Article

Personal Exposure to Fine Particles (PM$_{2.5}$) in Northwest Africa: Case of the Urban City of Bamako in Mali

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Abstract: Personal exposure to particulate matter (PM) from anthropogenic activities is a major concern in African countries, including Mali. However, knowledge of particulates is scant. This study was undertaken to characterize personal exposure to PM$_{2.5}$ microns or less in diameter (PM$_{2.5}$) in the city of Bamako in Mali. The exposure to PM$_{2.5}$, through daily activities was observed from September 2020 to February 2021. Participants wore palm-sized optical PM$_{2.5}$ sensors on their chest during their daily activities. The exposure levels in four different groups of residents were investigated in relation to their daily activities. The variation in PM$_{2.5}$ concentration was measured during different activities in different microenvironments, and the main sources of exposure were identified. The highest average 10 min concentrations were observed at home and in bedrooms, while the participants were using specific products typically used in Africa, Asia, and South America that included insecticides (IST; 999 μg/m^3) and incense (ICS; 145 μg/m^3), followed by traffic (216 μg/m^3) and cooking (150 μg/m^3). The lowest average 10 min concentrations were also observed in the same microenvironment lacking IST or ICS ($\leq$14 μg/m^3). With no use of specific products, office workers and students were the least exposed, and drivers and cooks were the most exposed. The concentrations are up to 7.5 and 3 times higher than the World Health Organization's yearly and daily recommended exposure levels, respectively, indicating the need to promptly elaborate and apply effective mitigation strategies to improve air quality and protect public health. This study highlights the importance of indoor air pollution sources related to culture and confirms previous studies on urban outdoor air pollution sources, especially in developing countries. The findings could be applied to cities other than Bamako, as similar practices and lifestyles are common in different cultures.

Keywords: Bamako; air pollution; PM$_{2.5}$; daily activities; health; mitigation strategies

1. Introduction

Particulate matter (PM) is one of the most widespread pollutants in the atmosphere and has attracted the interest of numerous air-quality researchers. PM exists in the atmosphere as solid or liquid suspensions. They originate from natural sources, volcanic eruptions, sea salt, wildfires, and anthropogenic sources, like road traffic, biomass combustion, and waste incineration. They can be dispersed by wind. When directly emitted from pollution sources, particles are referred to as primary PM. Secondary PM is produced by the reaction of primary precursor gases entering the atmosphere. Particle sizes differ from a few

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nanometers to hundreds of micrometers. They are classified according to size from smallest to largest as the Nuclei mode (ultrafine fraction), Aitken mode (fine fraction), Accumulation mode, and Coarse mode. The mass distribution is dominated by the Accumulation and Coarse modes [1].

Depending on their size, the various PM types have multiple harmful effects on the environment and human health. Smaller particulate matter can undergo long-range transport and, in addition to local impacts, generate regional and global impacts. They are most involved in atmospheric reactions by natural processes. They directly affect climate change through their role as cloud condensation nuclei [1] and reduce visibility in the troposphere by scattering solar radiation [2]. Worldwide, many studies have provided evidence of the effects of PM on human health, especially the fine and ultrafine fractions, as they can reach the deepest regions of the respiratory system. Short-term variation and levels of urban particulate air pollution are associated with increases in lung function deterioration, respiratory diseases, number of hospital admissions, and mortality from cardiorespiratory problems and cancers [3]. Countries including China, India, France, Italy, and the United States have reported health issues related to exposure of $PM_{2.5}$ microns or less in diameter [4–7]. However, information is scant in developing countries.

In Africa, air pollution has reached a significant scale. The average concentration of $PM_{2.5}$, ranging up to 507 $\mu g/m^3$, has been recorded in multiple African cities. The concentrations exceed the World Health Organization Air Quality Guideline (WHO AQG) in nearly all African cities where $PM_{2.5}$ data are available [8]. Rapid population growth has led to the increased use of natural resources and the emission of chemical molecules that affect ecosystems. Air pollution in Africa and the resulting health effects are strongly related to socioeconomic status. The majority of risk factors, such as biomass combustion, transportation (vehicle age, motorcycle, taxis, and buses), unpaved roads, and street food preparation are more pronounced [9,10]. For instance, the majority of households in developing countries burn biomass fuels in open fireplaces, and the car fleets are older, poorly maintained, and use low-quality fuels with high lead concentrations, which generate high levels of pollutants [11]. Household air pollution from solid fuels contributes to ambient particulate matter pollution and has been identified as the second disease burden in most of sub-Saharan Africa, and the fourth globally [12,13]. To overcome these issues, international institutions have established international development goals in sustainable development (SDGs).

