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Environmental significance statement

This study shows that women with polluting domestic and commercial activity living in poor neighbourhoods in Abidjan, are exposed to high concentrations of $PM_{2.5}$, well above the WHO limits and the atmospheric concentrations previously measured in these neighborhoods. Four main sources of pollution (wood and charcoal combustion, trafic, indirect sources, anti-mosquitoes) are determined from the questionnaires each woman completed, to be responsible of such a situation. An estimation of their respective role to women $PM_{2.5}$ personal exposure shows that combustion activity is the first responsible for charcoal makers and fish-smoking women. This finding can be generalized to women in West Africa with similar living conditions and practices and helps inform strategies aimed at reducing the impact of these activities.

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ARTICLE

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

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Few studies have been carried out on the issue of personal exposure to fine particles linked to combustion activities in West Africa, despite the few high concentrations that have been measured and the health risks they pose. This study is a part of APIMAMA (Air Pollution Mitigation Action for Megacities in Africa) interdisciplinary research project. We focus on personal exposure to $PM_{2.5}$ of three groups of women heavily exposed to domestic and commercial combustions pollution through their daily work in Abidjan, Côte d'Ivoire, specifically in Yopougon. Groups are made up of: 30 housewives using wood or charcoal to cook food for their families or sell it, 29 women and 3 men using wood to make 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. Study shows alarming 24h-exposure levels: 224.7 (205 - 245.9) µg/m³ for housewives, 251.6 (207.9 - 306.3) µg/m³ for charcoal makers, and 269.2 (191.7 - 399.8) µg/m³ for fish-smoking women. These results are 15 to 18 times higher than WHO's 24-hour guideline (15 µg/m³), posing serious health risks. For each group, $PM_{2.5}$ concentrations and their diurnal variations are closely linked to all reported sources of exposure to which women are exposed, as indicated 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 play this role for the other two groups. This finding is consistent with the quantification of the 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 charcoal makers and fish-smoking women total daily exposure.

1. Introduction

In a context of rapid urbanization, West Africa is faced with an increase in anthropogenic emissions of particulate pollutants, which is impacting the air quality of its cities and the health of its populations, with one million premature deaths every 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] Domestic and commercial fires and open burning of waste come first. 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] In addition to the fact that access to less polluting energies as gas or electricity is difficult because they are more expensive, the use of wood and charcoal is also culturally based. Whatever the environment, people still use some practices such as wood or charcoal to cook some dishes that require slow cooking or that do not have the same flavor when cooked with gas. The two other major sources of emissions in West African cities are road traffic, with 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 envisaged.[6] In addition, it should be noted that most West African cities are subject to the impact of more distant sources, especially in the dry season (e.g. desert dust from the Sahel and Sahara, particles 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

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pollution ([3,4,13-19]) in urban West African areas and human health for the past decade. In terms of particulate pollution, these projects showed that the concentration levels of particulate pollutants at source sites and urban sites were 3 to 15 times higher than the standards recommended by WHO, with strong spatial variations, closely linked to the standard of living of the populations. The highest concentrations were 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]

Thanks 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 Xu *et al.*[19] (15 times higher than WHO standards) were obtained at source site, during personal exposure measurements of two women using wood for smoking meat.

Domestic and professional activities (food smoking, wood manufacturing) linked to the use of wood fires and charcoal are therefore 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.

Yet, 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, linked to poverty and/or social hierarchy, so that 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 the uncontained demographic explosion, that APIMAMA project (Air PollutIon Mitigation Actions for Megacities in Africa, ANR 2022-2026) has been set up. APIMAMA aims to seek solutions to reduce air pollution and health and social risks in African megacities including an interdisciplinary, participatory approach to enable participants to take ownership of the environmental health issues addressed by the project. One of the project's objectives is to study three vulnerable groups of women living in precarious neighborhood 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 they breathe.

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 when they use their traditional tools and practices for their domestic and commercial activities: the situation before the introduction of improved technology and practices. Secondly, this study shows the links between these results and the polluting sources to which women are exposed, as estimated from the analysis of health questionnaires. Finally, our paper quantifies the role of their domestic and commercial combustion activities on their 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 the progress of the studies conducted as part of the project.

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

2.1. Description of study sites and selection of participants

Abidjan is the main laboratory city for the APIMAMA project, and Yopougon is the commune chosen to implement the study protocol described here.

Yopougon is densely populated with 1 571 065 inhabitants and a density of 9 568 inhabitants/km².[30] The population is low to middle income. The three combustion sources we are studying (cooking, charcoal making and fish smoking) exist in Yopougon and are practiced mainly by women. Therefore, our study covers 3 measurement sites (Fig. 1) and three groups of female participants with distinct socio-professional activities:

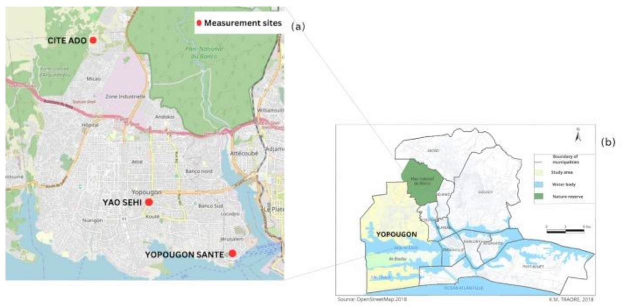

Fig. 1 Location of measurement areas, (a): zoom on the three measurement sites in the commune of Yopougon, (https://www.openstreetmap.fr/) and (b): the city of Abidjan and its communes.[31]

(1) Yao Sehi, neighborhood of Yopougon is selected for the studies on 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, have professional activities in the neighborhood: restaurant owners, 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 managing household waste and wastewater.[32] This neighborhood is densely populated with a low-income population and was recently divided in two for the construction of a bridge called the 4ᵉ bridge (in progress). The

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cooking fuels most used for domestic and commercial activities by this population are charcoal and wood. Gas is also used in combustion activities and all these energies are used alternatively depending on their efficiency and profitability, according to 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 - N'dotré road (Fig. 1). The area is sparsely populated and adjoins a forest. Informal charcoal-making activities using recovered wood (sawmills, pruning carried out by Abidjan town councils, etc.) take place there. The land occupied by the stocks of wood and charcoal millstones, was a wasteland unsuitable for urban development and once far from housing. As a result of demographic pressure, new buildings are now being erected on the edge of the charcoal making site, giving rise to conflicts between local residents and charcoal makers.

