Environmental Science: Atmospheres

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

Check for updates

Cite this: DOI: 10.1039/d6ea00027d

Impact of domestic and commercial combustion activities on women's personal exposure to $PM_{2.5}$ in Abidjan (Cote d'Ivoire)

Marie Yapo, *[a] Cathy Liousse,[a] Sylvain Gnamien,[b] Thierno Doumbia,[a] Jean-François Léon,[a] Marine Scandella,[c] Sylvia Becerra,[c] Nicolas Brou,[b] Coulibaly M'begnan,[d] Stéphane Ahoua,[b] Maria Dias Alves,[a] Eric Gardrat,[a] Isabella Annesi-Maesano,[e] Ayenon Junior Yapo[b] and Véronique Yoboué[b]

Received 16th February 2026
Accepted 31st May 2026

DOI: 10.1039/d6ea00027d

rsc.li/esatmospheres

Few studies have been carried out on personal exposure to fine particles linked to combustion activities in West Africa, despite the high concentrations that have been measured and the health risks they pose. This study is a part of the APIMAMA (Air Pollution Mitigation Action for Megacities in Africa) interdisciplinary research project. We focus on the personal exposure to $PM_{2.5}$ of three groups of women who are heavily exposed to domestic and commercial combustion pollution through their daily work in Abidjan, Côte d'Ivoire, specifically in Yopougon. The groups are composed of 30 housewives using wood or charcoal to cook food for their families or for sale; 29 women and 3 men using wood to produce charcoal; and 28 women using wood to smoke fish. All participants wore real-time $PM_{2.5}$ monitors during the dry season (November 2022–March 2023 for housewives and charcoal makers) and the wet season (July–September 2023 for fish-smoking women) for 15 to 30 days. This study shows alarming 24-h exposure levels: 224.7 (205–245.9) µg m^{-3} for housewives, 251.6 (207.9–306.3) µg m^{-3} for charcoal makers, and 269.2 (191.7–399.8) µg m^{-3} for fish-smoking women. These results are 15 to 18 times higher than the WHO's 24-hours guideline (15 µg m^{-3}), posing serious health risks. For each group, the $PM_{2.5}$ concentrations and their diurnal variations are closely associated with the reported sources of exposure identified in the health questionnaires. More specifically, the multivariate analysis highlighted the significant role of road traffic in the personal exposure of housewives to $PM_{2.5}$, whereas combustion activities were the dominant contributors for the other two groups. This finding is consistent with the quantified impact of combustion activities on daily exposure levels. Cooking activities with wood and charcoal contribute to 29% ± 10% of the housewives' total daily exposure, while charcoal making and fish smoking account for 31% ± 8% to 41% ± 13% and 18% ± 16% to 71% ± 18%, respectively, of the total daily exposure of the charcoal makers and fish-smoking women.

Environmental significance

This study shows that women conducting domestic and commercial activities that generate pollution, as well as those living in poor neighbourhoods in Abidjan are exposed to high concentrations of $PM_{2.5}$, well above the WHO-recommended daily limits and the atmospheric concentrations previously measured in these neighbourhoods. Four main sources of pollution (wood and charcoal combustion, traffic, indirect sources, and use of mosquito coils and repellents) were identified from the questionnaires completed by participants as being responsible for this situation. An estimation of their respective contribution to personal $PM_{2.5}$ exposure among women shows that combustion activities are the primary source for charcoal-making women and fish-smoking women. This finding can be generalized to women in West Africa with similar living conditions and practices and can help inform strategies aimed at reducing the impact of these activities.

1 Introduction

Owing to rapid urbanization, West Africa is experiencing an increase in anthropogenic particulate emissions, which is negatively impacting the air quality in its cities and adversely affecting the health of its populations, leading to one million

[a]Laboratoire d'Aérologie, Université de Toulouse, CNRS, IRD, Toulouse, France. E-mail: marie-alexia.yapo@univ-tlse3.fr; Tel: +33 7 49499473

[b]Université Félix Houphouët-Boigny, Abidjan BPV 34, Cote d'Ivoire

[c]Laboratoire Géographie de l'Environnement, CNRS, Université Toulouse Jean Jaurès, Toulouse, France

[d]Institut National d'Hygiène Publique, Bouaké, Cote d'Ivoire

[e]Institut Desbrest d'Épidémiologie et de Santé Publique, INSERM et Université de Montpellier, France

premature deaths each year, according to the World Health Organization (WHO).

Studies have identified four major anthropogenic sources of particulate pollution in the major cities of West Africa.[1–6] The first is domestic and commercial fires as well as the open burning of waste. The main sources of energy in African households are solid fuels such as charcoal, agricultural residues and wood.[7] In sub-Saharan Africa, these biofuels account for around 80% of total energy consumption.[8] Access to less polluting energies, such as gas or electricity, is limited because they are more expensive, and the use of wood and charcoal is also culturally based. Indeed, many people still continue to use wood or charcoal to cook dishes that require slow cooking or that are believed to have a better flavor than when cooked with gas. The other two major sources of emissions in West African cities are road traffic, characterized by vehicles that are often very old, and the agri-food and chemical industries. Studies have shown that Africa could become the leading emitter of anthropogenic pollutants from these 4 types of sources by 2030 if no reduction measures are implemented.[6] In addition, it should be noted that most West African cities are affected by more distant sources, especially during the dry season (*e.g.* desert dust from the Sahel and Sahara regions and particulate matter from savannah fires).

Faced with this cocktail of anthropogenic and natural sources, several scientific projects have been examining the effects of certain sources on gaseous pollution[9–12] and particulate pollution[3,4,13–19] in urban West African areas and human health for the past decade. In terms of particulate pollution, these projects have shown that the concentrations of particulate pollutants at source sites and urban sites are 3 to 15 times higher than the levels recommended by the WHO, with strong spatial variations closely linked to the standard of living of the populations. The highest concentrations have been found in the most deprived neighborhoods. Carbonaceous aerosols and desert dust are the main components of the aerosols studied. In terms of health issues, some studies have examined the link between high indoor and outdoor concentrations of particulate pollutants and some respiratory symptoms among vulnerable populations (*e.g.* children).[20–23] Owing to all these projects, particulate matter pollution and its health effects are fairly well documented in Abidjan, particularly in the Yopougon commune. However, it should also be noted that the highest concentrations observed in the study by Xu *et al.*[19] (15 times higher than the WHO guidelines) were obtained at the source site during personal exposure measurements of two women using wood for smoking meat.

Therefore, domestic and professional activities (food smoking and wood manufacturing) linked to the use of wood fires and charcoal are likely to be one of the main sources of fine particulate matter pollution, affecting those who engage in them.[24–27] Women living in the cities of West Africa are the main victims, as they play an important role in these activities.

However, very little research has been conducted on their personal exposure to particulate pollution in relation to each of their combustion activities.

Furthermore, Becerra *et al.*[28] have shown that air pollution is part of a range of hazards faced by people on a daily basis, and that it is linked to poverty and/or social hierarchy; consequently, the most socially vulnerable people are also those most vulnerable to air pollution.

It is against this backdrop, and in response to the health emergency caused by rapid population growth, that the APIMAMA project (Air Pollution Mitigation Actions for Megacities in Africa, ANR 2022–2026) was established. APIMAMA aims to develop solutions to reduce air pollution and associated health and social risks in African megacities through an interdisciplinary, participatory approach that enables participants to take ownership of the environmental health issues addressed by the project. One of the objectives of this project is to study three vulnerable groups of women living in precarious neighborhoods in the commune of Yopougon in Abidjan and involved in polluting domestic and commercial activities (cooking, charcoal making and fish smoking). This part includes measurements of individual exposure to particulate pollution for each of the participants, sociological interviews and health tests,[29] before and after the introduction of improved cooking techniques and practices, *i.e.* those designed to reduce the particulate pollution inhaled.

The work presented here shows first the results of measurements of personal exposure to fine particles ($PM_{2.5}$) for each of the women studied while they used traditional tools and practices in their domestic and commercial activities, corresponding to the situation before the introduction of improved technology and practices. Secondly, this study examines the relationship between these results and the polluting sources to which women are exposed, based on analyses of health questionnaires. Finally, this paper quantifies the contribution of domestic and commercial combustion activities to total daily personal exposure.

2 Materials and methods

A pilot group composed of researchers, local and national decision-makers and women's representatives from various neighborhoods of Abidjan was established to monitor the development and progress of the studies conducted as part of the project.

The first meeting of this group allowed for the selection of the measurement sites, women representatives within the pilot group, and measurement periods.

2.1. Description of study sites and selection of participants

Abidjan is the main pilot city for the APIMAMA project, and Yopougon is the commune selected to implement the study protocol described herein.

Yopougon is densely populated with 1 571 065 inhabitants and a population density of 9568 inhabitants per km^2.[30] The population is low to middle income. The three combustion sources studied (cooking, charcoal making and fish smoking) are present in Yopougon and are mainly carried out by women. Therefore, our study covers three measurement sites (Fig. 1) and

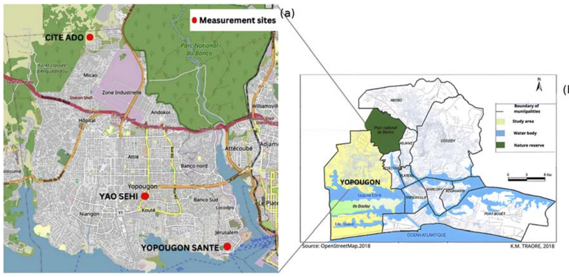

Fig. 1 Location of measurement areas: (a) zoomed view of the three measurement sites in the commune of Yopougon (https://www.openstreetmap.fr/), and (b) city of Abidjan and its communes.[31]

three groups of female participants with distinct socio–professional activities:

(1) Yao Sehi, a neighborhood in Yopougon, was selected for the study of personal exposure to domestic fires (housewives' group) and to fish smoking carried out in the neighborhoods (fish-smoking group). It is important to note that the "housewives" group is made up of participants who, for the most part, conduct professional activities in the neighborhood, including restaurant owners and sellers of crisps, bread, rubber, clothes, medicines, *etc.* Yao Sehi is a precarious neighborhood characterized by unpaved roads and a lack of adequate infrastructure for household waste and wastewater management.[32] This neighborhood is densely populated with a low-income population and was recently divided in two for the construction of a bridge known as the Fourth Bridge (currently under construction). The cooking fuels most commonly used for domestic and commercial activities in this population are charcoal and wood. Gas is also used in combustion activities and all these energy sources are used interchangeably depending on their efficiency and cost-effectiveness, as well as the types of dishes and/or cooking times.

(2) The charcoal production site is located next to Cité Ado neighborhood. Cité Ado is close to the civil prison on the N'dotré road (Fig. 1). This area is sparsely populated and adjoins a forest. Informal charcoal making using recovered wood (from sawmills, pruning carried out by Abidjan town councils, *etc.*) take place there. The land occupied by wood stocks and charcoal millstones was a wasteland unsuitable for urban development and once far from residential areas. However, due to demographic pressure, new buildings are now being constructed on the edge of the charcoal making site, leading to conflicts between local residents and charcoal makers.

(3) Yopougon santé site regroups the "Fatou Sylla" fish-smoking site and Abobodoumé market. These sites (Fatou Sylla and Abobodoumé market) are located in the villages of Yopougon santé and Abobodoumé, which belong to the communes of Yopougon and Attécoubé, respectively. The population of these villages is predominantly low-income and engages in many informal activities, including fish smoking to meet their daily needs. This activity has come into being thanks to the proximity of these villages to the Ébrié lagoon. The fuel used for smoking is rubber wood. It is important to note that previous studies have shown that particulate emissions associated with its combustion are very high compared with other types of wood (iroko, redwood, *etc.*).[33] Working conditions are difficult: smoking on traditional ovens is usually carried out under lean-tos or in confined spaces that trap smoke.

The protocol specified that 30 participants should be selected from each site. For the groups of housewives' and fish-smoking groups, this selection within the same neighborhood is associated with a 15% margin of error, according to Danieli *et al.*[34] However, for charcoal makers, the study targets a specific practice that is illegal in the city and therefore difficult to quantify.

One of the roles of the women's representatives in the pilot group was to provide a list of people for each site, the selection criterion being their use of charcoal and/or wood for domestic and commercial activities.

In total, we selected 31 housewives and 5 fish-smoking women in Yao Sehi. In Yopougon Santé, 23 fish-smoking women, and, in Cité Ado, 30 women and 3 men involved in charcoal production were selected.

While women were the primary social category targeted by the study, 3 men were included in the charcoal production group due to their work in setting up and monitoring the charcoal-making millstones, which meant that they spent a lot of time at the Cité Ado site. Men on the site are generally employed by women who run the business.