The vehicle fleet is predominately old in the city of Bamako, located in Mali in West Africa, as well as in many other developing countries that include Lagos in Nigeria [8], and Addis Ababa in Ethiopia [14]. Legislation on the importation of low-quality fuels that are potential sources of major pollutants including nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) is extremely lax. For instance, the importation of diesel fuel with a sulfur content of 10,000 ppm is legal in Mali, while the threshold allowed in Europe is only 10 ppm [15]. Recorded NO_2 and SO_2 values of 60 $\mu g/m^3$ and 29 $\mu g/m^3$, respectively, in traffic sites in Bamako exceed World Health Organization (WHO) guidelines [8]. In addition, waste incineration is the most widely used waste management technique. This, releases considerable quantities of fine particles and other pollutants into the atmosphere. Wood and charcoal are resources that account for 78% of the national energy balance [16]. They are extensively used in households and are a major source of PM emissions. In addition, the combustion of insecticides and incense, which produce a considerable amount of PM, is widespread. The city of Bamako is surrounded by hills [17], and so is poorly ventilated. Consequently, the city is subject to stagnant pollutants from the diverse aforementioned anthropogenic sources. The number of patients with respiratory diseases has increased in Bamako during the last few years [18].

There are no published data concerning population exposure to $PM_{2.5}$ particulate matter in Bamako. The present study addressed this. Personal exposure to $PM_{2.5}$ has been investigated in four different groups of local inhabitants. Participants wore a newly developed palm-sized particle sensor ($PM_{2.5}$ sensor) that was positioned in a lanyard on

the chest. The PM$_{2.5}$ sensor is portable, light, inexpensive, has low energy consumption and good data storage capacity, and is reliable. Nakayama et al. (2018) described the performance and characteristics of sensors [19].

The data obtained from the present study are essential to inform the local population about their exposure to PM$_{2.5}$ through daily activities and help increase awareness regarding adverse health effects. Additionally, the data could help to better understand the relationship between the control of environmental problems and promoting sustainable development. This study could provide the local government with reasonable strategies to reduce air pollutant emissions. Finally, this study provides background information on PM$_{2.5}$ exposure concentration in this region and can guide further studies on air pollution in Mali.

2. Materials and Methods

2.1. Sampling Location

PM sampling was performed within five months from September 2020 to February 2021 in different microenvironments in Bamako city (Figure 1). This urban city is the capital of the West African country of Mali. It is located in southwest Mali (12°39′0.00″ N–8°00′0.00″ W). The population is approximately three million [20]. The major possible sources of particles in this region are combustion from biomass and biofuel usage, soil dust resuspension, road vehicle tires, traffic, waste incineration, and natural processes, such as harmattan occurring during the dry season [21].
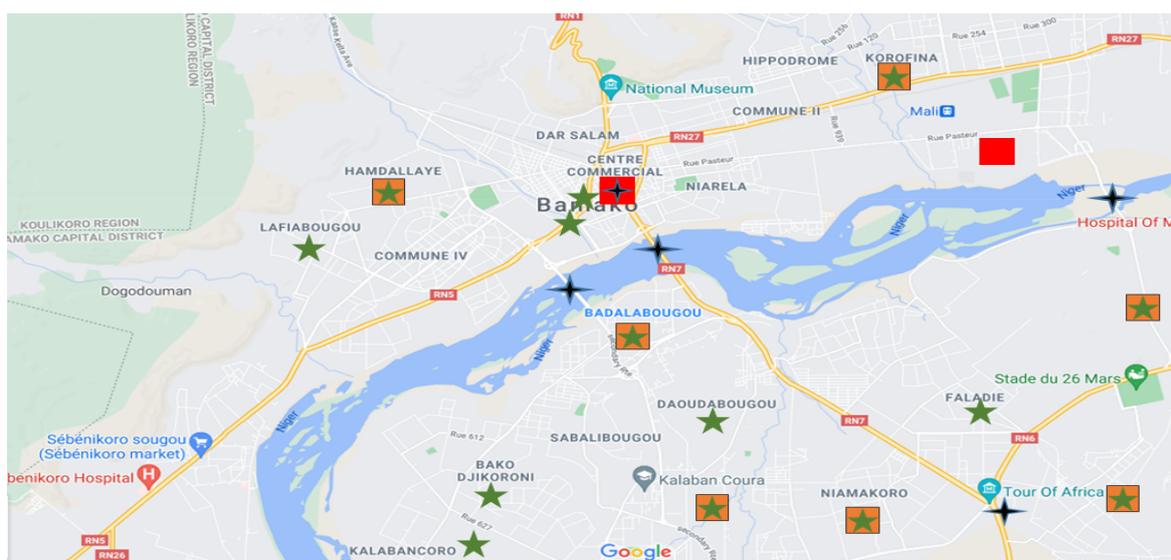
Figure 1. Different microenvironments' locations of the participants on Google Maps; green star (houses), orange square (work places), black star (high traffic areas), red square (industrial zones).

