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Air Quality outside Schools in Newcastle upon Tyne, UK: An Investigation into NO₂ and PM Concentrations and PM Respiratory Deposition

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Abstract: Air pollution is the principal environmental threat to public health in the UK. Ever-increasing evidence links ambient air pollutants, preventable diseases, and health inequalities. Children are particularly vulnerable to harmful effects due to their short height, developing lungs, and higher rate of respiration. Using data from air quality monitors around schools, we investigated 2018–2019 ambient NO₂, PM₁₀, PM_{2.5}, and PM₁ concentrations at 12 schools in Newcastle upon Tyne, UK. We compared findings with EU/UK air quality regulations and guidelines, identified patterns, and calculated PM respiratory deposition doses (RDDs). The range of annual average (AA) concentrations across the schools for the two-year period was 23.7–39.2 µg/m³ for NO₂, 7.4–22.2 µg/m³ for PM₁₀, 3.5–11.6 µg/m³ for PM_{2.5}, and 1.7–9.0 µg/m³ for PM₁. The highest PM RDD children were exposed to at school was 30 µg/h. One school's AA NO₂, two schools' hourly PM_{2.5} averages, and one school's 24-h PM₁₀ averages exceeded EU/UK regulations. All schools exceeded WHO₂₀₀₅ 24-h PM₁₀ and PM_{2.5} guidelines in 2018, less in 2019. All 12 schools would have exceeded WHO₂₀₂₁ NO₂ AA guidelines (10 µg/m³), 2 the WHO₂₀₂₁ PM₁₀ AA (15 µg/m³), and 10 the WHO₂₀₂₁ PM_{2.5} AA (5 µg/m³). Evidence-based policy is required to improve school ambient air quality and reduce children's exposure.

Keywords: schoolchildren; air quality; nitrogen dioxide; particulate matter; respiratory deposition dose



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1. Introduction

Ambient air pollution is a public health issue of global concern and the principal environmental threat to public health in the United Kingdom (UK) [1]. An ever-increasing body of evidence demonstrates both associative and causal relationships between ambient air pollutants, preventable diseases, and health inequalities [2,3]. Air quality is an area of rapidly evolving policy; however, effecting change presents a significant challenge as ambient air pollutants are by-products of processes that are fundamental to how we currently live our lives [1].

Ambient air pollutants adversely affect human health and children are among the most vulnerable to these harmful effects due to their short stature, developing lungs, and higher rate of respiration [1,4,5]. The effects of ambient air pollutants on children's respiratory systems include suppression of lung growth, an increased risk of new-onset asthma and wheeze, an increased risk of bronchitis, and an increased risk of problematic respiratory symptoms [5–7]. Considering the impacts on children's other systems, exposure to ambient air pollution is associated with decreased concentration and alertness in children and may

be associated with insulin resistance, decreased brain development, and an increased risk of attention deficit hyperactivity disorder (ADHD) [5,8,9]. Lastly, ambient air pollution is classified as a group one carcinogen by the World Health Organization (WHO) International Agency for Research on Cancer (IARC), with particulate matter (PM) being a pollutant most strongly associated with increased cancer incidence [10]. The health effects of exposure to PM are dependent on the size of the particles and the duration of exposure [1]. PM₁₀ can enter the body as far as the nose and throat, whereas ultrafine particles <0.1 µm in diameter may be able to enter the bloodstream [1]. The evidence suggests that there is no threshold below which particles <2.5 µm (PM_{2.5} and smaller) are not harmful to human health. There is consensus among experts that, rather than aiming for a given threshold value of PM_{2.5}, concentrations of PM_{2.5} should be reduced as low as possible [11,12].

At a national level, European Union (EU) air quality policy is the key driver of UK policy [13]. The 2008 Directive on Ambient Air Quality and Cleaner Air for Europe is a legislative document setting legally binding limit values (regulations) for key pollutants that are transposed into UK law [13,14]. The directive acknowledges that advances in the understanding of the harmful effects of pollutants have increased the urgency and drive to improve air quality and protect health [15]. EU/UK legal limit values and WHO guideline values for ambient air quality can be found in the Supplementary Materials Table S1 [11,12,16].

Several school air quality studies have been conducted in the UK, mostly in London [17]. Concentrations of nitrogen dioxide (NO₂), PM₁₀, and PM_{2.5} have been measured and modelled at high resolution across the capital. The Greater London Authority (GLA) estimated that, in 2013, 24% of London primary schools were in locations with annual mean NO₂ concentrations that exceeded 40 µg/m³ [18]. The GLA found that 82% of the schools in high NO₂ concentration locations were also in areas of deprivation [18,19]. Updated reports from 2017 estimated that a similar proportion of London schools were in locations that breached the annual mean NO₂ national air quality standard [20]. Additional information on UK-based school air quality studies can be found in the Supplementary Materials Table S2.

Luciulli et al. (2020) measured indoor and outdoor concentrations of the polyaromatic hydrocarbon pollutants benzene, toluene, ethylbenzene, and xylene (BTEX) at schools in Italy as these pollutants are associated with vehicle emissions and are harmful to children's health [21]. They found that mean outdoor concentrations varied from 0.10 to 4.23 µg/m³ (benzene), 0.10 to 28.18 µg/m³ (toluene), 0.10 to 11.1 µg/m³ (ethylbenzene), and 0.10 to 14.45 µg/m³ (xylene) [21]. A similar study found high levels of aromatic pollutants at schools in Portugal and that subsequently, the total cancer risk of 8–10-year-old children exceeded the United States Environmental Protection Agency (USEPA) recommended guideline [22].

This study focuses on four key pollutants known to be harmful to human health: NO₂ and inhalable particles sized <10 µm (PM₁₀), <2.5 µm (PM_{2.5}), and <1 µm (PM₁) in diameter. The principal anthropogenic source of NO₂ in the UK is small vehicle emissions, with non-road transport, domestic heating, power generation, and industry also contributing [1].

The present study took place in Newcastle Upon Tyne (widely known as Newcastle) [23–25]. Information on the urban design, meteorology, and wind direction and speed can be found in the Supplementary Materials, including Figures S1 and S2. The city's council, Newcastle City Council (NCC), has declared two air quality management areas (AQMA) [26]. AQMA are locations where a local authority has identified that the UK national air quality objectives are either not likely to be achieved or are not achieved [27]. NCC declared one AQMA in the city centre in 2006 and one in an area of the city called Gosforth in 2008 [26]. Both AQMA were declared due to annual mean NO₂ exceedances [26]. Figure 1 shows the locations of the two AQMA.

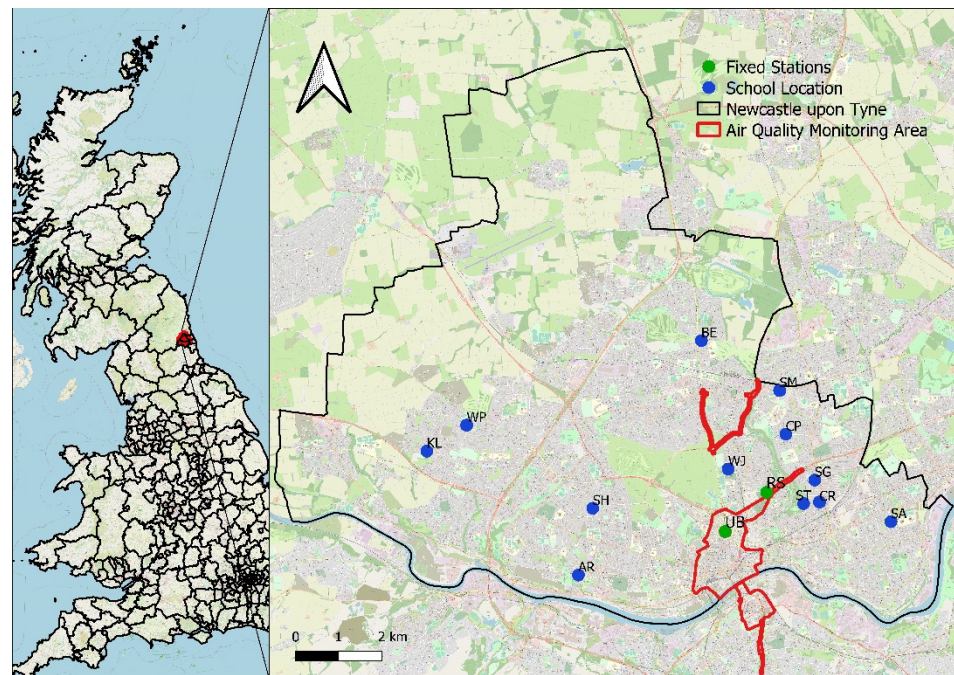


Figure 1. The city of Newcastle Upon Tyne with the location of the 2 fixed monitoring stations, the 2 AQMAs, and the 12 schools with air quality monitors mapped.

There are 92 government-funded schools and 9 independent schools in Newcastle [28]. In total, 22 schools in Newcastle have static air quality monitors (AQMs): 21 government-funded schools and 1 independent nursery. These AQMs have been provided to the schools through a partnership between NCC and the Newcastle Urban Observatory (UO) as part of a project called ‘The Healthy Schools Project’ [29]. The aim of the air quality work within this project is to raise awareness and engage schools, parents, and children in monitoring school ambient air quality [29].

