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# Assessment of personal $PM_{2.5}$ exposure of children living in Bandung, Indonesia and Kathmandu, Nepal

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## Abstract

$PM_{2.5}$ (particulate matter (PM)with a diameter of 2.5 micrometres or smaller) air pollution is a major contributor to the global burden of disease and poses particular risks to children due to its impacts on respiratory health and overall well-being. Children's exposure to $PM_{2.5}$ in two highly polluted cities (Bandung, Indonesia and Kathmandu, Nepal) was investigated over a week-long period. The research aimed to determine (1) children's overall $PM_{2.5}$ exposure levels, (2) the environments or activities contributing most to such exposure, and (3) any differences in exposure between the two study populations. Low-cost $PM_{2.5}$ sensors (PurpleAir) and Global Positioning System devices were carried by 61 children aged 6–13 years in custom-designed backpacks, alongside questionnaires used to characterize home and school environments and the child's routine. Children were recruited from four schools, at which PurpleAir sensors were also installed outdoors to measure ambient $PM_{2.5}$ concentrations. Mean personal $PM_{2.5}$ concentrations were 48.0 $\mu g\ m^{-3}$ in Bandung and 45.8 $\mu g\ m^{-3}$ in Kathmandu. School environments had the lowest mean $PM_{2.5}$ (41.2 and 33.7 $\mu g\ m^{-3}$, respectively) whereas home, commuting, and other microenvironments showed higher mean $PM_{2.5}$ concentrations, up to 53.9 $\mu g\ m^{-3}$. Comparison with World Health Organization guidelines suggests these children are regularly exposed to $PM_{2.5}$ concentrations exceeding guidance levels. No specific source driving the elevated concentrations in the home was identified. While commuting, travelling by scooter or walking were associated with the highest $PM_{2.5}$ levels. These findings emphasize the urgent need for effective interventions to protect children from high pollution levels in urban environments.

## 1. Introduction

$PM_{2.5}$ (particulate matter (PM) with a diameter of 2.5 micrometres or smaller) air pollution is recognized as a significant contributor to the global burden of disease, causing millions of premature deaths and a substantial loss of healthy life years worldwide (Lelieveld *et al* 2023). The World Health Organization (WHO) has set guidelines for $PM_{2.5}$, these being an annual mean concentration of 5 micrograms per cubic metre ($\mu g\ m^{-3}$) and a 24 h mean concentration of 15 $\mu g\ m^{-3}$ (WHO 2021). These guideline levels are based on comprehensive assessments of the health effects of $PM_{2.5}$ exposure. The WHO guidelines also highlight the vulnerability of certain populations, including children, the elderly, and individuals with pre-existing health conditions, to the health effects of $PM_{2.5}$ pollution.

$PM_{2.5}$ air pollution is particularly important to children's health due to its significant impacts on respiratory health and overall well-being. Infants and children are more likely to manifest adverse respiratory symptoms from air pollution exposure due to various factors such as having an immature immune

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and respiratory system, higher breathing rates (per kilogram body weight) and typically spending more time outdoors and being more physically active (Fonderson *et al* 2024). Research shows that exposure to pollutants during pregnancy can affect foetal development and longer term respiratory and cardiovascular health (Johnson *et al* 2021, Fonderson *et al* 2024).

$PM_{2.5}$ also plays an important role in the onset and exacerbation of childhood asthma (Khreis *et al* 2019, Steinle *et al* 2020, Zhang *et al* 2023), with direct association between $PM_{2.5}$ and the severity of bronchiolitis also being reported (Milani *et al* 2022). $PM_{2.5}$ pollution can also worsen the severity of respiratory allergies, which can increase the risk of acute respiratory infections (Adhikary *et al* 2024). Research suggests that exposure to PM may also have neurodevelopmental impacts on children, having been associated with autism spectrum disorder (Morales-Suárez-Varela *et al* 2017) and attention deficit hyperactivity disorder (ADHD) (Markevych *et al* 2018), although the need for further, high quality studies has been highlighted to clarify the association between PM exposure and ADHD (Donzelli *et al* 2019).

The International Agency for Research on Cancer has classified particulate air pollution, in particular $PM_{2.5}$, as a Group 1 carcinogen (Loomis *et al* 2013, Outdoor air pollution, IARC monogrpahs 2015) and it has been reported that chronic exposure can affect every organ in the body, further complicating and exacerbating existing health conditions (Schraufnagel *et al* 2019). Air pollution disproportionately affects marginalized populations of lower socioeconomic status, and children of lower socioeconomic status are more likely to be exposed to increased outdoor (as well as indoor) air pollution (Mathiarasan and Hüls 2021).

It is important to fully understand children's personal exposures to $PM_{2.5}$ air pollution as the information can be used in heath impact assessments, providing evidence-based recommendations to improve positive health outcomes and minimize adverse health effects that children may experience. By understanding the specific sources and levels of $PM_{2.5}$ exposure that children experience, and in what environments, targeted interventions and regulations can also be designed and implemented to reduce pollution in areas where children spend most of their time. In addition, parents and caregivers can take more effective action to minimize their children's exposure in situations where high pollution occurs. By better understanding children's personal exposures to $PM_{2.5}$, society will be better placed to protect their health, fostering a healthier generation, as the information generated will allow for the development of evidence-based recommendations and policies.

The factors affecting childhood exposures to urban particulates (FACE-UP) project aimed to reduce the lifetime vulnerability of urban children, particularly in Indonesia and Nepal, to noncommunicable diseases by reducing childhood exposure to particulate air pollution through suitable personal interventions (https://face-up-consortium.webspace.durham.ac.uk). The study focussed on two Development Assistance Committee listed countries because children in low- and middle-income countries (LMICs) are disproportionately affected by air pollution, facing high exposure levels from both outdoor and indoor sources. In LMICs in the South-East Asia Region, 99% of all children under 5 years old are exposed to levels of $PM_{2.5}$ higher than the WHO guidelines (WHO 2018).

Kathmandu, Nepal and Bandung, Indonesia both suffer from severe anthropogenic pollution and are the focus of the present study. These cities also have similarly high population densities, exceeding 15 000 people per $km^2$ (World Population Review 2024). The 2023 world air quality report (+IQAir 2023) summarizes $PM_{2.5}$ air quality data from ground-level air monitoring stations from 7,812 cities spanning 134 countries. Nepal was ranked 8th and Indonesia 14th of the 134 included countries with respect to highest annual average population-weighted $PM_{2.5}$ concentrations.

Nepal consistently ranks as having one of the worst particulate air pollution concentrations worldwide. One of the worst affected areas in Nepal is the Kathmandu Valley, located in the mid-hills of Nepal (Becker *et al* 2021). Kathmandu is especially vulnerable due to its topography (bowl-shaped basin surrounded by mountains), atmospheric conditions (temperature inversion and seasons), increase in population, rapid urban development, poor road network and poor-quality vehicles, crop residue burning as well as other PM sources such as burning of solid waste (Becker *et al* 2021). Air quality issues in Kathmandu have been further compromised by the rebuilding efforts following the earthquake in 2015 (Mishra and Adhikari 2019).

According to the IQAir website, Bandung is ranked second among cities in Indonesia with the worst air quality, with an air quality index value of 175 (which is classed as unhealthy) and $PM_{2.5}$ concentration nearly 18 times the WHO annual air quality guideline value (+IQAir 2024). The dispersion of pollutants in Bandung City is affected by local factors and monsoon phenomena. As with Kathmandu, the city is surrounded by higher land and mountains, forming a basin, with such topographical conditions affecting atmospheric circulation and the distribution of pollutants. Dispersion of pollutants across the city also varies between the wet and dry months (Pontoh *et al* 2023). Temperatures in Kathmandu range from >25 °C in summer to <5 °C during winter, whereas the mean temperature in Bandung is generally around 25 °C year-round (Bandung Pusal Statistik Kota Bandung 2023).