2.2. Materials

To obtain information about personal exposure, each participant wore a palm-sized optical PM$_{2.5}$ sensor (P-sensor; Figure 2a). The palm-sized sensor was specifically designed to give the mass concentration (in μg/m^3) of particulate matters of 2.5 microns or less in diameter. A P-sensor works based on the principle of heat convection transfer and light-scattering of the particles. A heater inside the instrument directs the particles toward a light-emitting diode, where they will be irradiated and will scatter lights with intensities proportional to their sizes [19]. According to the specifications, the P-sensor is optimized to measure particles >10 μg/m^3. Therefore, lower values would be less reliable [22]. In addition to real-time personal exposure sampling, each participant used a time diary to indicate their locations and activities during the sampling period.

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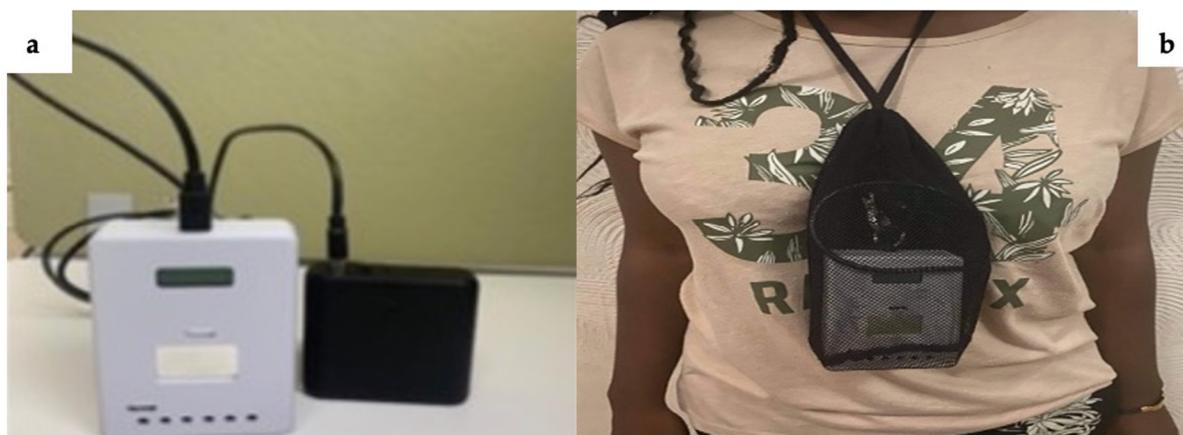
Figure 2. The P-sensor (**a**) and its typical orientation (**b**).

2.3. Sampling Procedure

Personal exposure to $PM_{2.5}$ was measured in participants who lived in Bamako using palm-sized portable $PM_{2.5}$ sensors. The participants were selected based on major occupations in the city: office workers (OW), drivers (DRI), cooks (COOK), and students (ST). Participants in these occupations were selected with no restrictions on gender, age, area of residence, house conditions, and personal habits (smoking, exercising, etc.). Each participant provided personal information after agreeing to take part in the research. For each occupational group, at least three participants were sampled for 3 days. The sensor was worn around the neck on the chest, close to the breathing zone (Figure 2b). The real-time mass concentrations of $PM_{2.5}$ were recorded at 5 s intervals. The sensor was removed during bathing, sleeping, and battery charging. At those times, it was placed on a support located in the same microenvironment. Each participant recorded their daily activities in a diary, describing the specific activities they performed and the respective microenvironments. They gave notice whenever they switched their microenvironment or activities. The diaries provided information on the time, location, and activities of the participants for 72 h. The time and location were characterized by different activities and microenvironments indoors (such as home, home with incense and insecticides, workplace, classroom, other activities) and outdoors (such as market, cooking, driving, other activities). $PM_{2.5}$ exposure data for a participant's total exposure were then obtained from measurements in various locations during the sampling period. The participants' information (occupation, gender, age, mean of transportation, and personal habits) was collected using Table S2.

2.4. Quality Assurance and Control

The palm-sized $PM_{2.5}$ was evaluated by its developers using two types of standard beta attenuation monitors (DKK-TOA, model FPM-377 and Kimoto, model PM-712) at four different locations in Japan (Fukuoka, Kadoma, Kasugai, and Tokyo). The daily averaged mass concentration obtained from the $PM_{2.5}$ sensors were in good agreement with the standard instruments (with R between 0.89 to 0.95) [19].