This study aimed to investigate ambient air quality for 12 Newcastle schools. Specific objectives were to: (1) determine concentrations of NO_2 , PM_{10} , $\text{PM}_{2.5}$, and PM_1 outside schools in Newcastle and investigate temporal, geographical, and meteorological patterns; (2) determine whether concentrations of these pollutants regularly exceed the WHO guideline values or EU/UK regulations; and (3) estimate students’ exposure to inhalable particles.

2. Methods

2.1. Data Collection

Our study used Newcastle UO data [29,30], which are publicly available on the UO website. The UO collects ambient air quality data for the city of Newcastle and surrounding areas [31,32]. These data had not yet been formally analysed at the inception of this study, presenting an invaluable opportunity to do so.

Eleven schools in Newcastle had AQMs installed in 2017 or early 2018 after being identified by NCC as being located in potential pollution hotspots, one school already had an AQM in place, and a further 10 schools applied for an AQM as part of NCC’s Healthy Pupil Capital fund and had AQMs installed in 2019. The UO’s Healthy Schools Project uses fixed-location AQMesh pod AQMs to collect ambient air quality data. AQMesh pods are low-cost indicative AQMs manufactured in the UK that provide real-time ambient air quality data [33]. Electrochemical sensors in the monitors measure NO_2 and light-scattering optical particle counters measure PM [34]. AQMesh pods are continuous monitors and generate an average reading every 1–15 min [34]. Technical information on AQMesh pod Quality Assurance can be found in the Supplementary Materials. Placement of the monitors outside the schools in the Healthy Schools Project is carefully considered by experts at

the UO to ensure optimum data quality and they are commonly attached to lampposts at school entrances (Supplementary Materials Figure S3).

This study used meteorological data collected at the Albemarle Airfield weather station, west of the city. This station collects hourly data on wind speed, wind direction, temperature, atmospheric pressure, and humidity.

2.2. Data Analysis

Due to the varying installation dates of AQMs and start dates of data collection, only schools with sufficient data to provide annual averages were included in each analysis. This study included 12 schools and further information on the schools can be found in the Supplementary Materials Table S3. Figure 1 shows the location of the 12 schools included in this study on a map. The schools are Atkinson Road Primary Academy (AR), Broadway East First School (BE), Chillingham Road Primary School (CR), Craggside Primary School (CP), Knop Law Primary School (KL), Sacred Heart Catholic High School (SH), St Alban's R C Primary School (SA), St Gabriel's Children's Day Nursery (SG), St Mary's Catholic School (SM), St Teresa's Primary School (ST), Westerhope Primary School (WP), and West Jesmond Primary School (WJ).

Specialist air quality data analysis was performed using “openair”, an R package for air quality data analysis [35]. Data flagging was conducted to highlight outliers based on the Breathe London study [36]. Breathe London's NO₂ data flags use parts per billion (ppb), but the UO Healthy Schools project collects NO₂ data in µg/m³; therefore, the NO₂ conversion factor of 1 ppb = 1.925 µg/m³ was used in this study [37]. Data flagging values can be found in Supplementary Materials Table S4. The EU Air Quality Directive 2008 outlines data quality objectives and states that the minimum data capture from AQMs should be 90% for NO₂, PM_{2.5}, and PM₁₀; therefore, this value was adopted as a data quality measure [11].

Fixed monitoring site air quality data at the urban background and roadside locations in Newcastle were obtained from the UK-AIR database to compare school air quality with the air quality of the wider city (Figure 1). At urban background sites, ambient pollutants are not influenced by a single source but instead represent city-wide background concentrations [38]. The Newcastle urban background air quality monitoring site collects NO₂, PM₁₀, and PM_{2.5} data. Roadside air quality monitors are located at sites where concentrations of ambient pollutants are determined by nearby traffic emissions [39]. The Newcastle roadside air quality monitoring site collects NO₂ and PM₁₀ data.

2.3. Respiratory Deposition Dose (RDD)

Aerosolised particles, such as PM, become harmful to health when they are inhaled and deposited (remain after expiration) in the respiratory tract. Understanding the dose of PM deposited in different settings helps us to understand the health risk posed by the PM concentrations in these settings [40]. RDD estimates provide an indication of PM₁₀, PM_{2.5}, and PM₁ deposition in the respiratory tract [41]. RDD is calculated using Equation (1) [41,42]:

$$RDD (\mu g) = DF \times V_T \times f \times C \times T \quad (1)$$

where *DF* is the deposition fraction of particles in the respiratory, *V_T* is the volume of air inhaled per breath (m³), *f* is the respiratory rate (breaths/minute), *C* is the concentration of particles in the air (µg/m³), and *T* is the exposure time, the amount of time spent in an activity or setting (minutes) [42–44]. *DF* is the fraction of inhaled particles that deposit in the respiratory tract from the extrathoracic region to deep in the thoracic region [45,46]. RDD regional depositions are calculated (head airways, tracheobronchial region, and alveolar region) and the total deposition in the respiratory tract is the sum of the regional depositions [40].

The deposition of aerosolised particles within the respiratory system is complex and determined by the characteristics of both the exposed individual and the inhaled

particle [43–45]. Characteristics of the particle that impact on DF include its shape, density, chemical composition, and size [43]. DF is estimated using Equation (2):

$$DF = IF \left(0.0587 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln d_p)} + \frac{0.943}{1 + \exp(0.508 - 2.59 \ln d_p)} \right) \quad (2)$$

where d_p is the particle size (μm) and IF is the inhalable fraction (fraction of ambient particles present in the volume of air before inspiration that enter the nose and mouth) used in the International Commission on Radiological Protection (ICRP) model [47]. IF is estimated using Equation (3):

$$IF = 1 - 0.5 \left(1 - \frac{1}{1 + (0.00076d_p)^{2.8}} \right) \quad (3)$$

where $(V_T \times f \times T)$ for light activity was calculated as $0.90 \text{ m}^3/\text{h}$ for school students in this study [41,42,48].

3. Results

3.1. Ambient Air Quality in Newcastle during the Study Period

Data from the two precision air quality monitoring sites in Newcastle were analysed to understand urban background and roadside air quality in the city (see Supplementary Material Table S5). Data captured at the two precision monitoring sites ranged from 83–99%. In 2018, the annual mean NO_2 concentration (\pm standard deviation) at the urban background site was $28.6 \pm 16.4 \mu\text{g}/\text{m}^3$ and at the roadside site, it was $39.0 \pm 26.2 \mu\text{g}/\text{m}^3$. In 2019, the annual mean NO_2 concentration at the urban background site was $32.1 \pm 15.8 \mu\text{g}/\text{m}^3$ and at the roadside site, it was $38.3 \pm 27.7 \mu\text{g}/\text{m}^3$. In 2018, the annual mean PM_{10} concentration at the urban background site was $12.4 \pm 12.7 \mu\text{g}/\text{m}^3$ and at the roadside site, it was $15.5 \pm 11.8 \mu\text{g}/\text{m}^3$. In 2019, the annual mean PM_{10} concentration at the urban background site was $15.3 \pm 30.1 \mu\text{g}/\text{m}^3$ and at the roadside site, it was $16.4 \pm 12.2 \mu\text{g}/\text{m}^3$. In 2018, the annual mean $\text{PM}_{2.5}$ concentration at the urban background site was $9.1 \pm 7.8 \mu\text{g}/\text{m}^3$ and in 2019, it was $8.9 \pm 7.8 \mu\text{g}/\text{m}^3$.

When comparing pollutant concentrations at the two sites, these data indicate that in both 2018 and 2019, NO_2 and PM_{10} concentrations were higher at the roadside site than at the urban background site. When comparing pollutant concentrations by year, these data suggest that concentrations of PM_{10} increased between 2018 and 2019 at both the urban background site and the roadside site. Daily average NO_2 , PM_{10} , and $\text{PM}_{2.5}$ concentrations at the urban background and roadside sites from 1 January 2018–31 December 2019 are shown in Figure 2.

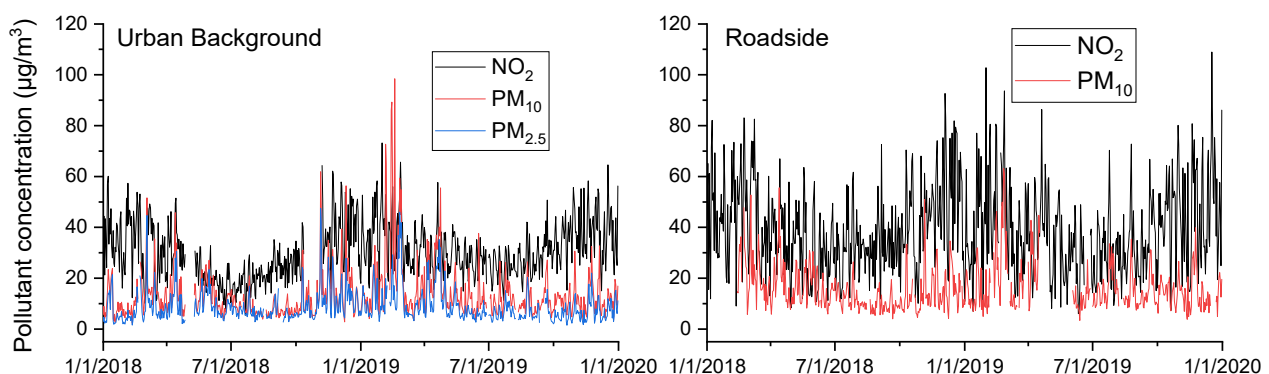


Figure 2. Daily average pollutant concentrations at the Newcastle urban background site and roadside site from 1 January 2018–31 December 2019.