2.2. Measurement protocols and materials deployed

Before each measurement campaign, meetings were held with all the participants in the same group to present the APIMAMA study protocol, including physicochemical measurements and health questionnaires.

In terms of physicochemical measurements, two types of portable equipment were used: (1) optical sensors to measure fine particles ($PM_{2.5}$) in real time, which were worn on the arms by all the people in each group, and (2) filtration systems to study the mass and chemical composition of the aerosol, as well as its oxidizing potential (Fig. 2).

The filtration system was attached to the clothing at chest level and close to the breathing zone. All sensors were worn

Fig. 2 Photographs of measuring instruments worn by the participants in this study: (a) a housewife at Yao Sehi, (b) a charcoal-making woman at Cité Ado and (c) a fish-smoking woman at Yopougon Santé. Source: photos S. Chastanet, OMP (Observatoire Midi-Pyrénées).

continuously and were only removed briefly, remaining in the same microenvironment as the participant (kitchen, bedroom, workplace, *etc.*) during activities such as bathing, sleeping, charging the battery, or performing sudden movements (*e.g.*, preparing certain dishes, throwing earth for charcoal production, using public transport during rush hour, *etc.*).

The measurement campaigns were carried out during periods when exposure to pollution is expected to be at its highest: in the dry season from 22 November to 22 December 2022 and from 14 to 28 March 2023 for housewives and charcoal makers, respectively, and in the wet season for fish-smoking women (from 18 to 31 July 2023 at Yao Sehi and from 01 August to 01 September 2023 at Yopougon Santé). In fact, it is during the wet season that the activity of fish smoking is most intense.

2.2.1. Portable filtration system. The filtration system consisted of a portable PEM system (personal environmental monitor[19]) that included a battery-powered SKC pump (SKC Inc., Fullerton, CA, USA) drawing air at a rate of 4 L min^{-1}, a cylindrical stainless-steel cut-off head removing particles larger than 2.5 μm in diameter from the air stream, and a cassette containing a 37-mm quartz fiber filter (Fig. 2a). A gravimetric method is used to determine the mass concentration of aerosol collected.

This method has been validated and used by several projects.[13–16] For each study group, flow rates were verified at the beginning and end of each sampling event. Sampling times were recorded both manually (laboratory notebook) and directly (on the pumps).

This device was worn by 3 participants at each site (4 at Cité Ado site) for 15 days. The filters were changed every 24 h.

The results obtained with the filtration system were used in the present study solely as a reference method for assessing $PM_{2.5}$ mass concentrations. Analysis of the chemical composition of the aerosol and its oxidizing potential, also carried out on these filters, will be the subject of another study.

2.2.2. Portable optical sensors

2.2.2.1 Sensor description. We used low-cost GAIA APIMAMA sensors (https://aqicn.org/gaia/apimama/). These sensors were custom-designed by the manufacturer for the project and include a GPS module and two sensors (PMS 5003), enabling us to obtain spatiotemporal concentrations of $PM_{2.5}$ over two-minute intervals. GAIA APIMAMA is an optical sensor that uses the principle of light scattering.[35] According to a study on the evaluation of low-cost Plantower sensors (PMS 5003 and PMS 1003), they cover a concentration range from 6 to around 1000 μg m^{-3}.[35] These sensors were designed to be lightweight, easy to wear and battery-powered, requiring no internet connection for start-up, operation and data retrieval. They can collect data for up to one week.

2.2.2.2 Measurement protocol. During the various campaigns, which lasted one month for housewives and fish-smoking women and 15 days for charcoal makers, the sensors were worn on the arm of all participants (Fig. 2). The measurement protocol devised with the participants was as follows: the sensor was worn at all times, except during specific periods (see above) when they place it nearby. Data was collected twice a week. Before the sensors were used on a site, they were checked to ensure that they were working properly.

2.2.2.3 Sensor calibration. Low-cost measuring devices must be calibrated against reference instruments.[36] Calibration is a challenging process because the measurements performed using low-cost optical sensors depend on operating conditions (relative humidity, temperature, and particle mass concentration), as well as on the characteristics of the aerosols being measured (aerosol composition, particle size distribution, and hygroscopicity). These characteristics are closely linked to the emission source.[37–39] Several studies on calibrating low-cost sensors in tropical areas use models that take into account meteorological conditions (temperature and relative humidity).[40] Other studies compare measurements obtained using low-cost optical sensors with the $PM_{2.5}$ mass measured on filters in parallel (see, for example, Gnamien *et al.*[16]).

In this study, due to the lack of real-time meteorological data, we used the latter option to evaluate and correct the measurements of $PM_{2.5}$ concentrations obtained from the optical sensors. To do this, we used the daily filters (14 filters) worn by three or four participants in each group (10 participants in all, *i.e.* 138 filters in total) and collected with the filtration system. We then determined the $PM_{2.5}$ concentrations recorded by the optical sensors for the same measurement periods as those of the filtration system experiments and compared the values obtained with the two sampling methods. The comparison was performed separately for each group. Indeed, aerosol characteristics, including chemical composition, size and hygroscopicity, are expected to differ among the groups because they are influenced by different emission sources. The results of the comparison show a significant correlation between the data obtained from the two measuring instruments (housewives: $y = 5.5x$, $R^2 = 0.8$, $p < 10^{-10}$, see Fig. S1; charcoal makers: $y = 7.04x$, $R^2 = 0.8$, $p < 10^{-10}$, see Fig. S2; and fish-smoking women: $y = 5.03x$, $R^2 = 0.8$, $p < 10^{-10}$, see Fig. S3). We applied these correction factors (5.5, 7 and 5) to the optical sensor data to obtain the adjusted $PM_{2.5}$ mass concentrations for all participants. It is worth noting that these correction factors are higher than the values reported in the literature, which could be explained by (1) the ambient relative humidity levels measured in the field of around 90%, which are higher than those in previous studies and (2) the aerosol composition, which was dominated by combustion-derived organic aerosol. Indeed, previous studies (*e.g.* Zhang *et al.*[41]) show that organic carbon (OC) plays a significant role in increasing the aerosol liquid water content (ALWC) during biomass combustion, which affects the aerosol optical properties when the relative humidity exceeds 60%. This would explain the underestimation of $PM_{2.5}$ by the PMS5003 sensor and the need for higher correction factors than those in the literature. Moreover, the higher values (7) obtained for charcoal makers may also be explained by the chemical composition of the combustion aerosol, which is affected by the presence of ground ash that is resuspended (see Fig. 2b).

2.2.3. Ambient $PM_{2.5}$ concentration measurement. Ambient $PM_{2.5}$ concentrations were measured weekly from November 2022 to April 2026 in Yao Sehi (see Section 2.1 (1)) to characterize ambient pollution in Yopougon using the INDAAF ambient air-pumping technique (Djossou *et al.*[13] and Gnamien *et al.*[16]).

Briefly, the sampling system consisted of a mini Partisol sampling impactor for $PM_{2.5}$ operating at a flow rate of 5 L min^{-1}, an NILU online filter holder, a KNF pump with a flow rate of 9 L min^{-1} (N89 KNE-K version 220 V), a Cole Palmer ball flow meter with a micrometric valve (flow range adjustable from 0 to 10 L min^{-1}, accuracy $\pm 5\%$) and a GALLUS-type G4 gas meter (accuracy of ± 0.01 m^3). The air was sampled for 15 min every hour, leading to a total volume of sampled air of about 12.6 m^3 per week. The particles were collected on 47-mm quartz fibre filters for gravimetric measurements.

The sampling system was installed more than 2 m above the ground, on the roof of the house of Yao Sehi's chief. Similar to the portable filtration system, flow rates were verified at the beginning and end of each sampling event, and sampling times were recorded manually in a laboratory notebook.

2.2.4. Health questionnaire. All APIMAMA researchers contributed to the development of the health questionnaire, which was based on existing instruments and adapted to the conditions of our study.[42–45] In this questionnaire, administered at the beginning of each measurement campaign, all 92 participants in the study were invited to provide personal information on their occupation, living conditions, health, and perception of pollution. In this study, we focused particularly on the information on their activities, general lifestyle habits, culinary habits and fuels used, nature of their job, workplace and working hours, and commuting mode and duration. Moreover, participants were asked questions about their daily activities during the data collection to better understand the results of the different physicochemical instruments presented below.

2.3. Data analysis

In this study, all $PM_{2.5}$ values below 6 μg m^{-3} were removed from the raw values, which are continuous, real-time data with a time step of 2 min.[35] With this threshold, a total of 2%, 8% and 9% of the data were excluded for housewives, charcoal makers and fish-smoking women, respectively. Then, for each day of valid measurements, we calculated the daily geometric mean $PM_{2.5}$ concentration to determine the personal exposure of each participant to $PM_{2.5}$. A day was considered valid when at least 50% of the measurements were available (*i.e.*, more than 360 measurements per day), well distributed over the 24-h sampling. Under these conditions, we excluded 17%, 31% and 30% of the data for housewives, charcoal makers and fish-smoking women, respectively.

As a result, we retained 90 participants who met our criteria and had valid data (30 housewives, 32 charcoal makers, and 28 fish-smoking women), out of the 92 initially equipped. Data were anonymized according to the study groups. Thus, the identifier YSI01 designates the first participant (01) from the housewives' group of Yao Sehi (YS) for phase I of the study. The identifier DL was used for all fish-smoking women, while CA was used for charcoal makers.

2.3.1. Establishment of an individual code linked to impacting pollution sources. Due to the diversity of the data, each participant was assigned a three-term code based on the responses from the health questionnaire, summarizing the sources of pollution to which they were exposed during a typical week.

The first term of the code (ranging from 1 to 9) characterizes the combustion sources related to the participants' professional activities.

For housewives, it corresponds to the cooking source and is calculated using eqn (1), as follows:

$$\text{Cooking source} = v \times \sum_{r \in \{i,j,k\}} t_r \times \mathrm{EF}_r \tag{1}$$

where r represents the fuel used (wood, charcoal or gas); t_r the cooking and water heating time depending on the fuel used and obtained from the menus prepared by each participant during a typical week; EF_r the emission factor of the fuel used representative of the particle emissions associated with different fuels;[33] and v a ventilation coefficient derived from the characteristics of the cooking location (*e.g.*, near a door, in the yard, and in the house) and the presence of a window in the home.

For charcoal makers and fish-smoking women, the first term corresponds to combustion source and is calculated using eqn (2), as follows:

$$\text{Combustion source} = t \times \mathrm{EF} \tag{2}$$

where EF represents the emission factor of the fuel used (mixed wood for charcoal production and rubber wood for fish smoking) according to Keita *et al.*[33] and t the activity time, which is the number of exposure hours per day multiplied by the number of workdays in the week that participants devote either to charcoal production for charcoal makers or fish-smoking activities for fish-smoking women.

For the following, we assumed that the number 9 represents the highest value for the various combustion sources (cooking, fish smoking and charcoal making), and using the rule of three, we deduced the corresponding numbers for all calculated values.

The second term of the code (ranging from A to D) indicates the relative importance of road traffic as a pollution source for all participants. We observed that some groups of women (CA and DL) work at sites different from their residences, while those residing at the same site (YS) sometimes engage in activities elsewhere. The participants generally use communal taxis, commonly called wôrô–wôrô, and minivans (gbaka) for transportation. It was important for us to include road traffic in this analysis because it is one of the anthropogenic sources of air pollution to which the participants are exposed. It is evaluated according to eqn (3), as follows:

$$\text{Road traffic source} = t \times \mathrm{EF}_i \tag{3}$$

where i represents the type of fuel used (gasoline or diesel depending on the transport); EF_i the emission factor according

Table 1 Description of the codes related to the combustion sources impacting women

Position	Type	Meaning	Description
1	Number	YS: Cooking CA: Charcoal making DL: Fish smoking	From 1 to 9 with 1 being low
2	Letter	Road traffic	From *A* to *D*, with *A* being low
3	Number	For YS: fan, incense, tobacco, traffic, and construction road For CA and DL: cooking, fan, tobacco, traffic, incense, and fish smoking at home	From 1 to 9 with 1 being low
4	Lowercase letter	Use of mosquito-repellent coils	*m*

to Keita *et al.*;[33] and *t* the daily commute time and/or travel time required for participants to get to their workplace.

Letter *A* is assigned to low intensity of road traffic exposure, *B* to moderate intensity, *C* to high intensity, and *D* to very high intensity.