Furthermore, we tested the performance of the palm-sized $PM_{2.5}$ sensor by comparing it to a Grimm model 1.109 optical particle counter (OPC). Sampling was performed at Kyoto University, Yoshida South Campus (Figure S2) from 1–22 December and from 7 January to 20 February. The particle number distribution over 250 nm in diameter by the Grimm OPC covered >80% of the volume fraction and was converted into mass concentration using a typical mass density of ambient particles of 1.2 g cm^{-3} [23–25]. The typical size distribution of PM provided by OPC Grimm showed that the mass concentration of PM was dominated by $PM_{2.5}$ (Figure 3b). The results showed an agreement in the time variation (Figure 3c) and a good correlation between the two instruments (R = 0.90 and 0.82 for the 1 h and 24 h average, respectively; Figure 3a and S1b). This correlation coefficient was similar to the one

obtained by Nakayama et al. in 2018 [19]. Additionally, data obtained from the Japanese Ministry of Environment's website (AEROS) available at (http://soramame.taiki.go.jp/, accessed on the 26 June 2021) were used for comparison [26]. The results showed good agreement in time variation between Yamashina station (5.8 km from Kyoto University, Yoshida South Campus) and the P-sensor from 16 November to 20 February (Figure S1a).
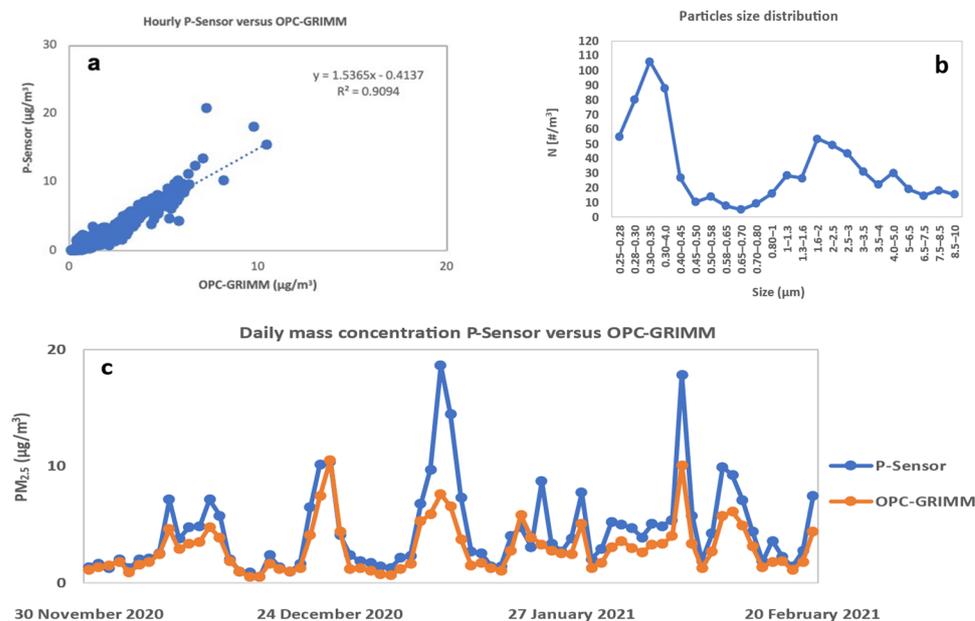
Figure 3. (**a**) Correlation plots of the P-sensor versus the GRIMM OPC from 30 November to 22 December 2020, and from 7 January to 20 February 2021; hourly average concentration. (**b**) Typical size distribution of PM from the GRIMM OPC. (**c**) Daily variation of $PM_{2.5}$ concentration for the GRIMM OPC versus the P-sensor.

To ensure the quality of the data collected on personal exposure to $PM_{2.5}$, the participants were given lectures to explain to them the content of the study, as well as its objectives and methods prior to data collection. They were instructed on how to record detailed information during the sampling period. The lecture also included demonstrations on how to operate the sensors. Each participant was given a chance to operate a sensor before the official start of the samplings. The communication between the participants and the research team was constant during the sampling period so that any problem or question could immediately be addressed. Batteries were regularly charged during sleep time without interrupting the samplings, to prepare for the next day. This was possible, as the batteries have multiple connection ports. Data were downloaded and saved from the sensors after each participant completed the required sampling period. Sensors and batteries were checked for any malfunction before assigning them to the next participants. Only data obtained from participants providing clear information on time, location, and activity were used for the data analysis.

2.5. Data Analysis

The diaries and the recorded concentrations from the devices were used to calculate personal exposure to $PM_{2.5}$. Background concentrations were considered as concentrations recorded in absence of local emission sources. These concentrations were very low compared to those recorded during the participants' daily activities, and were included in our calculations.

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Personal Exposure Calculation Method: Case of the Office Workers

The personal exposure to $PM_{2.5}$ was calculated using the recorded concentrations for different activities and microenvironments along with the time spent for these activities and microenvironments.

$$OW1d_1 = \frac{\sum_{i=1}^{n} OW1C_{1i}t_{1i}}{24} \qquad (1)$$

where $OW1d_1$ is the average exposure of office worker 1 for day 1(d_1). $\sum_{i=1}^{n} OW1C_{1i}t_{1i}$ represents the integrated exposure concentration of the office worker on d_1. It was obtained from the product of the total average concentration ($\mu g/m^3$) recorded in all the microenvironments (C_{1i}) on d_1, such as home, office, transportation, and stores, and the time (hours) spent in the microenvironments (t_{1i}). Note that 24 is one day in hours.