The advent of relatively accurate and precise low-cost, portable air quality sensors has enabled personal exposure studies in recent years. Very few studies have been conducted on children, however, and none on children in Nepal or Indonesia. Previous studies which monitored particulate exposures during children's daily routines have been conducted in South Korea (Woo *et al* 2019, Kim *et al* 2021), Africa (6 countries; Lim *et al* 2022), the USA (Ryan *et al* 2015), Vietnam (Vy *et al* 2025) and the United Kingdom (Varaden *et al* 2021, Wei *et al* 2026). Several of these studies found the home to have the highest PM concentrations (Ryan *et al* 2015, Woo *et al* 2019, Lim *et al* 2022, Vy *et al* 2025, Wei *et al* 2026).

To our knowledge, our study is the first to investigate children's personal exposure to PM in both Indonesia and Nepal. The study involved week-long exposure monitoring campaigns with children, aged 6–13 years old, that aimed to assess and characterize their exposure to air pollution, specifically $PM_{2.5}$, using low-cost sensors and Global Positioning System (GPS) units. The exposure monitoring campaigns were focussed to address the following research questions: (1) What are the $PM_{2.5}$ exposure levels for children living in Bandung, Indonesia and Kathmandu, Nepal?; (2) What environments/activities lead to their highest $PM_{2.5}$ exposures?; (3) What similarities or differences in $PM_{2.5}$ exposure are there between the two study populations?

## 2. Methods

### 2.1. Study design and participants

The children were recruited from four schools: a public school (financed by the government) and private school (financed by educational fees paid directly to the school, typically by the child's guardian) in each city. The study period covered 26 d in Bandung and took place near the start of the dry season (from April until October, usually). The study period was longer in Kathmandu, running for 90 d, starting in the dry season at the end of winter (when the highest level of air pollution is expected) and overlapped with the very start of the monsoon season (usually mid-June; table 1).

The selection of the study periods was informed through consultation with local partners, who provided context-specific guidance on expected air pollution patterns and feasible windows for the fieldwork, including school availability (periods without exams or vacations). In Kathmandu, the intention was to conduct sampling during the winter season, when air pollution levels are typically elevated compared to other seasons (Bhatta *et al* 2025). Although logistical constraints (including procurement of equipment, ethical approvals, training local researchers, co-location experiments and coordination with participating schools) delayed deployment, the campaign was ultimately conducted toward the end of the winter period. In Bandung, local expertise indicated that air pollution exhibits less pronounced seasonal variability, with influences more evenly distributed throughout the year (Lung *et al* 2025). While regional biomass burning can episodically affect air quality in Indonesia, these events are less predictable and were not the primary determinant of the sampling window. Instead, alignment with the Nepal campaign and overall project timelines necessitated concurrent fieldwork.

A study protocol was developed which described the steps to be implemented to conduct the week-long exposure monitoring campaigns (supplementary information). Training sessions on the study protocol were held with the local research teams.

The schools were asked to assist in identifying children eligible for the study and, as far as possible, an equal distribution of genders, age ranges, socioeconomic characteristics and distance of home residence from school was recruited. Schools were also asked to try to identify children with a variety of school commuting methods. Informed consent was provided by parents/carers with the children also providing assent. The aim was to have 30 participants from each country. The initial age range for recruitment was 7–12 years old, but this was later amended to 6–13 years old (including an approved ethics application amendment) when it was found that a small number of younger children were recruited due to inconsistencies in their date of birth between the demographic questionnaires completed by their parents/carers, and the information held by the school. A small number of children also turned 13 during the period of the study. Full details on the recruitment procedure can be found in the study protocol (supplementary information).

For each child, week-long personal exposure monitoring campaigns were conducted. A longer measurement period was considered unethical by the project team, due to the young age of some of the children, likelihood of non-compliance, and the increased burden put on the child and family to participate. The participants carried a PurpleAir II SD device (hereafter referred to as PurpleAir), battery

**Table 1.** Summary of information on the four schools involved in the study including data collection dates, environmental factors (from questionnaires and researcher observations) and descriptive statistics from the PurpleAir devices installed at each of the schools.

| Descriptor | Public school, Bandung | Private school, Bandung | Public school, Kathmandu | Private school, Kathmandu |
|---|---|---|---|---|
| Socioeconomic range[a] | Low to middle | Middle to high | Mixed | Middle to high |
| Participant data collection | 10 May–3 June 2023 | 11 May–4 June 2023 | 15 May–14 Jun 2023 | 17 March–11 May 2023 |
| Data collection by PurpleAir installed at schools | 9 May–12 June 2023 | 9 May–12 June 2023 | 18 April–19 June 2023 | 29 March–18 May 2023 |
| *School environment* | | | | |
| Number of roads[b] | 3 | 2 | 4 | 3 |
| Number of unpaved roads[b] | 0 | 0 | 1 | 0 |
| Number of dusty roads[b] | 3 | 1 | 4 | 3 |
| Outdoor play area | Yes | No | Yes | Yes |
| Number of industries[b] | 0 | 0 | 2 | 4 |
| Number of construction activities[b] | 1 | 1 | 4 | 2 |
| Street cleaning[b,c] | No | No | Yes | No |
| Street cooking[b,c] | Yes | No | Yes | Yes |
| Garbage burning[b,c] | No | No | No | No |
| Air conditioning | No | Yes | No | No |
| Air filters | No | No | No | No |
| Extraction fan | No | No | Yes | No |
| Air circulating fan | No | No | No | No |
| *Ambient $PM_{2.5}$ Data*[d] | | | | |
| Number of data points | 1293 | 702 | 1882 | 1213 |
| Descriptive statistics $PM_{2.5}$ ($\mu$g m$^{-3}$) | | | | |
| Median | 44.9 | 44.6 | 37.6 | 43.8 |
| Arithmetic mean | 45.4 | 44.6 | 38.6 | 47.9 |
| Standard deviation | 13.1 | 12.9 | 10.7 | 19.3 |
| Standard error | 0.5 | 0.4 | 0.2 | 0.6 |
| Minimum | 19.0 | 18.0 | 12.2 | 17.7 |
| Maximum | 146.3 | 132.9 | 96.1 | 118.2 |

[a] Information on socioeconomic range of students at the school provided by each school. Further details can be found in Supplementary Information.
[b] Within 20 m of school.
[c] During time of researcher visit.
[d] Descriptive statistics are calculated for dates and times when participants attended school.

pack and a Q-Starz GPS device, with the aim of capturing exposure data for both school days and non-school days. When not at home, the children carried the PurpleAir sensor, a battery pack and the GPS device in custom-designed backpacks, which were also large enough to carry schoolbooks and equipment. The bag was designed so that airflow around the sensor was not compromised (see supplementary information figure S1). When at home, the PurpleAir devices were connected to the mains power supply and hung on a hook or nail, at approximately seated head height, in the room that the child spent most of their waking time. When the child was at school, the bag containing the device was either hung on the back of their chair, placed on their desk or placed on a shelf in close proximity to the child inside the classroom (depending on the school's protocol for bag storage), again taking care to ensure that the PurpleAir sensor inlet was not compromised. The bag was not taken outside during the participants' breaks or at lunch time due to concerns about impeding play and potential for either damage or the sensor inlet to be obscured.

Demographic information on each participant's family, as well as information about the household, school environment and planned activities, was collected through researchers' observations and surveying parents/carers and teachers. Questionnaires gathered information on activities near the home that may affect $PM_{2.5}$ exposure, such as construction, industry, roads (number and type), rubbish burning, street cooking and street cleaning; the same information was gathered for each of the schools (supplementary information). Details of the home itself, such as number of rooms, number of windows, time windows are open for, air conditioning/filters or fans present and information on cooking (fuel, ventilation, oil change frequency), smoking, incense burning and mosquito coil burning were collected. Questions on each participant's routine were asked before and after the study. Field researchers prepared floor layout diagrams of each participant's home which were scanned and stored as PDF files.

