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RESEARCH

Quantifying Residential Particulate Pollution and Human Exposure in Ibadan, Nigeria, Using Low-Cost Sensors

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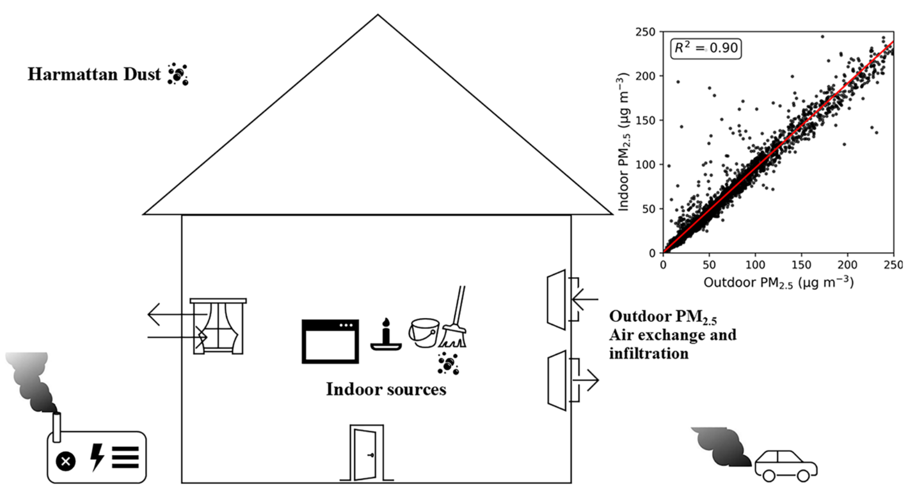
Abstract

Exposure to fine particulate matter ($PM_{2.5}$) pollution, both outdoors and indoors poses a significant health burden in Africa, where concentrations are often high, but there are limited measurements. Two types of low-cost sensors were used during two distinct measurement phases conducted in Ibadan, Nigeria. In Phase I, indoor and outdoor $PM_{2.5}$ concentrations were measured for a two-week period in twelve households using a total of twenty-four Atmotube PRO sensors. Phase II consisted of a seven-month extended monitoring study conducted in two households (each equipped with one indoor and one outdoor sensor) and a school (1 sensor only) using five PurpleAir sensors. Across the twelve households in Phase I, daily median $PM_{2.5}$ concentrations ranged from 12.0 to 18.0 μgm^{-3} indoors, and from 12.2 to 20.0 μgm^{-3} outdoors. The overall $PM_{2.5}$ indoor-outdoor (I/O) median ratio was 0.9 indicating that outdoor levels were typically slightly higher than indoors. In January (the dry harmattan season), daily median $PM_{2.5}$ concentrations were 98.0 μgm^{-3} indoors and 109.3 μgm^{-3} outdoors. In contrast, lower $PM_{2.5}$ concentrations of 21.4 μgm^{-3} indoors and 24.5 μgm^{-3} outdoors were recorded in May, a rainy season. In Phase II, we find that a substantial part (~ 90%) of $PM_{2.5}$ concentrations can be explained by variance in the outdoor concentrations. There was exceedance of WHO interim target IT-1 of 75 μgm^{-3} for $PM_{2.5}$ during the dry harmattan season. The findings highlight the need for continuous air quality monitoring infrastructure to track pollutant trends and offering insights for future research.

Graphical Abstract



Keywords Indoor · Outdoor · $PM_{2.5}$ · Low-cost sensors · I/O ratio

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1 Introduction

The air we breathe is critical to our health and well-being, and the burden of disease associated with both outdoor and household air pollution is of considerable concern. According to Health Effects Institute (2024), air pollution was responsible for 8.1 million deaths worldwide in 2021, with household air pollution accounting for approximately 38% of these deaths. The impact of air pollution is particularly more pronounced in low-and-middle-income countries (LMICs) (WHO 2024). Both indoor and outdoor air pollution present significant health risks to humans (WHO 2021). Agbo et al. (2021) reported that household pollution poses a greater risk due to higher exposure levels than those associated with outdoor pollution in Africa. This is particularly due to the dependence on solid fuels for cooking and heating (UNICEF 2019; Williams et al. 2025). Over the span of the last decade (2010–2020), there has been a reduction in the global health impact caused by household air pollution, reflecting years of effort to move to cleaner energy sources (HEI 2020). According to ESMAP (2021), global efforts have led to an 11% overall reduction in the use of solid fuels for cooking. Access to modern energy cooking services in developing regions varies, with Latin America at 57%, East Asia at 36%, South Asia at 27%, Southeast Asia at 21%, and the lowest access observed in Sub-Saharan Africa at just 10% (ESMAP 2021). This disparity highlights the uneven progress across the globe, as also noted by the United Nations (UNEP 2022).

Particulate matter (PM) is responsible for the largest air pollution health burden globally and it is a useful measure of air quality (AQ) in residential environments (HEI 2022). PM refers to a mixture of solid particles and liquid droplets in the air, with $PM_{2.5}$—particles with a diameter of 2.5 µm or smaller, being of particular concern due to their ability to penetrate deep into the lungs and enter the bloodstream, causing serious health impacts (Maynard et al. 2023). PM sources in Africa include emissions from unpaved or damaged tarred roads, industry, biomass burning, open waste burning, domestic combustion, and Saharan dust (Naidja et al. 2018; WHO 2021). Other sources include transportation, especially the use of second-hand vehicles with high emissions, and the widespread use of fossil fuel powered generators (Abaje et al. 2020). There is consistent and robust evidence for the ill effects of $PM_{2.5}$ on respiratory health. The acute effects of $PM_{2.5}$ exposure include an increase in hospital admissions, early childhood development of asthma (Lavigne et al. 2021; Leon Hsu et al. 2015). Long-term effects of outdoor $PM_{2.5}$ exposure are associated with cardiovascular and respiratory diseases; and lung cancer with records of increased mortality rates in cities with higher concentration of airborne PM (WHO 2021).