The average exposure of all office workers was calculated as follows:

$$AvgOW = \frac{(OW1d_1 + OW1d_2 + OW1d_3 + \ldots + OW2d_1 + OW2d_2 + \ldots + OWnd_3)}{N} \qquad (2)$$

where OW is the group of office workers, and OWn represents the total number of office workers. d_1, d_2, d_3 are sampling days 1, 2, and 3. N is the number of office workers multiplied by the number of sampling days.

The same method was applied to obtain the exposure concentrations for the group of students, cooks, and drivers.

3. Results

3.1. Daily Time-Series of $PM_{2.5}$ Concentration

Although the data presented in this study were collected during the COVID-19 pandemic, we presumed that the pandemic did not influence the results. The restrictions for coronavirus case reduction strategies were no longer applicable in Bamako. Citizens had already resumed their daily activities. Consequently, outdoor emission sources remained unchanged. Furthermore, household activities (house chore, cooking and other combustion sources) were sustained as they were not related to the COVID-19 restrictions in Bamako.

3.1.1. OW

Five participants were OW. Figure 4a shows a typical $PM_{2.5}$ concentration variation by OW2 between 7–9 October 2020. The air conditions of OW were mainly categorized as home, commuting, office, and home (IST/ICS). OW2 was exposed to a 3-day average of 50 $\mu g/m^3$ with daily concentrations of up to 102 $\mu g/m^3$. The green color in the figure represents the $PM_{2.5}$ concentration at home with an average value of 10 $\mu g/m^3$ and a maximum value of 29 $\mu g/m^3$. The recorded concentrations during the commute to work of OW2 averaged 21 $\mu g/m^3$ with a maximum of 79 $\mu g/m^3$. The concentration in the office, represented by the blue color, averaged 16 $\mu g/m^3$ with a maximum of 33 $\mu g/m^3$. A higher average concentration of 34 $\mu g/m^3$ was recorded during the participant's break time, represented in brown in the figure.

The red color in the figure shows concentrations at home when the participant was using insecticides (IST) and incense (ICS), which are popular in the region. The average and maximum values were 163 $\mu g/m^3$ and 460 $\mu g/m^3$, respectively. The home air with the use of insecticides and incense was separately categorized from the period when these products were not used, due to large differences in concentration. ICS is widely used in Bamako to provide a pleasant scent in the home and is part of the Malian culture. IST are used to prevent mosquito bites and reduce the risk of malaria. These products were typically used every day by the participants. As shown in Figure 4a, the highest exposures to OW2 were observed during the use of IST/ICS and the commute.
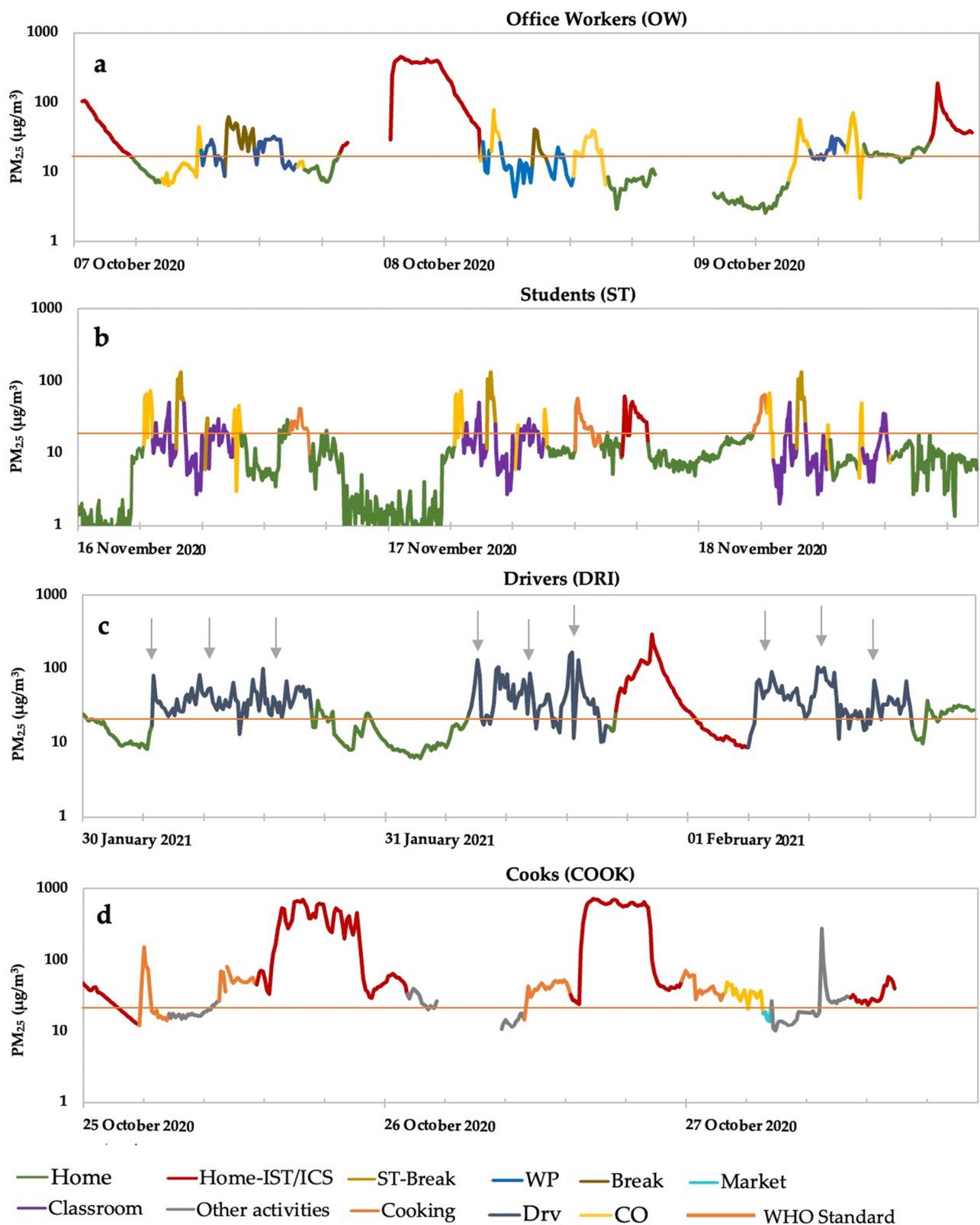
Figure 4. Typical daily personal profile adopted from OW2 (**a**), ST1 (**b**), DRI3 (**c**), and COOK1 (**d**) between September 2020 and February 2021. WHO: World Health Organization, IST/ICS: Insecticide/Incense, OW: Office workers, ST: Students, DRI: Drivers, WP: Workplace, Drv: Driving, CO: Commute. The grey arrows indicate the rush hours.