The self—administered consent forms and demographic questionnaires were administered in the local language, being translated and back translated before use to check accuracy of the translations. Completion was in writing unless there were literacy issues, in which case the researcher read the information out loud and recorded the participant's response on their behalf. Copies of the local language questionnaires are available in supplementary information. Questionnaires that were researcher-led (these being those focussed on the home environment, activities within the home and by the children and the end of measurement questionnaire), were delivered in the participants' local language with the researcher recording the responses in writing on the participants' behalf. The English language version of the questionnaires is provided in Supplementary Information (these were translated into the local language for use by the researchers). The local teams then translated the answers into English for analysis. The local research teams delivered instructions to participants and their parents/carers on the use of the measurement devices used in the survey in the local language.

Further information on the questionnaires can be found in supplementary information.

Ethics approval for the study was granted by the Durham University Psychology Ethics Committee (reference: PSYCH-2022-06-01T12_54_54-dps0jac), the Ethical Review Board of the Nepal Health Research Council (NHRC) (reference number 1773) and Bandung Institute of Technology (reference number KEP/II/2022/X/M240123DSA/FACE). All work was performed in accordance with the relevant guidelines and regulations.

### 2.2. Instrumentation

#### *2.2.1. Air quality sensor*

For this study, low-cost sensors were chosen for the following reasons: 1) the cost allowed procurement of 40 sensors (PurpleAir II SD; 20 for each country); 2) the size (85 mm × 85 mm × 125 mm) and weight (∼300 g) of the sensors allowed them to not only be portable but easily and comfortably carried by children in a backpack.

The PurpleAir II SD Classic air quality monitor (www2.purpleair.com/) consists of two Plantower PMS5003 laser particle counters, named channels A and B, which collect real-time measurements (sampled at *ca*. 1-second intervals and stored as 2min averaged values at 2 min intervals). The mass of particles with aerodynamic diameters ⩽1 $\mu$m ($PM_1$), ⩽ 2.5 $\mu$m ($PM_{2.5}$) and ⩽10 $\mu$m ($PM_{10}$) per metre cubed of air are reported as well as temperature, humidity and atmospheric pressure, plus the raw number of particles in each size bin across the particle distribution. For this study, $PM_{2.5}$ data were utilized, as the sensor has been shown to be less accurate for $PM_{10}$ (Air Quality Sensor Performance Evaluation Center 2024) and $PM_1$ is not generally used for regulatory data collection (comparison with regulatory air monitor data was required for colocation, see below). Data were stored on a microSD card and downloaded after each measurement period. Plantower provides two proprietary calibration options, calibration factor (cf) = 1 and cf = atm; the second option, cf = atm which is recommended for outdoor use, was employed for this study. This cf was used because the PurpleAir sensors were first colocated with reference monitors outdoors and the study was particularly concerned with outdoor sources of pollution.

Colocation of PurpleAir devices and reference monitors was conducted in both Indonesia and Nepal. The data were used to create location specific calibration equations. A full description of the colocation work can be found in supplementary information.

In addition to the child carrying a sensor, a PurpleAir device was installed in a sheltered outdoor location at each participating school. Ambient data were recorded throughout the time-period that children attending each school participated in the study, except for the private school in Kathmandu where the device was not installed until 29 March 2023 which was after five participants had completed their data collection (table 1). This delay was due to the unavailability of a continuous power supply as frequent power cuts, exacerbated by heavy rainfall, were occurring.

#### *2.2.2. GPS*

Password protected QSTARZ GPS devices (Schipperijn *et al* 2014) provided location coordinates (latitude, longitude) for the participants during the one-week monitoring period. The device is reported to be accurate to within 3 m (Schipperijn *et al* 2014) and the GPS location was logged every 30 s (or more frequently). In Bandung, the participants were instructed to turn off the GPS devices when at home (this decision was made by the local field team to preserve battery power), whereas participants in Kathmandu had the GPS device always turned on. In both locations, the GPS devices frequently suffered loss of signal with many gaps in the data; this was particularly pronounced in Kathmandu. The questionnaires (supplementary information) also provide information on location, and this enabled the assignment of microenvironment when GPS data were unavailable.

### 2.3. Data analysis

Data collected using the PurpleAir devices were reported at 2 min intervals. Hourly, daily, and overall values were derived directly from the 2 min resolution data, unless otherwise stated.

Data were excluded if the data channels' $PM_{2.5}$ values were <1 $\mu$g m$^{-3}$ or >1000 $\mu$g m$^{-3}$ which matches quality control measures used in previous studies (Bi *et al* 2022, Jaffe *et al* 2023). The percentage difference at each time point between channels A and B was calculated for each sensor and data only used if the difference was <30% (Bi *et al* 2022). The channel A and B $PM_{2.5}$ readings were then averaged (Bi *et al* 2021, Wallace *et al* 2021). The PurpleAir data were corrected using the appropriate calibration equation(s) generated from the colocation studies. An additional cleaning step after calibration involved removing corrected $PM_{2.5}$ values if <2 $\mu$g m$^{-3}$ because it has been reported that corrections on low $PM_{2.5}$ concentrations may result in negative values at high relative humidity (Jaffe *et al* 2023). Overall, the proportion of data excluded through these cleaning steps was minimal (0.05%).

The original data completeness requirements for a participant's data to be accepted for analysis were (1) at least 4 d of data; (2) ⩾50% of data non-missing on a given day; and (3) at least one non-school day. These criteria ensured there was sufficient data from each participant for analysis and therefore biases are expected to be minimal. Sensor issues affected the amount of data recorded, while school holidays and study days (where students study from home) affected the number of school days, particularly in Bandung. In Indonesia, children attend school from Monday to Friday. In Nepal, students attend school every day except Saturday so, in a week-long study, there was only one non-school day and eight participants did not have sufficient data recorded on this non-school day. For these reasons the criteria were altered to require at least three days of data for each participant, regardless of whether these were school or non-school days. The requirement for ⩾50% of data to be non-missing for any given day was tightened to require 12 h of data within a 24 h period with at least 6 h of data collected between the hours of 07:00 and 19:00.

Data for five participants in Bandung were removed from the study because of inaccurate timestamps recorded on the PurpleAir devices. It is understood that connection to Wi-Fi at the start of the measurement period is required to set the time accurately, however issues persisted even when this step was conducted. Timestamps were also observed to jump back in time and record multiple sets of data for the same time period. In Kathmandu two participants were removed as no data were recorded on the PurpleAir devices and a further three were removed for not having sufficient PurpleAir data.

Microenvironment was determined from a combination of the GPS and questionnaire data; each data point was assigned to one of four microenvironments: home, school, commuting and other. The 'other' category covered activities such as visits to relatives, shopping trips and extracurricular activities (including outdoor play), either before or after school or on non-school days. The home and school locations were geocoded for each participant. Data points were assigned as 'home' if they were within 30 m of the participant's home location (because the GPS signal was variable overnight) and school if within 100 m of school location (because of school grounds being variably extensive). These actual distances were chosen by testing various distances at times when the location of the child was known to be at home or at school and determining the distances which included the largest number of relevant points. Microenvironment was assigned as 'commuting' if a GPS data point was >100 m from the previous point. 'Other' was assigned to all remaining data points. The GPS data contained many gaps and erroneous points (presumed to be due to satellite signal issues), therefore all microenvironment assignments were checked manually and recoded using questionnaire information (e.g. school start/end times), where necessary.

The descriptive statistics for the outdoor sensors at the schools were calculated using only the data for times when the participants were at school (i.e. no overnight data or data for days when no participant attended school). The 2 min $PM_{2.5}$ data were rounded to the nearest 5 min and averaged, to allow the data collected by school devices to be temporally matched with the data collected by the child devices.

Spearman's correlations were run to determine the relationship of hourly $PM_{2.5}$ concentrations measured by the school outdoor devices, reference monitor data in Kathmandu and participant devices. As no operational air quality reference monitoring station was available in Bandung, reference monitor data were not included in the correlations for Bandung.

$PM_{2.5}$ concentrations above 50 $\mu$g m$^{-3}$ were assigned as peaks, with this concentration being chosen as it is between the maximum 24 h average $PM_{2.5}$ concentrations in the Nepalese and Indonesian standards which are 40 and 55 $\mu$g m$^{-3}$, respectively (Ministry of Science and Technology 2012, Greenpeace Indonesia, 2021, Peraturan Pemerintah, 2021).