(3) Yopougon santé site regroups "Fatou sylla" fish smoking sites and Abobodoumé market. These sites (Fatou sylla and Abobodoumé market) are respectively in the villages of Yopougon santé and Abobodoumé belonging to the communes of Yopougon and Attécoubé respectively. The population of these villages is predominantly low-income and engages in many informal activities, including smoking fish 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 rubberwood. It is important to note that previous studies have shown that particulate emissions associated to its combustion were 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 indicated that 30 participants should be selected from each site. For the groups of housewives and fish-smoking women, this selection in the same neighborhood is associated with a 15% margin of error, according to Danieli *et al.*[34] For charcoal makers, the study targets a specific practice, which is illegal in the city and difficult to quantify.
One of the roles of the women representatives in the pilot group was to provide a list of people for each site, the selection principle being the participants' use of charcoal and/or wood for their domestic and commercial activities.
In total, we selected 31 housewives and 5 fish-smoking women at Yao Sehi. In Yopougon Santé, 23 fish-smoking women, and 30 women and 3 men who make charcoal in Cité Ado.
While women were the social category targeted by the study, 3 men were added to the charcoal makers group in view of their work setting up and monitoring the charcoal-making millstones, which meant they spent a lot of time on 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 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).

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

The filtration system was attached to the clothing, at chest level and close to the breathing zone. All the sensors are worn at all times. They are simply removed and placed in the same micro environment as the person (kitchen, bedroom, workplace, etc.) while bathing, sleeping, charging the battery and performing sudden movements (preparing certain dishes, throwing earth for charcoal, using public transport during rush hour, etc.).
The measurement campaigns were carried out during periods when exposure to pollution is supposed to be at its highest: in the dry season from 22 November to 22 December 2022 and from 14 to 28 March 2023 respectively for housewives and charcoal makers 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 consists of a portable PEM system (Personal Environmental Monitor,[19]) including a battery-powered SKC pump (SKC Inc. Fullerton, CA, USA) drawing in air at a rate of 4 L/min, 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 37mm 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 hours.

The results obtained with the filtration system were used in the present study solely as a reference method for studying $PM_{2.5}$ 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

Sensor description

We use a 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, two sensors (PMS 5003) enabling us to obtain spatiotemporal concentrations of $PM_{2.5}$ over a two-minute time interval. Gaia APIMAMA is an optical sensor, using the principle of light scattering.[35] According to the work on the evaluation of low-cost sensors of the Plantower type (PMS 5003 and PMS 1003), it covers a concentration range from 6 to around 1,000 µg/m³.[35] This sensor has been built to be lightweight, easy to wear and use with battery-powered and does not require an internet connection for start-up, operation and data retrieval. It can collect up to a week's worth of data.

Measurement protocol

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

Sensor calibration

Low-cost measuring devices must be calibrated using reference instruments.[36] Calibration is a challenging process as low-cost optical sensors measurements depend on operating conditions (relative humidity, temperature, particle mass concentration) and the characteristics of the aerosols being measured (aerosol composition, particle size distribution, hygroscopicity), which are closely linked to their 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 use comparison between measurements obtained using low-cost optical sensors with the mass of $PM_{2.5}$ weighed on filters sampled in parallel (see, for example, Gnamien *et al.*[16]).

In this study, due to a lack of real-time meteorological data, we used this latter option to evaluate and correct the measurements of $PM_{2.5}$ concentrations given by the optical sensors. To do this, we took the daily filters (14 filters) worn by three/four participants in each group (10 participants in all, i.e. 138 filters in total) and obtained with the filtration system. We determined the $PM_{2.5}$ concentrations collected with the optical sensors for the same measurement periods as those for the experiments with the filtration system and then compared the values obtained with the two sampling methods. The comparison has been performed separately for each group. Indeed, the aerosol characterization in terms of chemical composition, size and hygroscopicity is expected to differ from one group to another, affected by different emission sources. The results of the comparison show a significant correlation between the data obtained from the two measuring instruments ($y= 5.5x$, $R^2= 0.8$, $p< 10^{-10}$ for housewives : see Fig. S1; $y= 7.04x$, $R^2=0.8$, $p< 10^{-10}$ for charcoal makers : see Fig. S2; $y= 5.03x$, $R^2= 0.8$, $p< 10^{-10}$ for fish-smoking women : see Fig. S3). We applied these factors (5.5, 7 and 5) to the optical sensors data to obtain the corrected mass concentrations of $PM_{2.5}$ for all the participants. It is worth noting that these correction factors are higher than the values reported in the literature, which could be explained (1) by the ambient relative humidity levels measured in the field around 90% which are higher than those in previous studies and (2) by the aerosol composition dominated by combustion organic aerosol. Indeed, previous studies (e.g. Zhang *et al.*[41]) show that Organic Carbon (OC) play 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 an underestimation of $PM_{2.5}$ by the PMS5003 sensor and the need of higher correction factors than those of literature. Moreover, the higher values (7) obtained for charcoal makers may be also explained by the chemical composition of the combustion aerosol, affected by the presence of ash covering the ground, that is resuspended (see Figure 2b).

2.2.3. Ambient $PM_{2.5}$ concentration measurement

Ambient $PM_{2.5}$ concentrations have been measured at a weekly time step from November 2022 to April, 2026 in Yao Sehi (cf section 2.1. (1)) to document the ambient pollution in Yopougon, by using the INDAAF ambient air pumping technique (Djossou *et al.*[13] and Gnamien *et al.*[16]).

Briefly, the sampling system uses a mini Partisol sampling impactor for $PM_{2.5}$ working at a flow rate of 5 L/min, a NILU online filter holder, a KNF pump with a flow rate of 9 L/min (N89 KNE-K version 220v), a Cole Palmer ball flow meter with a micrometric valve (flow range adjustable from 0 to 10 L/min, accuracy 5 %) and a GALLUS-type G4 gas meter (accuracy of 0.01 m³).The air is sampled for 15 min every hour, leading to a total volume of sampled air of about 12.6 m³ by week. The particles are collected on 47 mm quartz fibre filters for gravimetric measurements.

This sampling system is installed more than 2 meters above the ground, on the roof of the house of Yao Sehi's chief. Like the portable filtration system, flow rates were verified at the beginning and end of each sampling event and sampling times were recorded manually in laboratory notebook.

2.2.4. Health questionnaire

All researchers from APIMAMA contributed to developing the health questionnaire based on and adapted it to the conditions of our study.[42-45] In this questionnaire, administered at the beginning of each measurement campaign, each of the 92 participants in the study was invited to provide personal information about their occupations, living conditions, health and perception of pollution. In this study, we will focus particularly on the information on their activities, general lifestyle habits, culinary habits and fuel used, nature of the job, workplace and working time, commuting mode and time, etc. Moreover, questions about the participants' daily activities were also asked during the data collection in order 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/m³ were removed from the raw values, which are continuous, real-time data with a time step of 2 minutes[35]. With this threshold, a total of 2%, 8% and 9% of the data were excluded respectively for housewives, charcoal makers and fish-smoking women. Then, for each day of measurements considered valid, we calculated the daily geometric mean $PM_{2.5}$ value to determine each participant's personal exposure to $PM_{2.5}$. A day is valid when it has at least 50% of measurements (i.e., more than 360 measurements per day), well distributed over the 24 hours sampling. With these conditions, we excluded 17%, 31% and 30% of the data for housewives, charcoal makers and fish-smoking women respectively.