Despite the high health burden, there are limited in-situ studies of air pollution concentrations in Africa (Mead et al. 2023; Naidja et al. 2018). Nigeria is the most populous country in Africa with approximately 230 million people, it is ranked fifth for premature deaths associated with air pollution) (HEI, 2020). The World Health data report indicates that in Nigeria, lower respiratory infections linked to air pollution increased in severity, rising from the fourth leading cause of premature death in 2007 to the leading cause by 2017 (Pona et al. 2021). About 185 children under the age of five die every day from pneumonia due to air pollution in Nigeria (UNICEF 2021). This demonstrates the need to tackle air pollution and indicates how impactful reductions in air pollution could be for improving population health. Measurement of air pollution in Nigeria and many other African nations are sparse (Mead et al. 2023; Pona et al. 2021). Due to lack of static reference-grade monitors in Nigeria, there is reliance on shorter term studies to understand air pollution. Shittu et al., (2019) reported the $PM_{2.5}$ levels ranged from 4 to 25 µg m^{-3} using a CW_HAT200 handheld portable particle counter for $PM_{2.5}$ measurements in different indoor environments within a university campus in Lagos during the rainy season. Similarly, Jelili et al., (2020) reported a higher cumulative mean of indoor and outdoor $PM_{2.5}$ of 41.6 and 46.3 µg m^{-3} respectively in Ogbomosho in a 4-week study using GT_531 mass particle counter. A total mean $PM_{2.5}$ concentration of 31.6 and 53.6 µg m^{-3} in Ibadan for indoor and outdoor $PM_{2.5}$ levels respectively was reported by Onabowale and Owoade, (2015) using elemental analysis of filter samples, providing a baseline study for indoor and outdoor PM measurements in Ibadan. Using satellite data, outdoor PM exposure has been found to be within the range of 5–212 µg m^{-3} in various locations in Lagos (Abulude et al. 2021). According to Akinfolarin et al. (2017), air quality in Port-Harcourt was classified as moderate during the rainy season, with an air quality index (AQI) ranging from 23 to 60, while the dry season recorded hazardous levels, with AQI values between 225 and 273. Some studies have also used surveys and questionnaires to identify impacts of household pollution (Ana et al. 2009; Jelili et al. 2020; Oluwole et al. 2017, 2013).

Several PM low-cost sensors ($200–$2500) have become commercially available (AQMD 2020; Badura et al. 2019; Barkjohn et al. 2022; Kang et al. 2022). These sensors are portable, lightweight, and capable of providing high-resolution, near real-time data (Morawska et al. 2018; Rai et al. 2017). The use of low-cost sensor networks is increasing in low- and middle-income countries (LMICs), where continuous monitoring with reference-grade equipment is often sparse or unavailable. These sensors hold great potential to provide valuable air quality information for researchers and communities, enabling more frequent and widespread monitoring, particularly in areas lacking government or research-grade instruments (Chatzidiakou et al. 2019; Morawska et al. 2018). In addition, they are relatively easy to use, requiring minimal training, thus broadening access to air quality data. Recent studies in Nigeria have employed low-cost PM sensors to assess air quality in various locations, including Ekiti, Lagos, Enugu, Awka, and Ile-Ife (Abulude et al. 2021; Awokola et al. 2020; Omokungbe et al. 2020). These studies consistently reported $PM_{2.5}$ concentrations exceeding the WHO recommended 24-h limit of 15 μgm^{-3}. Awokola et al., (2020) reported frequent power outages and inconsistent internet connectivity as significant challenges associated with the use of low-cost sensors for air pollution monitoring in LMIC settings.

There is an urgent need for more comprehensive air quality measurements in Nigeria, particularly within homes, where people spend much of their time. Despite the high burden of air pollution, air quality studies in Nigeria remain insufficient, making local measurements essential to better understand and mitigate the potential health impacts of exposure. Our study aims to quantify the abundances of residential $PM_{2.5}$ pollution concentrations, characterise monthly $PM_{2.5}$ variability, and investigate the association of indoor and outdoor $PM_{2.5}$ concentrations in the city of Ibadan, Nigeria, where reference-grade monitoring instruments are not available. We deployed low-cost Atmotube PRO and PurpleAir sensors to monitor continuous indoor and outdoor $PM_{2.5}$ over several months, establishing an initial air quality baseline for the city.

2 Methods

2.1 Study Area

The study area was in Ibadan, Southwestern Nigeria. The study was carried out in two phases; a first shorter-term but more intensive phase that used Atmotube PRO sensors, followed by a second longer-term but less-intensive phase using Purple Air Sensors. In Phase I, twenty-four Atmotube PRO sensors we placed in twelve houses in Ibadan, in each house one sensor was placed indoors and the other outdoors. Sampling took place, over a two-week period between 5 and 17th November 2023. The houses were spread across a central area: University (6 households), Akobo (2 households), Ajibode (1 household), Bashorun (1 household), Iwo Road (1 household) and Total Garden (1 household). Indoor sensors were placed in a communal area (living room), while the outdoor sensor was hung on the entrance door outside the building (to allow ease of charging with the power bank). As power cuts are common in Nigeria, participants were given a power bank to charge the sensors. These were replaced every 2-days with a fully charged unit.

Phase I was followed by a longer-term measurement campaign (Phase II), in which five PurpleAir sensors were deployed in two houses and a school building. The monitoring period for Phase II was 5th November 2023 to 22nd May 2024, covering both the dry and rainy seasons. Each of the two participating houses (University and Akobo) had two PurpleAir sensors installed; one indoors and one outdoors. Finally, an additional sensor was installed in the reception area of a secondary school within the University campus, this sensor location was designated a hybrid indoor/outdoor environment due to an unobstructed exchange of indoor and outdoor air. In the houses, indoor PurpleAir sensors were placed in the living room, while the outdoor sensors were placed under the cover of an overhanging roof (to avoid being affected by rainfall or strong winds). Figure 1 shows the study area and locations of all sensors. However, some sensor markers overlap due to the proximity of the participating households. All participating households reported the use of liquified petroleum gas (LPG) for cooking.

A summary of the sensor locations and a brief description of the site for both Phase I and Phase II is given in Table 1.

2.2 Sensors

In Phase I, Atmotube PRO sensors were used to measure $PM_{2.5}$ in the participating houses, these sensors are portable, low-cost and commercially available. The Atmotube PRO device contain a Sensirion $PM_{2.5}$ sensor which reports the estimated mass concentration of particles with an aerodynamic diameter of < 1 µm, < 2.5 µm and < 10 µm (PM_1, $PM_{2.5}$ and PM_{10}) using light scattering principle (Atmotube 2024; Voultsidis et al. 2023). The Atmotube PRO sensor has a $PM_{2.5}$ measurement range of 1 to 1000 $\mu g\ m^{-3}$. The Atmotube PRO device also has a BOSCH BME280 sensor that records temperature and relative humidity (RH) data. The sensors log $PM_{2.5}$ concentrations every second and this is used to calculate 1 min average $PM_{2.5}$ concentrations (Masri et al. 2022; Shittu et al. 2025).

