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# Schoolchildren's personal exposure to ultrafine particles in and near Accra, Ghana

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ABSTRACT

Exposure to air pollution is a significant health risk, and children who are exposed to it are likely to have lifelong consequences. Ultrafine particles (UFPs) are emitted by all combustion sources, and can be used as a proxy for the presence of combustion products. The present study, the first of its kind to be conducted in Africa, assessed schoolchildren's exposure to UFPs, and apportioned their daily exposure to seven different microenvironments that they inhabited on a typical school day. The personal exposure of 61 pupils attending three junior high schools was measured for 24 h each using wearable monitors over a period of 10 weeks. Two of the schools were located in suburbs of Accra and the third in Berekuso, a nearby rural community. The results of our study revealed the complex nature of children's UFP exposure and its overall high to very high levels, significantly influenced by the locality (suburb) of residence and the type of activities in which the children were engaged. The mean (±standard error) daily exposure to UFPs ($cm^{-3}$) was$6.9 \times 10^4 (\pm 6.8 \times 10^3)$, $4.9 (\pm 1.0) \times 10^4$ and $1.6 \times 10^4 (\pm 1.9 \times 10^3)$for pupils attending the Ashia Mills, Faith Baptist and Berekuso Basic Schools, respectively. Pupils attending the schools in urban Accra received higher exposure than those attending the school in the rural environment of Berekuso. The highest mean microenvironmental exposure was registered in the *Home other* microenvironment in an urban school and in *Bedroom* in another urban school and the rural school. The high exposure in *Home other* was due to pupils conducting trash burning and encountering environmental tobacco smoke, and the high exposure in *Bedroom* microenvironment was due to the burning of mosquito coils at night to prevent malaria. The principal sources that heightened exposure to UFPs were emissions from cooking (using firewood and charcoal), vehicular traffic and combustion of biomass and trash. All pupils recorded the highest exposure intensity in the *Kitchen* microenvironment.

## 1. Introduction

According to the World Health Organization (WHO, 2016b), 92% of the world's population live in places where air quality levels exceed recommended limits. It is estimated that over 5.5 million premature deaths per year globally, are caused by poor air quality (Landrigan et al., 2018; Brauer et al., 2016). The economic cost of urban air pollution is projected to amount to 2% of gross domestic product (GDP) in advanced countries, and 5% of GDP in low-income countries (Lanzi et al., 2018). The health, environmental and economic consequences of urban air pollution are more severe in low-income countries than in advanced countries (Cohen et al., 2017; Petkova et al., 2013).

Personal exposure, a critical determinant of health risk, is quantitatively expressed as the product of the concentration of a specific pollutant and the duration (time) of contact with the pollutant (Morawska et al., 2013; Koehler and Peters, 2015; Lioy and Weisel, 2014). People are exposed to different levels of pollutants in different urban microenvironments such as in homes, offices, schools, recreational grounds and on roads during commutes. Quantifying and characterizing people's exposure to air pollutants with respect to time and space in urban microenvironments significantly aids health risk assessment and policymaking (Koehler and Peters, 2015).

A number of methods are applied to quantify personal exposure to air pollution (Koehler and Peters, 2015; Arku et al., 2015; Steinle et al., 2013). These include the use of pollutant concentration data collected from airshed, combined with time-activity dairies (TAD) and

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questionnaires to estimate respondents' exposure, and the application of wearable personal monitoring devices with or without GPS receivers along with TAD to estimate subjects' personal exposure (Ferrero et al., 2017; Steinle et al., 2015). Quantifying personal exposure in urban microenvironments is challenging, particularly in low-income countries where few resources are allocated to air quality research.

Ghana is a low-income country in Africa with a high burden of disease attributable to ambient particulate matter pollution (WHO, 2016a). Records of the Ministry of Transport in Ghana indicate that the average age of a vehicle in Ghana is 14.2 years, meaning that many vehicles in use in the capital city of Ghana (Accra), are old and therefore, less fuel-efficient. The National Petroleum Authority of Ghana reports that, as of July 2017, the sulfur content in diesel in Ghana was 3000 ppm, much higher than the allowed limit of 15 ppm in advanced countries such as the USA. Some communities in Accra are known to be characterized by poor environmental practices such as open burning of trash (Rooney et al., 2012; Arku et al., 2015). Large numbers of old vehicles, high sulfur content in diesel fuel, and anthropogenic activities such as open burning of trash bring about increased particulate matter pollution (Ristovski et al., 2006; HEI, 2010; Kelly and Fussell, 2012).

Ultrafine particles (UFPs, < 0.1 μm) have a higher number of particles per volume of air and higher deposition efficiency than larger particles. UFPs are potentially more toxic than larger particles because they have greater surface area and penetrate more deeply into the respiratory tract (Goel et al., 2016; Oberdörster, 2004). Epidemiological studies have linked exposure to UFPs to increased risk of neurodevelopmental and cognitive disorders (Ohlwein et al., 2019). Despite their potential high toxicity, UFPs in urban microenvironments are less studied, particularly in African countries, as most of the studies have tended to focus on particle mass concentration, and so literature relating to studies on personal exposure to UFPs in African cities is non-existent.

Relative to adults, children experience more severe health consequences from exposure to UFPs because they are still developing, and also inhale more air relative to the size of their lungs (Clifford et al., 2018; Heinzerling et al., 2016; Burtscher and Schüepp, 2012). Although children's exposure to UFPs occurs in different microenvironments as they go about their day, the school is a critical environment that contributes to children's daily exposure because they spend a considerable amount of time there (Mazaheri et al., 2014; Mejía et al., 2011). Assessing children's exposure to UFPs is challenging because of the unique time-activity patterns children have, coupled with the high spatial variability associated with UFPs. Studies on children's exposure to UFPs have mainly been conducted in high-income countries, most of which focused on traffic-related sources (Buonanno et al., 2012; Mazaheri et al., 2014; Mazaheri et al., 2016; Ferrero et al., 2017). No study has investigated children's exposure to UFPs in Africa (Branco et al., 2014). It is important that children's exposure to UFPs is monitored in order to inform intervention strategies (Burtscher and Schüepp, 2012; Branco et al., 2014).

The Environmental Protection Agency (EPA) of Ghana has a few sparsely distributed monitoring stations in and around Accra. Because air pollutant concentrations in urban microenvironments vary spatiotemporally, the EPA's data lacks the measurement density required for it to be used in estimating personal exposure to air pollution of residents in Accra. The very few personal exposure studies conducted in Accra, investigated exposure to particle mass concentration (Arku et al., 2015; Zhou et al., 2011). To date, no study quantifying and characterizing children's exposure to UFPs has ever been conducted in Ghana.