As a result, we have retained 90 participants who meet our criteria and have valid data (30 housewives, 32 charcoal makers, and 28 fish-smoking women), out of the 92 who were 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 this phase of the study, called I. The identifier DL was chosen for all fish-smoking women and CA is designated for charcoal makers.

2.3.1. Establishment of an individual code linked to impacting pollution sources

Due to the diversity of data, we assigned each participant a three-term code based on the completed health questionnaire responses, in order to summarize 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 cooking source and is calculated according to (Eq. 1)

$$\textit{Cooking source} = v * \sum_{r\in\{i,j,k\}} t_r * EF_r \qquad \text{(Eq.1)}$$

Where r represent 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 factors of the fuel used representative of the particle emissions associated with different fuels;[33] v is a ventilation coefficient derived from the characteristics of the cooking location (e.g., near the door, in the yard, in the house) and the presence of a window in the home.

For Charcoal makers and fish-smoking women, this first term corresponds to combustion source and is calculated according to (Eq. 2)

$$\textit{Combustion source} = t * EF \qquad \text{(Eq. 2)}$$

Where EF represent the emission factor of the fuel used (mixed wood for charcoal production and rubberwood 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 on 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 a 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 importance of the road traffic source for all participants. We found that some groups of women (CA and DL) work at a different site from their residences, and those residing on the same site (YS) sometimes engage in activities outside of it. The means of transport they generally use are communal taxis, commonly called "wôrô-wôrô," and minivans "gbaka." It was important for us to include road traffic in this analysis because road traffic is one of the anthropogenic sources of air pollution to which the participants are exposed. It is evaluated according to (Eq. 3)

$$\textit{Road traffic source} = t * EF_i \qquad \text{(Eq. 3)}$$

Where i represent the type of fuel used (gasoline or diesel depending on the transport); EF_i the emission factor according to Keita *et al*.[33] and t the daily commuting time and/or travel time obtained from participants to get to their workplace.

Letter A is assigned for low intensity of the road traffic source. Letter B for moderate intensity, C for high intensity and letter D corresponds 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 the dwelling (traffic). Additionally, it is worth noting the presence of major construction work in Yopougon for the construction of a bridge (the 4th bridge of the city of Abidjan) connecting Yopougon to the administrative commune (Plateau). These construction works may have affected the participants of the Yao Sehi group who live near the site of construction, 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 items of the indirect sources listed for housewives. It should be noted that the "construction site" item existing for YS is replaced here by the proximity of their home 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, 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 in order to obtain the third term of our code, ranging from 1 to 9. We then summed the values of each item, and using a 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: it 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 summarizes the source code establishment.

Finally, we wanted to determine the level of exposure to all the sources (LES) to which the women were exposed, by summing the value of each term in the source code. To do this, we assigned a value of 9 to traffic source code D and using a rule of three, we determined the corresponding value for all the other letters (A, B, and C) in the code. Similarly, we assigned a value of 9 when the women used 'mosquito' and a value of 0 when they did not.

Table1 Description of the code related to the combustion sources impacting women

Position	Type	Signification	Explication
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

2.3.2. Contribution of domestic and commercial combustion activities to total daily personal exposure

Total daily personal exposure (DPE_T) was calculated from the equations defined by He *et al.*[47] and Sidibe *et al.*[48]

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$$DPE_T = DPE_{CA} + DPE_O \quad \text{(Eq. 4)}$$

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

$$DPE_{CA} = (C_{CA} * t_{CA}) / 24 \quad \text{(Eq. 5)}$$

$$DPE_O = (C_O * t_O) / 24 \quad \text{(Eq. 6)}$$

Where C_{CA} (Co) are the personal exposure to $PM_{2.5}$ measured during the combustion activity (during the other activities) and t_{CA} (t_O), the fraction of time spent on the combustion activity (on other activities) in hours, the total time fraction 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 the other activities) for each participant. Data use to determined DPE_{CA} and DPE_O 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 followed:

$$\%CA = 100*DPE_{CA}/DPE_T \quad \text{(Eq. 7)}$$

3. Results and discussion

3.1. Housewives

3.1.1. Personal exposure to $PM_{2.5}$

Fig. 3a shows for each participant, the variation in personal exposure to $PM_{2.5}$ on valid days of the measurement period (November 22 to December 22, 2022). We note that this variation as well as the mean value differ from one participant to another. This could be explained by the various activities and practices carried out by the participants. First, there is the frequency of the 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 inside or outside the house. Second, although they are all housewives who cook with charcoal and/or wood, some of them run businesses such as restaurants, food stalls, clothing shops, etc. The participants who have businesses are based in the Yao Sehi neighborhood or are street traders in contact with road traffic. In addition, we note the use of incense, mosquito repellent and fans by some participants, which may also contribute to these different variations in personal exposure to $PM_{2.5}$.

As presented in Fig. 3a, the mean PM2.5 women daily exposure ranges from 178.6 ± 33.7 to 399 ± 167 µg/m³ and is 12 to 27 times higher than WHO daily standard (15 µg/m³). It is also worth noting that these values are 4 to 8 times higher than the ambient measurements (47.9 µg/m³) in Yao sehi, Yopougon during the same measurement period. This ambient value is of the same order of magnitude as the most recent level measured

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in the neighborhood of Yao sehi by Gnamien et al.[16] in 2019. To better understand the variation in participants' personal exposure to $PM_{2.5}$, we decided to use data from the questionnaire, which provides information on the participants' lifestyles, practices and activities.

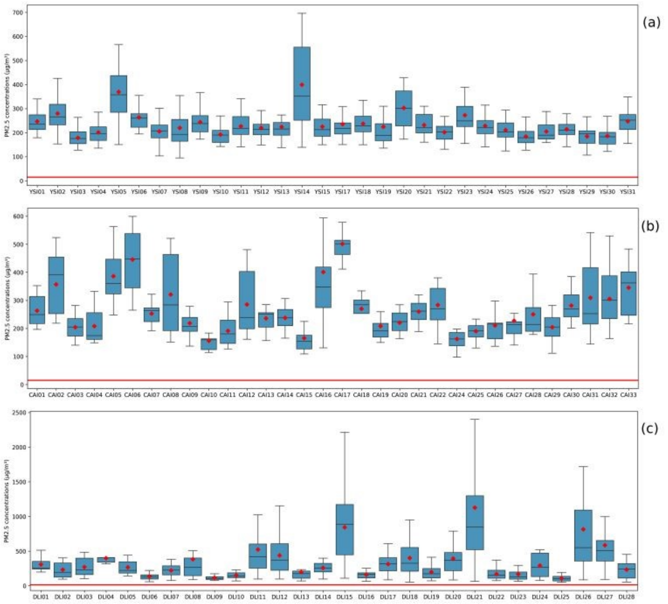

Fig. 3 Mean daily personal exposure to PM2.5 for each participant: (a) Housewives; (b) Charcoal makers; (c) Fish-smoking women. Box represents the variation in personal exposure to PM2.5 during the valid days of our measurement period; the red triangle in the box is PM2.5 mean and the red line, WHO standards (15µg/m3).