In Phase II, PurpleAir sensors were also used to monitor $PM_{2.5}$ for an extended period. PurpleAir sensors are a widely used device around the world, and are popular among individual researchers, community organisations and others interested in monitoring local air quality. Each PurpleAir sensor contains two Plantower PMS5003 sensors, labelled as channel "A" and "B". The sensors record two-minute averaged data (Barkjohn et al. 2022, 2021; Zimmerman et al. 2018). Plantower sensors use the laser light scattering principle to measure particle size. Estimated particle mass with aerodynamic diameters PM_1, $PM_{2.5}$ and PM_{10} are reported, as well as particle counts in six size bins (> 0.3, > 0.5, > 1.0, > 2.5, > 5.0 and 10.0 µm). PurpleAir, like many other

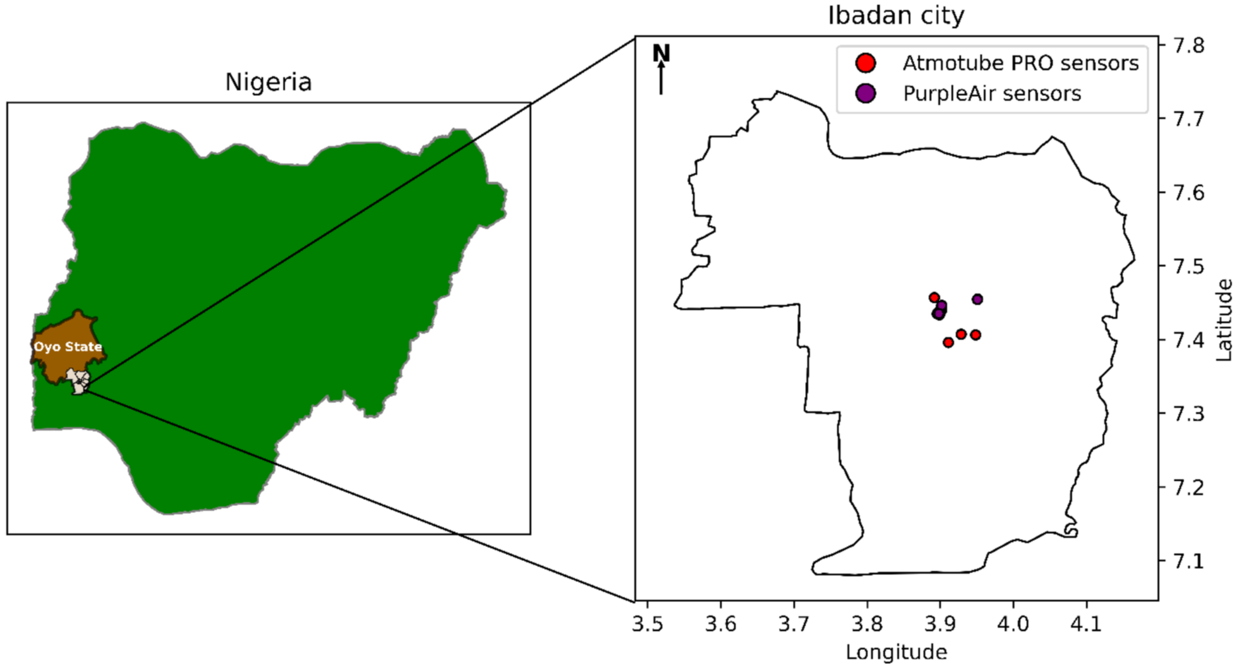

Fig. 1 Map of Nigeria highlighting the study area, Ibadan, Oyo State, and the location of the sensors deployed for the study

Table 1 The sampling areas, household ID, their coordinates and site description

Sampling area	ID	Site description
Phase I: Atmotube PRO sensors		
Ajibode	A	Road to the house has low usage and broken road surface
Iwo-Road	B	Residential area and has connecting tarred road from main road
University	C	Highrise building with multiple flats (8)
	D	A bungalow within a secondary school surrounded by trees
	E	Mini flat next to the secondary school playground area
	G	Duplex surrounded by trees, next to a tarred road
	H	Highrise building with multiple flats (same building with I)
	I	Highrise building next to a tarred road, some planted hedges as well
Total garden	F	Building in a dense urban environment and in proximity to a major roundabout with traffic at peak periods
Bashorun	J	Residential area with connecting minor tarred road
Akobo	K	A bungalow situated in a residential area close to a main tarred road
	L	Building behind house K
Phase II: PurpleAir sensors		
University	UI	Building close to a tarred busy road at the University
Akobo	AK	Building situated in an estate with untarred road
Secondary school	School	School building is located within the University. Sensor site is at the school office reception

low-cost sensors, have unpublished assumed particle densities used for the conversion from number concentration to mass concentration (Giordano et al. 2021; Jaffe et al. 2023).

Like Atmotube PROs, PurpleAir sensors use the BOSCH BME280 sensor to record temperature and relative humidity (RH). In addition, PurpleAir have a Wi-Fi chip that uploads data to the cloud in near real time. The sensor also stores data locally on an SD card, which is useful for study areas without Wi-Fi or as a backup of the data in case of connectivity issues. For this study, data collected at 2-min intervals were downloaded from online sensors and retrieved data from the SD cards of the sensors due to poor Wi-Fi connectivity in our area of study. Data was saved in.csv format for further analysis in Python. These short-term averages were then aggregated into hourly averages. To ensure data quality, only hourly averages with at least 70% completeness were calculated.

While we cannot validate the low-cost sensor performance in this study due to a lack of ground-based reference grade monitoring in the region, Shittu et al., (2025) undertook a detailed assessment of these sensors against a reference grade instrument finding good agreement. The Atmotube PRO and PurpleAir sensors had an accuracy using coefficient of determination (R^2) of (0.86 and 0.85) and an error of (3.4 μg m^{-3} and 4.8 μg m^{-3}), respectively, in comparisons to the reference grade instrument. Pearson's coefficient of correlation (r) value > 0.84 indicated strong inter-sensor agreement as shown in supplementary Fig. S1. Therefore, we have confidence in application of these low-cost sensors for indicative $PM_{2.5}$ measurements in this study.

2.3 Data Processing and Analysis

Descriptive statistics used for analysis of the raw data include the arithmetic and geometric mean, standard deviation, median, percentiles, and maximum values. These metrics are calculated for the indoor and outdoor $PM_{2.5}$ for each household are summarized in Supplementary Tables S1 and S2. Due to the non-gaussian data distribution of the $PM_{2.5}$ data and the presence of high-value outliers, the analysis was restricted to the minimum value and the 99th percentile to minimize the impact of the extreme or anomalous observations. The median was used as a measure of the central tendency, as it is less sensitive to skewed distributions compared to the arithmetic means, providing a more robust summary of $PM_{2.5}$ levels in our study. The indoor/outdoor (I/O) relationship was assessed by calculating I/O ratios and determining the Pearson coefficient of determination (R^2) between indoor and outdoor measurements. R^2 represents the variance proportion in a dependent variable explained by an independent variable, ranging from 0 (no explained variance) to 1 (complete explained variance). Diurnal variations for the longer-term measurements were investigated for $PM_{2.5}$. Python software (v3.11.9) was used for data analysis. Linear regression was performed using the SciPy package (v1.13.1) in Python.

3 Results and Discussion

3.1 Phase 1: Atmotube PRO sensor

There were some data gaps logged by the Atmotube PRO instruments during the period of study. Eight and ten households had indoor and outdoor data coverage exceeding 75% respectively, while three households had indoor and two had outdoor coverage over 50%. Only one household had indoor data coverage of < 50% (38%). All participating households reported the use of liquified petroleum gas (LPG) for cooking.