The third term of the code (ranging from 1 to 9) characterizes the indirect sources to which participants are exposed. For housewives (YS), this refers to the use of incense, exposure to tobacco smoke, and the presence of vehicles near their dwelling (traffic). Additionally, it is worth noting the presence of major construction work in Yopougon for the construction of a bridge (the Fourth Bridge of the city of Abidjan) connecting Yopougon to the administrative district (Plateau). These construction works may have affected the participants of the Yao Sehi group who live near the construction site, especially due to emissions from vehicles (traffic and construction dust).

For charcoal makers and fish-smoking women, the "cooking" item (presented in the previous section) is added to the indirect exposure sources listed for housewives. It should be noted that the "construction site" item used for YS is replaced here by the proximity of participants' homes to a neighborhood fish-smoking site.

To digitize the responses obtained for each item, we used a binary system (positive response to the question about the item = 1 and negative = 0). For charcoal makers and fish-smoking women, the "cooking" item is scored out of 4, and the other indirect sources are scored out of 5 to obtain the third term of our code, ranging from 1 to 9. We then summed the values of each item, and using the rule of three, we determined the third term, considering that the highest sum corresponded to the number 9.

The fourth term of the code characterizes the 'mosquito' coil combustion source, which refers to the mosquito-repellent coils that people burn in their homes for protection.[46] As the indoor combustion of these coils is highly polluting, we deemed it important to mention this source.

Table 1 provides a summary of the source code implementation.

Finally, to determine the level of exposure to all sources (LES) for each woman, we summed the values assigned to each term in the source code. To do this, we assigned a value of 9 to traffic source code *D*, and using the rule of three, determined the corresponding value for the other source codes (*A*, *B*, and *C*). Similarly, we assigned a value of 9 when a woman used a 'mosquito' coil and a value of 0 when she did not.

2.3.2. Contribution of domestic and commercial combustion activities to total daily personal exposure. Total daily personal exposure (DPE_T) was calculated using the equations defined by He *et al.*[47] and Sidibe *et al.*[48]

$$DPE_T = DPE_{CA} + DPE_O \tag{4}$$

where DPE_{CA} and DPE_O are the daily personal exposure related to combustion activities and other activities, respectively.

$$DPE_{CA} = (C_{CA} \times t_{CA})/24 \tag{5}$$

$$DPE_O = (C_O \times t_O)/24 \tag{6}$$

where C_{CA} (C_O) is the personal exposure to $PM_{2.5}$ measured during the combustion activity (during other activities) and t_{CA} (t_O) is the time spent on the combustion activity (on other activities) in hours, with the total time being 24 hours. To determine C_{CA} (and C_O), we calculated the arithmetic mean of hourly concentrations during the combustion activity period (and during other activities) for each participant. The data used to determine DPE_{CA} and DPE_O were based on observed activity schedules and questionnaire responses.

Finally, the contribution (% CA) of each combustion activity to the total daily personal exposure of the different participant groups (housewives, charcoal makers, and fish-smoking women) was calculated as follows:

$$\%\,CA = 100 \times DPE_{CA}/DPE_T \tag{7}$$

3 Results and discussion

3.1. Housewives

3.1.1. Personal exposure to $PM_{2.5}$. Fig. 3a shows the variation in personal exposure to $PM_{2.5}$ for each participant on valid days during the measurement period (November 22 to December 22 2022). We note that both this variation and the mean value differ from one participant to another. This could be explained by the various activities and practices of the participants. First, there is the frequency of cooking activities (several times a day, once a day, every other day, *etc.*) and the characteristics of how they are carried out, for example, in kitchens with varying degrees of ventilation (doors and mosquito nets instead of windows) located either inside or outside the house. Second, although all the participants are

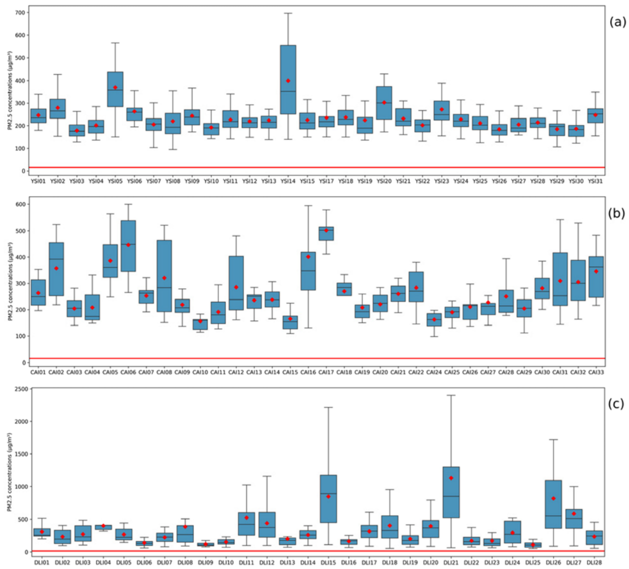

Fig. 3 Mean daily personal exposure to $PM_{2.5}$ for each participant: (a) housewives; (b) charcoal makers; and (c) fish-smoking women. The box represents the variation in personal exposure to $PM_{2.5}$ during the valid days of the measurement period; the red triangle in the box is the mean $PM_{2.5}$ concentration and the red line is the WHO recommended daily limit (15 µg m^{-3}).

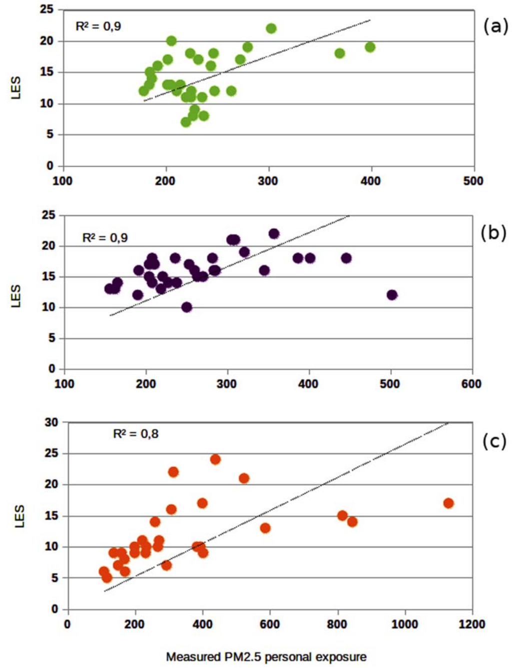

Fig. 4 Correlation between level of exposure to all the sources (LES) and measured $PM_{2.5}$ personal exposure for: (a) housewives; (b) charcoal makers and (c) fish-smoking women.

housewives who cook with charcoal and/or wood, some of them also run businesses such as restaurants, food stalls, and clothing shops. These participants were either based in the Yao Sehi neighborhood or worked as street vendors and thus exposed to road traffic. In addition, we note that some participants used incense, mosquito repellents and fans, which may also contribute to these variations in personal exposure to $PM_{2.5}$.

As presented in Fig. 3a, the mean $PM_{2.5}$ daily exposure of the women ranges from 178.6 ± 33.7 to 399 ± 167 µg m^{-3}, which is 12 to 27 times higher than the WHO recommended daily limit (15 µg m^{-3}). It is also worth noting that these values are 4 to 8 times higher than the ambient $PM_{2.5}$ concentration measured in Yao Sehi, Yopougon during the same measurement period (47.9 µg m^{-3}). This ambient value is of the same order of magnitude as the most recent level measured in the Yao Sehi neighborhood by Gnamien *et al.*[16] in 2019. To better understand the variation in participants' personal exposure to $PM_{2.5}$, we used data from the questionnaire, which provides information on their lifestyles, practices and activities.

3.1.2. Relationship between daily personal exposure of women and the polluting source to which they are exposed represented by the source code. First, we aimed to establish a link among the reported sources to which women were exposed (LES number, see Section 2.3.1) and their measured personal exposure to $PM_{2.5}$.

As shown in Fig. 4a, which presents LES number as a function of $PM_{2.5}$ personal exposure measured for the housewives, the $PM_{2.5}$ concentration increases as the source intensity increases. Also, there is a strong correlation between the two datasets ($y = 0.06x$, $R^2 = 0.9$, p-value < 10^{-10}). Therefore, there is overall consistency between the measured data and the data obtained from the health questionnaire.

Here, we examine the relative contribution of the various sources in the code to the measured $PM_{2.5}$ levels. Fig. 5a shows the source code plotted as a function of $PM_{2.5}$ concentration for the housewives. The source code is sorted in ascending order of combustion activity (the first term in the code is sorted from lowest to highest). We present the same graph in the Appendix, firstly with the source code ranked in ascending order based on road traffic (Fig. S4a, the second term of the source code is ranked from lowest to highest). Secondly, with the source code ranked in ascending order based on indirect sources (Fig. S5a, the third term of the source code is ranked from lowest to highest).

In Fig. 5a, the highest concentrations are observed for YSI14, YSI05 and YSI20 (399 ± 167, 369.4 ± 142.6 and 302.7 ± 81.2 µg m^{-3}), corresponding to codes 3D7, 9B4, and 3B5m, respectively (Table S1). The high $PM_{2.5}$ concentration measured for YSI14 can be explained by the traffic source (see term *D* of the code) and indirect sources (use of incense, a fan, and exposure to tobacco smoke; see term 7). Regarding the concentration for YSI05, the code indicates a high value for cooking source (see term 9). This seems correct, as this participant prepared dishes throughout the day for sale, mainly using wood as the cooking fuel. For the concentration obtained for YSI20, the code indicates the use of mosquito coils to protect against mosquitoes at night (see term *m*), and the tests conducted on the combustion of mosquito coils used by the participants confirm high particle emissions. In contrast, the relatively low concentration of 178.6 ± 33.7 µg m^{-3} observed for YSI03 can be explained by the low

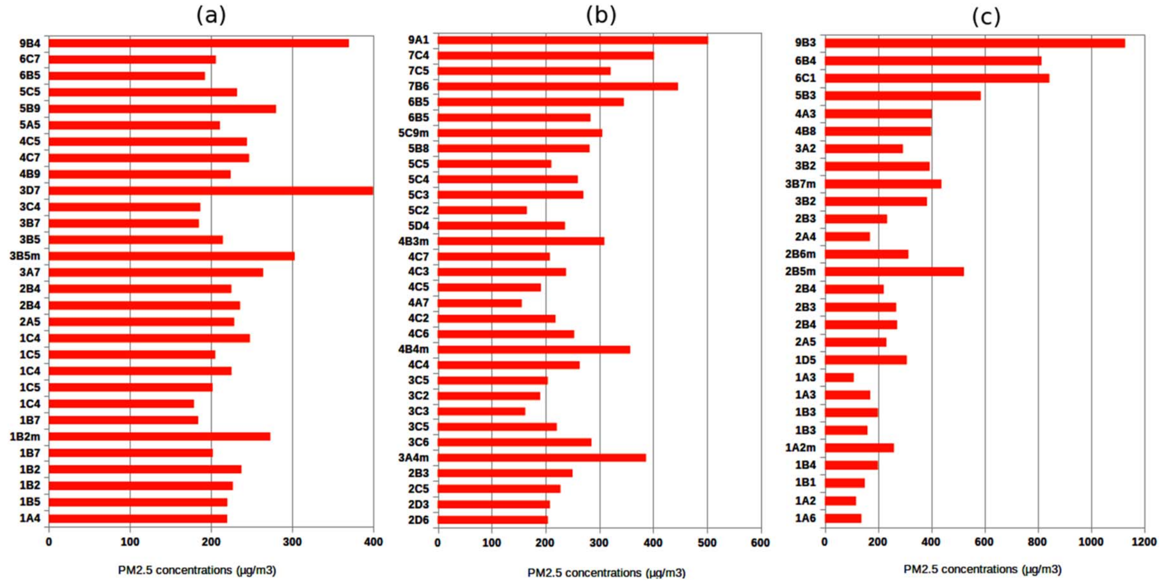

Fig. 5 Representation of the mean daily personal exposure to $PM_{2.5}$ of each participant according to the polluting source to which they are exposed represented by the source code: (a) housewives; (b) charcoal makers; and (c) fish-smoking women.

contribution from a cooking source (see term 1 of code 1C4). The terms 3 and B of code 3B7 also indicate a low impact from cooking and traffic sources for participant YSI29 (184.6 ± 41.9 µg m^{-3}). The participants YSI03 and YSI31 have the same code (1C4) but different concentrations (178.6 ± 33.7 and 247.5 ± 54.5 µg m^{-3}, respectively). The sociological interviews conducted alongside this study can explain this observation in some cases. Some participants are aware of their exposure to smoke and adopt certain practices, such as ventilating their homes, which help reduce their exposure to $PM_{2.5}$. This could explain why, with similar source codes, personal exposure to $PM_{2.5}$ may vary. Investigations are ongoing with sociologists from the APIMAMA project to correlate source codes and perceptions of pollution in data analysis.