3.1.2. ST

Figure 4b shows the daily representative $PM_{2.5}$ concentration variations for one individual (ST1) from 16–18 November 2020. The microenvironments and activities describing air conditions for ST1 were mainly home, commuting, school, break time at school (outside), and home (ISC/IST). The green color represents the concentration of $PM_{2.5}$ at home (average concentration 8 $\mu g/m^3$). The participant's room was located near the kitchen, which increased the average concentration from 8 to 29 $\mu g/m^3$ during cooking, represented in orange. Yellow indicates the concentration during the commute (walking or driving) between home and school, which averaged 37 $\mu g/m^3$. Heavy-traffic areas emitting high levels of $PM_{2.5}$ have a higher health impact than other pollutants on pedestrians [27]. Purple indicates the concentration at school during classes, which averaged 14 $\mu g/m^3$. The highest concentration for ST1 was observed during break time, with an average and maximum value of 80 and 133 $\mu g/m^3$, respectively. The high concentration during break time can be explained by soil dust resuspension, as the schoolyard was dry (Figure S6). The use of ICS is represented by a red color. The average and maximum concentrations were 34 and 62 $\mu g/m^3$, respectively. The daily $PM_{2.5}$ concentrations in this group were affected by the commute and break time. The findings indicate high exposure to $PM_{2.5}$ both indoors and outdoors for the ST group.

3.1.3. DRI

Two microenvironments and one activity were categorizing air conditions for public transportation drivers: home, driving, and home (IST/ICS). These are represented in green, gray, and red (Figure 4c). The daily representative $PM_{2.5}$ concentration variations for a public transportation driver (DRI3) from 30 January 2020 to 1 February 2021, are presented. DRI3 was exposed to 14 $\mu g/m^3$ on average at home, increasing to 43 $\mu g/m^3$ on average during working hours corresponding to driving. The concentration reached 167 $\mu g/m^3$ during rush hours, generally between 7:00 to 9:00 a.m., 11:30 a.m. to 1:00 p.m., and 3:30 to 7:00 p.m. (gray arrows). The highest concentration was 81 $\mu g/m^3$ on average with a maximum of 290 $\mu g/m^3$ recorded at bedtime after the use of insecticides. DRI3 was highly exposed to $PM_{2.5}$, for a considerable amount of time.