3.1.2. Relationship between the women daily personal exposure and the polluting source to which they are exposed represented by the source code

First, we try to establish a link between all the reported sources to which women are exposed (LES number, see paragraph 2.3.1) and the measured levels of personal exposure to $PM_{2.5}$.

As shown in Fig. 4a which presents LES numbers as a function of $PM_{2.5}$ personal exposure measurement for housewives, $PM_{2.5}$ concentrations increase as the intensity of the sources increases. Also, there is a strong correlation between the two datasets (y = 0.06x, R^2= 0.9 et p-value <10^{-10}). There is therefore a global consistency between the measured data and the data reported from the health questionnaire.

We will now 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 according to $PM_{2.5}$ concentrations for housewives. The source code is sorted in ascending order of combustion activity (the first term in the code is sorted from lowest to highest). In the appendix, we present the same graph, 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). And 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).

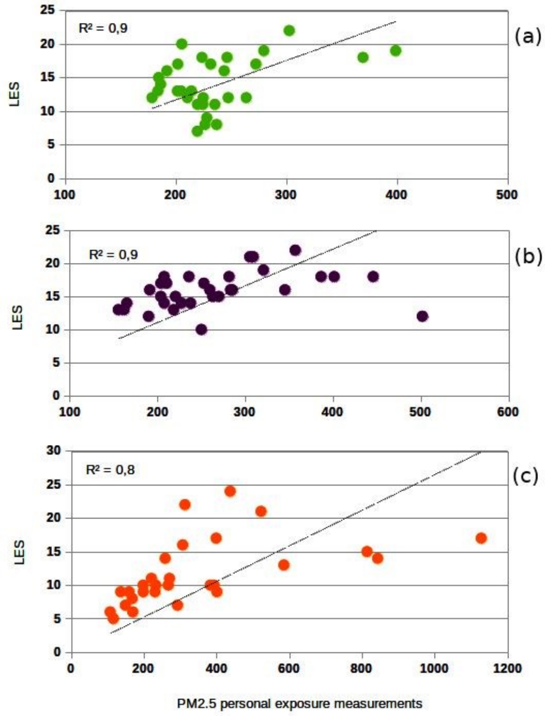

Fig. 4 Correlation between level of exposure to all the sources (LES) and $PM_{2.5}$ personal exposure measurements for: (a) housewives; (b) Charcoal makers and (c) Fish-smoking women.

In Fig. 5a, we observe that the highest concentrations are respectively in YSI14, YSI05 and YSI20 (399 ± 167, 369.4 ± 142.6 and 302.7 ± 81.2 µg/m³), and the corresponding codes are 3D7, 9B4, and 3B5m (Table S1). The high $PM_{2.5}$ concentration measured in 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 because this participant prepares dishes all day long to sell, mainly using wood to cook them. For the concentration obtained in YSI20, the code indicates the use of mosquito coils to protect against mosquitoes at night (see term m), and the tests we conducted on the combustion of mosquito coils used by the participants confirm high particle emissions. In contrast, we note that the low concentration of 178.6 ± 33.7 µg/m³ observed in YSI03 is explained by a low contribution from 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/m³). The participants YSI03 and YSI31 have the same code (1C4) but different concentrations (178.6 ± 33.7 and 247.5 ± 54.5 µg/m³). 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 APIMAMA project to correlate source codes and perceptions of pollution in data analysis.

For housewives, Fig. 5a and the figures in appendix (Fig. S4a and Fig. S5a) show that there is no covariance between the source code represented by each of these terms and $PM_{2.5}$ levels. This would suggest that, all sources contribute to explaining $PM_{2.5}$ levels. To test this hypothesis, we use 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 the same weight to each variable. As previously shown, we evaluated road traffic and the use of mosquito coils on a scale of 1 to 9, as were combustion activities and indirect sources. We finally obtained 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 equation:

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

For the rest of our analysis and despite the previous result, we will consider only the first term of the source code, focusing on combustion activities.

3.1.3. Participant's grouping according to their cooking combustion activity

Table 2 shows the score of cooking source (first digit of the source code, see paragraph 2.3.1) to allow to group housewives' participants 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.

Median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 are respectively 219.7 (201.8 - 229.1), 228.1 (214.2 - 263.8) and 231.7 (210.7 - 246.5) µg/m^3. As shown with p values, subgroups median daily personal exposures are not statistically different (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 concentrations increase with exposure (G1 < G2 < G3).

3.2. Charcoal makers

3.2.1. Personal exposure to $PM_{2.5}$

Fig. 3b presents the mean daily personal exposures to $PM_{2.5}$ of each charcoal making participant. Although all participants in this group engage in the same activity, we note differences between the measured values. Several factors may explain this observation. First of all, charcoal making activity varies in importance depending on the participants. For example, wood supply capacities vary from one charcoal making woman to another, ranging from once a month to every day. Secondly, some participants are more involved in the delivery of charcoal than in the charcoal-making process. In addition, their homes are located in the vicinity of the Cité Ado site, ranging from a 5 minutes-walk to an hour by public transport. Finally, as in the case of housewives, the frequency and characteristics of cooking, and the use of incense, mosquito repellent 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.

Mean daily personal exposure values range from 155.7 ± 34.7 to 501.8 ± 76.4 µg/m^3 (Table S2) and are 10 to 33 times higher than WHO daily standard. 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 µg/m³. 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]