For housewives, Fig. 5a and the figures in the Appendix (Fig. S4a and S5a) show no covariance between the source code represented by each of these terms and $PM_{2.5}$ levels. This suggests that all sources contribute to the $PM_{2.5}$ levels. To test this hypothesis, we used a multivariate linear regression model, in which the independent variables are x_1 (cooking activity), x_2 (road traffic), x_3 (indirect sources) and x_4 (use of mosquito coils). To use this model, we assigned equal weight to each variable. As previously shown, we evaluated road traffic and the use of mosquito coils on a scale of 1 to 9, similar to combustion activities and indirect sources. We finally found that road traffic is the primary contributor to the $PM_{2.5}$ levels measured among housewives, followed by indirect sources and mosquito coil use, according to the following equation:

$$y = 12.2x_1 + 20.3x_2 + 14.8x_3 + 10.3x_4;\ R^2 = 0.9;$$
$$p\text{-value }(x_1) = 0.06,\ p\text{-value }(x_2) = 0.0003,$$
$$p\text{-value }(x_3) = 0.02 \text{ and } p\text{-value }(x_4) = 0.02.$$

For the remainder of the analysis, and despite the previous result, we only considered the first term of the source code, focusing on combustion activities.

3.1.3. Grouping of participants according to their cooking combustion activity. Table 2 shows the cooking source score (the first digit of the source code, see Section 2.3.1), allowing the housewives to be grouped into 3 subgroups: G1, G2 and G3.

Thus, participants who obtained scores of 1, and 2 and 3 for the cooking source constitute subgroups G1, and G2, respectively. When this score is between 4 and 9, the housewives form the G3 subgroup.

The median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 is 219.7 (201.8–229.1), 228.1 (214.2–263.8) and 231.7 (210.7–246.5) µg m^{-3}, respectively. As indicated by the p-values, the median daily personal exposure of the subgroups does not statistically differ (statistical significance set at $p < 0.05$; $p = 0.23$ for G1 and G2, 0.89 for G2 and G3 and 0.20 for G1 and G3). However, the concentration shows an increasing trend across exposure groups (G1 < G2 < G3).

3.2. Charcoal makers

3.2.1. Personal exposure to $PM_{2.5}$. Fig. 3b presents the mean daily personal exposure to $PM_{2.5}$ for each charcoal-making participant. Although all participants in this group engaged in the same activity, we noted differences between the measured values. Several factors may explain this observation. First, the scale of charcoal making activity varies among participants. For example, wood supply capacity varies from one charcoal-making woman to another, ranging from once a month to daily. Second, some participants are more involved in the delivery of charcoal than in charcoal making process. In addition, their homes are located in the vicinity of the Cité Ado site, ranging from a 5 min-walk to an hour by public transport.

Table 2 Median daily personal exposure to $PM_{2.5}$ of subgroups (G1, G2 and G3) of each group studied (housewives, charcoal makers and fish-smoking women)

Study group	Sub-group	Score	*n*	Median $PM_{2.5}$ (IQR) ($\mu g\ m^{-3}$)
Housewives	G1	1	12	219.7 (201.8–229.1)
	G2	2–3	9	228.1 (214.2–263.8)
	G3	4–9	9	231.7 (210.7–246.5)
Charcoal makers	G1	2–3	10	214.3 (204.0–244.5)
	G2	4–5	16	245.4 (209.9–273.0)
	G3	6–9	6	373.3 (327.0–434.7)
Fish-smoking women	G1	1	9	159.9 (137.0–198.8)
	G2	2–3	13	293.1 (233.2–283.3)
	G3	4–9	6	700.1 (447.5–836.3)

Finally, as in the case of housewives, the frequency and characteristics of cooking, as well as the use of incense, mosquito repellents and fans, vary from one participant to another. It is interesting to note that the personal exposure to $PM_{2.5}$ of the men in this group is similar to that of women.

The mean daily personal exposure values range from 155.7 ± 34.7 to 501.8 ± 76.4 $\mu g\ m^{-3}$ (Table S2), which are 10 to 33 times higher than the WHO recommended daily limit. It should also be noted that the ambient concentrations measured in Yopougon during the same measurement period (from March 14 to 28, 2023) is 23.1 $\mu g\ m^{-3}$. This value is 7 to 22 times lower than the personal exposure levels and in the same order of magnitude as that observed in the Cité Ado neighborhood.[16]

3.2.2. Relationship between the daily personal exposure of participants and the polluting source to which they are exposed represented by the source code. As with the group of housewives, we first aimed to establish a relationship between all the reported sources to which women were exposed (LES) and their measured personal exposure to $PM_{2.5}$. Fig. 4b shows that there is a strong correlation between the level of exposure to all the sources (LES) and $PM_{2.5}$ ($y = 0.06x$, $R^2 = 0.9$, p-value < 10^{-10}). As previously observed for the housewives, the measured data and the data obtained from the health questionnaire for charcoal makers are consistent.

G1 represents the least exposed participants, G2 indicates moderately exposed participants and G3 indicates highly exposed participants. Score is the first term of the source code (domestic and commercial combustion activity) and *n* the participant number in each sub-group. Median $PM_{2.5}$ is the median of participants' personal exposure in the subgroup, and IQR the interquartile range (Q1–Q3).

Second, we examined the relative contribution of the various sources in the code to the measured $PM_{2.5}$ levels (Fig. 5b, S4b and S5b). The highest concentrations were observed for CAI17, CAI06, and CAI16 (Fig. 5b; 501.8 ± 76.4, 445.8 ± 117.5, and 401.4 ± 233.6 $\mu g\ m^{-3}$), corresponding to codes 9A1, 7C6, and 7C4, respectively (see Table S2). The mean $PM_{2.5}$ concentration measured for CAI17 can be explained by the significant contribution of the charcoal making source (see term 9). Indeed, the participant lives 5 min on foot from the measurement site, and thus she spent more time carrying out her activity. Regarding the concentrations for CAI06 and CAI16, the codes indicate a combination of sources: charcoal making, traffic, and indirect sources (see 7C6 and 7C4, respectively). Although both participants live 30 min on foot from the measurement site, CAI06 used incense and was exposed to tobacco smoke, whereas CAI16 is not exposed to any of these sources and cooks mostly with gas. We also note that the low concentration of 155.7 ± 34.7 $\mu g\ m^{-3}$ observed for CAI10 can be explained by the low contribution of the charcoal making and road traffic sources (see terms 4 and A in code 4A7, respectively). Terms 3 in code 3C3 also indicate a low intensity of charcoal production and indirect sources for participant CAI24 (162.2 ± 44.8 $\mu g\ m^{-3}$).

For charcoal makers, Fig. 5b and the figures in the Appendix (Fig. S4b and S5b) show a covariance between the source code classified solely based on the first term and $PM_{2.5}$ levels. This suggests that charcoal making activity is the main contributor to the measured $PM_{2.5}$ levels. To verify this hypothesis, we used a multivariate linear regression model in which independent variables were x_1 (charcoal making activity), x_2 (road traffic), x_3 (indirect sources) and x_4 (use of mosquito coils), assigning equal weight to each variable. We finally found that charcoal making activity is the primary contributor to the $PM_{2.5}$ levels measured among charcoal makers, followed by the use of mosquito coil, according to the following equation:

$$y = 43.3x_1 + 5.4x_2 + 6.4x_3 + 16.3x_4;\ R^2 = 0.9;$$
$$p\text{-value } (x_1) < 0.0001,\ p\text{-value } (x_2) = 0.2,$$
$$p\text{-value } (x_3) = 0.2 \text{ and } p\text{-value } (x_4) = 0.0002.$$

For the remainder of the analysis, we only considered the first term of the source code.

3.2.3. Grouping of participants according to their charcoal making activity. Here, we divided the participants into three subgroups (G1, G2, and G3) based on their charcoal making activity, as indicated by the first digit of the source code. Tables 2 and S2 (in the Appendix) present the methodology used to establish the subgroups and the distribution of participants within them: participants who obtained scores of 2 and 3 and of 4 and 5 constitute subgroups G1 and G2, respectively. When their score is between 6 and 9, the participants are included in the G3 subgroup.

The median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 is 214.3 (204.0–244.5), 245.4 (209.9–273.0) and 373.3 (327.0–434.7) $\mu g\ m^{-3}$, respectively. Subgroups G1 and G2 are not statistically different ($p = 0.65$), whereas subgroup G3 differs statistically from G1 and G2 ($p = 0.01$ for G3 and G1 and 0.02 for G3 and G2). The median personal exposure to $PM_{2.5}$ in G3 is 1.7 times higher than G1 and 1.5 times higher than G2. These differences highlight the importance of occupational exposure to fine particulate matter related to charcoal making activity.

3.3. Fish-smoking women

3.3.1. Personal exposure to $PM_{2.5}$. Fig. 3c shows the mean daily personal exposure of each fish-smoking participant. The differences observed between the participants may be explained by the fact that they are involved to varying degrees in fish smoking. The amount of fish smoked per day varies considerably from one woman to another, ranging from 2 to 22 boxes of fish (*i.e.*, 40 to 440 kg, with each box weighing an average of 20 kg). This involvement also depends on the participant's status within the fish-smoking group. Participants were either contract workers or oven owners. Contract workers spend their days smoking fish and work for oven owners. Some oven owners also spend the whole day smoking the fish sold by fish traders. Others, however, hire contract workers to help them smoke fish and devote more time to buying and selling their own goods. Finally, as with the other groups studied, the variation in personal exposure to $PM_{2.5}$ may also be due to the frequency and characteristics of cooking, as well as the use of incense, mosquito repellents and fans, which also vary from participant to participant. It is important to note, that in the group of fish-smoking women, (1) 23 participants performed their activity at smoking sites near the lagoon (Yopougon Santé and Abobodoumé, where more than 50 women work), and (2) 5 other participants were selected from the Yao Sehi site to study the impact of fish smoking in neighborhoods and markets. This practice is widespread in West African cities, where small groups of women (5 to 10 people) carry out their activities in residential areas, which may affect their health and that of nearby residents, as shown in the study by Coulibaly *et al.*[49] It should be noted that the concentrations measured in (1) and (2) are in the same order of magnitude.

The mean daily personal exposure to $PM_{2.5}$ in this group ranges from 107.9 ± 44.5 to 1128.5 ± 970.0 μg m^{-3} (Table S3), which is 7 to 75 times higher than the WHO recommended daily limit. Furthermore, these personal concentrations values are 2 to 21 times higher than the ambient concentration (53.6 μg m^{-3}) measured in Yopougon during the same measurement period. This concentration is consistent with that reported by Gnamien.[16]

3.3.2. Relationship between the daily personal exposure of participants and the polluting source to which they are exposed represented by the source code. Similar to the two previous study groups, we aimed to establish a relationship between all the reported sources impacting women (LES) and the measured personal exposure to $PM_{2.5}$. Fig. 4c shows that there is a strong correlation between LES and $PM_{2.5}$ ($y = 0.03x$, $R^2 = 0.8$ and p-value < 10^{-5}). Therefore, there is also good consistency between the measured data and the data obtained from the health questionnaire.

Here, we examined the relative contribution of the various sources in the codes to the measured $PM_{2.5}$ levels. As shown in Fig. 5c, the highest concentrations are observed for DLI21, DLI15 and DLI26 (1128.5 ± 970.0, 843.6 ± 550.8 and 814.4 ± 639.0 μg m^{-3}), corresponding to codes 9B3, 6C1, and 6B4, respectively (Table S3). The mean $PM_{2.5}$ concentration measured for DLI21 can be explained by the strong contribution of the fish-smoking source (see term 9). Indeed, this participant spends day and night smoking fish (21 h day^{-1}), resting very little during the day. Regarding the concentration measured for DLI15, the code indicates the importance of fish-smoking and the road traffic sources (see terms 6 and C, respectively). This participant also spends the night at the smoking site during the week and travels long distances to return home on weekends. Participant code DLI26 indicates the same intensity for the fish-smoking activity as DLI15, but with a higher indirect pollution source and a lower traffic source intensity, which may explain the measured concentration. We also note that the low concentration of 107.9 ± 44.5 μg m^{-3} observed for DLI25 can be explained by the low contribution of fish-smoking, road traffic, and indirect sources (cooking and using a fan, see code 1A3). The causes identified for DLI25 are the same as those for participant DLI09 (116.7 ± 34.9 μg m^{-3}), with the only difference being that DLI09 did not use a fan (see 1A2).