This figure demonstrates that temporal variations exist in the NO₂ concentrations at the two precision sites in Newcastle over the course of a year. NO₂ concentrations are at their highest at both sites between November and January (late autumn to mid-winter), gradually decline to their lowest in July (mid-summer), and then gradually increase again through autumn and winter months. This apparent decline in the urban background and roadside NO₂ concentrations during the spring and summer months in Newcastle could be attributable to the increased temperatures in these months leading to less personal vehicle use, greater use of active travel (such as walking or cycling), and lower heating requirements.

PM concentrations show less noticeable variation over the course of a year; however, they do show occasional spikes in concentration, with the most obvious spike between January and July 2019 at the urban background site. Spikes in PM concentrations could be attributable to specific events, such as occasions when fireworks displays occur or emissions of dust from construction works. Spikes in the winter months could be attributable to increased fuel usage for heating and increased use of personal vehicles.

3.2. Ambient Air Quality Outside the 12 Schools in the Study Period

Data capture and data flagging of school data are reported in the Supplementary Materials (Tables S6–S8).

3.2.1. NO₂ Concentrations

In 2018, annual mean NO₂ concentrations outside the 12 schools ranged from $23.4 \pm 15.9 \mu\text{g}/\text{m}^3$ (Atkinson Road Primary) to $38.3 \pm 26.7 \mu\text{g}/\text{m}^3$ (St Gabriel's Children's Day Nursery). The combined annual mean NO₂ concentration of the 12 schools in 2018 was $31.3 \pm 23.8 \mu\text{g}/\text{m}^3$, which is greater than the urban background precision site 2018 annual mean ($28.6 \pm 16.4 \mu\text{g}/\text{m}^3$) but lower than the roadside precision site 2018 annual mean ($39.0 \pm 26.2 \mu\text{g}/\text{m}^3$).

In 2019, annual mean NO₂ concentrations ranged from $21.7 \pm 11.2 \mu\text{g}/\text{m}^3$ (West Jesmond Primary) to $40.0 \pm 33.4 \mu\text{g}/\text{m}^3$ (Sacred Heart Catholic High). The combined annual mean NO₂ concentration of the 12 schools in 2019 was $29.8 \pm 16.4 \mu\text{g}/\text{m}^3$, which is lower than the urban background precision site 2019 annual mean ($34.0 \pm 13.7 \mu\text{g}/\text{m}^3$) and lower than the roadside precision site 2019 annual mean ($38.3 \pm 27.7 \mu\text{g}/\text{m}^3$).

No schools exceeded the WHO₂₀₀₅ guideline or EU/UK regulations for the annual mean NO₂ concentration in 2018. However, all schools would have exceeded the updated WHO₂₀₂₁ guideline for the annual mean NO₂ concentration if it had been in place. In 2019, Sacred Heart Catholic High met the WHO₂₀₀₅ guideline and EU/UK regulations for the annual mean NO₂ concentration ($40 \mu\text{g}/\text{m}^3$), but no other schools met or exceeded this value in this year. The 2018 and 2019 annual mean NO₂ concentrations outside the 12 schools are shown in Table S5 and Figure 3a.

The monthly mean NO₂ concentrations for all 12 schools combined can be seen in Figure 4a. The overall mean NO₂ concentrations are lowest in the late spring, summer, and early autumn months (May–September) and highest in the winter months (October–February). When considering monthly NO₂ concentrations at an individual school level, consistently high monthly mean NO₂ concentrations were observed from April to November 2019 (range $40\text{--}53.7 \mu\text{g}/\text{m}^3$) at Sacred Heart Catholic High, and NO₂ concentrations remained $>40 \mu\text{g}/\text{m}^3$ throughout the winter months at St Gabriel's Children's Day Nursery. The high monthly average NO₂ concentrations in January and February 2018 were due to high NO₂ concentrations at St Teresa's Primary School (60.5 and $78.5 \mu\text{g}/\text{m}^3$ in January and February 2018, respectively). Early morning peaks at this school reached around $100 \mu\text{g}/\text{m}^3$. This school's AQM is located near a busy road with a large church, a row of shops and cafes, and a traffic light-controlled pedestrian crossing next to the AQM. Overall, the higher NO₂ concentrations seen in the winter highlight the impact that the burning of fossil fuels for heating and energy and increased vehicle usage have on ambient NO₂ levels in Newcastle in the colder months.

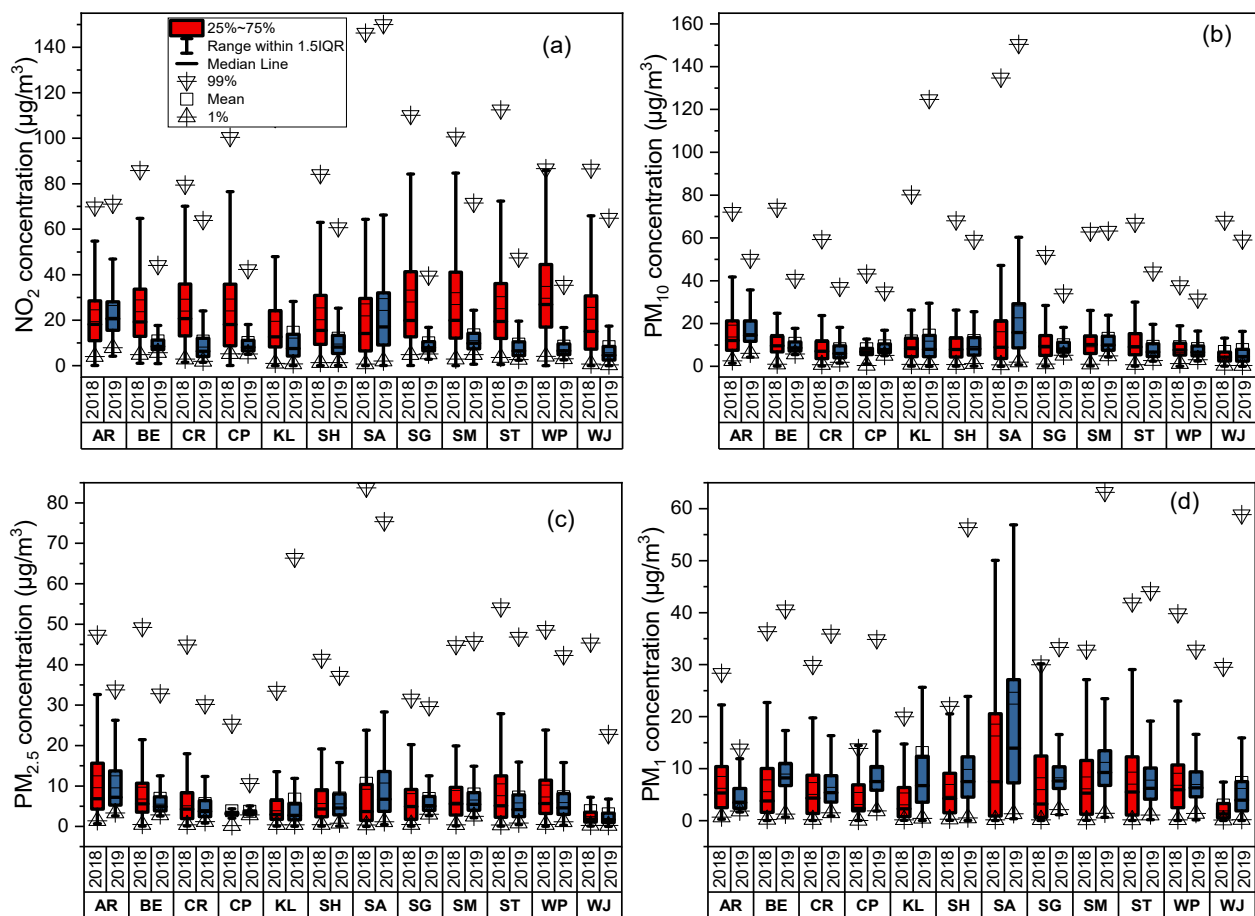


Figure 3. Boxplot of the annual mean concentrations of (a) NO_2 , (b) PM_{10} , (c) $\text{PM}_{2.5}$, and (d) PM_1 at individual schools based on the available data during 2018–2019.

3.2.2. Annual Mean PM Concentrations

In 2018, the annual mean PM_{10} concentrations at participating schools ranged from $7.0 \pm 15.2 \mu\text{g}/\text{m}^3$ (Westerhope Primary) to $19.0 \pm 29.5 \mu\text{g}/\text{m}^3$ (St Alban's RC Primary). In 2019, the annual mean PM_{10} concentrations ranged from $7.8 \pm 18.6 \mu\text{g}/\text{m}^3$ (Westerhope Primary) to $25.4 \pm 30.0 \mu\text{g}/\text{m}^3$ (St Alban's RC Primary). These are the same two schools that had the lowest and highest annual mean PM_{10} in 2018, indicating a consistent pattern in the concentrations of PM_{10} at these schools over the time of the study (Table S5 and Figure 3b).