In view of the existing research gaps, this study aimed to characterize and quantitatively assess the personal exposure to UFPs of a sensitive population group – school children in and near Accra – with a view to apportioning daily exposure to different microenvironments and identifying factors that drive personal exposure to UFPs in the microenvironments.

## 2. Materials and methods

### 2.1. Study design

Personal exposure measurements were carried out on 61 school children attending three junior high schools. The measurements were conducted on weekdays over a period of 10 weeks between October and December 2017. Prior to the start of the measurements, the schools were visited, and presentations were made to the teachers, pupils and parents to explain the aims and benefits of the study, and to request participation. The study was approved by the Ethical Review Committee of the Radiological and Medical Sciences Research Institute at the Ghana Atomic Energy Commission (GAEC) in Accra, Ghana (approval no.: RAMSRI-ERC-PHD/002/16) and the Office of Research Ethics and Integrity at the Queensland University of Technology (reference no.: 1700000324), Brisbane, Australia.

### 2.2. Study locations and population

The three schools (S1, S2, and S3) were located in suburbs characterized by diverse socioeconomic, demographic, land use, traffic, and urbanization conditions. Two of the schools, S1 and S3, were located in suburbs of Accra, and the third school, S2, was located in Berekuso, a rural community near Accra. The locations of the schools are shown on the map presented in Fig. 1.

- S1 is the Faith Baptist Community School Complex located near the heavily trafficked Accra-Aburi highway in Madina, a commercial hub and a suburb of Accra. Madina is a densely populated low-to-middle-income community, with a lot of street vending and other commercial activities. Charcoal and LPG are the cooking fuels used in most homes in the community. S1 is a private school walled around a compound of long single-storey, 3-storey and 4-storey buildings. The schoolyard is partially paved with a rectangular playing field situated in the middle. School hours are 7:30 to 15:00. The school runs a bus service that transports some pupils to and from their homes on school days. GPS coordinates of the school site are latitude 5.677853 (5° 40′ 40.27″ N) and longitude −0.173621 (0°10′ 25.04″ W).
- S2 is the Presbyterian Basic School located in Berekuso, a sparsely populated rural community 23 km away from the central business district of Accra, with a single untarred road passing through it. Farming and petty trading are the major economic activities in the community, where the economic status of the majority of the residents is low-income. Most homes in the community use firewood and charcoal as cooking fuels. The school is a public one with two parallel single-storey buildings on its compound. The schoolyard is grassed and dotted with trees. School hours are 7:30 to 14:30. The GPS coordinates of the school are latitude 5.753431 (5° 45′ 12.35″ N) and longitude −0.230933 (0° 13′ 51.36″ W).
- S3 is the Ashia Mills Basic School in the Ayalolo cluster of schools located in the heart of the city of Accra, near the bustling urban Agbogbloshie Market, and close to a scrapyard where e-waste (discarded electronic devices) and car tires are recycled through open burning by scrap-metal scavengers. Trading and commercial activities at the market take place on all weekdays and on Saturdays. The community is characterized by slums, and the economic status of the residents ranges from low to middle-income. Firewood, charcoal and LPG are used as household cooking fuels. The school is a public one, with a cluster of single-storey buildings on its compound. The schoolyard is unpaved and is dotted with trees. School hours are 7:30 to 14:30. The GPS coordinates of the school are latitude 5.547005 (5° 32′ 49.22″ N) and longitude −0.217376 (0°13′ 2.55″ W).

Pupils aged 11–16 were recruited to participate in the study with

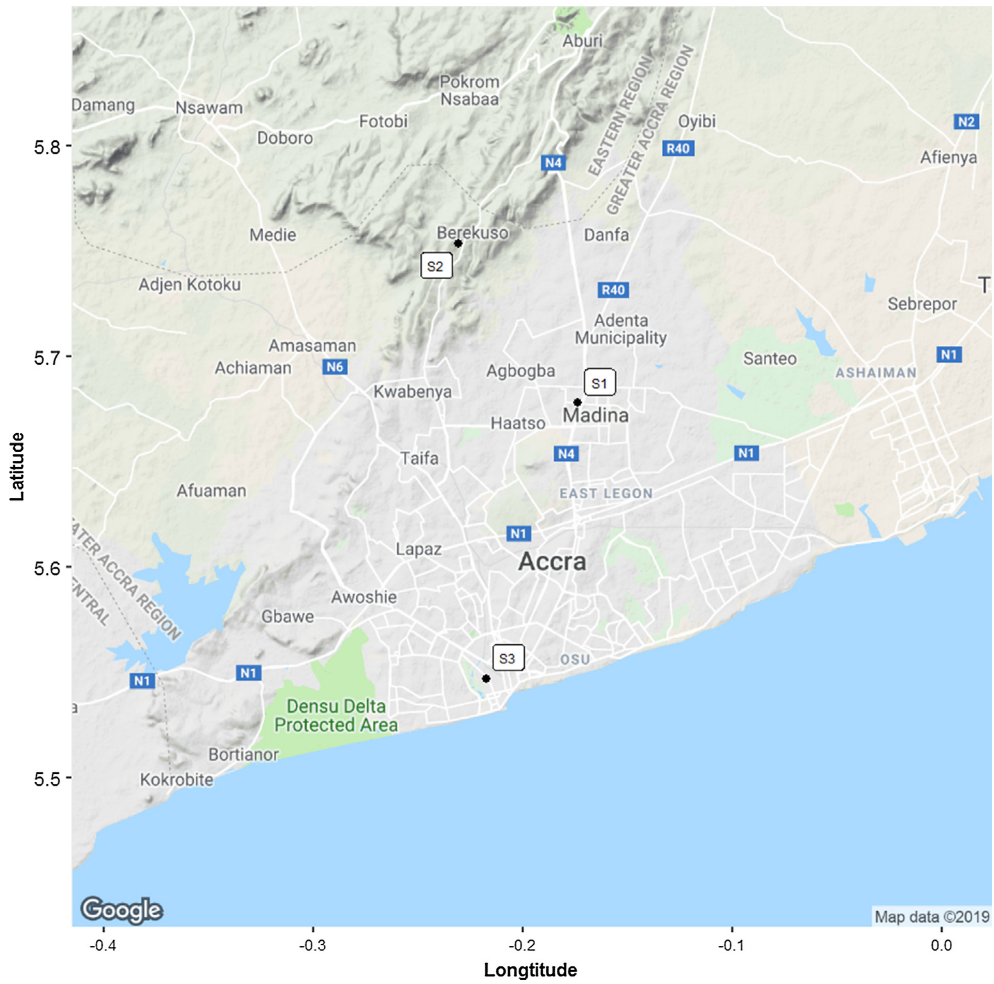


**Fig. 1.** Map of the study area showing the locations of the schools and the suburbs.

the help of their school teachers. School children in this age bracket were recruited because: i) they could be instructed on the handling and operation of the instrument used for the study; and ii) they could be trusted with the proper handling of the instrument to generate reliable data. The criteria for selection of a school child to participate in the study was the willingness to take part in the study voluntarily and competence in instrument handling. Written consents were obtained from parents and children.