Participants DLI03 and DLI07 have the same code (2B4) but different concentrations (271.0 ± 143.2 and 221.3 ± 80.4 μg m^{-3}, respectively). This is the same for participants DLI22 and DLI25 with code 1A3 and concentrations of 170.2 ± 82.8 and 107.9 ± 44.5 μg m^{-3}, respectively. As mentioned earlier, some participants are aware of their exposure to smoke and adopt certain practices that help reduce their exposure to $PM_{2.5}$.[28] As a result, they have lower concentrations.

For the fish-smoking women, Fig. 5c and the figures in the Appendix (Fig. S4c and S5c) show a covariance between the source code classified solely based on the first term and $PM_{2.5}$ levels. This suggests that fish-smoking activities mainly contribute to the observed $PM_{2.5}$ levels. To verify this hypothesis, we used a multivariate linear regression model in which the independent variables were x_1 (charcoal making activity), x_2 (road traffic), x_3 (indirect sources) and x_4 (use of mosquito coils) and we assigned equal weight to each variable. We finally found that fish-smoking activity is the primary contributor to the $PM_{2.5}$ levels measured among the fish-smoking women, followed by the use of mosquito coils, as well as road traffic and indirect sources according to the following equation:

$$y = 117.3x_1 + 16.6x_2 - 13.7x_3 + 16.3x_4;\ R^2 = 0.94;$$
$$p\text{-value } (x_1) < 0.0001,\ p\text{-value } (x_2) = 0.003,$$
$$p\text{-value } (x_3) = 0.01 \text{ and } p\text{-value } (x_4) < 0.0001.$$

For the remainder of the analysis, we considered only the first term of the source code.

3.3.3. Grouping of participants according to their fish-smoking activity. Considering the relative importance of fish-smoking activity, as indicated by the first digit of the source code, participants were grouped into 3 sub-groups: G1, G2 and

G3 (Table S3). As shown in Table 2, participants who obtained scores of 1, and 2 and 3 constitute subgroups G1 and G2, respectively. When this score is between 4 and 9, the fish-smoking women are included in the G3 subgroup.

The median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 is 159.9 (137.0–198.8), 293.1 (233.2–283.3) and 700.1 (447.5–836.3) μg m^{-3}, respectively. These values are statistically different ($p < 0.05$). $PM_{2.5}$ personal exposure in G3 is 4.4 times higher than G1 and 2.4 times higher than G2. G2 personal exposure to $PM_{2.5}$ is 1.8 times higher than G1. It is important to highlight that the G3 subgroup is composed of oven owners who spend the whole day (and night for some) smoking fish for several people. G2 mainly consists of participants who work with contract workers but on their own goods only, whereas oven owners who just supervise the fish cooking process form the G1 subgroup. The large differences in the median concentrations across the 3 subgroups highlight the importance of occupational status in measuring exposure to fine particulate matter.

3.4. Comparison of results

3.4.1. Comparison of results between study groups. Comparing the results obtained for the three different groups of women may prove challenging, as the experimental campaigns did not take place during the same time of the year. Therefore, seasonal variations in meteorology and regional aerosol transport are expected to impact $PM_{2.5}$ personal exposure.

It should be noted that the measurement campaigns took place in November 2022, March 2023, and July–August 2023 for housewives, charcoal makers and fish-smoking women, respectively. In terms of meteorological conditions, no significant differences were observed between these. Specifically, mean temperatures were 27.7 °C, 28.6 °C and 26.3 °C (https://www.infoclimat.fr/climatologie/annee/2023/abidjan/valeurs/65578.html), and the relative humidity values were 90%, 89% and 97% (https://metar-taf.com/fr/climate/abidjan) for the housewives, charcoal makers and fish-smoking women campaigns, respectively. With regard to regional variations in aerosol transport, primarily linked to the transport of desert dust, the ambient concentrations measured in Yopougon showed no significant differences across the three monitoring campaigns. In fact, due to the regional transport of desert dust, ambient $PM_{2.5}$ concentrations during the dry season are expected to be higher than those during the wet season. However, this is not the case in our study: the ambient $PM_{2.5}$ levels are comparable (47.9 μg m^{-3} and 23.1 μg m^{-3} during dry season for housewives and charcoal makers, respectively, and 53.6 μg m^{-3} during the wet season for fish-smoking women). For these two reasons, we consider it possible to compare the levels of personal exposure to $PM_{2.5}$ obtained by the study groups without taking into account the different seasons in which the measurements were performed.

Personal exposure to $PM_{2.5}$ among housewives, charcoal makers and fish-smoking women was assessed by calculating the median daily exposure to $PM_{2.5}$ for all participants in each group, which is 224.7 (205–254.9), 251.6 (207.9–306.3) and 269.2 (191.7–399.8) μg m^{-3}, respectively (Table 3). The values for the group of housewives and those for the group of women who smoke fish ($p = 0.02$) differ significantly, unlike those observed between the values for the group of charcoal makers and the other two groups ($p = 0.07$ for charcoal makers *vs.* housewives and $p = 0.11$ for charcoal makers *vs.* women who smoke fish). Despite this, the $PM_{2.5}$ concentrations increase in the order of housewives < charcoal makers < fish-smoking women, and the concentration for fish-smoking women is 1.2 times higher than that for housewives. As expected, charcoal makers and fish-smoking women exhibit higher concentrations than housewives because they engage in occupational activities that generate pollution. Also, the fish-smoking women remain close to the oven to monitor the cooking process, while charcoal makers sometimes move away from the smoke because they have sheds near their kilns. Furthermore, it is important to note that the wood (rubber wood) burned by fish-smoking women emits more particles than the wood burned by charcoal makers.

3.4.2. Comparison of results with the literature. Table 3 presents a comparison of our results with the literature in terms of personal exposure to $PM_{2.5}$. It is important to mention here that the values in the literature have been grouped according to their levels for easier reading (*A* values are below 100 μg m^{-3}, *B* values are between 100–200 μg m^{-3}, *C* values are between 200–500 μg m^{-3} and *D* values are above 500 μg m^{-3}).

The first focus is on the personal exposure to $PM_{2.5}$ of housewives using charcoal as cooking fuel.

Firstly, we note that the value for the housewives' group is higher than those for group *A* (ref. 27) and *C* (ref. 24). This discrepancy may be due to the differences in measurement periods among the studies. Indeed, the measurements in rural areas of central Ghana[27] and in Rwanda[24] were conducted during the wet season (from July to December 2007 and from October 2021 to March 2022, respectively), while our measurements of participants using charcoal were conducted during the dry season. Outdoor particle pollution is lower during the wet season due to atmospheric rain deposition, which may explain the lower personal exposure levels found in the studies by Ishigaki *et al.*[24] and Van Vliet *et al.*[27] Furthermore, this difference can also be explained by the participants' practices. Among the housewives studied here, some use both charcoal and wood, leading to higher personal exposure to $PM_{2.5}$ (*e.g.*, YSI05). Finally, the concentrations reported in the literature were measured at a rural site in Ghana, whereas our study was conducted in an urban setting with a higher population density.[27] Also, as pointed out in the study by Sidibe *et al.*,[48] rural residents travel less for their daily activities than urban residents. Therefore, they are less exposed to outdoor pollution, such as that caused by traffic, than the housewives in Abidjan, who, as demonstrated earlier, are strongly affected by this source.

Secondly, our main value is lower than that reported for group *D* (ref. 26), which is expected. Indeed, this study focuses on the personal exposure of a single participant, a secondary school teacher living in Njombe (Tanzania) who cooks in a room adjacent to the main living area, with the windows closed and the door slightly open.

Table 3 Range of personal $PM_{2.5}$ exposure associated with wood and/or charcoal use reported in the literature from studies published between 2011 and 2024. The values obtained in this work are included for comparison

Range	Concentration of $PM_{2.5}$	Fuel used	Sampling period	Study area	Ref.
A (<100) μg m^{-3}	61 μg m^{-3}	Wood	September 2012	China (Rural Sichuan)	Shan *et al.*[50]
	45 μg m^{-3}	Wood	June 2017 to September 2019	China	Shupler *et al.*[51]
	89 μg m^{-3}	Wood	June 2017 to September 2019	India	Shupler *et al.*[51]
	39 μg m^{-3}	Wood	June 2017 to September 2019	Chile and Colombia	Shupler *et al.*[51]
	44.6 μg m^{-3}	Charcoal	July to December 2007	Ghana	Van Vliet *et al.*[27]
B (100–200) μg m^{-3}	115.7 μg m^{-3}	Wood	February to June 2016	Uganda	Okello *et al.*[25]
	119.9 μg m^{-3}	Wood	July to September 2016	Ethiopia	Okello *et al.*[25]
	114 μg m^{-3}	Wood	August to September	Sri Lanka (Anagi Stove)	Chartier *et al.*[52]
	141.9 μg m^{-3}	Wood	July to December 2007	Ghana	Van Vliet *et al.*[27]
	153 μg m^{-3}	Wood	June 2017 to September 2019	Tanzania and Zimbabwe	Shupler *et al.*[51]
	148 μg m^{-3}	Wood	June 2017 to September 2019	Bangladesh and Pakistan	Shupler *et al.*[51]
C (200–500) μg m^{-3}	249 μg m^{-3}	Wood	Dec. 2013 to Nov. 2016	Indian	Elf *et al.*[53]
	293.1 ± 79.2 μg m^{-3}	Wood	Sept. 4 to 21 2016	China (Nanliu Village, Hw3)	Xu *et al.*[54]
	201 μg m^{-3}	Wood	Aug. to Sept	Sri Lanka (traditional stove)	Chartier *et al.*[51]
	265 μg m^{-3}	Wood	Oct. 2021 to March 2022	Rwanda	Ishigaki *et al.*[24]
	289 μg m^{-3}	Wood	Aug. 2008 to Feb. 2009 and March to June 2009	China (Xuanwei and Fuyuan)	Hu *et al.*[55]
	205 μg m^{-3}	Charcoal	Oct. 2021 to March 2022	Rwanda	Ishigaki *et al.*[24]
	304.6 ± 284.5 μg m^{-3}	Wood	April to June 2016	Côte d'Ivoire (Yopougon)	Xu *et al.*[19] (wet season)
	224.7 (205–245.9) μg m^{-3}	Charcoal and wood	Nov. to Dec. 2022	Côte d'Ivoire (Yopougon)	This work (housewives)
	251.6 (207.9–306.3) μg m^{-3}	Wood	March 2023	Côte d'Ivoire (Yopougon)	This work (charcoal makers)
	269.2 (191.7–399.8) μg m^{-3}	Wood	July to Sept. 2023	Côte d'Ivoire (Yopougon)	This work (fish-smoking women)
D (>500) μg m^{-3}	541.14 μg m^{-3}	Wood	April 30 to May 03, 2019	Nepal	Johnston *et al.*[56]
	1574 ± 287 μg m^{-3}	Wood	March 2007	Tanzania (Uwemba)	Titcombe and Simcik[26]
	588 μg m^{-3}	Charcoal	Feb. 2007	Tanzania (Njombe)	Titcombe and Simcik[26]

The second focus is on the exposure to $PM_{2.5}$ of people when wood is used as a fuel. As shown in Table 3, the concentrations for charcoal makers (251.6 μg m^{-3}) and fish-smoking women (269.2 μg m^{-3}) in our study using wood are higher than those reported in the literature for groups *A* ($PM_{2.5}$ < 100 μg m^{-3}) and *B* (100 < $PM_{2.5}$ < 200 μg m^{-3}), comparable to those reported for group *C* (200 < $PM_{2.5}$ < 500 μg m^{-3}), and lower than those reported for group *D* ($PM_{2.5}$ > 500 μg m^{-3}).

The literature data from groups *A* and *B* concern individuals who mainly use wood for cooking activities, with a shorter daily exposure time compared to the occupational exposure studied in our work.

In groups *C* and *D*, the majority of studies were conducted in Asia (71%) and during the cold season. Wood is used not only for cooking but also for heating, which can result in higher personal exposure to $PM_{2.5}$.[55] We note that the very high values obtained by Titcombe and Simcik[26] refer to the exposure of a person living in Uwemba (Tanzania) under very precarious conditions, cooking traditionally on an open wood fire with three large stones used to hold the pot. However, it is worth noting that the personal exposure to $PM_{2.5}$ of some participants in the fish-smoking group (*e.g.*, DLI21, DLI15, DLI26, *etc.*) is of the same order of magnitude as those in group *D*.