In 2018, no schools exceeded the WHO₂₀₀₅ guideline or EU/UK regulations for the annual mean PM_{10} concentration. However, two schools (Atkinson Road Primary and St Alban's RC Primary) would have exceeded the updated WHO₂₀₂₁ guideline. In 2019, St Alban's RC Primary had an annual mean PM_{10} concentration of $25.4 \pm 30.0 \mu\text{g}/\text{m}^3$, higher than the WHO₂₀₀₅ guideline, but no schools exceeded the EU/UK regulations. In 2019, the same two schools (Atkinson Road Primary and St Alban's RC Primary) would have also exceeded the updated WHO₂₀₂₁ guideline.

The average monthly PM_{10} concentrations for all 12 schools combined can be seen in Figure 4b. The monthly mean PM_{10} values are generally lowest in the late spring, summer, and early autumn months. During the study period, the highest monthly PM_{10} concentrations were observed in November 2018, February 2019, April 2019, and November 2019. At an individual school level, the highest monthly mean PM_{10} concentrations over the study period were all observed at St Alban's RC Primary School. They occurred in the months of November 2018 ($38.0 \mu\text{g}/\text{m}^3$), February 2019 ($45.3 \mu\text{g}/\text{m}^3$), and April 2019 ($63.3 \mu\text{g}/\text{m}^3$). In these same three months, the mean PM_{10} concentration for all schools com-

binned was relatively high overall at $20.8 \pm 7.8 \mu\text{g}/\text{m}^3$ (November 2018), $18.2 \pm 10.1 \mu\text{g}/\text{m}^3$ (February 2019), and $19.5 \pm 15.1 \mu\text{g}/\text{m}^3$ (April 2019).

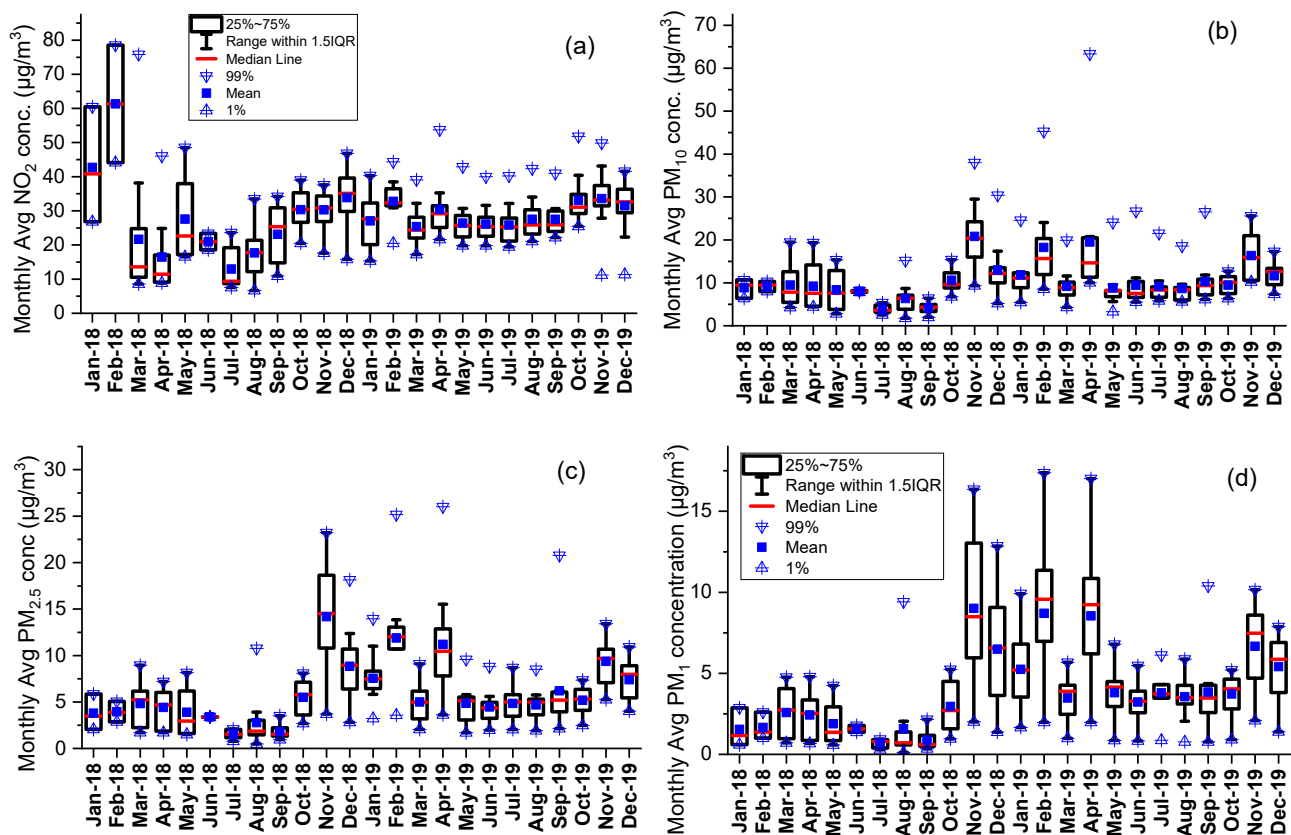


Figure 4. Boxplot of the monthly average concentrations of (a) NO_2 , (b) PM_{10} , (c) $\text{PM}_{2.5}$, and (d) PM_1 , for all schools combined, from January 2018 to December 2019.

In 2018, the annual mean $\text{PM}_{2.5}$ concentrations ranged from $3.8 \pm 5.3 \mu\text{g}/\text{m}^3$ (Craggs Primary) to $11.0 \pm 10.2 \mu\text{g}/\text{m}^3$ (Atkinson Road Primary Academy) (Table S5 and Figure 3c). In 2019, the annual mean $\text{PM}_{2.5}$ concentrations ranged from $3.1 \pm 4.7 \mu\text{g}/\text{m}^3$ (Westerhope Primary) to $12.2 \pm 15.8 \mu\text{g}/\text{m}^3$ (St Alban's RC Primary). These are the same two schools that had the lowest and highest annual mean PM_{10} concentrations in 2018 and 2019, further demonstrating the strength of the pattern emerging. Atkinson Road Primary and St Alban's RC Primary exceeded the WHO_{2005} guideline in 2018 and 2019, but no schools exceeded the EU/UK regulations. In both 2018 and 2019, 10 of the 12 schools would have exceeded the updated WHO_{2021} guideline and the same two schools would not have exceeded the guidelines in both years (Craggs Primary and Westerhope Primary).

The average monthly $\text{PM}_{2.5}$ concentrations were lowest in the late spring, summer, and early autumn months (May–October) and highest in the late autumn and winter months (November–February) (Figure 4c). Over the two-year study period, no month exceeded the EU/UK annual mean $\text{PM}_{2.5}$ regulations but three months exceeded the WHO_{2005} annual mean $\text{PM}_{2.5}$ guideline. These three months were November 2018 ($14.2 \pm 5.6 \mu\text{g}/\text{m}^3$), February 2019 ($11.9 \pm 5.6 \mu\text{g}/\text{m}^3$), and April 2019 ($11.2 \pm 5.9 \mu\text{g}/\text{m}^3$). The school with the highest $\text{PM}_{2.5}$ in these months was St Alban's RC Primary, with a monthly mean of 23.2, 25.2, and $26.0 \mu\text{g}/\text{m}^3$ in November 2018, February 2019, and April 2019, respectively.

In 2018, the annual mean PM_1 ranged from $2.1 \pm 2.2 \mu\text{g}/\text{m}^3$ (Craggs Primary) to $7.6 \pm 8.8 \mu\text{g}/\text{m}^3$ (West Jesmond Primary). The combined annual mean PM_1 concentration of all 12 schools in 2018 was $5.6 \pm 9.5 \mu\text{g}/\text{m}^3$. In 2019, the annual mean ranged from $1.3 \pm 1.8 \mu\text{g}/\text{m}^3$ (Westerhope Primary) to $10.3 \pm 18.0 \mu\text{g}/\text{m}^3$ (St Alban's RC Primary). St Alban's RC Primary 2018 and 2019 annual mean PM_1 concentrations appear noticeably

higher than concentrations outside the other 11 schools in both years (Figure 3d). The combined annual mean PM_1 of all 12 schools in 2019 was $5.0 \pm 6.8 \mu\text{g}/\text{m}^3$.

The monthly mean PM_1 concentrations (Figure 4d) show similar patterns to the monthly mean PM_{10} and $PM_{2.5}$. Considering the monthly mean PM_1 concentrations at an individual school level, St Alban's RC Primary had the highest concentrations over the two-year study period. These occurred in the months of November 2018 ($16.4 \mu\text{g}/\text{m}^3$), February 2019 ($17.4 \mu\text{g}/\text{m}^3$), and April 2019 ($17.0 \mu\text{g}/\text{m}^3$). St Teresa's Primary ($14.8 \mu\text{g}/\text{m}^3$) and West Jesmond Primary ($14.9 \mu\text{g}/\text{m}^3$) also had high monthly mean PM_1 concentrations in November 2018.