Most families in the study area prepare two meals on weekdays, in the morning (between 05:00 and 07:00) and in the evening (between 17:00 and 20:00). Open burning of trash is a common practice in the study area. Some level (3.8%) of tobacco smoking is reported among the adult population in Ghana (Owusu-Dabo et al., 2009). Many households in the low-income bracket, burn mosquito coils at night as a means of keeping mosquitos out of their bedrooms. The conventional mode of transport in and around Accra is by vehicular transport, which is the reason for high vehicular traffic during rush hours. The city experiences three rush-hour periods on weekdays. The morning rush hour is from 6:00 to 9:30, when people leave home for work, the lunch-time rush hour occurs in the afternoon between 12:30 to 14:00, and the evening rush hour is from 16:30 to 20:30, when people leave work for home. On some weekdays, especially Fridays, the lunch-time rush hour extends over to the evening rush hour.

### *2.3. Instrumentation and quality assurance*

Three Aerasense NanoTracers (NT Model PNT1000; Philips, The Netherlands) were used to conduct the measurements. The NT is a 0.75 kg battery-operated hand-held device that measures particle number concentrations (PNC) up to $1 \times 10^6$ cm$^{-3}$ in the size range of 10–300 nm (Fig. A1). The device also measures mean particle diameter in the size range of 20–120 nm. The NT has a 7-h battery life and a 7-h charging time and operates in two modes: fast mode and advanced mode. The fast mode has user adjustable sampling times down to 3 s, but reports measurements only in PNC, while the advanced mode has a 16 s sampling time and reports measurements in both PNC and mean particle diameter. In this study, the NTs were operated in the advanced mode. The NT offers advantages over many other instruments for personal exposure monitoring because it is portable, compact, wearable, and can be used for continuous measurements. The ability of the NT to measure both PNC and mean particle diameter offers it a great utility.

For the purpose of data quality assurance, prior to their use in the study, the NTs were tested in the International Laboratory for Air Quality and Health (ILAQH), Queensland University of Technology (ILAQH, QUT), in Brisbane, Australia, by benchmarking them with a more advanced instrument, the condensation particle counter (CPC, Model 3025A; TSI). An intercomparison was done in: i) a clean mechanically-ventilated laboratory at ILAQH; and ii) on the fifth level balcony of a 5-storey building characterized by urban ambient particles. The NTs and the CPC were co-located and run continuously for 7 h in each case. The mean PNC of the three NTs were $2.14 \times 10^3$, $2.81 \times 10^3$ and $2.84 \times 10^3$ for the laboratory environment and $1.26 \times 10^4$, $1.23 \times 10^4$ and $1.46 \times 10^4$ for the urban ambient environment, respectively. The NTs readings correlated very well with each other ($0.75 \leq r \geq 0.91$). Correction factor, defined as ratio of mean PNC of CPC to mean PNC of NT, was determined for each NT. These results were used to assess the performance of the NTs against each other and to confirm whether readings from the NTs were similar. This approach was adopted because no standard reference PNC counter was available for use in Accra, bearing in mind that UFP concentrations and size distribution in Brisbane, a city in a developed country, are not the same as in Accra, a city in a low-income country.

### 2.4. Data collection

Before commencing the measurements, each participant was trained on how to handle and charge the NT and was requested to demonstrate the process. The pupils who showed competence in the task were those enrolled for the study. The internal clocks of the NTs were synchronized to the local time in Accra.

The personal exposure of each participating pupil was measured for 24 h as they spent their time in different microenvironments. The NT was kept in their proximity while the participants were asleep at home, washing down, charging it in the classroom, and playing in the school playground. It was worn over the waist, with the sample inlet tube attached to the breathing zone while the participants were commuting to and from school. The participants were instructed to place the NTs on charge overnight at home and while in the classroom during the day to ensure the battery would not run out. They were also instructed to record their activities during the sampling period, including time spent in different microenvironments such as in the classroom, bedroom, living room, kitchen, on playground, and in daily commute, by indicating the start and end times for each activity in the TAD provided to them. The 24-h measurements of each participant commenced in the afternoon and ended in the afternoon of the following day. Data from the NT were downloaded after it was retrieved from participants. Each week's measurements were conducted for four days (starting from Monday afternoon to Friday afternoon). A stepwise approach of completing measurements in one school before moving to the next school was adopted. The measurement were conducted for five weeks in S1, three weeks in S2 and two weeks in S3.

### 2.5. Data description and analysis

In all, 61 schoolchildren participated in the study. Each participant's data were checked for completeness and processed into a single time-stamped dataset. The 24-h exposure profiles of all participants were plotted and examined to identify missing data, times with high exposure and possible reasons for the high exposure. Only 22 participants had complete 24-h data. Although the pupils showed somewhat positive attitudes towards participating in the study, their compliance with the study protocol was poor, and their interest in science was lukewarm. As a result, a number of them did not complete their TAD properly. 23 participants did not return their TAD because they were misplaced. Of the 38 who returned their TADs, only 6 had entries for the 24-h period of measurement, the rest of them had missing spaces in their TADs. To ensure that the required information of all the participants was adequately captured by the research team, the teachers were relied on to provide time-location information on the participants during school hours, to complement the information recorded in the TAD. Based on this information, the microenvironments the participants inhabited during the 24-h were determined and the duration spent in the microenvironments was estimated (Table 3). The mean UFP concentration apportioned to each microenvironment was calculated, based on which, the time-weighted exposure was also computed for the 22 participants with complete 24-h data using Eq. (1). Each participant's exposure in the microenvironments was summed over 24-h to determine daily exposure to UFPs.

$$E_i = \sum_{j=1}^{n} \bar{C}_{ij} t_{ij} \tag{1}$$

where $E_i$ is the time-weighted exposure of participant $i$ in microenvironment $j$, $\bar{C}ij$ is the average UFP concentration of participant $i$ in microenvironment $j$, $t_{ij}$is the fraction of time participant $i$ spent in microenvironment $j$, and $n$ is the number of times that participant $i$ resided in microenvironment $j$ during the 24-h period.