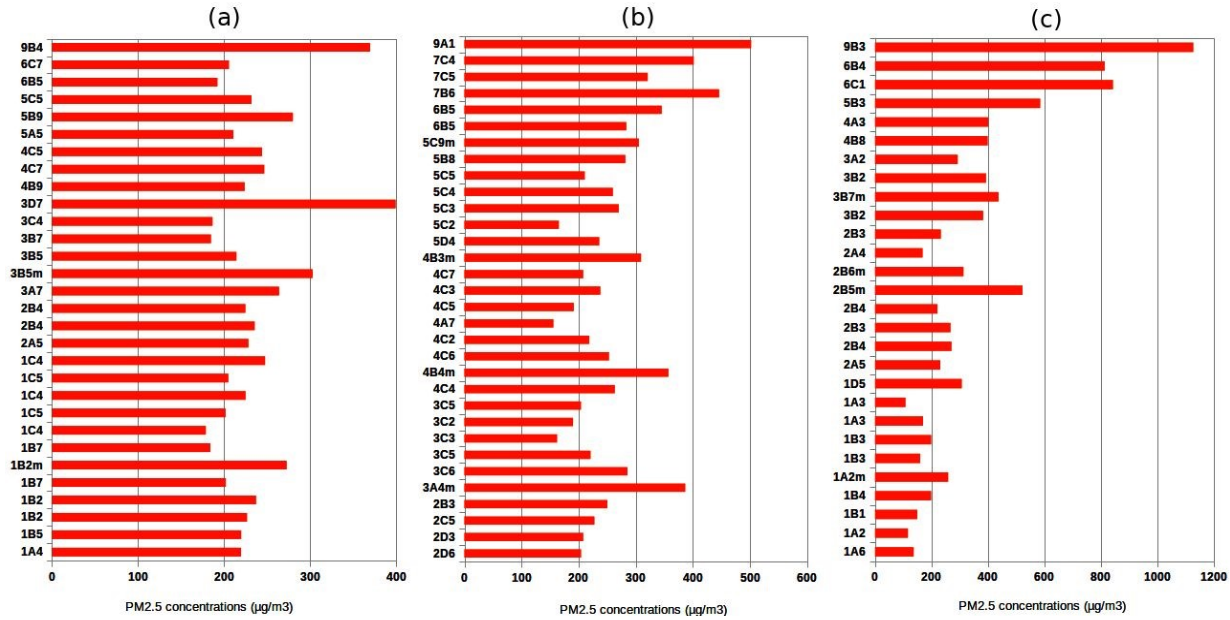

Fig.5 Representation of the mean daily personal exposure to PM2.5 of each participant according to the polluting source to which they are exposed represented by the source code: a) Housewives; b) Charcoal makers; c) Fish-smoking women

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3.2.2. Relationship between the participant daily personal exposure and the polluting source to which they are exposed represented by the source code

As with the group of housewives, firstly we try to establish a link between all the reported sources to which women are exposed (LES) and the measured levels of 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 $PM_{2.5}$ ($y = 0.06x$, $R^2= 0.9$ et p-value $<10^{-10}$). As previously noticed for the housewives, there is therefore a consistency between the measured data and the data reported from the health questionnaire for charcoal makers.

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) (µg/m³)
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)

With G1 representing the least exposed participants, G2 moderately exposed and G3 very exposed. Score is the first term of the source code (domestic and commercial combustion activity) and n, the participants 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).

Secondly, we examine the relative contribution of the various sources in the code to the measured $PM_{2.5}$ levels (Fig. 5b, Fig. S4b and Fig. S5b). The highest concentrations are found respectively in CAI17, CAI06, and CAI16 (Fig. 5b; 501.8 ± 76.4, 445.8 ± 117.5, and 401.4 ± 233.6 µg/m³), with the corresponding codes being 9A1, 7C6, and 7C4 (see Table S2). The average $PM_{2.5}$ concentration measured in CAI17 can be explained by the significant contribution of the charcoal-making source (see term 9). Indeed, the participant lives 5 minutes on foot from the measurement site, so she spends more time carrying out her activity. Regarding the concentration in CAI06 and CAI16, the code indicates a combination of sources: charcoal making, traffic, and indirect sources (see 7C6 and 7C4). Although both participants live 30 minutes on foot from the measurement site, CAI06 uses incense and is 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 µg/m³ observed in CAI10 is explained by a low contribution from the charcoal making and road traffic sources (see terms 4 and A in code 4A7). Terms 3 in code 3C3 also indicate a low intensity of the charcoal making and indirect sources for participant CAI24 (162.2 ± 44.8 µg/m³).

For charcoal makers, Fig. 5b and the figures in appendix (Fig. S4b and Fig. S5b) show that there is a covariance between the source code classified solely based on the first term and $PM_{2.5}$ levels. This would suggest that, charcoal making activity mainly contribute to explaining $PM_{2.5}$ levels. To verify this hypothesis, we use a multivariate linear regression model in which the independent variables are x_1 (charcoal making activity), x_2 (road traffic), x_3 (indirect sources) and x_4 (use of mosquito coils) and we assign the same weight to each variable. We finally obtained 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 equation:

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

For the rest of our analysis, we will consider only the first term of the source code.

3.2.3. Participant's grouping according to their charcoal making activity

We will now divide 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. Table 2 and Table S2 (in the appendix) show the methodology used to establish the subgroups and the distribution of participants within them: charcoal makers 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.

Median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 are respectively 214.3 (204.0 - 244.5), 245.4 (209.9 - 273.0) and 373.3 (327.0 - 434.7) µg/m³. Subgroups G1 and G2 are not statistically different (p=0.65) whereas subgroup G3 is statistically different from G1 and G2 (p= 0.01 for G3 and G1 and 0.02 for G3 and G2). G3 median personal exposure to $PM_{2.5}$ is 1.7 times higher than G1 and 1.5 times higher than G2. These differences highlight the importance of professional exposure to fine particle related to charcoal making.

3.3. Fish-smoking women

3.3.1. Personal exposure to $PM_{2.5}$

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Fig.3c shows the mean daily personal exposures of each fish smoking woman here studied. 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 status of the woman within the fish-smoking group. Participants are either contract workers or oven owners. Contract workers spend their days smoking fish and work for oven owner. Some oven owners also spend the whole day smoking the fish sold by fish sellers. Others, however, hire contract workers to help them smoke the fish and devote more time to buying and selling their own goods. Finally, as with the other groups studied, variation in personal exposure to $PM_{2.5}$ may be also due to the frequency and characteristics of cooking and the use of incense, mosquito repellent and fans which vary also from participant to participant. It is important to recall that in the group of fish-smoking women (1) 23 participants perform its 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 activity in residential areas, which can affect their health as well as the health of nearby residents, as shown by the study of Coulibaly *et al*.[49] It should be noted that the concentrations measured in (1) and (2) are in the same order of magnitude.

Mean daily personal exposure to PM2.5 in this group ranges from 107.9 ± 44.5 to 1128.5 ± 970.0 µg/m^3 (Table S3) and is 7 to 75 times higher than WHO daily standard. 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 equivalent to that of Gnamien. [16]

3.3.2. Relationship between the participant daily personal exposure and the polluting source to which they are exposed represented by the source code

Like the two previous study groups, we try to establish a link between all the reported sources impacting women (LES) and the measured levels of 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 $< 10^{-5}$). There is therefore here also, a consistency between the measured data and the data reported from the health questionnaire.