Questionnaire data were transcribed into Qualtrics (Qualtrics, Provo, UT) and exported as comma separated files (.csv).

All data analysis was conducted using R Statistical Software (v 4.3.0; R Core Team 2023).

### 2.4. Linear mixed effects model

The association of $PM_{2.5}$ concentration with spatial and temporal parameters (microenvironment and time of day) was investigated across six statistical models with various levels of confounder adjustment using mixed effects regression modelling with random intercept for participant. The natural logarithm of the 2 min $PM_{2.5}$ concentrations were used as the outcome variable to account for the skewed distribution (Milà *et al* 2018, Mueller *et al* 2022).

All models included robust standard errors. Models were fitted in R Statistical Software (v 4.3.0; R Core Team 2023) using the lme4 package (v 1.1–33) and robust errors were calculated using the clubSandwich package (v 0.5.10). See Supplementary Information for further details.

## 3. Results

Data for 51 participants (26 in Kathmandu and 25 in Bandung) aged 6–13 years were included in the analysis (table 2). The overall gender split was reasonably equal with 27 females and 24 males. The overall mean $PM_{2.5}$ concentrations recorded by the participants' PurpleAir devices are slightly higher for Bandung (48.0 $\mu$g m$^{-3}$) than Kathmandu (45.8 $\mu$g m$^{-3}$) (table 2).

Many of the home environment factors that are known to contribute to elevated $PM_{2.5}$ concentrations are more common in Kathmandu, for instance the numbers of homes that burn incense and mosquito coils are all higher in Kathmandu than Bandung (Yadav *et al* 2022). Kathmandu also has a higher number of participant homes with industries and construction activities nearby, as well as street cooking and garbage burning (table 2).

Overall, 323 d of data from 51 participants were collected during this study. The mean 24 h $PM_{2.5}$ concentration was calculated for each of these days, and the majority (299 d) were found to be in the 15–75 $\mu$g m$^{-3}$ range. These 24 h concentrations were compared to the WHO 24 h target concentration of 15 $\mu$g m$^{-3}$, the fourth and highest interim WHO target of 75 $\mu$g m$^{-3}$, as well as local air quality standards. Air quality standards mean 24 h $PM_{2.5}$ concentrations are 40 and 55 $\mu$g m$^{-3}$ for Nepal and Indonesia (Ministry of Science and Technology 2012, Greenpeace Indonesia 2021, Peraturan Pemerintah 2021), respectively. One participant (in Bandung) experienced one day with a 24 h mean of less than 15 $\mu$g m$^{-3}$ (table 3). Several participants experienced days with 24 h means greater than 75 $\mu$g m$^{-3}$, however only three participants recorded such a high average for more than half their days during the study period. Local 24 h standards were exceeded to a higher degree in Kathmandu, in terms of both percentage of days and number and percentage of participants having more than half their days above the standard, however the standard concentration is lower in Kathmandu.

To demonstrate the pattern of exposures of different microenvironments across the week, figure 1 shows a typical plot, for a single child, of time versus $PM_{2.5}$ concentration with microenvironment assigned from GPS and questionnaire data. An increase in $PM_{2.5}$ concentrations during commuting and at home in the mornings and evenings can be observed. The school environment has similar or lower concentrations to the lowest concentrations observed in the home.

Table 4 summarizes the $PM_{2.5}$ concentrations in the different microenvironments in which the children carried the devices. In Bandung, by mean concentration of $PM_{2.5}$, the most polluted microenvironment is 'other' (which includes playing outdoors) whereas in Kathmandu, the home and commuting environments are the worst. Between cities, the home microenvironments are similarly polluted whereas the school and 'other' microenvironments are more polluted in Bandung than Kathmandu. However, in both cities, the school microenvironment has the lowest concentrations, overall. Further detail on the home, school and commuting microenvironments is provided in the following sections;

**Table 2.** Descriptive statistics and information on 51 participants (based on study questionnaire responses). Values are number of participants with percentage of participants in parentheses unless stated otherwise.

| Descriptor | Bandung, Indonesia | Kathmandu, Nepal | Overall |
|---|---|---|---|
| *Participants* | | | |
| Female: male | 15:10 | 12:14 | 27:24 |
| Mean age (SD[a]) | 9.9 (1.0) | 9.5 (1.7) | 9.7 (1.4) |
| Public school | 9 (36%) | 16 (62%) | 25 (49%) |
| Private school | 16 (64%) | 10 (38%) | 26 (51%) |
| *Home environment* | | | |
| Smoker in home | 7 (28%) | 8 (31%) | 15 (29%) |
| Pets[b] | 13 (52%) | 6 (23%) | 19 (37%) |
| Burns incense | 0 | 20 (77%) | 20 (39%) |
| Burns mosquito coils | 3 (12%) | 12 (46%) | 15 (29%) |
| Burns oil lamps[c] | 0 | 13 (50%) | 15 (29%) |
| Mean number of rooms (SD[a]) | 8.3 (2.8) | 2.3 (1.2) | 5.3 (3.7) |
| Mean number of roads (SD[a])[d] | 2.5 (1.0) | 2.6 (0.9) | 2.5 (0.9) |
| Arterial or sub-arterial roads[d,e] | 0 | 9 (35%) | 9 (18%) |
| Industries[d] | 1 (4%) | 15 (58%) | 16 (31%) |
| Construction activities[d] | 4 (16%) | 14 (54%) | 18 (35%) |
| Unpaved roads[d] | 0 | 2 (8%) | 2 (4%) |
| Dusty roads[d] | 1 (4%) | 3 (12%) | 4 (8%) |
| Street cleaning[d] | 21 (85%) | 24 (92%) | 45 (88%) |
| Street cooking[d] | 1 (4%) | 8 (31%) | 9 (18%) |
| Garbage burning[d] | 7 (28%) | 11 (42%) | 18 (35%) |
| Chimney/exhaust fan for cooking smoke | 4 (16%) | 3 (12%) | 7 (14%) |
| Time windows open[f,g] | 7.9 | 13.1 | 10.5 |
| Air-conditioning[f] | 1 (4%) | 0 | 1 (2%) |
| Air filter[f] | 1 (4%) | 0 | 1 (2%) |
| Fan[f] | 7 (28%) | 8 (31%) | 15 (29%) |
| Monthly household income[h] | | | |
| Equivalent to USD 25–35 | 3 (6%) | 0 (0%) | 3 (6%) |
| Equivalent to USD 35–80 | 3 (12%) | 2 (8%) | 5 (10%) |
| Equivalent to USD 80–400 | 8 (32%) | 14 (54%) | 22 (43%) |
| Equivalent to USD >400 | 0 | 4 (15%) | 4 (8%) |
| Prefer not to say | 11 (44%) | 6 (23%) | 17 (33%) |
| PurpleAir kept in kitchen | 0 | 12 (46%) | 12 (24%) |
| *Personal $PM_{2.5}$ Data*[i] | | | |
| Number of data points | 109 749 | 103 091 | 212 840 |
| Descriptive statistics $PM_{2.5}$ ($\mu$g m$^{-3}$) | | | |
| Median | 41.0 | 38.2 | 39.7 |
| Arithmetic mean | 48.0 | 45.8 | 47.0 |
| Standard deviation | 37.4 | 40.0 | 38.7 |
| Standard error | 0.11 | 0.12 | 0.08 |
| Minimum | 4.2 | 2.0 | 2.0 |
| Maximum | 723.3 | 630.5 | 723.3 |

[a] SD is standard deviation.
[b] one or more pets, kept either inside or outside the home.
[c] data on oil lamp use only collected from Kathmandu participants.
[d] within 20 m of home.
[e] arterial and sub-arterial defined as through traffic on a continuous route in Kathmandu and roads that can be passed by motorized vehicles with width <2.5 m, length <1.2 m, height <4.2 m and heaviest axle load of 8 tons in Bandung.
[f] in room where PurpleAir device was kept.
[g] reported value is mean time in hours per 24 h.
[h] Monthly household income using World Bank categories (U.S. dollars, USD) equivalent to Nepal rupee (NPR) and Indonesian rupiah (IDR): ⩽USD 25 (NPR 3320; IDR 1.5 million); USD 25–35 (NPR 3320–4547; IDR 1.5–2 million); USD 35–80 (NPR 4647–10 622; IDR 2–5 million); USD 80–400 (NPR 10 622–53 112; IDR 5–24 million); USD >400 (NPR 53 112; IDR 24 million).
[i] Data collected by participants' PurpleAir devices.