3.2.3. Short-Term Exceedances

In 2018, Knop Law Primary and St Teresa's Primary exceeded both the WHO₂₀₀₅ guidelines and the EU/UK regulations for short-term NO_2 exceedances. In 2018, Knop Law Primary had 24 occurrences of NO_2 level $>200 \mu\text{g}/\text{m}^3$ and St Teresa's Primary had 39 occurrences. In 2018, Atkinson Road Primary, Craggside Primary, Sacred Heart Catholic High, and St Gabriel's Children's Day all exceeded the WHO₂₀₀₅ guidelines on one occasion and Westerhope Primary exceeded these guidelines on 10 occasions. The highest NO_2 1-h means occurred at Knop Law Primary (range $201.8\text{--}521.5 \mu\text{g}/\text{m}^3$) and St Teresa's Primary (range $201.0\text{--}504.8 \mu\text{g}/\text{m}^3$). In 2019, no schools exceeded the WHO₂₀₀₅ guidelines or EU/UK regulations for NO_2 short-term exceedances (Figure S4a).

For PM_{10} , in 2018, all 12 schools exceeded the WHO₂₀₀₅ guidelines at least twice. The maximum total number of days exceeding the WHO₂₀₀₅ guideline in 2018 was 13 at St Alban's Primary. High 24-h mean PM_{10} concentrations were observed at Craggside Primary ($137.5 \mu\text{g}/\text{m}^3$), St Alban's Primary ($137.6 \mu\text{g}/\text{m}^3$), and St Teresa's Primary ($132.7 \mu\text{g}/\text{m}^3$) in 2018. In 2019, 6 of the 12 schools exceeded the WHO₂₀₀₅ guideline at least once and St Alban's RC Primary exceeded the EU/UK regulations, with 36 days of $PM_{10} >50 \mu\text{g}/\text{m}^3$. In 2019, the highest 24-h mean PM_{10} concentrations were observed at Knop Law Primary ($274.7 \mu\text{g}/\text{m}^3$) and St Alban's RC Primary ($174.1 \mu\text{g}/\text{m}^3$) (Figure S4b).

All schools exceeded the 24-h mean $PM_{2.5}$ WHO₂₀₀₅ guideline in 2018. The schools with the highest number of exceedances were St Alban's RC Primary (20 days), St Teresa's Primary (14 days), and West Jesmond Primary (11 days). The lowest number of exceedances (3 days) was observed at Craggside Primary. When the 24-h means that exceeded the WHO₂₀₀₅ guidelines in 2018 were combined and averaged at an individual school level for the three schools with the greatest number of exceedances, the combined mean daily $PM_{2.5}$ concentration was $42.4 \pm 18.2 \mu\text{g}/\text{m}^3$ at St Alban's Primary RC, $42.0 \pm 17.5 \mu\text{g}/\text{m}^3$ at St Teresa's Primary, and $42.1 \pm 15.4 \mu\text{g}/\text{m}^3$ at West Jesmond Primary. In 2019, 10 of the 12 schools exceeded the WHO₂₀₀₅ guidelines. The highest number of exceedances occurred at Knop Law Primary (12 days), St Alban's RC Primary (42 days), St Mary's Catholic (12 days), and St Teresa's Primary (17 days). When the 24-h means that exceeded the WHO₂₀₀₅ guidelines in 2019 were combined and averaged at an individual school level for these four schools, the mean daily average $PM_{2.5}$ concentration was $76.8 \pm 57.1 \mu\text{g}/\text{m}^3$ at Knop Law Primary, $40.8 \pm 15.4 \mu\text{g}/\text{m}^3$ at St Alban's RC Primary, $34.8 \pm 9.6 \mu\text{g}/\text{m}^3$ at St Mary's Catholic, and $33.1 \pm 7.6 \mu\text{g}/\text{m}^3$ at St Teresa's Primary (Figure S4c).

There are currently no guidelines or regulations for PM_1 concentrations. The ratio of $PM_1:PM_{2.5}$ in the 12 school sites (range 0.61 to 0.95) indicates higher PM_1 fractions in the $PM_{2.5}$ concentrations at these sites. Given the lack of current guidelines or regulations on PM_1 , and its potential for increased health risk, we chose to set our short-term exceedance limit to half that of the WHO₂₀₀₅ guidelines for $PM_{2.5}$ at $12.5 \mu\text{g}/\text{m}^3$. During the 2-year study period, 5 schools had >50 days where PM_1 concentrations exceeded $12.5 \mu\text{g}/\text{m}^3$. Broadway East exceeded this value on 55 days, St Alban's RC Primary exceeded it on 99 days, St Mary's Catholic on 55 days, St Teresa's Primary on 66 days, and West Jesmond Primary on 63 days. Over the 2-year study period, the highest average PM_1 concentration was $19.1 \pm 6.9 \mu\text{g}/\text{m}^3$ at Broadway East, $23.5 \pm 10.9 \mu\text{g}/\text{m}^3$ at St Alban's RC Primary,

$18.2 \pm 7.6 \mu\text{g}/\text{m}^3$ at St Mary's Catholic, $18.8 \pm 9.5 \mu\text{g}/\text{m}^3$ at St Teresa's Primary School, and $19.1 \pm 8.8 \mu\text{g}/\text{m}^3$ at West Jesmond Primary (Figure S4d).

3.2.4. Diurnal Variation

We produced time variation plots to investigate the diurnal variation of NO_2 , PM_{10} , $\text{PM}_{2.5}$, and PM_1 at schools in Newcastle. Only three schools were chosen to produce the time variation plot for each pollutant. These 3 schools were the school with the highest annual mean concentration, the school with the lowest, and the school with the annual mean concentration closest to the mean of all of the 12 schools.

The NO_2 levels outside the 3 chosen schools show a distinct pattern over 24 h (Figure 5a). Their distribution is bimodal, with noticeable morning and afternoon/evening peaks. The morning peak occurs at around 07:00–09:00 and the afternoon/evening peak occurs at around 16:00–18:00. The afternoon/evening peak is generally higher and has fewer steep gradients than the morning peak. The morning peak could be attributable to morning rush hour traffic and the afternoon/evening peak could be attributable to evening rush hour traffic. The greater height and less steep gradient of the afternoon/evening peak could be attributable to the fact that baseline NO_2 concentrations are higher before the evening rush hour begins than they are before the morning rush hour begins due to the accumulation of NO_2 during the day from ongoing traffic emissions.

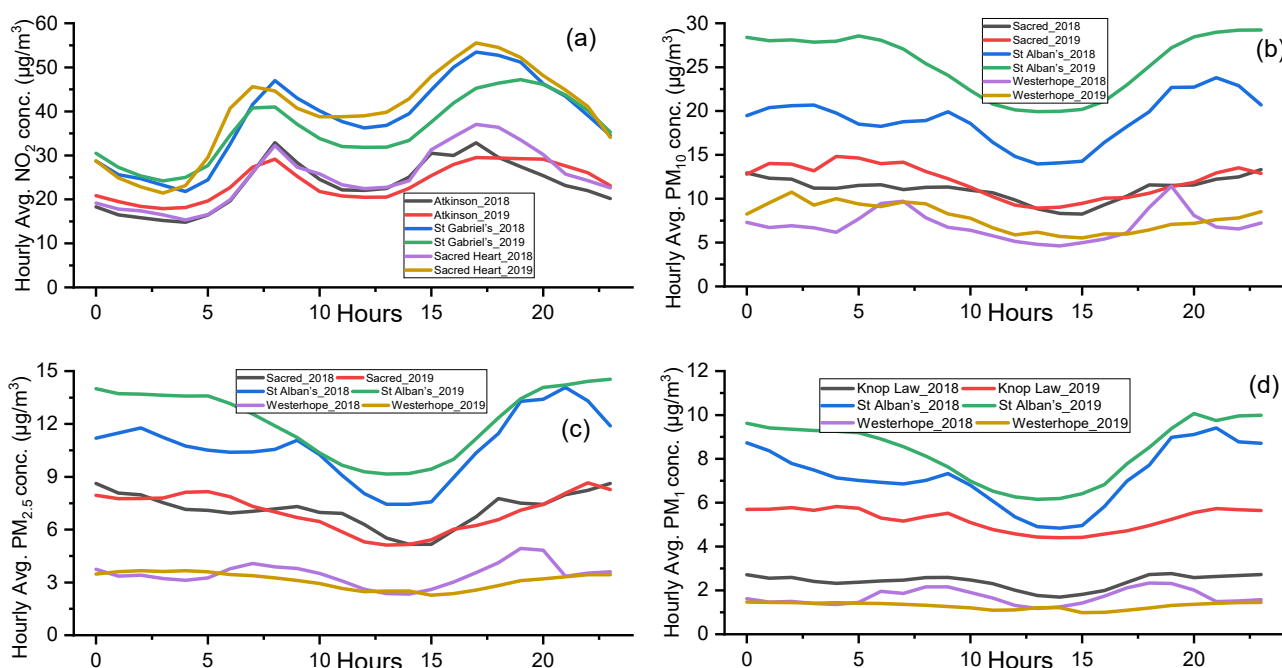


Figure 5. Diurnal variations of (a) NO_2 , (b) PM_{10} , (c) $\text{PM}_{2.5}$ and (d) PM_1 at those schools in Newcastle that had maximum, mean and minimum annual average pollution concentrations.