We know examine the relative contribution of the various sources in the code to the measured $PM_{2.5}$ levels. As shown in Fig. 5c, the highest concentrations are found in DLI21, DLI15 and DLI26 (1128.5 ± 970.0, 843.6 ± 550.8 and 814.4 ± 639.0 µg/m^3), with the corresponding codes being 9B3, 6C1, and 6B4 (Table S3). The average $PM_{2.5}$ concentration measured in DLI21 is explained by the strong contribution of the fish smoking source (see term 9). Indeed, the woman spends day and night smoking fish (21 hours/day), resting very little during the day. Regarding the concentration in DLI15, the code indicates the importance of the fish smoking source and the road traffic source (see terms 6 and C). The woman also spends the night at the smoking site during the week and travels a long distance to return home on weekends. Participant code DLI26 indicates the same intensity for the fish smoking activity as DLI15, but 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 in DLI25 is explained by a low contribution from fish smoking, road traffic, and indirect sources (cooking and using a fan, see code 1A3). The causes identified for DLI25 are the same for participant DLI09 (116.7 ± 34.9 µg/m^3), with the only difference being that DLI09 does 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). The same is true 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 fish-smoking women, Fig. 5c and the figures in appendix (Fig. S4c and Fig. S5c) show that there is a covariance between the source code classified solely based on the first term and $PM_{2.5}$ levels. This would suggest that, fish-smoking activity mainly contribute to explaining $PM_{2.5}$ levels. To verify this hypothesis, we use a multivariate linear regression model in which the independent variables are x_1 (charcoal making activity), x_2 (road traffic), x_3 (indirect sources) and x_4 (use of mosquito coils) and we assign the same weight to each variable. We finally obtained that fish-smoking activity is the primary contributor to the $PM_{2.5}$ levels measured among fish-smoking women, followed by the use of mosquito coil, road traffic and indirect sources according to the equation:

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

For the rest of our analysis, we will consider only the first term of the source code.

3.3.3. Participant's grouping according to their fish-smoking activity

With the relative importance of fish-smoking activity as indicated by the first digit of the source code, we can group the participants into 3 sub-groups: G1, G2 and G3 (Table S3). As shown in Table 2, participants who obtained scores of 1 and of 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.

Median daily personal exposure to $PM_{2.5}$ in G1, G2 and G3 is respectively 159.9 (137.0 - 198.8), 293.1 (233.2 - 283.3) and 700.1 (447.5 - 836.3) µg/m^3. These values are statistically different ($p < 0.05$). G3 personal exposure to $PM_{2.5}$ 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 underline that the G3 subgroup is composed by oven owners who spend the whole day (and night for some of them) 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 difference between the median concentration of the 3 subgroups highlights the importance of the women professional status on their exposure to fine particles.

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 year. Indeed, impact of seasonal variations of meteorology and regional aerosol transport on $PM_{2.5}$ personal exposure may be expected.

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, we may observe that these three periods do not present significant differences. Specifically, the temperature readings are 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 readings are 90%, 89% and 97% (https://metar-taf.com/fr/climate/abidjan) respectively for housewives, charcoal makers and fish-smoking women campaigns. With regard to regional variations in aerosol transport, primarily linked to the transport of desert dust, the ambient concentrations measured in Yopougon show no significant difference 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: ambient $PM_{2.5}$ levels are equivalent (47.9 µg/m³ and 23.1 µg/m³ during dry season for housewives and charcoal makers respectively and 53.6 µg/m³ during 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 taken.

Personal exposure to $PM_{2.5}$ for housewives, charcoal makers and fish-smoking women were obtained by calculating the median daily personal exposure to $PM_{2.5}$ for all participants in each group and is respectively 224.7 (205 - 254.9), 251.6 (207.9 - 306.3) and 269.2 (191.7 - 399.8) µg/m³ (Table 3). There is a statistical difference between the value for the group of housewives and that for the group of women who smoke fish ($p = 0.02$), unlike what is observed between the value for the group of charcoal makers and the other two groups ($p = 0.07$ for charcoal makers and housewives, 0.11 for charcoal makers and women who smoke fish). Despite this, concentrations increase in the following order: housewives < charcoal makers < fish-smoking women and value of fish-smoking women is 1.2 times higher than that of housewives. As expected, charcoal makers and fish-smoking women have higher concentrations than housewives because they engage in polluting professional activities. Also, fish-smoking women stay close to the oven watching the cooking, while charcoal makers sometimes move away from the smoke because they have sheds near their kilns. Furthermore, it is important to remember that the wood (rubberwood) 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 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/m³, B values between 100 - 200 µg/m³, C values between 200 - 500 µg/m³ and D values above 500 µg/m³).

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

Firstly, we note that the value for the housewives' group is higher than that for group A (i.e.,[27]) and C (i.e.,[24]). This discrepancy may be due to the different measurement periods in these 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 on participants using charcoal were conducted during the dry season. Outdoor particle pollution is lower during the wet season due to atmospheric rain deposition, which could explain the lower personal exposures 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 housewives here studied, some use both charcoal and wood, leading to higher personal exposure to $PM_{2.5}$ (e.g., YSI05). Finally, value is for a rural site in Ghana whereas our study is being conducted in an urban setting with a higher population density.[27] Also, as pointed out in the study of Sidibe *et al.*[48] rural residents travel less than urban residents for their daily activities. They are therefore less exposed to outdoor pollution, such as that caused by traffic, than the housewives in Abidjan, who, as we saw earlier, are strongly affected by this source.

Secondly, our main value is lower than that for group D (i.e.,[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 with the windows closed and the door slightly open in a room, adjacent to the main living area.

The second focus is on the personal exposures to $PM_{2.5}$ of people when wood is used as a fuel. As shown in Table 3, charcoal makers (251.6 µg/m³) and fish-smoking women (269.2 µg/m³) in our study using wood, are higher than the literature data from groups A ($PM_{2.5}$ <100 µg/m³) and B (100 < $PM_{2.5}$ <200 µg/m³), similar to those from group C (200 < $PM_{2.5}$ <500 µg/m³), and lower than group D ($PM_{2.5}$ >500 µg/m³).

Table 3 Range of personal exposure to $PM_{2.5}$ due to the use of wood and/or charcoal obtained in literature from studies published between 2011 and 2024. Values of this work are added for comparison.

Range	Concentrations of $PM_{2.5}$	Fuel used	Sampling period	Study area	Reference
A (<100) µg/m³	61 µg/m³	Wood	Sept. 2012	China (Rural Sichuan)	Shan *et al.*[50]
	45 µg/m³	Wood	June 2017 to Sept. 2019	China	Shupler *et al.*[51]
	89 µg/m³	Wood	June 2017 to Sept. 2019	India	Shupler *et al.*[51]
	39 µg/m³	Wood	June 2017 to Sept. 2019	Chile & Colombia	Shupler *et al.*[51]
	44.6 µg/m³	Charcoal	July to Dec. 2007	Ghana	Van Vliet *et al.*[27]
B (100 - 200) µg/m³	115.7 µg/m³	Wood	Feb. to June 2016	Uganda	Okello *et al.*[25]
	119.9 µg/m³	Wood	July to Sept. 2016	Ethiopia	Okello *et al.*[25]
	114 µg/m³	Wood	Aug. to Sept.	Sri Lanka (Anagi stove)	Chartier *et al.*[52]
	141.9 µg/m³	Wood	July to Dec. 2007	Ghana	Van Vliet *et al.*[27]
	153 µg/m³	Wood	June 2017 to Sept. 2019	Tanzania &Zimbabwe	Shupler *et al.*[51]
	148 µg/m³	Wood	June 2017 to Sept. 2019	Bangladesh &Pakistan	Shupler *et al.*[51]