**Table 3.** Percentage of days where 24 h mean $PM_{2.5}$ concentration for personal measurements was greater than or equal to WHO or local standard concentrations and number and percentage of participants for whom more than half of the days measured were greater than or equal to these standards. Local standards are 40 $\mu g\ m^{-3}$ for Nepal and 55 $\mu g\ m^{-3}$ for Indonesia.

| | Bandung, Indonesia | Kathmandu, Nepal |
|---|---|---|
| Percentage of days $\geqslant$15 $\mu g\ m^{-3}$ | 99% | 100% |
| Number (%) of participants with $\geqslant$50% of days $\geqslant$15 $\mu g\ m^{-3}$ | 25 (100%) | 26 (100%) |
| Percentage of days $\geqslant$local standard | 22% | 54% |
| Number (%) of participants with $\geqslant$50% of days $\geqslant$local standard | 3 (12%) | 17 (65%) |
| Percentage of days $\geqslant$75 $\mu g\ m^{-3}$ | 6% | 8% |
| Number (%) of participants with $\geqslant$50% of days $\geqslant$75 $\mu g\ m^{-3}$ | 1 (4%) | 2(8%) |

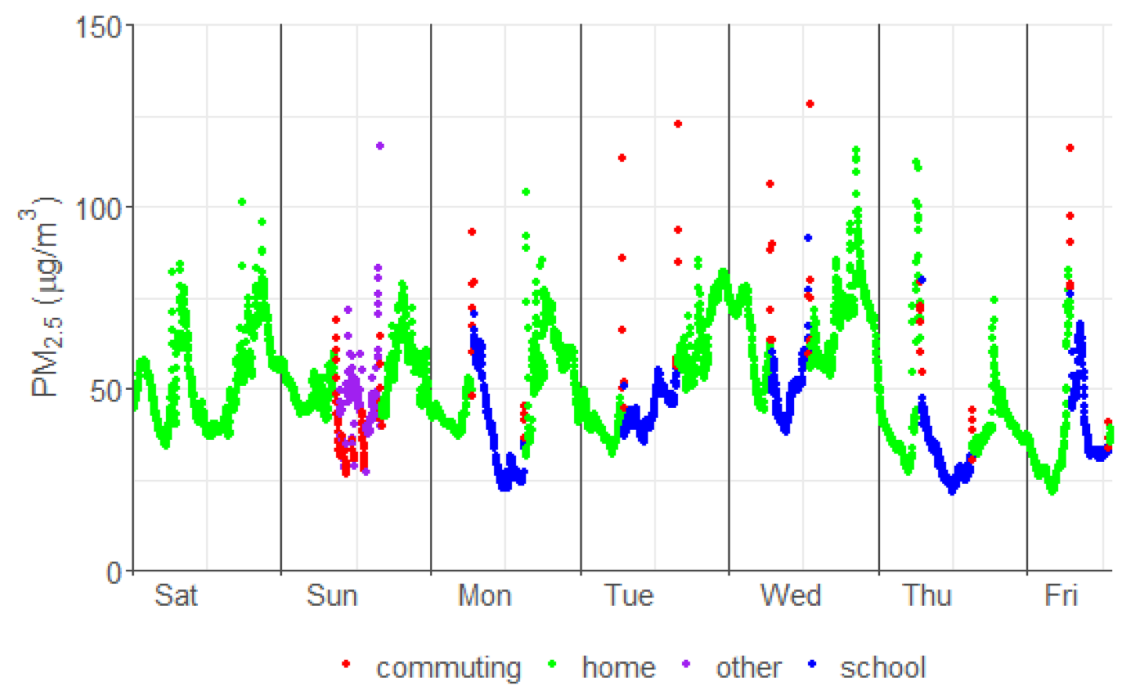


**Figure 1.** $PM_{2.5}$ concentrations for a participant's personal measurements from Bandung, Indonesia with microenvironment assigned for each data point. Commute to school was by scooter/motorbike; Saturday and Sunday were non-school days. Data points are every two minutes.

as the activities in the 'other' category were so varied, this microenvironment is not elaborated further.

### 3.1. $PM_{2.5}$ in the home

The children in this study spent the largest amount of their time in the home, where high levels of $PM_{2.5}$ were often encountered. All 51 participants experienced periods of time where $PM_{2.5}$ concentrations were greater than 50 $\mu g\ m^{-3}$ in the home. These high $PM_{2.5}$ levels were generally not short, sharp peaks and the elevated concentrations often lasted many hours. There were 229 peaks where the $PM_{2.5}$ concentrations were above 50 $\mu g\ m^{-3}$ for more than 2 h and these peaks occurred for 46 of the 51 participants.

Figure 2 demonstrates fluctuations in $PM_{2.5}$ concentrations in the home environment. The home data are plotted against outdoor concentrations measured on the devices placed at the schools during the study. The number of data points used to create the hourly averages of $PM_{2.5}$ in the home in figure 2 varies. Overnight (19:00–06:59) there were >3800 data points for each hour but during the day when participants were often at school this decreased to 750–1000 data points in Kathmandu (11:00–15:00) and 2000–3000 data points in Bandung (07:00–15:00). The differences in the number of data points during the day in each country reflects the higher number of holidays and study days which occurred during the data collection period in Bandung (resulting in children spending more time at home). The peak in figure 2 for the Kathmandu data which occurs at 10:00 is almost solely caused by one participant who had a very high and prolonged $PM_{2.5}$ peak on one day (a 2 h 45 min period where $PM_{2.5}$ was

**Table 4.** Descriptive statistics of $PM_{2.5}$ concentration by microenvironment and city, collected by participants' devices. The 'other' category includes any activity or location that was not assigned home, school or commuting. Data points were recorded at 2 min intervals.

| Microenvironment | Number of data points | $PM_{2.5}$ concentration ($\mu g\ m^{-3}$) Mean (standard deviation) | Median | Minimum | Maximum |
|---|---|---|---|---|---|
| *Bandung, Indonesia* | | | | | |
| Home | 83 573 | 48.9 (39.3) | 41.0 | 4.2 | 679.1 |
| School | 16 269 | 41.2 (15.4) | 40.3 | 15.5 | 354.5 |
| Commuting | 3010 | 46.7 (21.3) | 43.0 | 9.3 | 278.5 |
| Other | 6897 | 53.9 (52.1) | 41.1 | 10.0 | 723.3 |
| *Kathmandu, Nepal* | | | | | |
| Home | 75 895 | 49.1 (45.0) | 39.3 | 2.0 | 630.5 |
| School | 21 761 | 33.7 (13.9) | 32.3 | 2.0 | 290.1 |
| Commuting | 4182 | 49.0 (22.6) | 45.5 | 3.0 | 328.3 |
| Other | 843 | 44.3 (23.6) | 41.3 | 7.9 | 296.7 |