The exposure intensity of each microenvironment was calculated for each participant using Eq. (2) (Buonanno et al., 2012; Mazaheri et al., 2014).

$$Exposure \quad intensity = \frac{Mean \ \ exposure \ \ in \ \ microenvironment}{Mean \ \ exposure \ \ of \ \ the \ \ day} \tag{2}$$

## 3. Results

Out of the 61 schoolchildren who participated in the study, 33 were in S1, 18 in S2, and 10 in S3. There were 34 boys (56%) and 27 girls (44%). Of all the participants, 23 did not return their TADs because they misplaced them. Of those who returned their TAD, 36 had missing spaces in their TAD, which implied that they did not provide activities to cover the entire 24-h period of measurement. Due to lack of access to power and failure to put the NT on to charge as instructed, 40 participants (64%) had some values missing in their continuous minute-by-minute data. This included 19 pupils from S1, 13 from S2, and 7 from S3. Table 1 presents a summary of the demographic characteristics of the study population.

### 3.1. Activities in microenvironments

Based on the information provided by the teachers and that contained in the TADs, a typical time-space-activities pattern was developed for all the participants including those who did not return their TAD. The participants' 24-h period was split into microenvironments, activities, and average times spent in each microenvironment. It was found that the participants spent their time in seven distinct microenvironments, which we termed: *Bedroom*, *Classroom*, *Commute*, *Home other, Kitchen*, *Living room* and *School outdoor,* undertaking different activities. Table 2 presents a summary of the seven microenvironments, with typical activities undertaken and approximate times spent in each microenvironment.

The participants spent a large fraction of their time at home (average of 15.2–15.7 h, representing 63.3–65.4%). These numbers refer to the average times spent by a participant. The average times varied between participants and what is given is the range of values. At home, the pupils were engaged in a variety of activities in the different home microenvironments. The participants spent approximately 2 h (8.3% of their time) in the *Kitchen* microenvironment cooking and eating, which generally occurred between 05:00 and 06:00 in the morning and 18:00 and 19:00 in the evening. The participants typically went to bed at 21:30 in the evening and woke up at 05:00 in the morning, which means that on average, they spent 7.5 h (31.3% of their time) in the *Bedroom* sleeping. Most participants spent approximately 2.5 h (10.4% of their time) in the *Living room* microenvironment studying, relaxing, and watching TV. The rest of the participants' time at home was spent in the *Home other* microenvironment carrying out household chores and engaging in social activities. Common household chores of Ghanaian children include cleaning, sweeping, trash clearing (which may include trash burning) and running errands. Their social activities include attending evening prayer services and visiting extended family members.

Pupils in all the schools reported to school at 07:30 in the morning and spent between 07:30 and 07:55 tidying-up the school grounds and attending morning assembly (on Mondays, Wednesdays and Fridays), or morning devotion (on Tuesdays and Thursdays). The first lesson in the morning commences at 08:00 on all weekdays in all the schools. The first (long) and the second (short) break are taken from 09:50 to 10:20 and 12:45 to 13:10 respectively in all the schools. S1 closes at

**Table 1**
Summary of demographic characteristics of the study population. The participant's mode of transport, commute time, housing characteristic, cooking fuel, time of cooking morning and evening meals and socioeconomic status were obtained through questionnaires and interviews.

| Characteristic | School | | |
|---|---|---|---|
| | S1 (n = 33) Urban | S2 (n = 18) Rural | S3 (n = 10) Urban |
| | % | % | % |
| *Sex* | | | |
| Boys | 58 | 44 | 70 |
| Girls | 42 | 56 | 30 |
| *Mean age* | | | |
| Boys | 13 | 14 | 15 |
| Girls | 13 | 14 | 15 |
| *Mode of commute to school* | | | |
| Walking | 49 | 83 | 100 |
| Private vehicle | 15 | – | – |
| Public bus | 30 | 17 | – |
| School bus | 6 | – | – |
| *Commuting time* | | | |
| < 20 min | 28 | – | – |
| 20–40 min | 48 | 100 | 100 |
| 41–60 min | 18 | – | |
| > 60 min | 6 | – | – |
| *House type* | | | |
| Multi-storey | 9 | – | 20 |
| Flat | 9 | – | – |
| Self-contained | 36 | 6 | 20 |
| Compound | 46 | 94 | 10 |
| Single room | – | – | 50 |
| *Courtyard* | | | |
| Paved/cemented | 79 | 50 | 60 |
| Unpaved | 15 | 50 | 40 |
| Grassed | 6 | – | – |
| *Cooking fuel* | | | |
| LPG | 79 | 28 | – |
| Charcoal | 3 | 33 | 80 |
| LPG and charcoal | 18 | 28 | 20 |
| Firewood | – | 11 | – |
| *Socio-economic status* | | | |
| Middle class | 73 | – | 10 |
| Lower class | 27 | 100 | 90 |
| *Hours monitored* | | | |
| Min | 4 | 2 | 2 |
| Median | 7 | 4 | 5 |
| Max | 24 | 24 | 23 |

15:00, while S2 and S3 close at 14:30. When school closes, the pupils take between 15 and 20 min to disperse from the school environment. On a typical school day, pupils in S1 spent 7 h and 50 min (32.6% of their time) at school, while those in S2 and S3 spent 7 h and 20 min (30.5% of their time) at school. Pupils in S1 spent 6 h and 5 min (25.35% of their time) in the classroom and those in S2 and S3 spent 5 h and 35 min (22.9% of their time) in the classroom. All the pupils spent 1 h and 45 min (7.3% of their time) in the *School outdoor* microenvironment.

Approximately 94% of the participants spent up to one hour, which is 4.2% of their time, in the active commute from home to school and back (Table 1). Most pupils left home for school between the hours 06:00 and 07:00 in the morning and returned home from school around 15:00 and 15:30 in the afternoon. The two major modes of transport were walking and vehicle. The vehicle mode included private cars, school buses and public buses (Table 1). Walking to and from school was used by 48% in S1, 83% in S2, and 100% in S3. All pupils in S2 and S3, and 75.2% in S1 spent 40 min or less commuting to and from school. More pupils attending S2 and S3 lived close to their schools than those in S1.