Range	Concentrations of $PM_{2.5}$	Fuel used	Sampling period	Study area	Reference
C (200 - 500) μg/m³	249 μg/m³	Wood	Dec. 2013 to Nov. 2016	Indian	Elf *et al.*[53]
	293.1 ± 79.2 μg/m³	Wood	Sept. 4 to 21, 2016	China (Nanliu village, Hw3)	Xu *et al.*[54]
	201 μg/m³	Wood	Aug. to Sept.	Sri Lanka (Traditional stove)	Chartier *et al.*[51]
	265 μg/m³	Wood	Oct. 2021 to March 2022	Rwanda	Ishigaki *et al.*[24]
	289 μg/m³	Wood	Aug. 2008 to Feb. 2009 and March to June 2009	China (Xuanwei and Fuyuan)	Hu *et al.*[55]
	205 μg/m³	Charcoal	Oct. 2021 to March 2022	Rwanda	Ishigaki *et al.*[24]
	304.6 ± 284.5 μg/m³	Wood	April to June 2016	Côte d'Ivoire (Yopougon)	Xu *et al.*[19](wet season)
	224.7 (205 - 245.9) μg/m³	Charcoal & wood	Nov. to Dec. 2022	Côte d'Ivoire (Yopougon)	This work (Housewives)
	251.6 (207.9 - 306.3) μg/m³	Wood	March 2023	Côte d'Ivoire (Yopougon)	This work (Charcoal makers)
	269.2 (191.7 - 399.8) μg/m³	Wood	July to Sept. 2023	Côte d'Ivoire (Yopougon)	This work (Fish-smoking women)
D (>500) μg/m³	541.14 μg/m³	Wood	April 30 to May 03, 2019	Nepal	Johnston *et al.*[56]
	1574 ± 287 μg/m³	Wood	March 2007	Tanzania (Uwemba)	Titcombe and Simcik.[26]
	588 μg/m³	Charcoal	Feb. 2007	Tanzania (Ndjombe)	Titcombe and Simcik.[26]

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– 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 professional exposure studied in our work.

– In groups C and D, the majority of studies were conducted in Asia (71%) and during cold seasons. 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 & 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 fish smoking group (e.g., DLI21, DLI15, DLI26, etc) are of the same order of magnitude as those in group D.

Finally, comparison between fish-smoking women group with Xu *et al.*[19] shows similarities terms of the targeted population, the measurement site (Yopougon, Abidjan), the use of rubberwood for professional activity, the season (wet season) and the practices (use of charcoal and gas by participants for cooking at home, clean 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 study during a 3 days measurement period (from July 5 to 7),[19] while our study includes 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 Xu *et al.*[19] study). It would be interesting to validate this hypothesis with the measurement of emission factors for different smoked foods.

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

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

3.5.1. Daily profiles of personal exposure of study groups

Fig. 6 present 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 tests previously described. Indeed, the three subgroups of the housewives' group have roughly the same daily profile (Fig. 6a). For charcoal makers, subgroups G1 and G2 have similar profiles while the G3 one is different (Fig. 6b). In contrast, the three subgroups of the fish-smoking women group have different profiles (Fig. 6c). In Fig. 6a (housewives' group), we note high concentrations of $PM_{2.5}$ 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, it 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 previous study which also shows a large evening peak in domestic activities.[16]

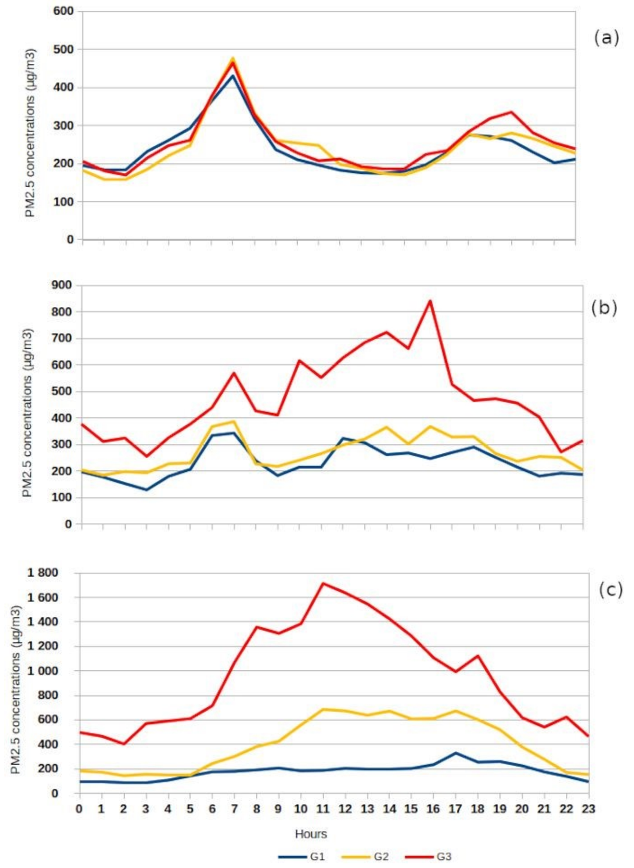

Fig. 6 Daily profile of personal exposure to $PM_{2.5}$ of the three subgroups (G1, G2, and G3) of (a) Housewives, (b) Charcoal makers and (c) fish-smoking women groups.

Daily profiles of the charcoal makers group also present two peaks but at different times (Fig. 6b): one from 6 am to 7 am and another one from 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) to travel to their work site (morning peak) and they are working between 10 am and 6 pm (diurnal peak). We observe 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 group of women smoking fish (Fig. 6c), we observe a peak throughout the day that is attributed to fish smoking activity. We can see that subgroup G3 has very high concentrations during this period compared to profile G2, which itself has high concentrations compared to profile G1. As previously mentioned in 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

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underlines the appropriateness of selecting subgroups G1, G2, and G3 for the group of fish-smoking women by demonstrating the significance of fish-smoking on diurnal variations in personal exposure to $PM_{2.5}$.

In Fig. 7, we compared the daily profile of personal exposure to $PM_{2.5}$ 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 concentration values during the day (from 11 am to 5 pm) than of housewives who stay at home. Furthermore, during this period, the concentration of fish-smoking women is higher than that of charcoal makers. This can be explained by the points mentioned above (3.4.1.). In summary, the time spent in smoke and the fuel used differ for these two groups.
We also note that, all groups have high personal exposure to $PM_{2.5}$ 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: housework, which generally takes place after waking up; the impact of traffic when they take their children to school and go to the market, etc. Also, most of fish-smoking women live close to the smoking site and walk there through narrow alleys.
From 5 to 9 pm, we observe a peak due to cooking activities in housewives' group whereas for the other two professional groups, the concentrations tend 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, they return to their homes and engage in cooking activities at around 9 pm. It is important to note that the health questionnaire revealed that women with professional activities cook every other day, while housewives cook every day.