PM_{10} levels outside of the 3 chosen schools show an almost opposite shape to NO_2 concentrations over 24 h (Figure 5b). Rather than two distinct peaks, PM_{10} concentrations show a “U-shape” and are at their highest from midnight until early morning and their lowest in the middle of the day. This indicates that, when compared to NO_2 concentrations, PM_{10} concentrations are less associated with traffic volumes. Both the 2018 and 2019 maximum hourly PM_{10} concentrations occurred at St Alban's RC Primary and were 23.8 and $29.3 \mu\text{g}/\text{m}^3$, respectively. These peak PM_{10} concentrations were higher than the peak PM_{10} concentrations at both the urban background and roadside monitoring sites in 2018 and 2019.

The time variation plots of $PM_{2.5}$ and PM_1 show similar patterns to that of PM_{10} (Figure 5c,d). Of note, variation in the PM concentrations over 24 h appear more marked outside of schools with the highest overall PM concentrations.

3.3. Exposure Assessment

The AQMesh pod AQMs that collected the data used in this study are commonly attached to lampposts at school entrances. Therefore, when children are outside during the school day (while arriving at and leaving school, while on outdoor breaks, or while undertaking outdoor physical education (PE) lessons), it is likely that they are exposed to PM concentrations that are similar to those of the AQMesh pod microenvironment.

During the study period, the highest total PM_{10} RDDs ($\mu\text{g}/\text{h}$) occurred outside Atkinson Road Primary (12.5 $\mu\text{g}/\text{h}$), Knop Law Primary (10.8 $\mu\text{g}/\text{h}$), and St Alban's RC Primary (17.7 $\mu\text{g}/\text{h}$). The lowest total PM_{10} RDDs occurred outside Chillingham Road Primary (6.3 $\mu\text{g}/\text{h}$), West Jesmond Primary (6.3 $\mu\text{g}/\text{h}$), and Westerhope Primary (5.8 $\mu\text{g}/\text{h}$). The highest total $PM_{2.5}$ RDDs occurred outside Atkinson Road Primary (8.7 $\mu\text{g}/\text{h}$), St Alban's RC Primary (9.2 $\mu\text{g}/\text{h}$), and St Mary's Catholic (6.2 $\mu\text{g}/\text{h}$). The lowest occurred outside Cragside Primary (2.9 $\mu\text{g}/\text{h}$) and Westerhope Primary (2.5 $\mu\text{g}/\text{h}$). The highest total PM_1 RDDs occurred at West Jesmond Primary (2.5 $\mu\text{g}/\text{h}$) and St Alban's RC Primary School (3.0 $\mu\text{g}/\text{h}$). The estimated RDDs of each pollutant at each of the 12 schools can be seen in Figure 6. The estimated RDD is an indicator of the health risk posed by ambient PM concentrations for the children attending those schools [9].

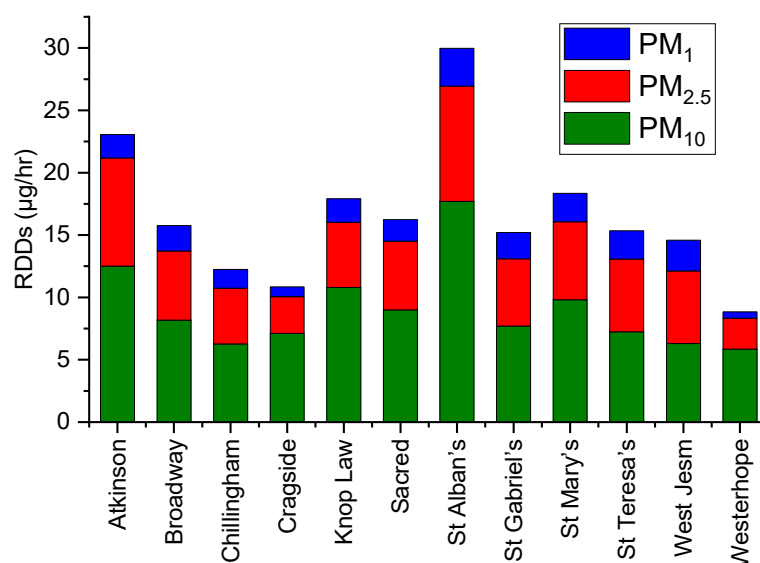


Figure 6. Estimated respiratory deposition doses (RDDs) of PM per hour of exposure at school environments in Newcastle.

4. Discussion

Overall, the findings of this study indicate that the annual mean ambient NO_2 concentrations outside schools in Newcastle do not regularly exceed the WHO₂₀₀₅ guidelines and EU/UK regulations. In contrast, modelling studies conducted in London have consistently found that around 25% of all schools in London are in areas where the WHO₂₀₀₅ guideline and EU/UK regulations for annual mean NO_2 are regularly exceeded [20,49,50]. This suggests that the annual mean NO_2 levels outside schools in Newcastle may present a lower risk to children's health when compared to those in the country's capital city.

Annual mean NO_2 concentrations outside schools in this study ranged from $21.7 \pm 11.2 \mu\text{g}/\text{m}^3$ to $40.0 \pm 33.4 \mu\text{g}/\text{m}^3$ over the 2-year study period. Ambient NO_2 levels outside schools were measured over four weeks and ranged from 6–25 $\mu\text{g}/\text{m}^3$ in Berlin, 25–41 $\mu\text{g}/\text{m}^3$ in London, 20–43 $\mu\text{g}/\text{m}^3$ in Madrid, 26–52 $\mu\text{g}/\text{m}^3$ in Paris, and

16–32 $\mu\text{g}/\text{m}^3$ in Sophia [50]. These findings are not directly comparable given their shorter monitoring period and capital city location but indicate that NO_2 levels outside schools in Newcastle are not markedly different from those outside schools in other European cities. Osborne et al. (2021) used automatic urban and rural network (AURN) monitoring stations located in school grounds or within 150 m of a school to capture ambient pollution concentrations outside 30 schools in the UK in 2017 [49]. They found that the annual mean NO_2 concentrations outside these 30 schools ranged from 6.2–56.5 $\mu\text{g}/\text{m}^3$ and that AURN stations marked as “traffic urban” generally had the highest NO_2 concentrations [49].

The patterns of NO_2 concentrations outside schools in Newcastle are consistent with those of other studies investigating schools’ ambient air quality. This study found evidence for a relationship between NO_2 concentrations outside schools in Newcastle and rush hours (and therefore small vehicle traffic volumes). The Breathe London Wearables study found that children’s exposure to ambient pollutants was high during the morning rush hour and that main roads and busy junctions were associated with higher NO_2 concentrations due to traffic density [51]. Studies conducted outside of Europe also demonstrate the relationship between traffic density, particularly small vehicle traffic density in streets surrounding schools, and ambient NO_2 concentrations outside schools [52,53].

Overall, PM levels outside schools in Newcastle exceed the WHO₂₀₀₅ guidelines relatively frequently, particularly short-term (24-h) exceedances. This indicates that children at schools in Newcastle may be at greater risk of harm from PM than NO_2 . Furthermore, the patterns of PM concentrations outside schools are consistent across years and the size of particles. There is evidence that some schools experience noticeably worse ambient PM concentrations than other schools and this would benefit from both further monitoring and action to reduce the risk to children at these schools.

The annual mean PM_{10} concentrations outside schools in this study ranged from $7.0 \pm 15.2 \mu\text{g}/\text{m}^3$ to $25.4 \pm 30.0 \mu\text{g}/\text{m}^3$ in the 2 years and annual mean $\text{PM}_{2.5}$ concentrations ranged from $3.1 \pm 4.7 \mu\text{g}/\text{m}^3$ to $12.2 \pm 15.8 \mu\text{g}/\text{m}^3$. The Health and Environment Alliance (HEAL) Report (2019) estimated that ambient $\text{PM}_{2.5}$ concentrations outside London schools range from 1 $\mu\text{g}/\text{m}^3$ to 17 $\mu\text{g}/\text{m}^3$ while Osborne et al. (2019) found that annual mean ambient $\text{PM}_{2.5}$ concentrations ranged from 7.3 $\mu\text{g}/\text{m}^3$ to 14.1 $\mu\text{g}/\text{m}^3$ [49,50]. Osborne et al. (2019) also found that high $\text{PM}_{2.5}$ concentrations existed at both urban traffic and urban background monitoring sites, in keeping with this study’s findings that ambient PM concentrations are less closely associated with small vehicle traffic density than ambient NO_2 concentration [49]. Tofful and Perrino (2015) reported that outdoor $\text{PM}_{2.5}$ concentrations in Rome vary from 17 to 56 $\mu\text{g}/\text{m}^3$ and some schools’ indoor $\text{PM}_{2.5}$ concentrations are higher than ambient concentrations [54]. A further study reported very high PM_{10} concentrations outside 39 schools in Barcelona (Spain) of around 50.1 $\mu\text{g}/\text{m}^3$ [55]. Janssen et al. (2001) also found that the closer a school is to a motorway, the higher its ambient $\text{PM}_{2.5}$ concentrations [53]. Furthermore, Patel et al. (2009) found that school ambient $\text{PM}_{2.5}$ levels in New York City were 1.8 times higher in dense urban settings than in suburban settings due to increased truck and bus volumes [56]. These findings help to explain the differences in the diurnal variations of PM and NO_2 concentrations and may provide a basis upon which to investigate why some schools in Newcastle experience noticeably worse ambient PM concentrations than others.