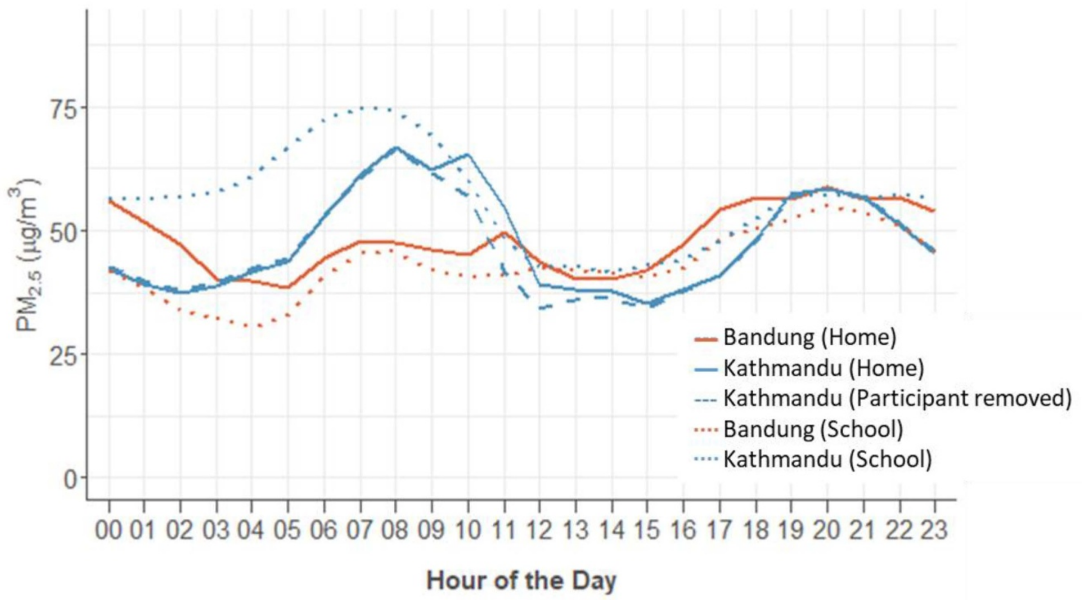


**Figure 2.** Mean $PM_{2.5}$ concentrations by hour of the day measured in the home by participant PurpleAir devices, and at school by PurpleAir devices installed outdoors. The school data are the mean of the two schools in each location. The blue dashed line represents the data for Kathmandu with one participant (who experienced very high $PM_{2.5}$ concentrations for a 2 h 45 min period on one day) removed.

>100 $\mu$g m$^{-3}$, reaching a maximum concentration of 630 $\mu$g m$^{-3}$). When data for this participant were removed, this 10:00 peak disappears (figure 2).

In the home there are two main periods of high $PM_{2.5}$ within a 24 h period (figure 2), these being in the morning and evening. The morning $PM_{2.5}$ concentrations for participants in Kathmandu (66.6 $\mu$g m$^{-3}$ at 08:00) are much higher than for Bandung (47.4 $\mu$g m$^{-3}$ at 08:00). It is noticeable that the Kathmandu outdoor concentrations peak at around 07:00 with the indoor peak occurring an hour later at 08:00. In Bandung, there is less of a clear morning peak, and the indoor concentrations are consistently higher than the outdoor concentrations. The evening $PM_{2.5}$ levels peak at roughly the same concentration (58.8 $\mu$g m$^{-3}$ for Bandung, 58.4 $\mu$g m$^{-3}$ for Kathmandu) but the elevated levels in the Bandung households start earlier and finish later (i.e. the peak lasts longer).

### 3.2. $PM_{2.5}$ at school

From the data recorded by the participants' devices, the school microenvironment is where the lowest levels of $PM_{2.5}$ are experienced by the children in the study (table 4). The two schools in Kathmandu had lower mean $PM_{2.5}$ concentrations than the two schools in Bandung when measured by the

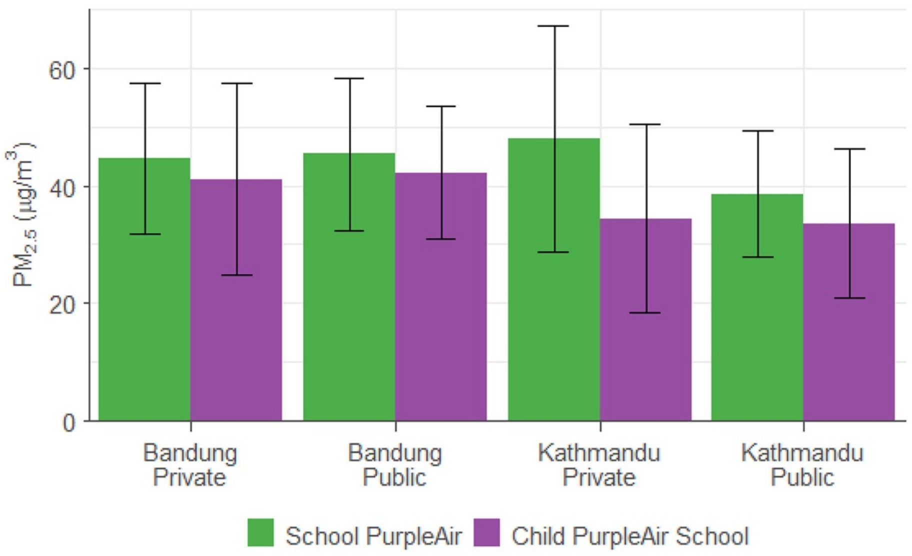


**Figure 3.** Mean $PM_{2.5}$ concentrations recorded at school, error bars represent standard deviation. 'School PurpleAir' is data recorded by sensors installed outdoors at the schools only for days and times participants attended. 'Child PurpleAir School' is data recorded by the sensors carried by participants when they were at school.

PurpleAir devices carried by the participants (figure 3, 'Child PurpleAir School' and table 4). However, the schools in Kathmandu had a higher number of factors that would be expected to increase $PM_{2.5}$ levels, for instance they had more industries and construction activities nearby (table 1).

The mean $PM_{2.5}$ concentrations for the outdoor sensors at the schools were calculated using only the data for times when the participants were at school (i.e. no overnight data or data for days when no participant attended school; the school hours were as follows: Indonesian private school *ca.* 07:00–15:00; Nepal private school *ca.* 10:00–16:00. For the Indonesian public school the hours varied according to the participants' class with one cohort attending 07:00–11:30 and the other attending 12:00–16:30. The Nepal private school started at 10:45 and finished between 15:00 and 16:45 depending on the season and grade of the child). These were then compared with the participants' sensor data during the times when they were at school. Data from the devices installed at each of the schools for the full measurement period (i.e. not restricted to school hours) can be found in table S1, supplementary information.

In Bandung, the outdoor school PurpleAir mean $PM_{2.5}$ concentrations (figure 3, 'School PurpleAir') were similar for the public and private school and were also comparable to the data collected by the participant sensors (figure 3, 'Child PurpleAir School'). In Kathmandu, higher mean $PM_{2.5}$ concentrations were recorded by the outdoor school sensors compared to the participant sensors. There was also a difference in the mean $PM_{2.5}$ concentrations recorded by the outdoor sensors at the public and private Kathmandu schools, with the private school exhibiting a higher mean $PM_{2.5}$ level. While figure 2 demonstrated higher $PM_{2.5}$ concentrations measured by the sensors installed at the schools in Kathmandu, compared to the data from participants' sensors while in the home, such concentrations were recorded during the early morning when participants were not yet at school.

### 3.3. $PM_{2.5}$ during commuting

As demonstrated in the time series graph showing a child's exposures throughout a week (figure 1), commuting can create short-term peaks in exposure which are substantially higher than concentrations experienced during other activities. Regarding the impact of different modes of transport on particulate concentrations during the children's commute, travelling by scooter/motorbike resulted in the highest mean $PM_{2.5}$ concentration for all commuting methods, and car had the lowest mean value (figure 4). However, it should be noted that, in cars, many of which have air filtration systems, concentrations were still substantially higher than the WHO 24 h guideline (15 $\mu$g m$^{-3}$). Walking or taking the bus had mean $PM_{2.5}$ concentrations between those of car and scooter/motorbike. The mean commute times for both cities were scooter/motorbike 13 min (SD = 9 min), walking 13 min (SD = 10 min), bus 49 min (SD = 24 min) and car 52 min (SD = 52 min).