Finally, the comparison between the fish-smoking women group with Xu *et al.*[19] shows similarities terms of the targeted population, the measurement site (Yopougon, Abidjan), the use of rubber wood for occupational activity, the season (wet season) and the practices (use of charcoal and gas by participants for cooking at home, cleaning daily, *etc.*). However, the personal exposure to $PM_{2.5}$ obtained by Xu *et al.*[19] is 1.1 times higher than the values in our study (Table 3). This difference could be explained by the difference in population sizes and measurement time. Indeed, only two participants were involved in their study during a 3-days measurement period (from July 5 to 7),[19] while our study included 28 participants over a one-month measurement period (from August 1 to September 1). Another explanation could be the difference in particle emissions based on the type of food being smoked (fish in our study *vs.* meat in the study by Xu *et al.*[19]). It would be interesting to validate this hypothesis with the measurement of emission factors for different smoked foods.

To conclude, the personal exposure to $PM_{2.5}$ measured in this study is in agreement with those found in the literature.

3.5. Contribution of domestic and commercial combustion activities to personal exposure to $PM_{2.5}$

3.5.1. Daily profiles of personal exposure of study groups. Fig. 6 presents the daily profiles of personal exposure to $PM_{2.5}$ of the three subgroups (G1, G2, and G3) of the (a) housewives, (b) charcoal makers and (c) fish-smoking women groups. Note that these profiles were obtained by calculating the median of the daily profiles of each participant comprising the subgroups. These results are consistent with the statistical analyses previously described. Indeed, the three subgroups within the housewives' group exhibit similar daily profiles (Fig. 6a). For the charcoal makers, subgroups G1 and G2 exhibit similar profiles, while that of G3 is different (Fig. 6b). In contrast, the three subgroups within the fish-smoking women group exhibit different profiles (Fig. 6c). In Fig. 6a (housewives' group), high concentrations of $PM_{2.5}$ can be observed at 7 am and from 5 to 9 pm. The morning peak is certainly due to water heating for bathing and contact with road traffic. From 5 to 9 pm, the high concentrations could be explained by cooking activities carried out in the evening at various times by the participants in this group. This observation is in agreement with a previous study, which also showed a large evening peak in domestic activities.[16]

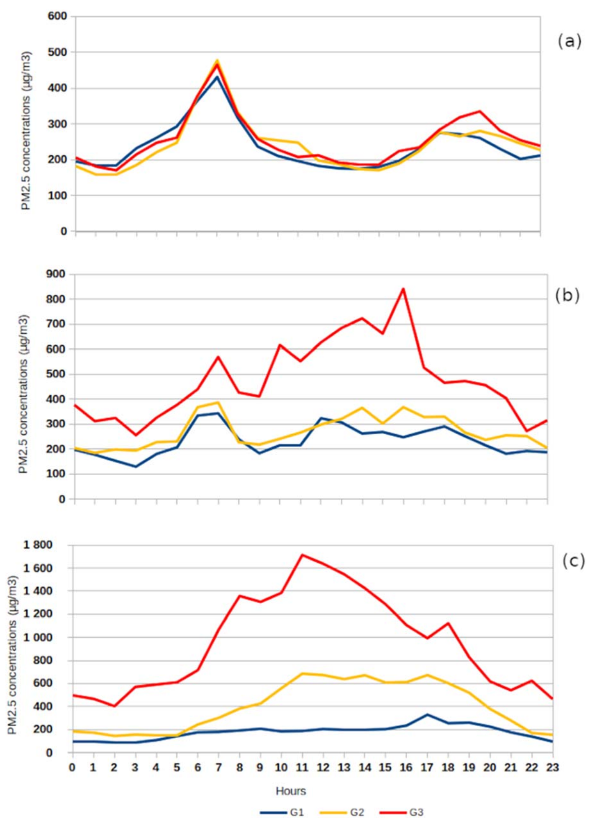

Fig. 6 Daily personal $PM_{2.5}$ exposure profiles of the three subgroups (G1, G2, and G3) within (a) housewives, (b) charcoal makers and (c) fish-smoking women groups.

The daily profiles of the charcoal makers group also exhibit two peaks but at different times (Fig. 6b): one between 6 am to 7 am and another between 10 am to 6 pm, which can be explained by exposure to road traffic and charcoal making activity, respectively. Indeed, charcoal makers mostly use "wôrô–wôrô" and "gbakas" (shared taxis and buses, respectively) to travel to their work site (morning peak) and work between 10 am and 6 pm (diurnal peak). We observed that the diurnal peaks of $PM_{2.5}$ concentrations in G3 are higher than those in G1 and G2, which is consistent with our previous results. G3 consists of participants whose charcoal-making activities are more intensive than those of the other two groups (G1 and G2).

With regard to the fish-smoking women group (Fig. 6c), we observed high concentrations throughout the day, which can be attributed to their fish-smoking activity. It can be observed that subgroup G3 has very high concentrations during this period compared to the profile of G2, which has high concentrations compared to profile G1. As previously mentioned in Section 3.3.3, G3 consists of participants with very high levels of fish-smoking activity, while G2 comprises participants with lower levels of this activity and G1 consists of participants less involved in fish-smoking activity. This finding highlights the appropriateness of selecting subgroups G1, G2, and G3 for the fish-smoking women group by demonstrating the significance of fish-smoking activity on diurnal variations in personal exposure to $PM_{2.5}$.

Fig. 7 presents a comparison of the daily profiles of personal $PM_{2.5}$ exposure for the three groups studied. Each profile was obtained by calculating the median of the profiles of all the participants in the group. This result is consistent with our previous findings as it clearly shows similar variations in concentrations of fish-smoking women and charcoal makers, with higher concentrations during the day (from 11 am to 5 pm) than for the housewives who remain at home. Furthermore, during this period, the concentration for the fish-smoking women is higher than that for the charcoal makers. This can be explained by the points mentioned above (Section 3.4.1). In summary, the time spent exposed to smoke and the fuel used differ for these two groups.

We also note that all groups exhibit high personal $PM_{2.5}$ exposure between 6 and 7 am, with higher values for housewives and lower values for fish-smoking women. There are several reasons that may explain the significance of this morning peak among housewives, including housework, which generally takes place after waking up and exposure to traffic when they take their children to school or go to the market. Also, most of the fish-smoking women live close to the smoking site and walk there through narrow alleys.

From 5 to 9 pm, we observed a peak due to cooking activities in the housewives' group, whereas for the other two professional groups, the concentrations tended first to decrease from 6 to 8 pm, and then increase from 8 to 10 pm. The concentration variations from 6 to 8 pm could be due to participants returning home. Indeed, for most of them, the workday ends at 5 pm. After this time, participants return home and engage in cooking

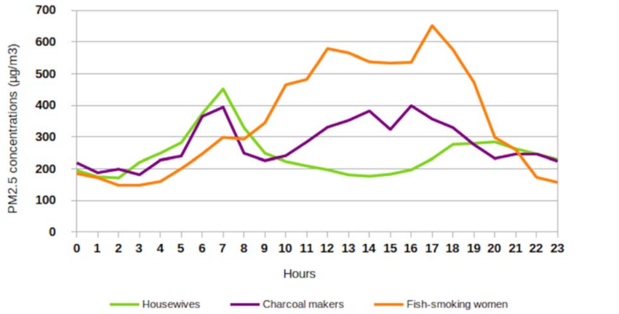

Fig. 7 Comparison of the mean daily profiles of personal $PM_{2.5}$ exposure of the three study groups (housewives, charcoal makers and fish-smoking women).

activities at around 9 pm. It is important to note that the health questionnaire revealed that employed women cook every other day, while housewives cook every day.

These results show that domestic and commercial combustion activities do not have the same impact on the daily personal exposure profiles of the different groups and subgroups. In this context, we aimed to quantify the contribution of domestic and commercial combustion activities to the total daily exposure of participants.

3.5.2. Quantification of the impact of domestic and commercial combustion activities on daily personal exposure to $PM_{2.5}$. As explained in Section 2.3.2, the contribution of domestic cooking (for the housewives' group and its subgroups) and commercial combustion activities (for charcoal makers and fish-smoking women groups and their subgroups) to total daily $PM_{2.5}$ exposure was calculated as follows:

$$\%\,CA = 100 \times DPE_{CA}/DPE_T$$

where DPE_{CA} is the daily personal exposure linked to the domestic or combustion activities of the women and DPE_T their total daily personal exposure. DPE_T is the sum of DPE_{CA} and DPE_O, representing the daily personal exposure linked to other activities than domestic and commercial activities.

Table S4 presents the DPE_{CA}, DPE_O and DPE_T values for the different groups and subgroups. It is interesting to mention that DPE_{CA} for the fish-smoking group (316 µg m^{-3} per day) is 3 times higher than those of the housewives (82 µg m^{-3} per day) and charcoal makers (113 µg m^{-3} per day) groups. It should also be noted that the differences in DPE_{CA} values for groups G1, G2, and G3 are very significant for the fish-smoking women. A comparison with data in the literature shows that the total daily personal $PM_{2.5}$ exposure of the housewives group (282.4 ± 100.4 µg m^{-3} per day) and its subgroups falls within the range of values obtained by Sidibe *et al.*[48] (432 µg m^{-3} per day) and Van Vliet *et al.*[27] (128.50 µg m^{-3} per day). The value found in Bamako (Mali) for the "Cook" group, consisting of 3 people is 1.5 times higher than that in our study.[48] The activities of these individuals include food preparation, dishwashing and house cleaning, shopping, and the use of charcoal and wood as fuels. The differences between our results and those of Sidibe *et al.*[48] could be explained by the fact that the individuals studied used incense and insecticides at night, whereas only some participants in our group of 30 women use them, which has a significant impact on total daily personal exposure. Furthermore, we observed that DPE_T strongly depends on the use of charcoal and wood, with higher exposure occurring when wood is used. In the housewives' group in our study, only 16% of participants used wood, whereas a higher proportion of participants in the "Cook" group used wood. This difference may explain the lower values in our study. The value found in Ghana is 2.2 times lower than that in our study.[27] This is consistent with the explanations given in the previous paragraph regarding the differences in personal exposure between our study and that of Van Vliet *et al.*[27]

Fig. 8 presents the relative contribution of domestic or commercial combustion activities to the total daily personal exposure (% CA, eqn (7)) for all the groups and their subgroups. The results presented in Fig. 8 confirm our previous findings. Cooking activities have a lower impact on total daily personal exposure than charcoal making, which in turn has a lower impact than fish smoking. We note that cooking activities contribute on average to 29% ± 10% to DPE_T for housewives (Table S4). For charcoal makers and fish-smoking women, combustion activities contribute 31% ± 11% to 41% ± 13% and 18% ± 16% to 71% ± 18%, respectively, depending on the subgroups.

The fact that the contribution of domestic combustion activities (cooking) and charcoal making activity is less than half of DPE_T among housewives and charcoal makers indicates that other pollution sources (road traffic, use of mosquito coils and indirect sources) contribute more to their DPE_T. However, it is important to highlight that these other sources of pollution have a greater impact on housewives than on the charcoal makers group, as previously shown by multivariate analysis.

On the other hand, the 62% ± 17% and 71% ± 18% contributions of combustion activities to the DPE_T of subgroups G2 (G2-DLI) and G3 (G3-DLI), respectively, of the fish-smoking women group, highlight the significant role played by the occupational activities of this group in their exposure to particulate pollution.

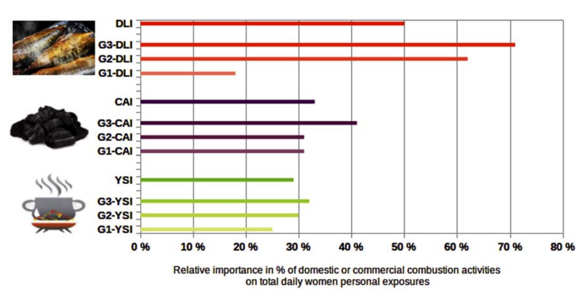

Fig. 8 Contribution of domestic and commercial combustion activities to total daily personal exposure of study groups and their subgroups (for housewives: YSI, G1-YSI, G2-YSI and G3-YSI, for charcoal makers: CAI, G1-CAI, G2-CAI and G3-CAI and for fish-smoking women, DLI, G1-DLI, G2-DLI and G3-DLI).

Therefore, we can conclude that commercial combustion activities have a significant impact on the total daily personal exposure of women.

4 Conclusion

Our main findings show that the median daily personal $PM_{2.5}$ exposure among women is 15, 17 and 18 times higher than the WHO recommended limit for the housewives, charcoal makers and fish-smoking women, respectively. Looking at the professional subgroups in detail, these values vary from 14 to 25 and from 11 to 47 depending on the intensity of the occupational activity of charcoal makers and fish-smoking women, respectively. By analyzing each participant's questionnaire responses, we were able to determine both the level of exposure to all sources to which the women were exposed and the contribution of each source. This innovative study demonstrates that (1) there is a correlation between personal $PM_{2.5}$ exposure in women and the identified sources, (2) traffic makes a significant contribution to the personal $PM_{2.5}$ exposure of housewives, and (3) occupational activities make a significant contribution to the personal $PM_{2.5}$ exposure of charcoal makers and fish-smoking women.