This study provides evidence upon which policy may be based to improve school ambient air quality. Given the association between NO_2 concentrations outside schools, small vehicle traffic density, and rush hours, measures, such as road closures outside schools (school streets initiative), anti-idling campaigns, staggered drop-off and pick-up times, relocating drop-off and pick-up sites away from school entrances and playgrounds, and active travel programmes, should be introduced (or continued). Action taken to reduce NO_2 concentrations outside schools will also help to reduce PM concentrations. Specific policy measures to reduce ambient PM concentrations outside schools highlighted by the findings of this study could include mitigation of schools’ proximity to sources of PM, such as motorways or roads with high volumes of large vehicles, and being aware of sporadic

weather events or anthropogenic events that may generate PM, putting mitigation measures in place where these are identified. Lastly, education for children, parents, and teachers on the health benefits of clean air and measures they can take to reduce schoolchildren's exposure to ambient air pollutants, particularly during the winter months, is essential.

Despite having some limitations (reported in the Supplementary Materials), this study addressed a gap in the understanding identified in the literature. In their systematic review, Osborne et al. (2021) highlighted that only 3 of the 14 UK-based studies investigating school air quality in their review used fixed location air quality monitoring; the remaining 11 used modelling to estimate concentrations of pollutants [17]. This study presents air quality data from fixed location continuous AQMs over two years and therefore addresses these identified gaps and adds value to the existing literature.

5. Conclusions

As evidence for the harmful effects of air pollution in children increases and becomes ever more robust, this study provides yet unseen insight into the ambient air quality of 12 schools in Newcastle Upon Tyne, UK, and highlights the need to act urgently to protect children's health. It provides an understanding of key ambient pollutant concentrations outside schools in urban areas, particularly urban areas that are outside of capital cities in developed countries with temperate climates. The findings in this study agree with other recent similar studies investigating school ambient air quality. This study, therefore, provides evidence upon which organisations can plan and implement policy at both a local and national level to protect children from the harmful effects of ambient air pollution during their day at school.

This study provides opportunities for further research that could both enhance and expand on the current findings. Further research suggestions include, but are not limited to, investigating Newcastle school indoor air quality, expanding this study to include more schools, repeating this study in a different area of the UK, and widening this study to include additional harmful pollutants, such as volatile organic compounds (VOCs), including BTEX.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos13020172/s1>, Study location description, Urban design, Meteorology, Technical information AQMesh pod Quality Assurance, Study limitations. Table S1. Comparison of WHO air quality guideline values (2005 and 2021) and EU/UK pollutant limit values for NO₂, PM_{2.5}, and PM₁₀ [11,12,16]. Table S2. Previous school air quality studies conducted in the UK. Please note: Much of this data (study numbers 1–14 in italics) has been taken from a table in Osborne et. al (2021) with kind permission from the authors [17]. Please refer to Osborne et. al for the original table and further detail. Table S3. Participating schools, pupil ages, air quality data collection start date and air quality monitor location information. Table S4. Data flagging values, adapted from the Breathe London project [36]. Table S5. Annual average and standard deviations of PM₁₀, PM_{2.5}, PM₁, and NO₂ concentrations at each of the participating schools during 2018 and 2019. Table S6. NO₂ data capture (%), and data flagging by school in 2018 and 2019. Table S7. PM₁₀ data capture (%), and data flagging by the school in 2018 and 2019. Table S8. PM_{2.5} data capture (%), and data flagging by school in 2018 and 2019. Figure S1. 2015 Index of Multiple Deprivation by ward in the city of Newcastle Upon Tyne [25]. Figure S2. Monthly wind rose profile for 2018 (bottom) and 2019 (top) in Newcastle Upon Tyne. Figure S3. Examples of Healthy Schools project air quality monitor locations in Newcastle Upon Tyne. Figure S4. Scatterplots of (a) 1-h average NO₂ concern, (b) 24-h average PM₁₀, (c) 24-h average PM_{2.5} and (d) 24-h average PM₁ for schools with the highest number of exceedances of short-term WHO guidelines during 2018–2019.

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References

- Public Health England. Health Matters: Air Pollution. Available online: <https://www.gov.uk/government/publications/health-matters-air-pollution/health-matters-air-pollution> (accessed on 9 July 2020).
- Department for Environment, Food, and Rural Affairs. Air Quality: A Briefing for Directors of Public Health. Available online: <https://laqm.defra.gov.uk/assets/63091defrairqualityguide9web.pdf> (accessed on 9 July 2020).
- Public Health England. Estimation of Costs to the NHS and Social Care Due to the Health Impacts of Air Pollution: Summary Report. Available online: <https://www.gov.uk/government/publications/air-pollution-a-tool-to-estimate-healthcare-costs> (accessed on 9 July 2020).
- World Health Organization. Health Effects of Particulate Matter: Policy Implications for Countries in Eastern Europe, Caucasus and Central Asia. Available online: https://www.euro.who.int/__data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf (accessed on 14 January 2021).
- Royal College of Physicians. Every Breath we Take: The Lifelong Impact of Air Pollution. Available online: <https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution> (accessed on 9 July 2020).
- Gauderman, W.J.; Avol, E.; Gilliland, F.; Vora, H.; Thomas, D.; Berhane, K.; McConnell, R.; Kuenzli, N.; Lurmann, F.; Rappaport, E.; et al. The Effect of Air Pollution on Lung Development from 10 to 18 Years of Age. *N. Engl. J. Med.* **2004**, *351*, 1057–1067. [CrossRef] [PubMed]
- Gasana, J.; Dillikar, D.; Mendy, A.; Forno, E.; Ramos Vieira, E. Motor vehicle air pollution and asthma in children: A meta-analysis. *Environ. Res.* **2012**, *117*, 36–45. [CrossRef] [PubMed]
- Thiering, E.; Cyrys, J.; Kratzsch, J.; Meisinger, C.; Hoffmann, B.; Berdel, D.; von Berg, A.; Koletzko, S.; Bauer, C.P.; Heinrich, J. Long-term exposure to traffic-related air pollution and insulin resistance in children: Results from the GINIplus and LISAplus birth cohorts. *Diabetologia* **2013**, *56*, 1696–1704. [CrossRef] [PubMed]
- Kumar, P.; Omidvarborna, H.; Barwise, Y.; Tiwari, A. Mitigating Exposure to Traffic Pollution in and around Schools: Guidance for Children, Schools and Local Communities. Available online: <https://www.surrey.ac.uk/sites/default/files/2021-01/mitigating-childrens-exposure-to-traffic-pollution-english-version.pdf> (accessed on 19 December 2021).
- World Health Organization International Agency for Research on Cancer. Outdoor Air Pollution a Leading Environmental Cause of Cancer Deaths. Available online: https://www.iarc.fr/wp-content/uploads/2018/07/pr221_E.pdf (accessed on 17 September 2020).
- European Union. Directive 2008/50/EC of the European Parliament and of the council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Off. J. Eur. Union* **2008**, *51*, 1–44. Available online: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF> (accessed on 9 July 2020).
- World Health Organization. *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide; Global Update 2005: Summary of Risk Assessment*; World Health Organization: Geneva, Switzerland, 2006; pp. 1–20.
- Department for Environment, Food & Rural Affairs. UK and EU Air Quality Policy Context. Available online: <https://uk-air.defra.gov.uk/air-pollution/uk-eu-policy-context> (accessed on 6 July 2020).
- European Commission. Environment: Commission Takes Action against UK for Persistent Air Pollution Problems. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_14_154 (accessed on 9 July 2020).
- Department for Environment, Food & Rural Affairs. September 2021: Air Quality Factsheet (Part 4). Available online: <https://www.gov.uk/government/publications/environment-bill-2020/10-march-2020-air-quality-factsheet-part-4> (accessed on 19 December 2021).
- World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*; World Health Organization: Geneva, Switzerland, 2021; p. 17.
- Osborne, S.; Uche, O.; Mitsakou, C.; Exley, K.; Dimitroulopoulou, S. Air quality around schools: Part I—A comprehensive literature review across high-income countries. *Environ. Res.* **2021**, *196*, 110817. [CrossRef] [PubMed]
- GLA London Atmospheric Emissions Inventory (LAEI) 2016. Available online: <https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2016> (accessed on 12 January 2022).
- King, K.; Healy, S. *Analysing Air Pollution Exposure in London; Report to Greater London Authority*; Aether Ltd.: Oxford, UK, 2013; pp. 17–20.