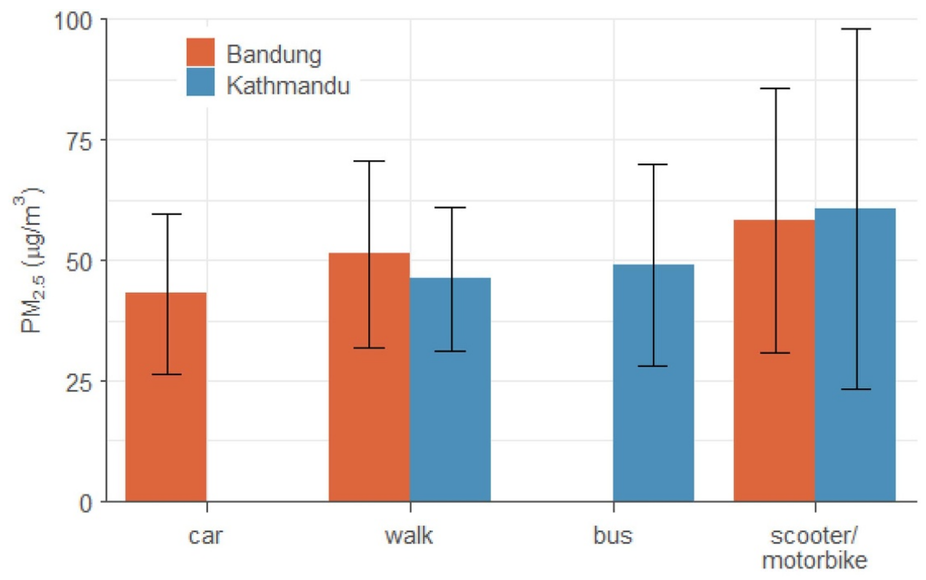


**Figure 4.** Mean $PM_{2.5}$ concentrations for different methods of commuting; error bars represent standard deviation.

### 3.4. Statistical modelling

Full regression analyses results are described in the Supplementary Information.

$PM_{2.5}$ concentrations were 20%–22% higher in home, commuting, and other microenvironments compared with school, which consistently had the lowest levels, in both countries. Day of the week had minimal influence, except for slightly higher concentrations on Monday compared with Friday. These relationships remained robust across models with additional covariate adjustments and sensitivity analyses, with some evidence of country-specific modification, particularly elevated morning concentrations (06:00–10:59) in Kathmandu. Further information can be found in supplementary information.

## 4. Discussion

This study investigated children's exposure to $PM_{2.5}$ in their daily routines in two highly polluted urban centres: Bandung, Indonesia and Kathmandu, Nepal. Both countries are attempting to reduce emissions of air pollutants (Riley *et al* 2021, Islam *et al* 2022) but, as demonstrated in this study and through official statistics, outdoor particulate concentrations remain substantially above WHO guidelines, and above country-level standards much of the time (Ministry of Science and Technology 2012, Greenpeace Indonesia 2021, Peraturan Pemerintah (PP) Nomor 22 Tahun 2021). Given the well-documented health risks for both adults and children of inhaling polluted air (Adhikary *et al* 2024, Donzelli *et al* 2019, Fonderson *et al* 2024, Johnson *et al* 2021, Khreis *et al* 2019, Markevych *et al* 2018, Milani *et al* 2022, Morales-Suárez-Varela *et al* 2017, Steinle *et al* 2020, Zhang and Zheng 2023), it is becoming critical that solutions are found to protect individuals until emissions are reduced, but understanding exposure in different parts of people's daily routine is an essential first step in the development of interventions. In section 4.1, the different microenvironments of children's exposure have been reviewed, in the context of research on potential personal interventions to reduce these exposures, whilst also recognizing that source control must be the primary effort.

A significant strength of this study was the use of harmonized standard operating procedures in both locations (supplementary information). Overall, there was excellent engagement with the study by the schools and participating parents/carers and children which gave reassurance that the measurement and recording devices were being used as instructed. A bespoke backpack enabled participants to carry the equipment as personal monitors without obstructing the air sensor inlets, and whilst also carrying their school equipment. Participant feedback on the backpack used to carry the PurpleAir and GPS devices was excellent; 88% of participants said it was easy to remember to take the bag wherever they went, 98% said it was comfortable and 61% said they were not embarrassed carrying it.

This study of children's exposure is important because it confirms that the children monitored in Kathmandu and Bandung are personally exposed to airborne pollutant concentrations at levels similar to those measured in the ambient environment. However, differences in the concentrations that children are exposed to in different microenvironments were observed. This knowledge allows informed decisions to be made about where to focus exposure reduction interventions.

### 4.1. Exposure in different microenvironments

In the home, children were often exposed to high $PM_{2.5}$ concentrations (>50 $\mu$g $m^{-3}$) for prolonged periods (>2 h), and morning and evening peaks of poor air quality were observed, particularly in Kathmandu, which somewhat coincided with outdoor peaks. Morning and evening $PM_{2.5}$ peaks in Kathmandu have been previously observed (Karki *et al* 2016) and both the $PM_{2.5}$ concentrations and times match very well with the data reported here (figure 2). Although substantial information about indoor habits which might increase or decrease particulate concentrations was collected, the study was unable to assign a consistent source to the indoor concentrations in the home, in either country. This makes it hard to suggest interventions to lessen particulate concentrations and exposures indoors, but common advice such as not smoking (tobacco), burning solid fuels nor combusting other products (oil lamps, mosquito coils, incense) are prudent, although some are part of cultural traditions. Ensuring good ventilation whilst cooking is also important.

The FACE-UP project considered testing a low-cost air purifier (desk fan with High-efficiency particulate filter ) to reduce indoor PM concentrations; however, initial tests by non-governmental organization Kopernik (Kopernik 2017) confirmed that their use was challenging, given that rooms must be sealed (windows, doors and other ventilation gaps) to stop outdoor pollutants ingressing. In both Nepal and Indonesia, ventilation is essential due to heat and limited use of air conditioning. In Nepal, government guidance to keep windows open year-round to disperse indoor pollutants further discourages this approach, as well as enabling outdoor pollution to ingress, as seen in this study. The FACE-UP project also tested the efficacy of children's facemask use (Sleeuwenhoek *et al* 2025) but mask-wearing in homes is neither practical nor appropriate except in the most severe air pollution crises. Therefore, public information campaigns which aim to change indoor pollution-generating behaviours (i.e. source control) are likely to be the most successful intervention at reducing children's exposure in the home.

The commuting microenvironment was identified as a risk factor for children in both countries in this study. Commuting (to school or other locations) by scooter/motorbike exposed the children to the greatest concentrations of particulate (compared to other modes of transport), although walking to school in Bandung involved similar exposure. It should be noted that the average commute time on scooters or walking was 13 min in this study, whereas average commute time by bus or car was around 3 times longer so overall exposures may be similar. A personal exposure study previously conducted in Bandung, on adults, found the same trend in $PM_{2.5}$ concentrations for commuting by car, walking and scooter/motorbike, with car being the lowest and scooter /motorbike being the highest (Sinaga *et al* 2020).

The children in this study carried the sensors in backpacks. Although the questionnaires included questions on facemask use (supplementary information), it is not known whether children wore facemasks during travel to and from school and other activities during the study period, and therefore whether their actual exposure was lower than the concentrations measured by the backpack sensors. However, previous studies (Mueller *et al* 2018, Steinle *et al* 2018) have shown that commonly used masks such as surgical and cloth masks have poor particulate filtration efficiency and poor fit, so the level of exposure reduction is likely not to be high. As part of the FACE-UP project, the filtration efficiency of child respirators (e.g. certified to KN95 or equivalent standard) from Nepal and Indonesia was tested. KN95 respirators are designed to filter at least 95% of airborne particles. Whilst six of the eight respirators tested met KN95 (or equivalent) filtration standards, two of the respirators did not (Gudgin Dickson *et al* 2025). The fit of the respirators which passed the filtration tests was then tested on children in Nepal and Indonesia (Sleeuwenhoek *et al* 2025), with low fit factors measured for most children, although these were improved with additional ear-loop clips to help create a better facial seal. This highlights the need for manufacturers to design child respirators which fit their face shapes and have features which improve fit, if they are to be used as a viable intervention (Szalajda *et al* 2025). The data from the current study, along with the fit-testing data from Sleeuwenhoek *et al* (2025) are being used to inform a Health Impact Assessment (Mueller *et al*, to be published) to determine the health benefit of children wearing KN95 masks in different microenvironments, such as during the school commute.