3.1.4. COOK

Activities of COOK were limited to food preparation and other household activities, such as cleaning the house, doing dishes, and groceries, indicating the exposure level in this group. Regular daily $PM_{2.5}$ concentration variations are shown in Figure 4d, adopted from COOK1 from 25–27 October 2020. COOK1 was exposed to a 3-day average concentration of 128 $\mu g/m^3$. The highest average concentration was observed at home during sleep (228 $\mu g/m^3$). The concentrations during such events reached very high peaks of up to 717 $\mu g/m^3$. Cooking time, shown in orange, represented the second-highest average concentration of 42 $\mu g/m^3$ with a maximum of 150 $\mu g/m^3$. A high concentration of 27 $\mu g/m^3$ on average was also observed when COOK1 performed other household activities (gray color). The use of specific products, charcoal, and wood as cooking fuel and a cooking stove not adapted for efficient combustion were sources of exposure to a high concentration of particles during the entire sampling period.

3.2. Comparison of Different Groups

Table 1 summarizes the $PM_{2.5}$ concentrations of the participants' daily activities averaged for each group. Information about the concentration for each group is provided in separate tables (Tables S3–S6) in the Supplementary Materials.

Table 1. Summary of PM$_{2.5}$ concentrations (μg/m^3) during the participants' daily activities. Numbers in parentheses show exposure time (hours).

	OW	ST	DRI	COOK	Average
Home	9	14	12	18	13 ± 4
Driving/commute	33 (1.9)	30 (1.6)	42 (11.6)		35 ± 6
Workplace	14 (5.7)				
Cooking	43 (2)			41 (3.1)	42 ± 1
Beauty salon	19 (1.7)				
School (classes)		16 (4.3)			
School (Break)		31 (0.8)			
Home (IST/ICS)	244 (3.8)	30 (2.6) *	78(4.1)	300 (4.5)	207 ± 115 **
Daily average	12	18	27	24	20 ± 7
Daily average (IST/ICS)	49	20 *	38	76	54 ± 20 **

* STs were exposed only to ICS and not to IST. ** ST was excluded.

The highest concentration of 207 μg/m^3 on average was observed at home with IST/ICS usage, followed by cooking (42 μg/m^3), driving and commuting (35 μg/m^3), school (Break; 31 μg/m^3, beauty salon (19 μg/m^3), school 16 μg/m^3), and home without IST/ICS usage (13 μg/m^3). In this study, concentrations in the same microenvironments and activities were similar, even in different groups (Table 1).

IST/ICS average values from this study (207 ± 115 μg/m^3) are comparable to the average value reported by Kumar (2014) in India (256.8 μg/m^3) [28]. In addition, road traffic PM$_{2.5}$ was 35 ± 6 μg/m^3 on average; a similar value of PM$_{2.5}$ from traffic was reported by Abera (2020) in Adama-Addis Ababa (33 μg/m^3), a lower value by Belarbi (2020) in Algeria (19.71 μg/m^3), and a higher value was reported by Ariunsaikhan (2020) in Mongolia (42,871 μg/m^3) [29–31]. Cooking represented 41 ± 1 μg/m^3, and a similar value of PM$_{2.5}$ from cooking was reported by Vliet al. (2013) in Ghana (46.6 μg/m^3) [12].

The DRI group displayed the highest daily averaged concentration (excluding periods involving usage of IST and ICS) of 27 μg/m^3, followed by COOK (24 μg/m^3), ST (18 μg/m^3), and OW (12 μg/m^3). The higher values for DRI and COOK were attributed to high PM$_{2.5}$ concentrations during daytime activities of driving and cooking, respectively. On the other hand, the low daytime PM$_{2.5}$ concentrations in offices and schools resulted in lower daily values for OW and ST, as shown in Table 1. However, when concentrations with IST/ICS at home were involved in the daily average estimation, the daily average concentration increased significantly. The concentration increased from 20 to 54 μg/m^3 (Table 1), which was twice as large as the WHO guideline. OW and COOK participants showed similar average concentrations of IST/ICS of 244 and 300 μg/m^3, respectively. In both groups, the participants reported the simultaneous use of IST and ICS in the diaries. Drivers presented lower values, which was attributed to the use of only IST in a microenvironment located near the participants' rooms. The group of students had the lowest concentration associated with the combustion of ICS only in the house.