20. Brook, R.; King, K. *Updated Analysis of Air Pollution Exposure in London; Report to Greater London Authority; Aether Ltd.*: Oxford, UK, 2017; pp. 3–32.
21. Lucialli, P.; Marinello, S.; Pollini, E.; Scaringi, M.; Sajani, S.Z.; Marchesi, S.; Cori, L. Indoor and outdoor concentrations of benzene, toluene, ethylbenzene and xylene in some Italian schools evaluation of areas with different air pollution. *Atmos. Pollut. Res.* **2020**, *11*, 1998–2010. [CrossRef]
22. Oliveira, M.; Slezakova, K.; Madureira, J.; de Oliveira Fernandes, E.; Delerue-Matos, C.; Morais, S.; do Carmo Pereira, M. Polycyclic aromatic hydrocarbons in primary school environments: Levels and potential risks. *Sci. Total Environ.* **2017**, *575*, 1156–1167. [CrossRef] [PubMed]
23. Newcastle City Council. Newcastle Upon Tyne City Profile April 2021. Available online: <https://www.newcastle.gov.uk/sites/default/files/your-council-and-democracy/2021%2004%20NFNA%20City%20Profile.pdf> (accessed on 19 December 2021).
24. Marmot, M.; Allen, J.; Boyce, T.; Goldblatt, P.; Morrison, J. *Health Equity in England: The Marmot Review Ten Years on*; Institute of Health Equity: London, UK, 2020; pp. 1–142.
25. Newcastle City Council. Newcastle Pharmaceutical Needs Assessment 2018–2021. Available online: [https://newcastle.gov.uk/sites/default/files/Public%20Health/PDFs/PNA%202018-21%20FINAL%20-%202019th%20Feb%20\(002\).pdf](https://newcastle.gov.uk/sites/default/files/Public%20Health/PDFs/PNA%202018-21%20FINAL%20-%202019th%20Feb%20(002).pdf) (accessed on 4 August 2020).
26. Newcastle City Council. 2021 Air Quality Annual Status Report (ASR). Available online: <https://www.newcastle.gov.uk/sites/default/files/Air%20Quality%20Annual%20Status%20report%202021.pdf> (accessed on 19 December 2021).
27. UK AIR. Air Quality Management Areas (AQMA). Available online: <https://uk-air.defra.gov.uk/aqma/> (accessed on 19 December 2021).
28. Newcastle City Council. Newcastle Schools. Available online: <https://www.newcastle.gov.uk/services/schools-learning-and-childcare/about-our-schools/newcastle-schools> (accessed on 1 September 2020).
29. Urban Observatory Healthy Schools. Available online: <https://schools.view.urbanobservatory.ac.uk/wdim/> (accessed on 19 December 2021).
30. Newcastle University. The Urban Observatory: UKRIC Integrated Urban Infrastructure Labs. Available online: <https://urbanobservatory.ac.uk/explore/ukcric> (accessed on 14 July 2020).
31. Newcastle University. Our Urban Observatory. Available online: <https://www.ncl.ac.uk/who-we-are/vision/urban-observatory/> (accessed on 14 July 2020).
32. James, P.; Smith, L.; Jonczyk, J.; Harris, N.; Komar, T.; Puussaar, A.; Clement, M.; Dawson, R.J. Urban Observatory Data Newcastle. Available online: <https://doi.org/10.25405/data.ncl.c.5059913.v4> (accessed on 20 January 2022). [CrossRef]
33. Environmental Instruments Ltd. AQMesh. Available online: <https://www.aqmesh.com/product/aqmesh/> (accessed on 20 August 2020).
34. Breathe London. Breathe London: Methodology. Available online: <https://breathelondon.edf.org/methodology.html#:~:text=Operating%20from%20late%202018%20through,to%20visualise%20and%20present%20data> (accessed on 20 August 2020).
35. Carslaw, D.C.; Ropkins, K. Openair—An R package for air quality data analysis. *Environ. Model. Softw.* **2011**, *27–28*, 52–61. [CrossRef]
36. Stidworthy, A.; (Cambridge Environmental Research Consultants, Cambridge, UK); Bramwell, L.; (Northumbria University, Newcastle Upon Tyne, UK). Personal Communication on Breathe London Data Flagging Values, 2020.
37. Ricardo-aea and Department for Environment, Food & Rural Affairs. Conversion Factors Between ppb and µg m^{−3} and ppm and mgm^{−3}. Available online: https://uk-air.defra.gov.uk/assets/documents/reports/cat06/0502160851_Conversion_Factors_Between_ppb_and.pdf (accessed on 24 August 2020).
38. London Air. LAQN Monitoring Sites. Available online: https://www.londonair.org.uk/london/asp/classification.asp?region=0&site=KC1&details=general&mapview=all&la_id=&network=All&MapType=Google (accessed on 19 December 2021).
39. UK AIR. Site Environment Types. Available online: <https://uk-air.defra.gov.uk/networks/site-types> (accessed on 19 December 2021).
40. Hinds, W.C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, 2nd ed.; John Wiley and Sons: New York, NY, USA, 1999.
41. Kumar, P.; Goel, A. Concentration dynamics of coarse and fine particulate matter at and around signalised traffic intersections. *Environ. Sci. Processes Impacts* **2016**, *18*, 1220–1235. [CrossRef] [PubMed]
42. Gupta, S.K.; Elumalai, S.P. Exposure to traffic-related particulate matter and deposition dose to auto rickshaw driver in Dhanbad, India. *Atmos. Pollut. Res.* **2019**, *10*, 1128–1139. [CrossRef]
43. Martins, V.; Minguillon, M.C.; Moreno, T.; Querol, X.; de Miguel, E.; Capdevila, M.; Centelles, S.; Lazaridis, M. Deposition of aerosol particles from a subway microenvironment in the human respiratory tract. *J. Aerosol Sci.* **2015**, *90*, 103–113. [CrossRef]
44. Deepthi, Y.; Shiva Nagendra, S.M.; Gummadi, S.N. Characteristics of indoor air pollution and estimation of respiratory dosage under varied fuel-type and kitchen-type in the rural areas of Telangana state in India. *Sci. Total Environ.* **2019**, *650*, 616–625. [CrossRef] [PubMed]
45. Löndahl, J.; Möller, W.; Pagels, J.H.; Kreyling, W.G.; Swietlicki, E.; Schmid, O. Measurement techniques for respiratory tract deposition of airborne nanoparticles: A critical review. *J. Aerosol Med. Pulm. Drug Deliv.* **2014**, *27*, 229–254. [CrossRef] [PubMed]
46. ICRP. Human Respiratory Tract Model for Radiological Protection. In *Annals of the ICRP*; ICRP Publication 66; Pergamon Press: Oxford, UK, 1994; Volume 24, p. 10.

47. Valentin, J. Guide for the Practical Application of the ICRP Human Respiratory Tract Model. In *Annals of the ICRP*; Pergamon Press: Oxford, UK, 2002; Volume 32, pp. 5–12.
48. Fleming, S.; Thompson, M.; Stevens, R.; Heneghan, C.; Plüddemann, A.; Maconochie, I.; Tarassenko, L.; Mant, D. Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: A systematic review of observational studies. *Lancet* **2011**, *377*, 1011–1018. [[CrossRef](#)]
49. Osborne, S.; Uche, O.; Mitsakou, C.; Exley, K.; Dimitroulopoulou, S. Air quality around schools: Part II—Mapping PM2.5 concentrations and inequality analysis. *Environ. Res.* **2021**, *197*, 111038. [[CrossRef](#)] [[PubMed](#)]
50. HEAL; Broekstra, N.; Luck, A.; Gordejevic, V. HEAL Report: Healthy Air, Healthier Children. Available online: https://www.env-health.org/wp-content/uploads/2019/06/HEAL-Healthy-air-children_EU.pdf (accessed on 19 December 2021).
51. Varaden, D.; Leidland, E.; Barratt, B. The Breathe London Wearables Study: Engaging Primary School Children to Monitor Air Pollution in London. Available online: https://www.london.gov.uk/sites/default/files/the_breathe_london_wearables_study_oct19.pdf (accessed on 19 December 2021).
52. Raysoni, A.U.; Sarnat, J.A.; Sarnat, S.E.; Garcia, J.H.; Holguin, F.; Luévano, S.F.; Li, W.-W. Binational school-based monitoring of traffic-related air pollutants in El Paso, Texas (USA) and Ciudad Juárez, Chihuahua (México). *Environ. Pollut.* **2011**, *159*, 2476–2486. [[CrossRef](#)] [[PubMed](#)]
53. Janssen, N.A.H.; van Vliet, P.H.N.; Aarts, F.; Harssema, H.; Brunekreef, B. Assessment of exposure to traffic related air pollution of children attending schools near motorways. *Atmos. Environ.* **2001**, *35*, 3875–3884. [[CrossRef](#)]
54. Tofful, L.; Perrino, C. Chemical Composition of Indoor and Outdoor PM2.5 in Three Schools in the City of Rome. *Atmosphere* **2015**, *6*, 1422–1443. [[CrossRef](#)]
55. Pacitto, A.; Stabile, L.; Viana, M.; Scungio, M.; Reche, C.; Querol, X.; Alastuey, A.; Rivas, I.; Álvarez-Pedrerol, M.; Sunyer, J.; et al. Particle-related exposure, dose and lung cancer risk of primary school children in two European countries. *Sci. Total Environ.* **2018**, *616–617*, 720–729. [[CrossRef](#)] [[PubMed](#)]
56. Patel, M.M.; Chillrud, S.N.; Correa, J.C.; Feinberg, M.; Hazi, Y.; Kc, D.; Prakash, S.; Ross, J.M.; Levy, D.; Kinney, P.L. Spatial and Temporal Variations in Traffic-related Particulate Matter at New York City High Schools. *Atmos. Environ.* **2009**, *43*, 4975–4981. [[CrossRef](#)]