Another intervention that could reduce exposures on commutes is to take a different route to school (either walking or in/on a vehicle) and this has been shown to be effective at reducing exposures where alternative routes with less traffic are available (Ahmed *et al* 2020, Varaden *et al* 2021). Through structured interviews with children and their parents/carers, the FACE-UP project has also investigated whether such interventions are viable in Kathmandu or Bandung (Covey *et al*, to be published).

The school microenvironment personal data, and ambient data, showed that the air quality was generally better in the classrooms than outside the classrooms. In general, the indoor school environment in both cities had the lowest mean $PM_{2.5}$ concentration (Bandung 41.2 $\mu$g $m^{-3}$, Kathmandu 33.7 $\mu$g $m^{-3}$) of any microenvironment. The schools in Kathmandu had lower mean $PM_{2.5}$ concentrations than the schools in Bandung but the questionnaire data and researcher observations related to ventilation of classrooms did not provide a clear reason why. It is worth noting that the private school in Bandung is entirely enclosed (children work and play indoors; the outdoor sensor was mounted at the outer entrance of the school) with air conditioning used at times, and windows opened at others. All of the other schools in the study did not have air conditioning and had constant ventilation through open doors and windows. For the data collected at the private school in Kathmandu, there was a period of high ambient $PM_{2.5}$ concentrations from 27th to 30 April 2024, which is also present in locally available reference-grade data and may have been caused by local forest fires which were widespread in Nepal during April 2023 (Poudel 2023). The data therefore indicate that, despite high ambient PM concentrations, the air quality inside the classrooms was substantially better, despite having no air conditioning/-filtration systems. This may simply be because there are no sources of particulate emissions in the classroom, unlike the home environment, and barriers such as windows and walls provide some protection from the pollution outside.

Many countries, including Indonesia and Nepal have policies that schools should be closed (or time at school limited) during air pollution crises. Given the findings of this study, it should be considered whether schools offer less polluted environments than the home environment, during air pollution episodes, although children must still travel to get to schools. Nevertheless, while air quality in the classroom was certainly better than outdoors, it was still a polluted environment compared to many locations around the world (and the WHO guidelines). The private school in Bandung used air conditioning for several hours daily but this did not appreciatively improve air quality in the classroom compared to the public school in Bandung, perhaps because windows were open at other times and possibly because not all air conditioners contain air purifier filters. It is not reasonable to suggest air conditioning as an intervention as most schools cannot afford them. There are, therefore, few interventions that can be easily applied to reduce exposure in the classroom. Facemasks are an option, but consideration needs to be given to the potential detrimental impact on learning and communication for children (Preest *et al* 2024).

### 4.2. Low-cost sensors for personal exposure monitoring

Regarding the use of low-cost sensors for monitoring personal exposures, a recent systematic review of studies measuring personal $PM_{2.5}$ exposure identified various techniques including time-integrated monitors which collect samples on a filter over a specific time period or time-resolved monitors, which provide temporal exposure information over the given measurement period (Lim *et al* 2022). The development of low-cost sensors, which also have low power requirements and are portable, has led to the ability to investigate personal exposure to PM in different microenvironments (Morawska *et al* 2018). In this study PurpleAir devices were used to record participants' exposure to $PM_{2.5}$ and, it is believed by the study team, there has only been one previous study (on adults) which has used this sensor for personal monitoring (McCarron *et al* 2023).

While low-cost sensors are clearly an excellent research tool, and the PurpleAir Plantower sensors are relatively precise and accurate for $PM_{2.5}$ (Air Quality Sensor Performance Evaluation Center, 2024), at least in the short-term after factory calibration, issues occurred with some devices, with several sensors having timestamp failures, and other having issues with data collection or data storage. The previous study which also used PurpleAir devices had 'sensor malfunction' issues for two of the twenty-eight participants (McCarron *et al* 2023). The other drawback of such sensors is that they are only factory calibrated which means that, to ensure that local climate variables are accounted for, and there is no data drift over time, they must be colocated with a reference-grade instrument ideally before and after deployment. A cf then must be developed so that the data are comparable. Without this, comparison to national or WHO particulate air quality regulations/guidelines should not be made and the data treated as indicative. It is important to note that low-cost sensors, therefore, should not be used as replacements for reference-grade monitors but they are a very useful tool for personal monitoring, given their portability and price, as long as their shortcomings are fully recognized and accounted for.

Issues were also encountered with the GPS units, with loss of or inaccurate signal. Difficulties with GPS data collection in Kathmandu have been previously reported (Edwards *et al* 2023). However, the authors do not believe that this substantially impacted microenvironment assignment, as cross-checks with the expected location of the child at the timepoint based on the caregivers' questionnaire was able to be undertaken.

At least five other studies have monitored children's personal exposure using (different) low-cost sensors (Ryan *et al* 2015, Woo *et al* 2019, Kim *et al* 2021, Varaden *et al* 2021, Lim *et al* 2022). While this study and these previous ones show that such real-time exposure monitoring with children is viable, the sample size is usually small (due to the number of available sensors and the common aim of trying to conduct the research within a seasonal timeframe) and the exposure duration is usually limited, as it is not ethical to ask children to carry the backpacks and sensors for pro-longed periods. Therefore, such studies are usually limited by these parameters and often struggle to capture annual or seasonal variations. It would be prudent to repeat the study during different seasons to capture children's exposures under different meteorological conditions, and seasonal periods of high emissions (e.g. due to wildfires and crop burning), but retention of child participants might be challenging. Overall, despite the practical considerations inherent in using low-cost sensors and GPS units, the strong potential of these technologies to enable detailed, microenvironment-specific assessment of children's personal exposure to $PM_{2.5}$ has been demonstrated.

## 5. Conclusion

This study on children's exposure to $PM_{2.5}$ in Bandung, Indonesia, and Kathmandu, Nepal successfully engaged schools, parents/carers, and children, with high compliance and positive feedback in relation to personal monitoring of children's exposure to particulate pollution over a one-week period. Comparison of the 24 h mean $PM_{2.5}$ concentrations that children experienced over the week with WHO guidelines and national standards suggests that children in both cities are regularly exposed to airborne concentrations of $PM_{2.5}$ substantially above these values. We found that children are exposed to different $PM_{2.5}$ concentrations depending on their location. Exposure was notably high in the home microenvironment but no specific source of indoor particulates that were driving these higher exposures were identified. Commuting by scooter or walking exposes children to the highest $PM_{2.5}$ concentrations, while car or bus commutes expose children to lower concentrations, although the longer duration of these commutes might offset this benefit. The air quality in classrooms was found to be marginally better than other microenvironments. However, classrooms still have significant $PM_{2.5}$ levels compared to WHO guidelines, and practical interventions to further reduce exposure are limited. Overall, the results of this study emphasize the urgent need for continued emissions reduction initiatives and the development of effective interventions to protect children from high particulate pollution.

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## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.17605/OSF.IO/XBT93.

Supplementary Information 1 available at https://doi.org/10.1088/2752-5309/ae8050/data1.

Supplementary Information 2 available at https://doi.org/10.1088/2752-5309/ae8050/data2.

## Conflict of interest

The authors declare no competing interests.

## Ethical approval

Ethics approval for the study was granted by the Durham University Psychology Ethics Committee (Reference: PSYCH-2022-06-01T12_54_54-dps0jac), the Ethical Review Board of the Nepal Health Research Council (NHRC) (Reference Number 1773) and Bandung Institute of Technology (Reference Number KEP/II/2022/X/M240123DSA/FACE). All work was performed in accordance with the relevant guidelines and regulations.

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