3.1.1 *Atmotube PRO $PM_{2.5}$ Measurements*

The median values for indoor and outdoor hourly $PM_{2.5}$ measurements for all 12 households are listed in Table 2. The median indoor values across households are relatively similar, with none deviating by more than 24.5% from the mean of all medians. However, there is a notable difference in the range of $PM_{2.5}$ concentrations. For example, house A and house D both recorded indoor $PM_{2.5}$ median values of 15.0 μg m^{-3}, however, house A had indoor range of 3.0–112.0 μg m^{-3} while house D had indoor range of

Table 2 Indoor and outdoor $PM_{2.5}$ concentrations for individual houses and their I/O relationship (AM = arithmetic mean)

ID	Indoor $PM_{2.5}$ concentration			Outdoor $PM_{2.5}$ concentration			Median
	AM	Median	Range	AM	Median	Range	I/O ratio
A	18.4	15.0	3.0–112.0	13.0	14.0	3.0–82.0	1.1
B	19.6	17.0	3.0–65.0	16.9	15.0	3.0–59.0	1.1
C	17.8	16.1	2.9–77.3	14.3	12.2	3.0–74.0	1.3
D	16.7	15.0	3.0–51.0	13.5	13.0	3.0–34.0	1.2
E	15.6	14.9	3.0–43.0	20.0	18.0	3.0–57.0	0.8
F	17.8	15.1	1.0–70.0	24.5	20.0	1.0–171.0	0.8
G	14.7	12.1	3.0–53.0	15.4	14.0	3.0–39.0	0.9
H	14.3	12.0	3.0–46.0	21.7	19.3	3.0–63.0	0.6
I	20.2	18.0	3.0–74.0	18.2	15.1	4.0–56.0	1.2
J	16.5	15.0	3.0–55.0	18.3	16.0	3.0–57.2	0.9
K	14.8	14.0	3.0–42.0	18.8	17.0	3.0–53.0	0.8
L	13.8	12.0	1.3–40.0	17.6	16.1	1.0–51.9	0.9
All	17.8	15.0	1.0–61.0	19.3	16.1	1–63.0	0.9

3.0–51.0 μg m^{-3}, indicating differences in the indoor level of $PM_{2.5}$ in both households. This could be due to the differences in the level of anthropogenic indoor activities in individual houses.

The median $PM_{2.5}$ values using hourly data for the houses ranged from 12.0 to 18.0 μg m^{-3} and 12.2 to 20.0 μg m^{-3} for indoor and outdoor measurements, respectively. The data shows seven households (E, F, G, H, J, K, L) had outdoor $PM_{2.5}$ concentrations higher than the indoor level while the other five houses had indoor concentrations higher than the outdoor measurements. Despite houses C, D, E, G, H, and I being in the same vicinity (within the university campus), there were two households showing a higher $PM_{2.5}$ measurements indoors compared to outdoors. On a house-by-house basis, there was insufficient evidence to conclude AQ is worse indoors or outdoors.

The comparison of the indoor and outdoor hourly measurements for all households combined throughout the two-week study period is illustrated in Fig. 2a. Outdoor $PM_{2.5}$ levels are slightly higher than indoor $PM_{2.5}$ levels. The daily geometric mean $PM_{2.5}$ concentrations for all households were 16.9 ± 1.5 μg m^{-3} and 18.2 ± 1.5 μg m^{-3} for indoor and outdoor measurements, respectively. Martins and Carrillho Da Graca (2018) reported that in the absence of significant internal sources, indoor PM levels are expected to be lower than outdoor PM levels. Indoors, high peaks were however recorded during the early hours of the day and in the evening which coincides with cooking periods.

Indoor and outdoor values were resampled to a daily mean resolution and Fig. 2b illustrates the geometric mean of the daily $PM_{2.5}$ values for houses A-L, respectively. The outdoor $PM_{2.5}$ concentrations for 83% of the households were higher than the daily AQG levels (15 μg m^{-3}) recommended by WHO. Although comparing with the interim targets set by the WHO (WHO 2021), these $PM_{2.5}$ levels were below the WHO interim targets of IT-1 (75 μg m^{-3}), IT-2 (50 μg m^{-3}), IT-3 (37.5 μg m^{-3}) and IT-4 (25 μg m^{-3}) for 24 h recommended limit. Outdoor sources in and around the study sites are typical of an urban environment, and include vehicular emissions along roads, generator emissions from residences and from commercial shops due to erratic power supply, as identified in Ogbomosho by Jelili et al., (2020). House F had the highest daily outdoor $PM_{2.5}$ mean of 21 μg m^{-3}, and this can be attributed to the fact that the building is close to

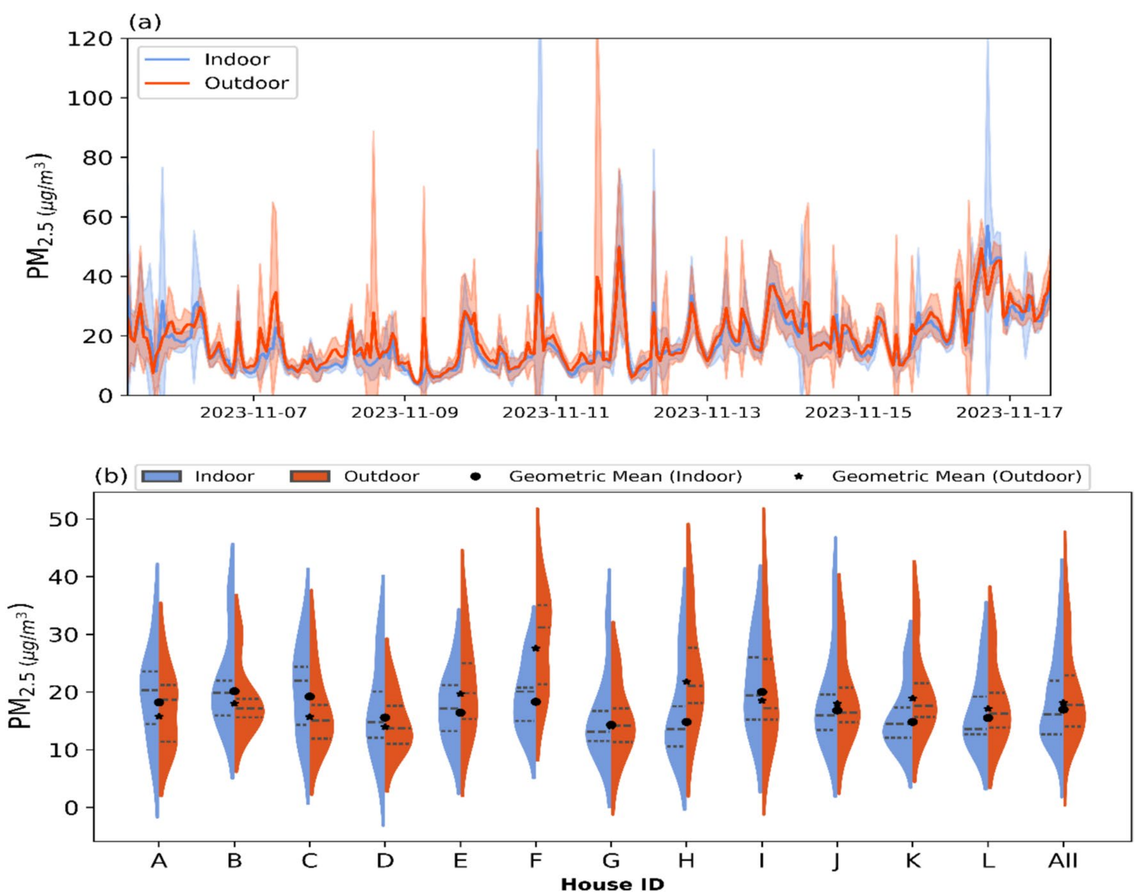

Fig. 2 **a** time series of hourly $PM_{2.5}$ mean for all participating households combined **b** Indoor and outdoor $PM_{2.5}$ 24 h data distribution for each household. The dashed black lines represent the 25th, 50th and 75th percentile of the data