### 3.2. Concentrations and sizes of UFP

The time-series plots of mean hourly UFP concentrations measured by the participants over 24 h are presented in Fig. 2. The fitted LOESS curve (mean of all the participants) shows two peaks occurring at 05:00 and 16:00. The increasing trend of UFP concentrations from 00:00 to 05:00 (midnight to early morning) could be attributed to: i) relatively high UFP concentrations in some bedrooms; and ii) combustion emissions from cookstoves in the kitchen during the preparation of morning meals. Emissions from cooking activities accounted for the peak at 05:00 when the pupils were in the kitchen with cookstove fires (firewood, charcoal and gas stoves) on to prepare the morning meal, which is usually done between 05:00 and 06:00.

The increasing trend of UFP concentrations from 12:00 to 16:00 (afternoon to evening) could be explained by: i) traffic-related emissions during the lunch-time rush hour (particularly at S1, which is close to the heavily trafficked Accra–Aburi highway), and ii) combustion activities such as open burning of trash that is undertaken by the pupils while they are home. The peak at 16:00 occurred when the pupils were home in the *Home other* microenvironment undertaking household chores including burning of trash and encountering environmental tobacco smoke. In particular, trash burning is usually done in the afternoon when the trash is dry and combustible. A somewhat increasing trend of UFP levels is observed from 18:00 to 23:00 (evening to midnight).

The lowest concentrations were measured in school (i.e. between 08:00 and 12:00). The sharp spikes observed in the graph are as a result of localized events such as the participant being close to a fire source or in the presence of environmental tobacco smoke. The mean UFP concentrations measured in the microenvironments are presented in Table A1.

The sizes of the particles measured by the participants ranged widely depending on the participant and school, with summary of the size distribution presented in Fig. 3. Berekuso.

### 3.3. Exposure

#### 3.3.1. Personal exposure to UFPs

Table 3 presents descriptive statistics of personal exposure received by the participants in each school. Pupils attending S3 received higher exposure followed by those attending S1 and S2. The participant with the highest exposure in S1, recorded extremely high concentrations for

**Table 2**
Summary of microenvironments, activities, and corresponding times spent in the microenvironments by the participants.

| Microenvironment | Activities undertaken | Mean time spent in microenvironment (hours) | Percentage of time (%) |
|---|---|---|---|
| Classroom | Taking lessons and studying | 6.0 | 25.4 |
| School outdoor | Cleaning up school grounds, eating at canteens and playing on playgrounds | 1.8 | 7.1 |
| Bedroom | Sleeping at home | 7.5 | 31.3 |
| Living room | Studying, relaxing, and watching TV | 2.5 | 10.4 |
| Kitchen | Cooking, eating and drinking | 2.0 | 8.3 |
| Home other | Carrying out household chores in the home and engaging in social activities | 3.2 | 13.3 |
| Commute | Commuting to and from school | 1.0 | 4.2 |

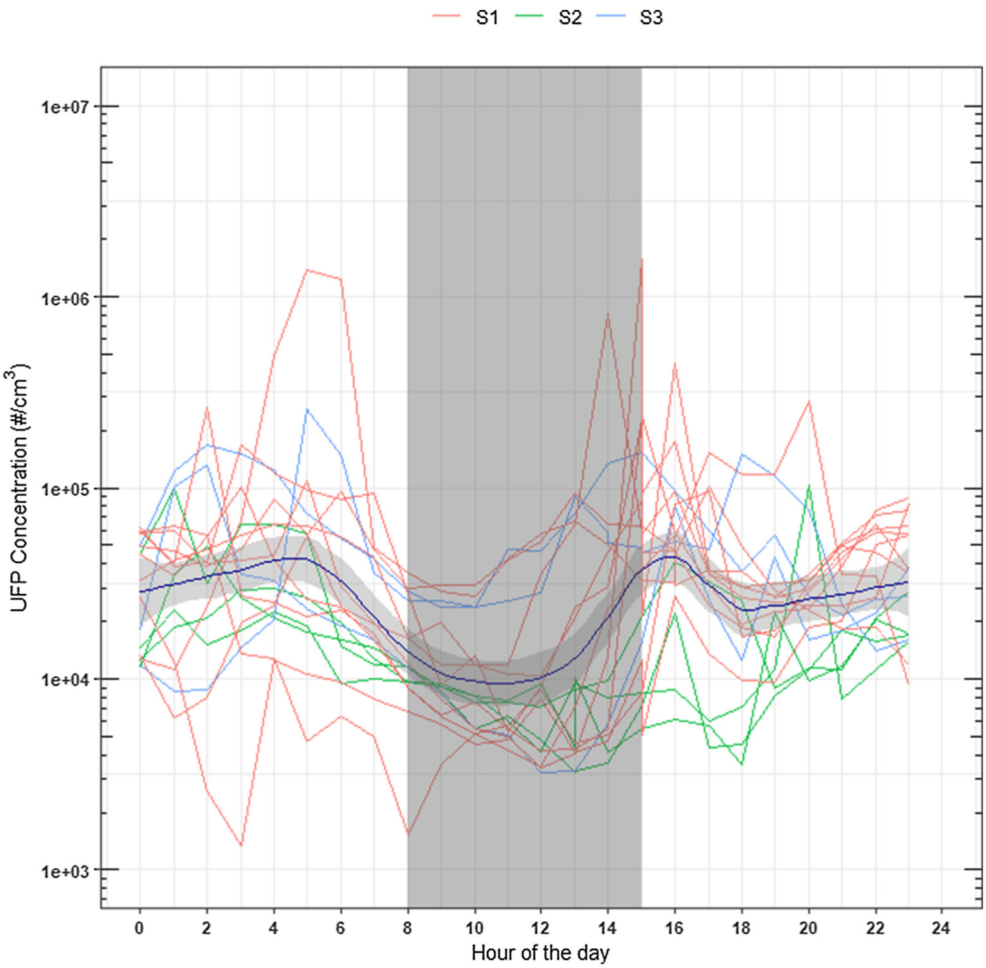


**Fig. 2.** Time-series plots of mean hourly UFP concentrations of 22 participants with 24-h data. The grey area represents typical school hours, the different line type represent average concentrations of the participants of the three schools and the blue line in the middle is the fitted LOESS curve, which represents the mean of all the participants.