This is an alarming situation and a real public health issue for women in Abidjan, but also for all women in West African cities who engage in similar practices. It is important to recall that smoking practices, whether for fish or meat, are very common in West Africa. These practices use traditional ovens and are often carried out under lean-tos or in confined spaces that trap smoke, frequently using highly polluting wood such as rubber wood.

These results highlight the fact that reducing women personal $PM_{2.5}$ exposure is now a necessity. We observed in our study that cooking activities represent, on average, 29% of the total daily personal exposure of housewives. This suggests that the use of improved cookstoves could have a significant impact on reducing $PM_{2.5}$ exposure among housewives.

The use of improved stoves combined with less polluting wood (instead of traditional stoves and rubber wood) could have an even more significant impact on $PM_{2.5}$ exposure among fish-smoking women, since 71% $\pm$ 18% of their exposure is related to occupational activities. However, reducing women's personal exposure is a complex and long-term process. Even if technical solutions exist, they will inevitably have an impact on domestic and commercial practices, and women will be the first to implement these changes. These changes will also affect relationships between different communities (professionals, customers, stakeholders, *etc.*). Therefore, these changes should be addressed in a holistic manner that goes beyond exposure reduction and technical control measures, requiring close collaboration between participating associations and stakeholders, as well as an interdisciplinary scientific approach. This is the plan for the next phase of the APIMAMA project, which will involve the introduction of improved cooking techniques and tools in the study groups. This will allow us to assess their impact on the personal $PM_{2.5}$ exposure of women across the different groups.

Ethics approval

The study protocol defined by the pilot group was submitted to and approved by the ethics committee of Côte d'Ivoire called Comité National d'Ethique des Sciences de la Vie et de la Santé (CNESVS) du Ministère de la Santé, de l'Hygiène Publique et de la Couverture Maladie Universelle). The reference number is 147–22/MSHP/CNESVS-km. All the participants in the project gave their consent for the present study.

Author contributions

Marie Yapo: investigation, software, formal analysis, data curation, writing – original draft, writing – review & editing, Cathy Liousse: conceptualization, investigation, supervision, validation, methodology, writing – original draft, writing – review & editing, Sylvain Gnamien: supervision, methodology, writing – review & editing, Jean-François Léon: methodology, writing – review & editing, Marine Scandella and Sylvia Becerra: investigation, writing – review & editing, Nicolas Brou, Coulibaly M'begnan: investigation and methodology, Stéphane Ahoua and Ayenon Junior Yapo: investigation, Maria Dias Alves, Eric Gardrat, Isabella Annesi-Maesano and Thierno Doumbia: methodology, Véronique Yoboué: conceptualization, supervision, methodology.

Conflicts of 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.

Data availability

Data supporting this article have been included as part of the supplementary information (SI). Supplementary information: measured $PM_{2.5}$ personal exposures are given for each woman of each group as well as values of daily personal exposures to $PM_{2.5}$ for women groups and subgroups by indicating the contribution of domestic and commercial activities. The health questionnaire data are not available to access. See DOI: https://doi.org/10.1039/d6ea00027d.

Acknowledgements

Firstly, we would like to thank the French National Research Agency (ANR) for its funding support to APIMAMA (Air Pollution Mitigation Actions for Megacities in Africa) project (grant number: ANR-21-CE22-0003), including M. Yapo PhD funding. Secondly, we would like to thank all the women from the three groups who generously gave their time to participate in the experiment and who made this work possible. We also thank the village chief Yao Sehi of Yopougon and the representatives of each women's group who welcomed us and helped us organize the different experiments as well as the various members of the APIMAMA pilot group. Our acknowledgments go to the other members of the APIMAMA project who helped us in the field and made this study possible: Akoua Adaye, Julien Bahino, Madina Doumbia, Flavie Evilafo, Azimi Gbane, Sékou Keita, Sophie Kouassi, Auriane Pajot, Ruth Vanié and Armelle Baeza. Our gratitude also goes to GAIA company for developing the $PM_{2.5}$ sensors for the APIMAMA project and to Dr Signo's team at UFHB for their maintenance. Finally, we would like to thank the administrative teams and the people in charge of communication for supporting us in the progress of the APIMAMA project.

References

1 M. O. Andreae and P. Merlet, Emission of trace gases and aerosols from biomass burning, *Global Biogeochem. Cycles*, 2001, **15**(4), 955–966, DOI: 10.1029/2000GB001382.

2 M. Doumbia, A. A. Kouassi, S. Silué, V. Yoboué, C. Liousse, A. Diedhiou, N. E. Touré, S. Keita, E.-M. Assamoi, A. Bamba, M. Zouzoua, A. Dajuma and K. Kouadio, Road Traffic Emission Inventory in an Urban Zone of West Africa: Case of Yopougon City (Abidjan, Côte d'Ivoire), *Energies*, 2021, **14**(4), 1111, DOI: 10.3390/en14041111.

3 T. Doumbia, C. Liousse, M.-R. Ouafo-Leumbe, S. A. Ndiaye, E. Gardrat, C. Galy-Lacaux, C. Zouiten, V. Yoboué and C. Granier, Source Apportionment of Ambient Particulate Matter (PM) in Two Western African Urban Sites (Dakar in Senegal and Bamako in Mali), *Atmosphere*, 2023, **14**(4), 684, DOI: 10.3390/atmos14040684.

4 S. Gnamien, C. Liousse, S. Keita, R. Kumar and V. Yoboué, High-Resolution Modeling of Air Quality in Abidjan (Côte d'Ivoire) Using a New Urban-Scale Inventory, *Atmosphere*, 2024, **15**(7), 758, DOI: 10.3390/atmos15070758.

5 S. Keita, C. Liousse, E.-M. Assamoi, T. Doumbia, E. T. N'Datchoh, S. Gnamien, N. Elguindi, C. Granier and V. Yoboué, African anthropogenic emissions inventory for gases and particles from 1990 to 2015, *Earth Syst. Sci. Data*, 2021, **13**(7), 3691–3705, DOI: 10.5194/essd-13-3691-2021.

6 C. Liousse, E. Assamoi, P. Criqui, C. Granier and R. Rosset, Explosive growth in African combustion emissions from 2005 to 2030, *Environ. Res. Lett.*, 2014, **9**(3), 035003, DOI: 10.1088/1748-9326/9/3/035003.

7 Z. Wang, C. Gu, F. Li, P. Bale and H. Sun, Active demand response using shared energy storage for household energy management, *IEEE Trans. Smart Grid*, 2013, **4**(4), 1888–1897, DOI: 10.1109/TSG.2013.2258046.

8 I. Ozturk and F. Bilgili, Economic growth and biomass consumption nexus: Dynamic panel analysis for Sub-Sahara African countries, *Appl. Energy*, 2015, **137**, 110–116, DOI: 10.1016/j.apenergy.2014.10.017.

9 M. Adon, V. Yoboué, C. Galy-Lacaux, C. Liousse, B. Diop, E. H. Doumbia, S. A. Ndiaye and C. Jarnot, Measurements of NO2, SO2, NH3, HNO3 and O3 in West African urban environments, *Atmos. Environ.*, 2016, **135**, 31–40, DOI: 10.1016/j.atmosenv.2016.03.050.

10 J. Bahino, V. Yoboué, C. Galy-Lacaux, M. Adon, A. Akpo, S. Keita, C. Liousse, E. Gardrat, C. Chiron, M. Ossohou, S. Gnamien and J. Djossou, A pilot study of gaseous pollutants' measurement (NO2, SO2, NH3, HNO3 and O3) in Abidjan, Côte d'Ivoire: contribution to an overview of gaseous pollution in African cities, *Atmos. Chem. Phys.*, 2018, **18**(7), 5173–5198, DOI: 10.5194/acp-18-5173-2018.

11 J. Dominutti, S. Keita, J. Bahino, A. Colomb, C. Liousse, V. Yoboué, C. Galy-Lacaux, E. Morris, L. Bouvier, S. Sauvage and A. Borbon, Anthropogenic VOCs in Abidjan, southern West Africa: from source quantification to atmospheric impacts, *Atmos. Chem. Phys.*, 2019, **19**(18), 11721–11741, DOI: 10.5194/acp-19-11721-2019.

12 J. Bahino, P. Dominutti, S. Keita, M. Doumbia, M. Adon, A. Colomb, C. Liousse, N. E. Touré, A. Bordon and V. Yoboue, Diurnal Variation and Health Risk Assessment of Anthropogenic VOCs Concentrations in Abidjan, Côte d'Ivoire: a Comparative Study of Traffic and Domestic Fire Sites, *Aerosol Air Qual. Res.*, 2025, **25**(8), 45, DOI: 10.1007/s44408-025-00049-3.

13 J. Djossou, J.-F. Léon, A. B. Akpo, C. Liousse, V. Yoboué, M. Bedou, M. Bodjrenou, C. Chiron, C. Galy-Lacaux, E. Gardrat, M. Abbey, S. Keita, J. Bahino, N. E. Touré, M. Ossohou and C. N. Awanou, Mass concentration, optical depth and carbon composition of particulate matter in the major southern West African cities of Cotonou (Benin) and Abidjan (Côte d'Ivoire), *Atmos. Chem. Phys.*, 2018, **18**(9), 6275–6291, DOI: 10.5194/acp-18-6275-2018.

14 A. J. Adon, C. Liousse, E. T. Doumbia, A. Baeza-Squiban, H. Cachier, J.-F. Léon, V. Yoboué, A. B. Akpo, C. Galy-Lacaux, B. Guinot, C. Zouiten, H. Xu, E. Gardrat and S. Keita, Physico-chemical characterization of urban aerosols from specific combustion sources in West Africa at Abidjan in Côte d'Ivoire and Cotonou in Benin in the frame of the DACCIWA program, *Atmos. Chem. Phys.*, 2020, **20**(9), 5327–5354, DOI: 10.5194/acp-20-5327-2020.

15 A. A. Kouassi, M. Doumbia, S. Silue, E. M. Yao, A. Dajuma, M. Adon, N. E. Touré and V. Yoboué, Measurement of atmospheric black carbon concentration in rural and urban environments: cases of Lamto and Abidjan, *J. Environ. Prot.*, 2021, **12**(11), 855–872, DOI: 10.4236/jep.2021.1211050.

16 S. Gnamien, V. Yoboué, C. Liousse, et al., Particulate Pollution in Korhogo and Abidjan (Cote d'Ivoire) during the Dry Season, *Aerosol Air Qual. Res.*, 2021, **21**(1), 200201, DOI: 10.4209/aaqr.2020.05.0201.

17 S. Gnamien, C. Liousse, S. Keita, S. Silué, J. Bahino, E. Gardrat, M. Kassamba-Diaby, A. Ochou and V. Yoboué, Chemical characterization of urban aerosols in Abidjan and Korhogo (Côte d'Ivoire) from 2018 to 2020 and the identification of their potential emission sources, *Environ. Sci.: Atmos.*, 2023, **3**(12), 1741–1757, DOI: 10.1039/D3EA00131H.

18 S. Val, C. Liousse, E. H. T. Doumbia, C. Galy-Lacaux, H. Cachier, N. Marchand, A. Badel, E. Gardrat, A. Sylvestre and A. Baeza-Squiban, Physico-chemical characterization of African urban aerosols (Bamako in Mali and Dakar in Senegal) and their toxic effects in human bronchial epithelial cells: description of a worrying situation, *Part. Fibre Toxicol.*, 2013, **10**(1), 10, DOI: 10.1186/1743-8977-10-10.