a major roundabout usually with lots of road traffic, vehicle idling at traffic light intersections, and the proliferation of vehicular exhaust emissions within the environment, especially at rush hour. Due to unreliable power supply, houses use generators as an alternative power supply and the emissions from these generators result in noise, oxides of carbon, nitrogen, sulphur, and particulates.

The indoor 24 h $PM_{2.5}$ measurement for the 12 households are shown in Fig. 2(b). These were higher than the 24 h AQG levels (15 μg m^{-3}) recommended by WHO for nearly all (91%) of the households. In previous studies, indoor PM has been attributed to household activities, such as cooking (Onabowale and Owoade 2015), use of incense (Kuo et al. 2015), candles, lightning, occupant's behaviour such as door and window opening behaviour (Fu et al. 2022) or resuspension of dust particles from sweeping and other anthropogenic activities.

Half of our study sites (C, D, E, G, H, and I) were within the University campus as indicated in Table 1. The outdoor $PM_{2.5}$ measurements (Atmotube PRO sensors) alongside the outdoor $PM_{2.5}$ measurements using PurpleAir sensors within close proximity at the University study sites showed similar temporal variations as shown in Fig. 3. However, the PurpleAir sensors recorded higher outdoor $PM_{2.5}$ concentrations, with a mean value of 29.3 ± 11.4 μg m^{-3}, compared to the Atmotube sensors, which reported a mean of 18.1 ± 11.2 μg m^{-3}. Bimodal elevated peaks were seen around 7am and 7 pm. Similar bimodal peaks at these times were observed in previous studies (Cholianawati et al. 2024; Gupta and Elumalai 2019; Thabethe et al. 2024). The early morning and evening peaks may be explained by stable boundary layer and poor vertical mixing at these times, trapping $PM_{2.5}$ emissions near to the surface and hence causing elevated concentrations (Aslam et al. 2017; Du et al. 2020; Wang et al. 2020). During the day, a rising boundary layer alongside other factors, such as increased atmospheric mixing and higher wind speed, allows for greater dilution and in turn lowers $PM_{2.5}$ concentrations. When visualised at a 5-min temporal resolution, distinct peaks in $PM_{2.5}$ concentrations (exceedingly 80 μg m^{-3}) were evident during early and late evening hours. The high concentrations may also be attributable to the operation of fossil fuel powered generators, which were reported by all participants as a commonly used alternative source of electricity. Given that all participating houses rely on natural ventilation, emissions from these generators can readily infiltrate indoor spaces, thereby contributing to indoor air pollution.

3.1.2 *Indoor/Outdoor $PM_{2.5}$ Relationship (Atmotube PRO)*

Previous studies have used or partly used diffusive sampling methods over a few days for indoor AQ measurements (Schneider et al. 2001). The distribution of indoor to outdoor (I/O) $PM_{2.5}$ ratios has been determined for varying building types (Chatzidiakou et al. 2020). However, these measurements have I/O ratios that take in to account considerable unoccupied periods, during which building operations and indoor sources are expected to differ (Stamp et al. 2022). In recent years, the use of real-time measurements with low-cost sensors has enabled continuous measurements and this can be used to complement qualitative data (surveys and questionnaires) to determine the impacts of these measured concentrations on resident's health. Improvements in these sensing technologies have resulted in more affordable measurements in more locations, as well as the ability to examine I/O ratios at high temporal resolution for a longer period (Chatzidiakou et al. 2019).

Figure 4 illustrates diurnal variation in I/O ratio, indoor and outdoor $PM_{2.5}$ concentrations. High peaks of indoor and outdoor $PM_{2.5}$ were recorded during early hours in the morning, around noon and early evenings leading to the general I/O ratio being below 1, generally. Both indoor and outdoor $PM_{2.5}$ levels were high, 18.6 and 21.3 μg m^{-3}, respectively

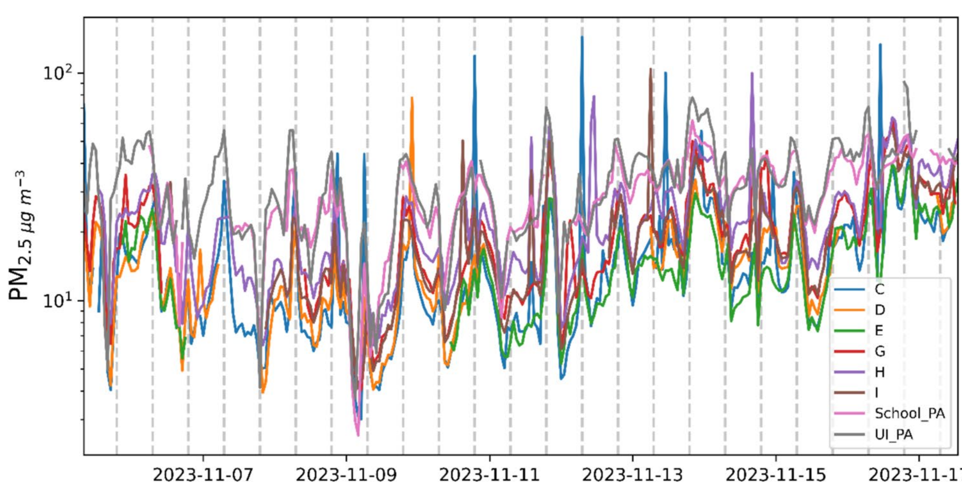

Fig. 3 Comparison of the hourly outdoor $PM_{2.5}$ data from Atmotube PRO And PurpleAir sensors deployed within the University showing similar temporal variations. y-axis represents logscale and the grey grid lines on the x-axis represent 7am and 7 pm alternately