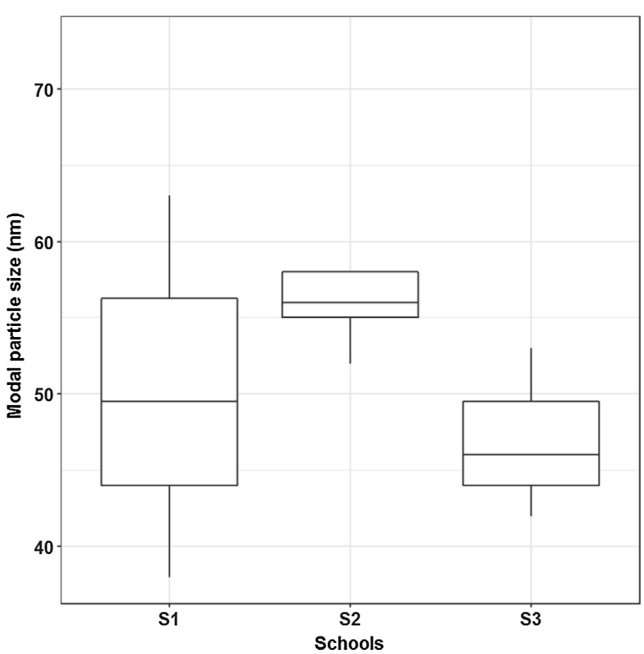


**Fig. 3.** Distribution of modal sizes of the particle measured by the participants grouped by schools.

30 min when near environmental tobacco smoke, which affected the daily exposure.

The distribution of exposure received by the participants in the seven microenvironments over 24-h grouped by schools is presented in Fig. 4. The exposure received in the microenvironments varied widely depending on the time spent in each microenvironment, conditions in the school, and the type of activities in which the participants were engaged. The exposure received by pupils in S1 had the widest spread, while those received by pupils in S2 had the least spread.

The *Bedroom* microenvironment had the highest median exposure for all the pupils (Table A1). The highest mean exposure was received in the *Home other* microenvironment by pupils in S1 and in the *Bedroom* microenvironment by those in S2 and S3 (Table A1). The second highest mean exposure was received in the *Bedroom* microenvironment followed by *Kitchen*, *Classroom*, *Commute*, *Living room*, and *School outdoor* (lowest) for pupils attending S1. For pupils in S2, the second highest mean exposure was registered in *Home other* followed by *Kitchen*, *Living room*, *Classroom*, *School outdoor* and *Commute* (lowest). For pupils attending S3, the second highest mean exposure was received in *Home other*, followed by *Classroom*, *Kitchen*, *Commute*, *Living room* and *School outdoor* (lowest).

### 3.3.2. Exposure intensity and contributions of microenvironments

The intensity of exposure in the different microenvironments is presented in Fig. 5. The figure shows that all the participants registered the highest mean exposure intensity in the *Kitchen* microenvironment. The intensity of exposure in the home microenvironments (*Bedroom*,

**Table 3**
Summary of participants' with 24-h data.

| School | Mean UFP concentration ($cm^{-3}$) | Highest daily exposure to a participant ($\#/cm^{-3}\cdot h/day$) | Mean daily exposure ( ± standard error) ($\#/cm^{-3}\cdot h/day$) | Median daily (interquartile range) exposure ($\#/cm^{-3}\cdot h/day$) |
|---|---|---|---|---|
| S1 | $5.23 \times 10^4$ | $1.4 \times 10^5$ | $4.9(\pm1.0) \times 10^4$ | $3.8(2.0 - 6.2) \times 10^4$ |
| S2 | $1.83 \times 10^4$ | $2.2 \times 10^4$ | $1.6 \times 10^4(\pm1.9 \times 10^3)$ | $1.7(1.5 - 1.8) \times 10^4$ |
| S3 | $8.93 \times 10^4$ | $8.1 \times 10^4$ | $6.9 \times 10^4(\pm6.8 \times 10^3)$ | $6.8(6.3 - 7.5) \times 10^4$ |

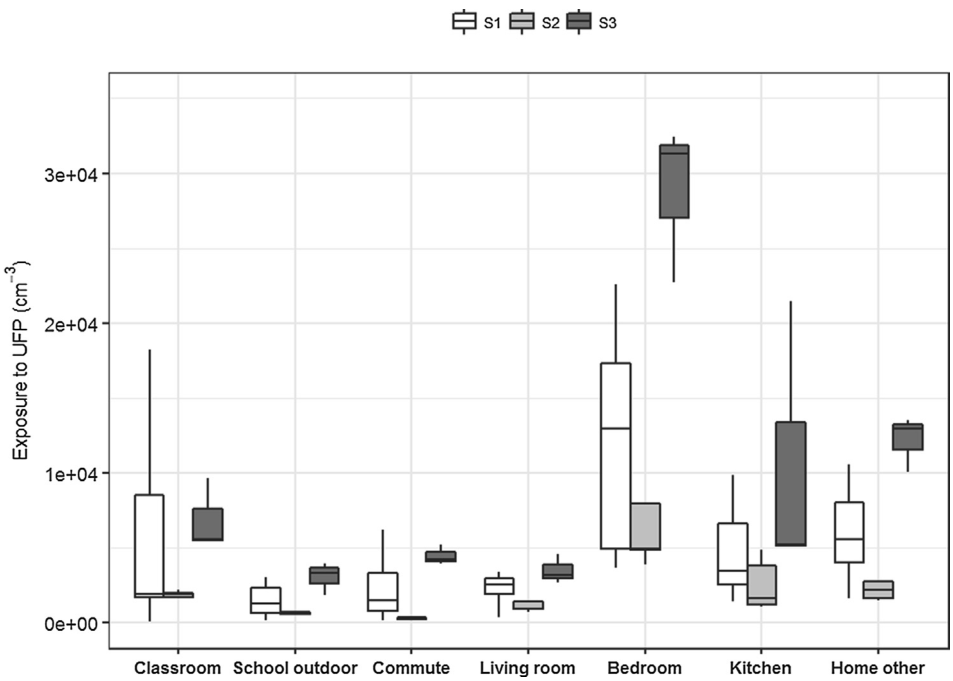


**Fig. 4.** The exposure to UFPs received by participants in seven microenvironments grouped by schools. The boxes represent the interquartile ranges, black lines in the boxes represent the medians, and the whiskers represent maxima and minima.

*Kitchen* and *Home other*) was relatively higher than in school microenvironments (*Classroom* and *School outdoor*). The exposure intensity during *Commute* was considerably higher for pupils attending S1 and S3, which are located in suburbs of Accra, particularly in the case of pupils in S1, where the commute time is longer.

