< 0.01
	Winter	38	4.7 (–0.6–9.0)	5.1 (7.1)	–6.6–19.9	
	Spring	63	19.4 (14.0–20.9)	17.9 (5.3)	4.3–27.6	
RH (%)	Fall	115	64 (50–75)	64 (17)	28–100	0.93
	Winter	52	56 (43–73)	58 (19)	27–100	
	Spring	63	57 (46–75)	58 (19)	23–95	
Wind speed (k/h)	Fall	120	8.7 (5.8–12.2)	9.6 (5.0)	2.9–29.9	0.02
	Winter	92	8.5 (5.8–15.4)	10.8 (7.1)	2.1–29.1	
	Spring	79	10.8 (7.2–14.7)	11.1 (4.3)	3.5–20.1	

^a25th and 75th percentiles

^bKruskal-Wallis p-value; Bold font denotes significance at 0.05 level

Table 4.

Determinants of indoor air pollutants in school classrooms (unless specified in the footnote, estimates represent % change in the outcome variable per unit increase in the continuous explanatory variable; for the categorical explanatory variables, the results are reported as % change in the outcome from the reference level)

Parameter	Estimate (95% CI)		
	PM _{2.5}	NO ₂	CO
T _{indoor} (°C)	4.7 (1.1, 8.2)	−3.5 (−5.7, −1.3)	NS [†]
T _{outdoor} (°C)	2.1 (0.6, 3.5)	−4.8 (−5.8, −3.9)	NS
RH _{indoor} (%)	3.1 (2.1, 4.1)	−2.1 (−2.8, −1.3)	0.9 (0.2, 1.6)
RH _{outdoor} (%)	NS	−4.1 (−6.1, −2.1)	1.3 (0.1, 2.4)
Wind speed (km/h)	−4.0 (−6.6, −1.5)	NS	−3.5 (−4.9, −2.1)
Open windows ^a	NS	NS	8.2 (1.1, 15.2)
PM _{2.5, outdoor} (µg/m ³)	NS	12.8 (8.2, 17.3)	NS
Nearby TRI sites ^b	NS	NS	2.7 (0.2, 5.2)
NO _{2, outdoor} (ppm)	NS	11.4 (9.0, 13.7)	NS
Nearby roads ^{c, ^} (m)	NS	66.0	NS
Room floor	Ref: 1 st floor		
2 nd floor	81 (7, 161) [*]	NS	NS
3 rd floor	111 (25, 197) [*]	NS	NS
Season	Ref: Fall		
Spring	NS	−6 (−32, 20)	−34 (−66, −3) [*]
Winter	NS	97 (71, 122) [*]	23 (2, 49) [*]
Grade	Ref: 3 rd		
6 th	−150 (−243, −56) [*]	NS	NS
Other	−25 (−62, 12)	NS	NS
Building defects ^d	Ref: No		
Yes	NS	101 (16, 187)	103 (59, 145)
Distance to curb ^e	Ref: < 7.5 m		
> 7.5 m	NS	NS	−58 (−124, −6)
Building type	Ref: Permanent		
Temporary	NS	130 (80, 198)	NS
Room AC ^f	Ref: No		
Yes	NS	−60 (−103, −19)	NS
Random Effects [#]			
School	0.226	0.23	0.20
Room	0.344	0.51	0.26

[†] Not statistically significant

^aNo. of open windows in the room

^bNo. of TRI sites within 2 kilometers of school

^cLength of all roads within 100 meters of school

^dLeaks in the roof, broken windows, broken plaster, peeling paint, peeling wall paper, cracks and holes in the walls (school-level)

^eDistance between the school building entrance and street curb

^fAir conditioning in the room

[^]% change in outcome per IQR (interquartile range) change in the parameter

^{*}Level of a categorical variable that is significantly different than the reference level (*p-value*<0.05)

[#]Standard deviation of the random intercept in each pollutant's null model