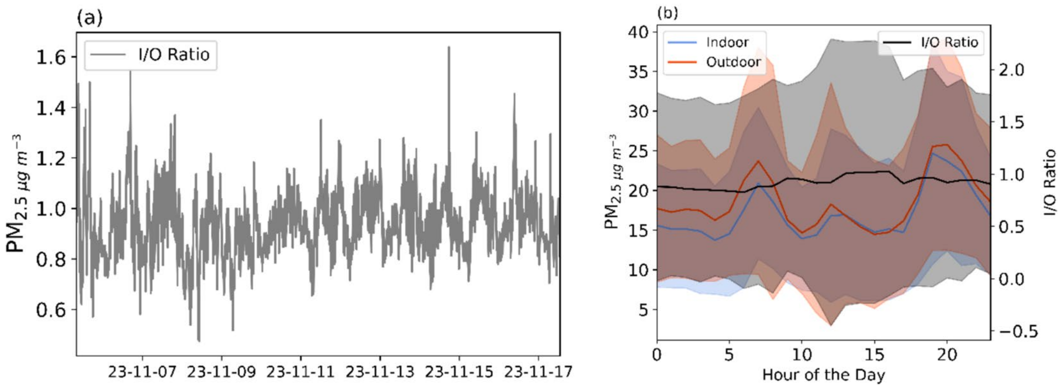

Fig. 4 The I/O ratio for all households. **a** Time series (5-min average) over the campaign **b** diurnal cycle illustrating I/O ratio, indoor and outdoor $PM_{2.5}$ (hourly averaged) measurements

during times of high indoor activity in the morning (between 6 and 8 am), leading to an I/O ratio of 0.88. Similarly, both indoor and outdoor $PM_{2.5}$ levels were high, 23.7 and 25.5 μg m^{-3}, respectively, during times of high indoor activity in the evening (between 6 and 8 pm), leading to an I/O ratio of 0.96. An I/O ratio close to 1 implies indoor activity produce enhancements in indoor $PM_{2.5}$ levels during high indoor activity period. However, during inactive periods (10 pm–5 am), we observed a decrease indoor $PM_{2.5}$ concentrations (15.1 μg m^{-3}) and an I/O ratio (0.86). This implied a more subdued response from indoor generated sources during inactive periods.

Stamp et al., (2022) investigated I/O ratios of UK apartments in the UK and reported a median I/O ratio for $PM_{2.5}$ of 0.65 when apartments were well ventilated (that is windows left open). Nadali et al., (2020), focussing on 20 building in Qom, Iran, reported $PM_{2.5}$ I/O ratios ranging 0.71–0.93. In this study, we found a median $PM_{2.5}$ I/O ratio of 0.93 which ranged from 0.63 to 1.32. Our study shows approximately 42% of the residences had an I/O ratio above 1.0, from a moderately sized sample, indicating indoor $PM_{2.5}$ is higher than outdoors. Households with I/O ratios exceeding 1 indicates higher levels of indoor pollution compared to outdoors. Elevated indoor $PM_{2.5}$ concentrations may arise from indoor sources such as cooking methods (e.g. frying and grilling), use of candles and incense, air fresheners and cleaning products (Chu et al. 2021; Radbel et al. 2024). This can further be exacerbated by insufficient ventilation, potentially resulting from infrequent window opening. All participating houses had natural ventilation with windows open and shut at intervals and none of the residents reported being smokers. Site observations in these houses had varying flooring types; concrete floors, tiles and some had floors covered with rugs. Other observations include faulty louvers for example in house D, which had old stiff windows, and this may hinder proper ventilation. House D also had rug laid over a concrete floor. In this case cleaning processes such as sweeping of the rugs can result in dust resuspension.

Aside from the I/O ratio, Chen and Zhao et al., (2011) reported other methods of quantifying the relationship between indoor and outdoor particulate abundances. An example is the infiltration factor, which represents the equilibrium fraction of outdoor particles that penetrate indoors and remain suspended in the building, and this varies tremendously from one building to another. The PM size, chemical components, ventilation rate, human behaviour, such as how frequently windows and doors are open and the use of air filter and cleaners, type of heating, lightning, ventilation type and air conditioning system are all primary drivers of variability in infiltration factors. Thus, it would be useful to get more detailed information from the participants to accurately understand the relationship between indoor and outdoor PM for each household.

3.2 Phase II: PurpleAir Sensors

3.2.1 *PurpleAir $PM_{2.5}$ Measurements*

Time series of 24-h mean $PM_{2.5}$ concentrations are shown in Fig. 5. Higher PM concentrations were seen in late December, January, and mid-February for all locations. This time of year (December-mid March) coincides with the dry harmattan season, when the air temperature is increased, and humidity is decreased. The dry harmattan season is also characterised by northeasterly winds which transport dust from the Saharan desert over West Africa. (Ayanlade et al. 2019) reported significant monthly variation in the distribution of aerosol optical depth (AOD) over Nigeria using Moderate resolution Imaging Spectroradiometer (MODIS) and the intensity is noticeably greater during harmattan season than the wet season in the Northern part of the country. We find elevated in-situ measurements of $PM_{2.5}$ during the dry