19 H. Xu, J.-F. Léon, C. Liousse, B. Guinot, V. Yoboué, A. B. Akpo, J. Adon, K. F. Ho, S. S. H. Ho, L. Li, E. Gardrat, Z. Shen and J. Cao, Personal exposure to $PM_{2.5}$ emitted from typical anthropogenic sources in southern West Africa: chemical characteristics and associated health risks, *Atmos. Chem. Phys.*, 2019, **19**(10), 6637–6657, DOI: 10.5194/acp-19-6637-2019.
20 A. K. R. Kouao, E. T. N'datchoh, V. Yoboue, S. Silue, H. Attoh, M. Coulibaly and T. Robins, Exposure to indoor and outdoor air pollution among children under five years old in urban area, *Global J. Environ. Sci. Manage.*, 2019, **5**(2), 191–202, DOI: 10.22034/gjesm.2019.02.00.
21 A. K. R. Kouao, K. Kouamé, S. Silue, T. H. Attoh, M. Coulibaly, L. Konan and V. Youboue, Prevalence of asthma in children under 5 years old exposed to air pollution in Abidjan,(Côte D'ivoire), *Int. J. Recent Sci. Res.*, 2019, **10**, 33353–33358, DOI: 10.24327/ijrsr.2019.1007.3524.
22 A. F. Eghomwanre, O. Oguntoke and A. M. Taiwo, Levels of indoor particulate matter and association with asthma in children in Benin City, Nigeria, *Environ. Monit. Assess.*, 2022, **194**(7), 467, DOI: 10.1007/s10661-022-10135-3.
23 A. Pajot, M. Yapo, S. Coulibaly, M. Doumbia, S. Gnamien, K. Kouao, S. Ahoua, S. A. Dje, C. Liousse, R. Moh, J. Orne-Gliemann, F. D. A. Tanoh, O. Marcy and V. Yoboue, Air pollution exposure, respiratory consequences, and perceptions among urban African children living in poor conditions–A case study in Abidjan, Côte d'Ivoir, *PLOS Glob. Publ. Health*, 2025, **5**(4), e0003703, DOI: 10.1371/journal.pgph.0003703.
24 Y. Ishigaki, S. Yokogawa, K. Shimazaki, T. Win-shwe and E. Irankunda, Assessing personal $PM_{2.5}$ exposure using a novel neck-mounted monitoring device in rural Rwanda, *Environ. Monit. Assess.*, 2024, **196**, 935, DOI: 10.1007/s10661-024-13106-y.
25 G. Okello, G. Devereux and S. Semple, Women and girls in resource poor countries experience much greater exposure to household air pollutants than men: Results from Uganda and Ethiopia, *Environ. Int.*, 2018, **119**, 429–437, DOI: 10.1016/j.envint.2018.07.002.
26 M. E. Titcombe and M. Simcik, Personal and indoor exposure to $PM_{2.5}$ and polycyclic aromatic hydrocarbons in the southern highlands of Tanzania: a pilot-scale study, *Environ. Monit. Assess.*, 2011, **180**(1), 461–476, DOI: 10.1007/s10661-010-1799-3.
27 E. D. Van Vliet, K. Asante, D. W. Jack, P. L. Kinney, R. M. Whyatt, S. N. Chillrud, L. Abokyi, C. Zandoh and S. Owusu-Agyei, Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana, *Environ. Res.*, 2013, **127**, 40–48, DOI: 10.1016/j.envres.2013.08.009.
28 S. Becerra, M. Belland, A. Bonnassieux and C. Liousse, Living with air pollution in Abidjan (Côte d'Ivoire): a study of risk culture and silent suffering in three occupational areas, *Health Risk Soc.*, 2020, **22**(1), 86–106, DOI: 10.1080/13698575.2020.1721443.
29 M. Scandella, C. Liousse, V. Yoboué, G. Carrère, S. Becerra and R. Vanié, Reducing Air pollution in Abidjan: from scientific ambition to field implementation, *Global Africa*, 2023, (4), 214–228, DOI: 10.57832/77g4-yw79.
30 RGPH, Recensement general de la population et de l'habitat, 2021, https://plan.gouv.ci/assets/fichier/RGPH2021-RESULTATS-GLOBAUX-VF.pdf, last access: 01/04/2025.
31 M. Traore, Mobilité, congestion et vulnérabilité territoriale dans la commune de Yopougon (Abidjan-Côte d'Ivoire), *DaloGéo*, 2020, **2**, 302–327. https://hal.science/hal-02919601.
32 D. M. Moro, F. R. Brou and M. Kouakou, Hygienic practices in precarious urban environments and the eco-sanitary challenge, *Research and Views from Africa Collection*, 2023, https://revues.acaref.net/wp-content/uploads/sites/3/2023/10/Dominique-Moro-MORO.pdf.
33 S. Keita, C. Liousse, V. Yoboué, P. Dominutti, B. Guinot, E.-M. Assamoi, A. Borbon, S. L. Haslett, L. Bouvier, A. Colomb, H. Coe, A. Akpo, J. Adon, J. Bahino, M. Doumbia, J. Djossou, C. Galy-Lacaux, E. Gardrat, S. Gnamien, J. F. Léon, M. Ossohou, E. T. N'Datcho and L. Roblou, Particle and VOC emission factor measurements for anthropogenic sources in West Africa, *Atmos. Chem. Phys.*, 2018, **18**(10), 7691–7708, DOI: 10.5194/acp-18-7691-2018.
34 Y. Danieli, *International Handbook of Multigenerational Legacies of Trauma*, Springer Science & Business Media, 1998.
35 T. Sayahi, A. Butterfield and K. E. Kelly, Long-term field evaluation of the Plantower PMS low-cost particulate matter sensors, *Environ. Pollut.*, 2019, **245**, 932–940, DOI: 10.1016/j.envpol.2018.11.065.
36 A. L. Clements, W. G. Griswold, A. RS, J. E. Johnston, M. M. Herting, J. Thorson, A. Collier-Oxandale and M. Hannigan, Low-Cost Air Quality Monitoring Tools: From Research to Practice (A Workshop Summary), *Sensors*, 2017, **17**(11), 2478, DOI: 10.3390/s17112478.
37 D. Kim, D. Shin and J. Hwang, Calibration of low-cost sensors for measurement of indoor particulate matter concentrations *via* laboratory/field evaluation, *Aerosol Air Qual. Res.*, 2023, **23**(8), 230097, DOI: 10.4209/aaqr.230097.
38 J. Ouimette, W. P. Arnott, P. Laven, R. Whitwell, N. Radhakrishnan, S. Dhaniyala, M. Sandink, J. Tryner and J. Volckens, Fundamentals of low-cost aerosol sensor design and operation, *Aerosol Sci. Technol.*, 2024, **58**(1), 1–15, DOI: 10.1080/02786826.2023.2285935.
39 Y. Guo, A. Catena, M. J. Schwab, A. Teora, O. V. Rattigan, V. Harder, Y. Hassanzadeh, J. J. Schwab and J. Zhang, Improving Low-Cost Optical PM Sensor Accuracy in Humid Conditions *via* Aerosol Liquid Water Estimation Using US EPA CSN Data, *ACS ES&T Air*, 2026, **3**(2), 326–335, DOI: 10.1021/acsestair.5c00225.
40 J. Bahino, M. Giordano, M. Beekmann, V. Yoboué, A. Ochou, C. Galy-Lacaux, C. Liousse, A. Hughes, J. Nimo, F. Lemmouchi, A. K. Amegahe and R. Subramanian, Temporal variability and regional influences of PM 2.5 in the West African cities of Abidjan (Côte d'Ivoire) and Accra (Ghana), *Environ. Sci.: Atmos.*, 2024, **4**(4), 468–487, DOI: 10.1039/d4ea00012a.
41 L. Zhang, M. Segal-Rozenhaimer, H. Che, C. Dang, J. Sun, Y. Kuang and P. Formenti, *Prominent Role of Organics in*

Aerosol Liquid Water Content over the South-Eastern Atlantic during Biomass Burning Season, *EGUsphere* [preprint], 2023, pp. 1–28, DOI: 10.5194/egusphere-2023-2319.

42 D. Charpin, I. Annesi-Maesano, P. H. Godard, M. C. Kopferschmitt-Kubler, M. Oryszczyn, J. P. Daures, E. Quoix, C. Rahérison, A. Taytard and D. Vervloet, *Prévalence des maladies allergiques de l'enfant: l'enquête ISAAC-France, Phase I*, BEH, 1999, https://www.allergique.org/IMG/pdf/beh_13_1999.pdf.

43 RECORD report, Une étude des disparités territoriales de santé, 2013, https://www.record-study.org/methodologie.html, last access: 01/09/2022.

44 Gazel report, The gazel cohort, 2021, https://www.gazel.inserm.fr/fr/la-cohorte-gazel, last access: 01/09/2022.

45 B. Chaix, S. Bista, L. Wang, T. Benmarhnia, C. Dureau and D. T. Duncan, MobiliSense cohort study protocol: do air pollution and noise exposure related to transport behaviour have short-term and longer-term health effects in Paris, France?, *BMJ Open*, 2022, **12**(3), e048706, DOI: 10.1136/bmjopen-2021-048706.

46 K. Dongo, F. K. Kouamé, B. Koné, J. Biém, M. Tanner and G. Cissé, Analyse de la situation de l'environnement sanitaire des quartiers défavorisés dans le tissu urbain de Yopougon à Abidjan, Côte d'Ivoire, *Electron. J. Environ. Sci.*, 2009, 8–3, DOI: 10.4000/vertigo.6252.

47 J. He, C. H. Huang, N. Yuan, E. Austin, E. Seto and I. Novosselov, Network of low-cost air quality sensors for monitoring indoor, outdoor, and personal $PM_{2.5}$ exposure in Seattle during the 2020 wildfire season, *Atmos. Environ.*, 2022, **285**, 119244, DOI: 10.1016/j.atmosenv.2022.119244.

48 A. Sidibe, Y. Sakamoto, K. Murano, O. A. Koita, I. Traore, Y. Dansoko and Y. Kajii, Personal Exposure to Fine Particles ($PM_{2.5}$) in Northwest Africa: Case of the Urban City of Bamako in Mali, *Int. Res. J. Publ. Environ. Health*, 2022, **19**(1), 611, DOI: 10.3390/ijerph19010611.

49 M. Coulibaly, H. Attoh-Toure, A. K. R. Kouao, P. D. Kouassi, V. Yoboue and I. Tiembré, Traditional Smoking and Personal Exposure to Particulate Matter ($PM_{2.5}$) in Urban Area in Abidjan (Côte D'ivoire), *J. Environ. Sci. Public Health*, 2021, **5**(2), 226–239, DOI: 10.26502/jesph.96120126.

50 M. Shan, X. Yang, M. Ezzati, N. Chaturvedi, E. Coady, A. Hughes, Y. Shi, M. Yang, Y. Zhang and J. A. Baumgartner, feasibility study of the association of exposure to biomass smoke with vascular function, inflammation, and cellular aging, *Environ. Res.*, 2014, **135**, 165–172, DOI: 10.1016/j.envres.2014.09.006.

51 M. Shupler, P. Hystad, A. Birch, D. Miller-Lionberg, M. Jeronimo, R. E. Arku, *et al.*, Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study, *Lancet Planet. Health*, 2020, **4**(10), e451–e462, DOI: 10.1016/S2542-5196(20)30197-2.

52 R. Chartier, M. Phillips, P. Mosquin, M. Elleddge, K. Bronstein, S. Nandasena, V. Thornburg, J. Thornburg and C. Rodes, A comparative study of human exposures to household air pollution from commonly used cookstoves in Sri Lanka, *Indoor Air*, 2017, **27**(1), 147–159, DOI: 10.1111/ina.12281.

53 J. L. Elf, A. Kinikar, S. Khadse, et al., Sources of household air pollution and their association with fine particulate matter in low-income urban homes in India, *J. Expo. Sci. Environ. Epidemiol.*, 2018, **28**(4), 400–410, DOI: 10.1038/s41370-018-0024-2.

54 H. Xu, Y. Li, B. Guinot, J. Wang, K. He, K. F. Ho, J. Cao, Z. Shen, J. Sun, Y. Lei, X. Gong and T. Zhang, Personal exposure of $PM_{2.5}$ emitted from solid fuels combustion for household heating and cooking in rural Guanzhong Plain, northwestern China, *Atmos. Environ.*, 2018, **185**, 196–206, DOI: 10.1016/j.atmosenv.2018.05.018.

55 W. Hu, G. S. Downward, B. Reiss, J. Xu, B. A. Bassig, H. D. Hosgood III, L. Zhang, W. J. Seow, G. Wu, R. S. Chapman, L. Tian, F. Wei, R. Vermeulen and Q. Lan, Personal and indoor $PM_{2.5}$ exposure from burning solid fuels in vented and unvented stoves in a rural region of China with a high incidence of lung cancer, *Environ. Sci. Technol.*, 2014, **48**(15), 8456–8464, DOI: 10.1021/es502201s.

56 J. D. Johnston, M. E. Hawks, H. B. Johnston, L. A. Johnson and J. D. Beard, Comparison of Liquefied Petroleum Gas Cookstoves and Wood Cooking Fires on $PM_{2.5}$ Trends in Brick Workers' Homes in Nepal, *Int. Res. J. Publ. Environ. Health*, 2020, **17**(16), 5681, DOI: 10.3390/ijerph17165681.