For pupils in S1, the mean exposure received in the *Home other* microenvironment was higher than in the home indoor (*Bedroom*, *Living room* and *Kitchen*) microenvironments, but for pupils attending S2 and S3, household exposure was higher than exposure in the outdoor home. The mean exposure received in the *School outdoor* microenvironment was lower than in the *Classroom* microenvironment for pupils in all three schools, because the pupils stayed in classrooms for longer than in the *School outdoor* microenvironment. The mean exposure received in the *Commute* microenvironment was the lowest for pupils in S2. Overall, the pupils received higher exposure in home microenvironments than in school microenvironments. Table A2 presents the mean percentage contribution of the microenvironments to daily exposure. The highest mean contribution to daily exposure was from the *Bedroom* microenvironment, which accounted for 29% in S1 and S3, and 38% in S2. The second highest mean contribution to daily exposure was from *Home other* (20%, 14% and 10%), followed by *Kitchen* (14%, 12% and 9%) and *Classroom* (9%, 11% and 7%) for S1, S2 and S3 respectively.

### 3.4. Comparison with other studies

The results of this study could not be directly compared to other studies that assessed personal exposure to UFPs in Ghanaian cities because no such studies have been reported. Therefore, we have compared our results with similar studies conducted around the world (Table A3). Fig. 6 is a graphical presentation of the comparison of personal exposure in this study with five cities and a rural environment.

From Table A3 and Fig. 6, it can be seen that the mean (24-h) concentrations in Berekuso were higher than in Cincinnati (USA) and in Brisbane (Australia), but lower than all the other locations. By contrast, the mean concentrations in Accra were higher than in all the places except Jakarta (Indonesia).

## 4. Discussion and conclusions

The lack of reliable personal exposure data in low-income countries presents one of the biggest challenges in the control of air pollution in their cities. This study assessed daily personal UFP exposure of pupils attending three schools in Accra and Berekuso. The personal exposure was apportioned into seven microenvironments that the pupils encountered on a typical school day. We demonstrated that the main driving forces of UFP exposure were lifestyle, sociocultural conditions and the location (suburb) of residence. The daily personal UFP exposure received by pupils attending the schools in Accra were relatively higher and widely varied than in Berekuso. The reasons for this are that Berekuso is a rural community and therefore UFP levels in many of the microenvironments are relatively low, and to greater extent homogenous, as there is little vehicular traffic, and the participants there live close to the school. For pupils living close to major traffic routes in Madina and Agbogbloshie, which are located in Accra, traffic-related emissions from the evening rush hour that occurs between 17:00 and 20:30; and cooking emissions during the preparation of evening meals,

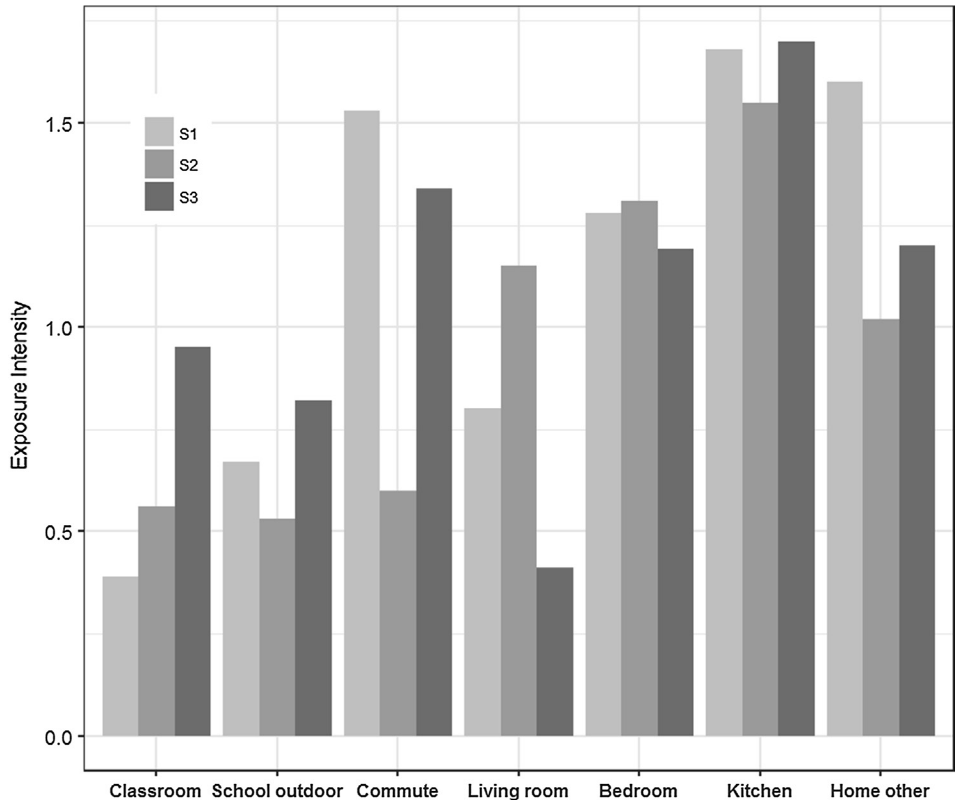


**Fig. 5.** Mean exposure intensity recorded in the seven microenvironments investigated.

usually around 18:00 are the main contributors to their exposure. Directly participating in trash burning and possibly going near environmental tobacco smoke elevated the exposure received outdoor at home, while emissions from cooking and burning of mosquito coils in bedrooms at night resulted in household indoor exposure.

Mosquitos bites are the major vector of malaria transmission in tropical countries including Ghana. Because malaria is a major health challenge in Accra, various approaches are used to prevent mosquito bites. Most households in the low-income bracket in the study area tend to burn mosquito coils in bedrooms at night to repel mosquitos. Mosquito coil burning is reported to generate significant levels of particles (Wang et al., 2018), therefore the burning of mosquito coils at night resulted in the generally high levels of UFPs in the bedrooms. Poor ventilation also likely contributed to high UFP levels in the bedrooms. Ventilation in bedrooms is poor in certain communities due to the way the houses were constructed. The houses are configured so that the bedrooms, which mostly adjoin the kitchen, have only one or two small-sized windows.

In addition to the reasons stated above, the fact that the pupils spent a longer time (about 7.5 h) in the bedroom with relatively high UFP concentrations also contributed to them receiving a greater portion of their daily exposure in the bedroom. Accordingly, pupils attending S1 and S2 received their lowest exposure in the *School outdoor* microenvironment because the concentrations of UFP in that microenvironment were relatively low (Table A3) and the pupils spent just 1.7 h (Table 1) in that microenvironment. Likewise, pupils in S2 received the lowest exposure in the *Commute* microenvironment because their mean UFP concentration for *Commute* was the second lowest with a short average commuting time.