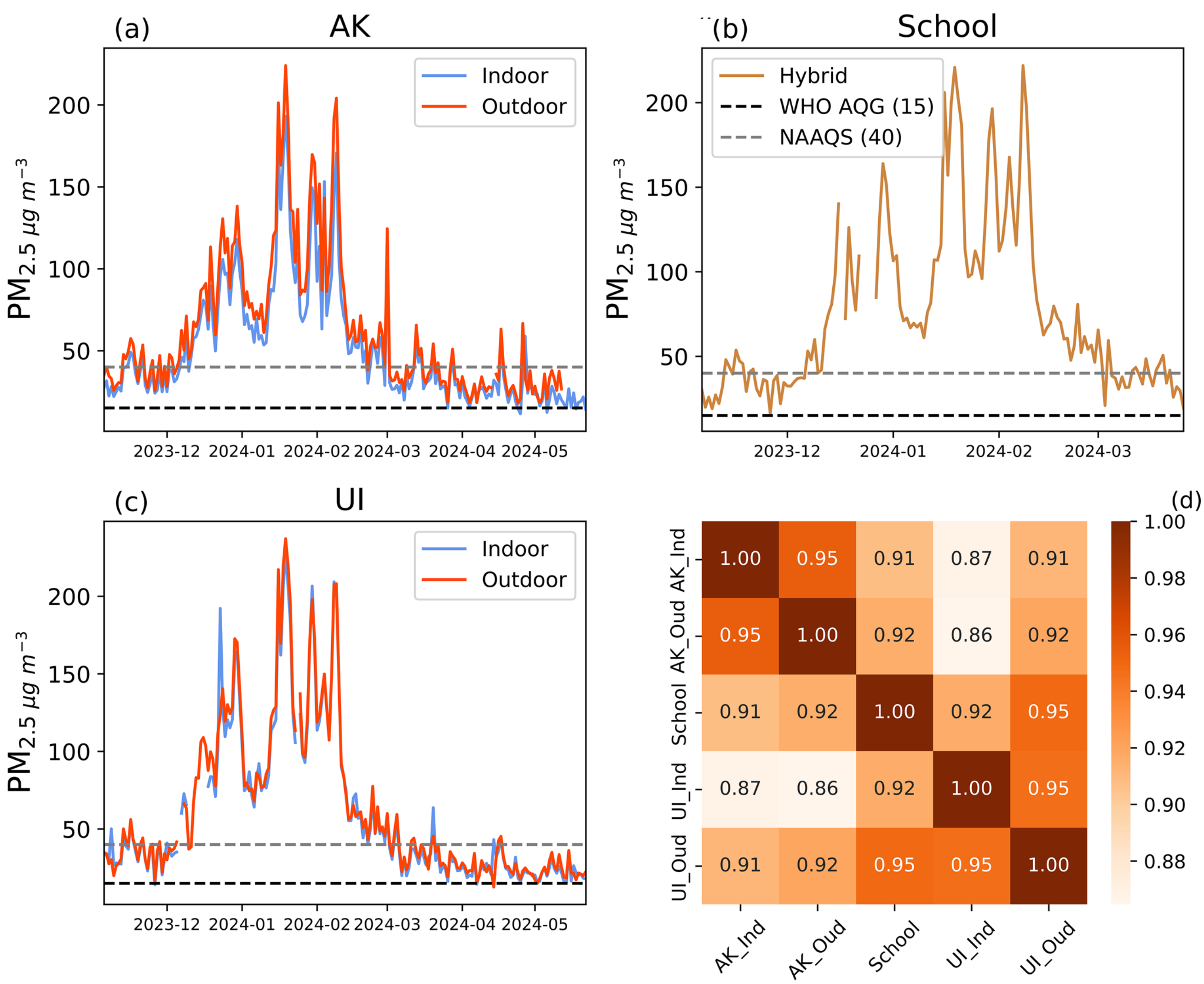

Fig. 5 **a–c** Time series showing daily averages of PurpleAir $PM_{2.5}$ data throughout the entire study period and highlighting WHO AQG and National Ambient Air Quality Standards (NAAQS) **d** Pearson's coefficient of correlation (r) for all study sites

harmattan period are also present in our study region in the south-western part of Nigeria.

House "AK" recorded daily averaged $PM_{2.5}$ values as high as 193 μg m^{-3} and 224 μg m^{-3} for indoors and outdoors measurements, respectively. Similarly high values were recorded for House "UI" which recorded daily averaged $PM_{2.5}$ value as high as 228 μg m^{-3} and 237 μg m^{-3} for indoors and outdoors respectively. The school sensor which is in a hybrid environment also recorded similarly high value of $PM_{2.5}$ of 152 μg m^{-3}. There was strong correlation ($r > 0.9$) of the school data and the indoor and outdoor measurements at both houses indicating outdoor $PM_{2.5}$ is a substantial contributor to indoor $PM_{2.5}$, as shown in Fig. 5d. Both outdoor and indoor $PM_{2.5}$ exceeded recommended 24-h WHO AQG of 15 μg m^{-3}. It also exceeded NAAQS of 24-h recommended limit of 40 μg m^{-3} for outdoor measurements (NESREA 2021). The WHO Interim target IT-1 (75 μg m^{-3}) was also exceeded during the dry harmattan period indicating very unhealthy levels of $PM_{2.5}$ exposure.

Outdoor and indoor $PM_{2.5}$ concentrations throughout the entire study were also investigated. Houses AK and UI recorded median outdoor $PM_{2.5}$ concentrations of 43.2 and 39.8 μg m^{-3} respectively while the indoor levels for recorded median $PM_{2.5}$ concentrations of 39.2 and 37.4 μg m^{-3}, respectively. The school hybrid environment had a median $PM_{2.5}$ concentration of 42.3 μg m^{-3}. Figure 6a demonstrates the variation in the monthly $PM_{2.5}$ distribution. For both houses, there was higher median average $PM_{2.5}$ concentration during the dry harmattan season, which peaks in January with daily averaged median $PM_{2.5}$ concentrations as high as 98.0 and 109.3 μg m^{-3} for indoor and outdoor environments, respectively. The lowest $PM_{2.5}$ concentrations were recorded in May with a peak daily median $PM_{2.5}$ concentrations of 21.4 and 24.5 μg m^{-3} for indoor and outdoor levels,

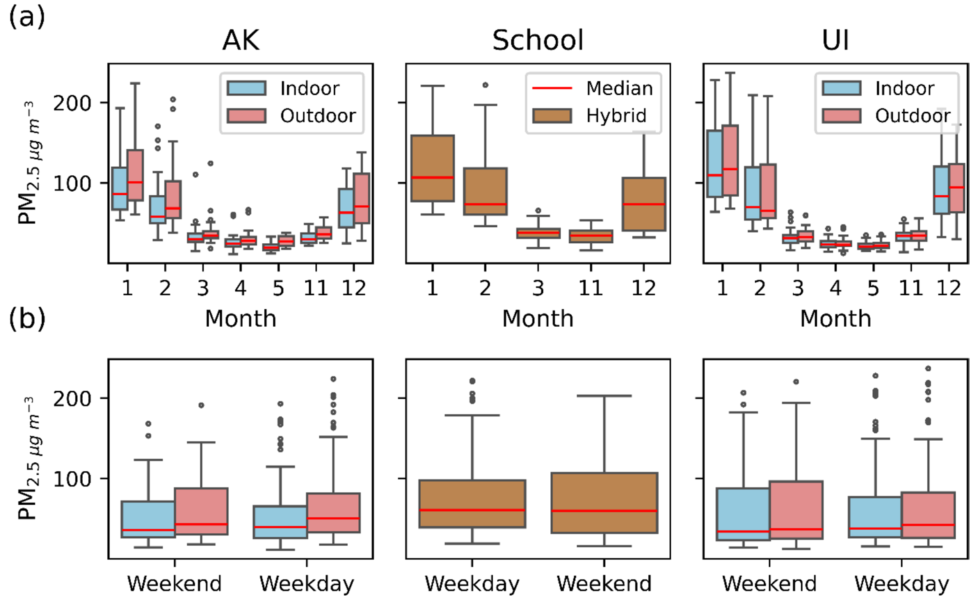

Fig. 6 **a** Diurnal variation of daily averages of PurpleAir $PM_{2.5}$ data throughout the entire study period, which spans months 11 and 12 of year 2023 and months 1–5 of year 2024. **b** Indoor and outdoor $PM_{2.5}$ concentrations comparing weekdays and weekend

respectively. The school hybrid environment also showed the highest median $PM_{2.5}$ concentration of 73.6 µg m^{-3} in January.