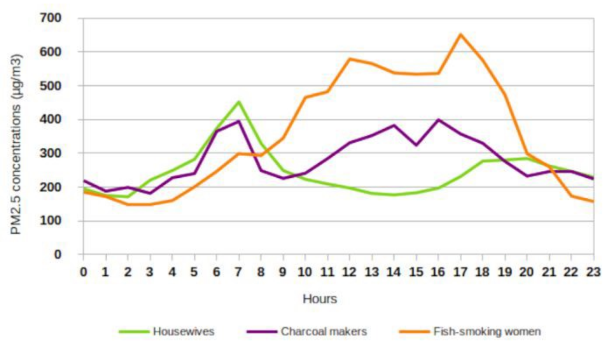

Fig. 7 Comparison of the mean daily profile of personal exposure to $PM_{2.5}$ of the three study groups (housewives, charcoal makers and fish-smoking women).

These results show that the domestic and commercial combustion activities studied don't have the same impact on the daily personal exposure profiles of each group and subgroup. In this context, we wanted to quantify the contribution of domestic and commercial combustion activities on total daily personal exposure of the 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 the section 2.3.2, the contribution of domestic cooking (for the housewives' group and its subgroups) and of commercial combustion activities (for charcoal makers and fish-smoking women groups and their subgroups) to their total daily personal exposure to $PM_{2.5}$ was calculated as followed:

$\%CA = 100*DPE_{CA}/DPE_T$

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

Table S4 present DPE_{CA}, DPE_O and DPE_T values for each group and subgroups. It is interesting to mention that DPE_{CA} for fish-smoking group (316 µg/m³ per day) is 3 times higher than values of housewives (82 µg/m³ per day) and charcoal makers group (113 µg/m³ per day). It should also be noted that the difference between the DPE_{CA} values for groups G1, G2, and G3 is very significant for the group of women who smoke fish. Comparison with existing data in the literature shows that total daily personal exposure of housewives group (282.4 ± 100.4 µg/m³ per day) and subgroups is included in the range of values obtained by Sidibe *et al.*[48] (432) and Van Vliet *et al.*[27] (128.50 µg/m³ per day). The value found in Bamako (Mali) for the "Cook" group, consisting of 3 people is 1.5 times higher than that of our study.[48] The activities of these individuals include food preparation, dish and house cleaning, shopping, and the use of charcoal and wood as fuels. The difference between our results and those of Sidibe *et al.*[48] could be explained by the fact that the individuals studied use 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 exposures occurring when wood is used. In housewives' group we studied, only 16% of participants use wood, while a higher percentage of participants in the "Cook" group do. This difference may explain the lower values in our study. The value found in Ghana is 2.2 times lower than that of our study.[27] This is in line 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 present the relative impact of domestic or commercial combustion activities to the total daily personal exposure (%CA, Eq.7) of all the study groups and their subgroups. The results presented in Fig. 8 confirms our previous findings. Cooking activity has a smaller impact on the total daily personal exposure than charcoal making, which in turn has a smaller impact than fish smoking. We note that cooking activities contribute on average to 29 ± 10 % to DPE_T for housewives

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(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.

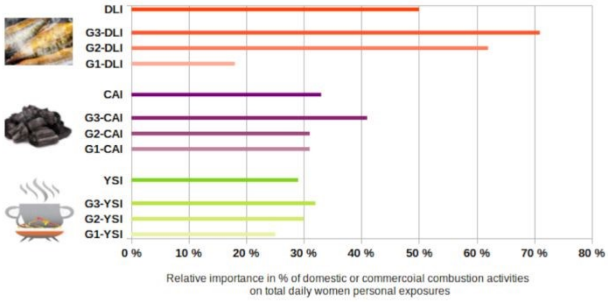

Fig. 8 Contribution of domestic and commercial combustion activities to the total daily personal exposure of study groups and their subgroups (for housewives: YSI, G1-YSI, G2-YSI and G3-YSI, for charcoal makers: CAI, G1-CAI, G2-CAI and G3-CAI and for fish-smoking women, DLI, G1-DLI, G2-DLI and G3-DLI.

The fact that the contribution of domestic combustion activity (cooking) and charcoal making activity is less than half of DPE_T for housewives and charcoal makers indicates that other sources of pollution (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 charcoal makers group as previously shown in the multivariate analysis.
On the other hand, the contributions of 62 ± 17% and 71 ± 18% of combustion activities to the DPE_T of subgroups G2 (G2-DLI) and G3 (G3-DLI) respectively of fish-smoking women group, highlight the significant role that the professional activity of this group plays in the particulate pollution to which they are exposed.
We can therefore 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 women personal exposures to $PM_{2.5}$ are 15, 17 and 18 times higher than the WHO recommended standard for the housewives, charcoal makers and fish-smoking women group 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 professional activity of charcoal makers and fish-smoking women respectively. By analyzing each woman's responses to the questionnaires, 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 allowed us to demonstrate that (1) there was a correlation between women's personal exposure to $PM_{2.5}$ and the sources identified, (2) the significant contribution of traffic to the personal exposure of housewives to $PM_{2.5}$, and (3) the significant contribution of the professional activities 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 Africa cities who engage in the same practices. It is important to recall here that smoking practices, whether for fish or meat, using traditional ovens and carried out under lean-tos or in confined spaces that trap smoke and often using highly polluting woods such as rubberwood, are very common in West Africa.
These results highlight the fact that reducing women personal exposure to $PM_{2.5}$ is now a necessity. We have seen in our study that cooking activities represents on average 29% of the housewives total daily personal exposure. This shows that the use of improved cookstoves could have a significant impact in the reduction of housewives' personal exposure to $PM_{2.5}$.
The use of improved stoves combined with less polluting wood (instead of traditional stoves and rubberwood) could have an even more significant impact on the personal exposure to $PM_{2.5}$ of women who smoke fish, since 71 ± 18% of their exposure is related to their occupational activity. 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 it is the women who will be the first to implement these changes. These changes will also affect relationships between different communities (professionals, customers, stakeholders etc.). To be studied, these changes must therefore be addressed in a holistic manner, beyond just exposure issues and technical solutions to control and reduce them, with close collaboration between participating associations, stakeholders, and an interdisciplinary scientific approach. This is what is planned to be tested in the next phase of the APIMAMA project, with the introduction of improved cooking techniques and tools in the groups studied. We will thus be able to assess their impact on the women personal exposure to $PM_{2.5}$ of the different study groups.

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.

Ethics approval and consent to participate

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.

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

The $PM_{2.5}$ data supporting this article have been included as part of the Supplementary Information and the health questionnaire data are not available to access.

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Data Availability Statement

The $PM_{2.5}$ data supporting this article have been included as part of the Supplementary Information and the health questionnaire data are not available to access.