Given that there were no visible UFP sources in the classrooms and in the schoolyards of the schools, it is clear that the UFP in both classrooms and school outdoor microenvironments were from outside the schools. The sources of UFPs in schools of Accra were different from those in the school of the rural community of Berekuso. The main sources of UFP in S1 were vehicular traffic, burning of trash and commercial activities, and those in S3 were vehicular traffic, burning of e-waste and car tires, and trading activities. The main sources of UFP in S2 were vehicular traffic and agricultural emissions. The variation in the sizes of particles measured in the suburbs is proof of the difference in the sources across the suburbs. Particles in fresher combustion emissions are smaller in size. Such small particles were more commonly observed in S1 and S3 than in S2 probably because more combustion activities were present in Madina and Agbogbloshie than in Berekuso. Aged and larger particles, which originate from numerous sources including agriculture, were more commonly observed in the rural community of Berekuso.

Although the results of this study could not be directly compared to studies conducted in Ghanaian cities because there are no such studies that assessed personal exposure to UFPs, we exppected that the sources contributing to UFP exposure, were similar to those contributing to particle mass concentration exposure. Arku et al. (2008)) measured $PM_{2.5}$, $PM_{10}$, sulfur dioxide ($SO_2$), and nitrogen dioxide ($NO_2$) in two neighborhoods of Accra over a period of 3 weeks, and found that biomass burning, traffic emissions, geologic materials, and marine non-combustion particles were the principal sources of particulate matter pollution in ambient Accra. Similarly, Rooney et al. (2012)) studied the spatial and temporal patterns of particulate matter sources in four communities of Accra, and found the use of firewood, charcoal, and other biofuels for household cooking, fish smoking, trash burning, e-waste burning and vehicle emissions as the major sources of particulate matter pollution in Accra. Arku et al. (2015)) also investigated personal exposure to $PM_{2.5}$ of students in eight schools that were located in four neighborhoods in Accra, and found the use of biomass fuels for cooking in schools and households, the nature of schoolyard and playground surfaces, and the location of the school relative to major roads to be the main predictors of exposure to $PM_{2.5}$.

Since personal exposure is the product of concentration present in the microenvironments in which a participant resides and the time they

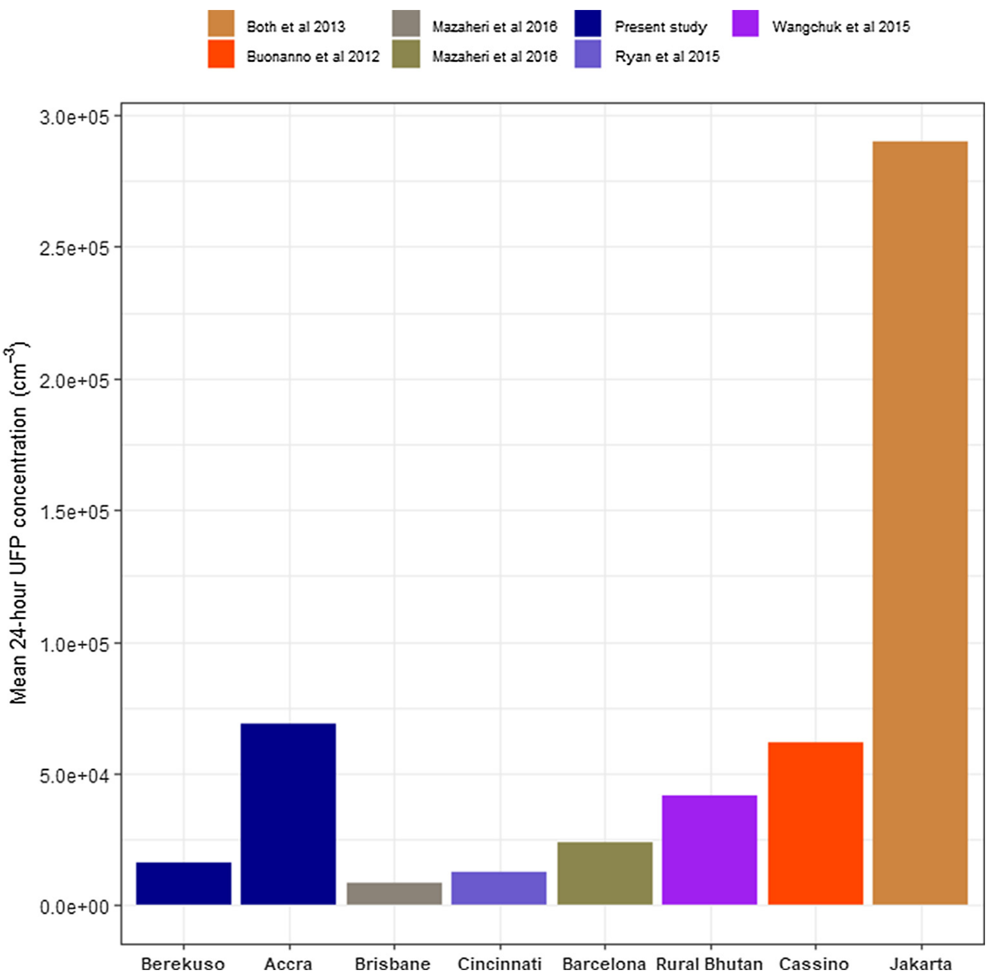


**Fig. 6.** Comparison of mean 24-h UFP concentration measured in Berekosu and Accra (this study) with those measured in five other cities and a rural environment around the world.

spend there, it is imperative that these two parameters are accurately measured. One of the main sources of uncertainty in personal UFP exposure assessment in this study was the low quality of information provided by the participants on their activities. The participants provided the TAD information that could not be fully relied on to determine how long they stayed in each microenvironment, although the teachers were responsible for providing other critical information including school hours and activities during school hours. It is important to point out that GPS-enabled wearable monitors, which allow the integration of information on participants' movements as a source of secondary data to pollutant concentrations, could have been used to reduce the challenge of inaccurate/incomplete TADs that was faced in this study. However, due to logistics constraints, we could not use geolocation tracking monitors (Steinle et al., 2013).

In general, personal exposure in Accra was among the highest reported in the world. Therefore, the outcomes of this study has highlighted the need to intensify air pollution control in Accra. There is also the need to raise awareness about air pollution and emphasize the importance of avoiding activities that heighten UFP exposure in the communities. We recommend the establishment of a special government agency that will be responsible for safeguarding children's respiratory health in Ghana, considering that children are vulnerable segment of the population.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105223.

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