The $PM_{2.5}$ concentrations during the weekend and weekdays were also compared, shown in Fig. 6b. House AK recorded a higher outdoor $PM_{2.5}$ median concentration during the weekdays (50.4 µg m^{-3}) in comparison with the weekends (42.9 µg m^{-3}). House UI also had a slightly higher outdoor median value during the weekdays (37.8 µg m^{-3}) in comparison with the weekends (37.0 µg m^{-3}). For indoor $PM_{2.5}$ concentrations, House AK recorded higher indoor median value during the weekdays (39.6 µg m^{-3}) in comparison with the weekends (36.0 µg m^{-3}) while house UI also recorded higher indoor median value during the weekdays (37.8 µg m^{-3}) in comparison with the weekends (33.9 µg m^{-3}). In general, both houses recorded slightly higher indoor and outdoor $PM_{2.5}$ concentrations during weekdays in comparison with weekends. School hybrid environments however, showed weekday and weekend $PM_{2.5}$ median values of 46.0 and 46.5 µg m^{-3}, respectively. The school is partly boarding and partly day-schooling, indicating that the human occupancy/activities in the school's reception lobby are also high on weekends. Although, highest $PM_{2.5}$ values recorded during weekday was 229.3 µg m^{-3} while the highest $PM_{2.5}$ values recorded during the weekend was 221.1 µg m^{-3}.

3.2.2 Indoor/Outdoor Relationship (PurpleAir sensors)

The relationship between outdoor and indoor measured $PM_{2.5}$ concentrations for the longer monitoring period was investigated using the I/O ratio. House AK had a $PM_{2.5}$ I/O ratio of 0.87, indicating outdoor $PM_{2.5}$ concentrations are higher than the indoor $PM_{2.5}$ concentrations. House UI recorded an average I/O ratio of 0.97, implying indoor $PM_{2.5}$ concentrations are more similar to outdoor $PM_{2.5}$ concentrations. As both houses are naturally ventilated, linear regression was conducted to further examine the relationship between indoor and outdoor $PM_{2.5}$ concentration in both households. The value of the coefficient of determination (R^2) between the indoor and outdoor $PM_{2.5}$ concentrations was calculated to investigate the proportion of variance in the indoor $PM_{2.5}$ concentrations that can be explained by the variance in the outdoor $PM_{2.5}$ concentrations as shown in Fig. 7. Here, the R^2 value for both houses were both 0.9. Therefore, a substantial proportion of the variability in indoor $PM_{2.5}$ concentrations is linked to temporal evolution in outdoor $PM_{2.5}$ concentrations. Here, large scale controls on outdoor $PM_{2.5}$ concentrations (for example, seasonality, synoptic weather/transport, or regional sources) may be influencing the measured indoor concentrations. That is, via outdoor infiltration of outdoor $PM_{2.5}$ into the indoor environment and dominating over indoor sources of $PM_{2.5}$. Other factors contributing to the remaining indoor variability of 9% and 10% are indoor $PM_{2.5}$ sources, potentially include cooking activities, use of candles and incense, household cleaning products, dust resuspension, building materials, inadequate ventilation, mould and mildew and other indoor anthropogenic activities.

4 Conclusion

We conducted indoor and outdoor $PM_{2.5}$ measurements in Ibadan, Nigeria where there is a lack of continuous in-situ monitoring infrastructure. Measurement is an essential first

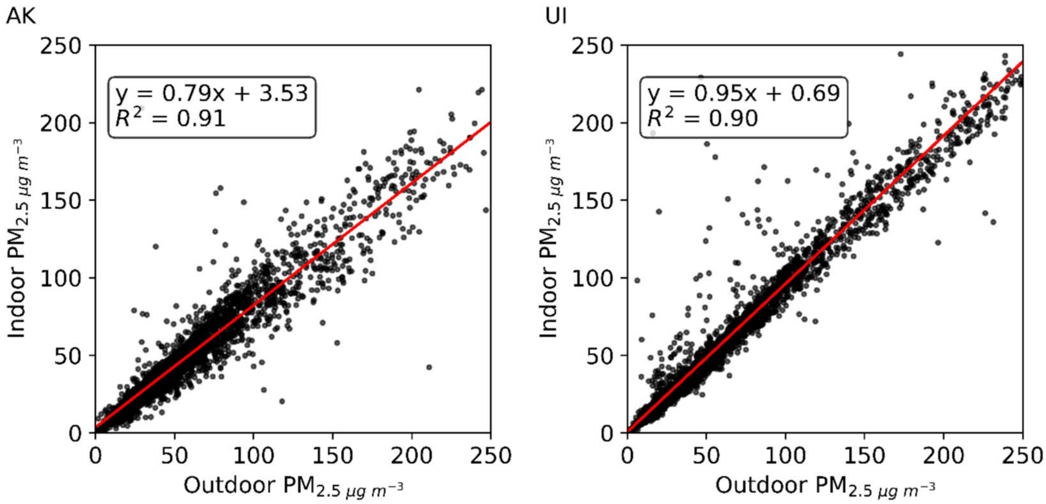

Fig. 7 Indoor-Outdoor relationship showing coefficient of determination (R^2) using hourly averaged $PM_{2.5}$ data for the PurpleAir sensor data

step in establishing baseline data for air quality studies, understanding, and reducing the public health impact of air pollution. This study recorded indoor and outdoor $PM_{2.5}$ concentrations of 15.0 and 16.1 µg m^{-3}, respectively during the short-term (2-week) monitoring period. The extended monitoring period (7-month) recorded higher concentrations, with indoor, outdoor and hybrid concentrations averaging 38.3, 41.5 and 42. 3 µg m^{-3} respectively. The elevated $PM_{2.5}$ concentrations observed in the extended study were largely driven by increased $PM_{2.5}$ concentrations during the dry harmattan season (i.e. transport of desert dust). Overall, the indoor-outdoor relationships showed median $PM_{2.5}$ I/O ratio of 0.93. A strong temporal correlation ($R^2 > 0.9$) was observed between indoor and outdoor $PM_{2.5}$ concentrations indicating synchronized variability driven by ambient conditions. $PM_{2.5}$ concentrations were also higher during the weekdays, in comparison to weekends. Despite the limitation in validating the accuracy of the low-cost $PM_{2.5}$ sensors used in this study, such validation was constrained by the absence of regulatory or reference-grade monitors within the study area or in nearby locations within the country. Our study has generated in-situ air quality data in a city where no continuous monitoring had previously been conducted over an extended period. This work highlights the urgent need for regulatory reference-grade monitors in Nigeria for ground air quality measurements and to assist with low-cost sensor data validation. Future study aims to include the estimation of indoor-generated emissions, documenting indoor activities of the participants using a survey, and conduct year-long monitoring period to assess how meteorological factors influence ambient $PM_{2.5}$ levels.

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Author contributions Conceptualisation—AS, Methodology—AS, RP, JM, KP, SA and GA, Data collection—AS and HS, Software—AS, Data analysis and visualisation – AS, Writing (Original draft preparation)—AS, Writing (Review and Editing)—AS, RP, AG, GA, KP, SA, and JM. All authors have read and contributed to the manuscript.

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Data availability Data from low-cost Atmotube Pro and Purple Air sensors used for the analysis have been uploaded to Zenodo and can be accessed via https://doi.org/10.5281/zenodo.14025023.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics Approval Ethics approval for the study was obtained from the University College Hospital/University of Ibadan Research Ethics Committee (UCHREC). Ethical approval from the University of Leeds Ethics Committee was also granted.

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