Figure 5 displays the estimated average maximum, minimum, and median PM$_{2.5}$ exposure concentrations indoors (a,b) and outdoors (c). The PM$_{2.5}$ maximum average concentrations reached very high levels for all indoor and outdoor activities and microenvironments. The highest average maximum and median values were attributed to indoor exposure (IST/ICS) and outdoor exposure (driving and cooking). The highest level of 999 μg/m^3 was observed indoors during the combustion of IST, which is consistent with results presented by Manigrasso et al. where indoor PM emissions were the highest while combustion sources, such as mosquito coil and incense coil, were present [32]. The second highest was attributed to driving (216 μg/m^3), followed by cooking at a concentration of 150 μg/m^3. The use of only ICS at home represented another high-exposure microenvironment, with an average maximum exposure of 145 μg/m^3. The highest median exposure occurred during special events at 82 and 46 μg/m^3, respectively, for IST and ICS. Driving and cooking were 34 μg/m^3. Fifty percent of the exposure concentration was higher than

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the median values. For most activities and microenvironments, the median concentration exceeded the WHO daily standard of 25 μg/m^3 [33]. The average minimum concentrations were ≤14 μg/m^3, depending on the activity and microenvironment.
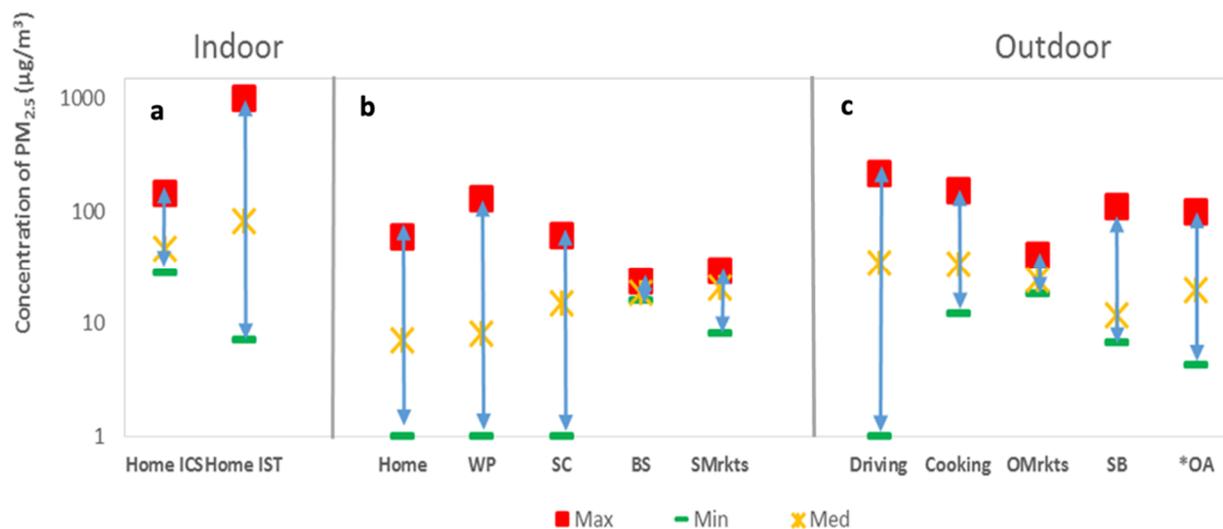
Figure 5. Average maximum (Max), minimum (Min), and median (Med) concentrations for different activities and microenvironments indoors (**a**,**b**) and outdoors (**c**). IST: Insecticide, ICS: Incense, WP: Workplace, SC: School (classes), BS: Beauty salon, Smrkts: Supermarkets, Omrkts: Open markets, SB: School break, OA: Other activities. * Activities recorded indoors and outdoors.

The indoor PM$_{2.5}$ concentration did not exceed 11 μg/m^3 without the combustion of the specific products. Therefore, indoor exposure could significantly decrease with a decrease in the use of IST/ICS. The outdoor average concentration was as low as 9 μg/m^3 in the neighborhood, while the concentration in the yards of houses reached 22 μg/m^3 (Table S1). For both indoor and outdoor environments, background concentrations were lower than the observed concentrations during anthropogenic activities. This implies that in Bamako, anthropogenic activities are the most likely factor of exposure, rather than outdoor elevated sources.

4. Discussion

4.1. Identification of Activities Producing Greatest Exposure to PM$_{2.5}$

Total integrated exposure, which is the product of concentration and exposure time, was calculated for each group to characterize the exposure during different common daily activities (Figure 6).

The integrated exposure varied in different microenvironments, depending on the activity and its duration. Special events were frequent and represented the highest integrated exposure for OW, COOK, and DRI (927, 1350, and 320 μg m^{-3} h, respectively). The combustion of IST/ICS is a common practice in households in a wide area (Africa, Asia, and South America). Although indoor air pollution has been widely addressed in the literature, the use of IST/ICS has received comparatively little interest.

Highly integrated exposures were also observed during traffic (driving and commuting). The DRI group with a value of 487 μg m^{-3} h presented the highest integrated exposure, followed by OW and ST groups (63 and 48 μg m^{-3} h, respectively).

Cooking represented another activity with high integrated exposure values of 127 and 86 μg m^{-3} h in the COOK and OW groups, respectively. In this study, the COOK group presented a significantly high integrated exposure of 432 μg m^{-3} per day compared to the one presented by Vliet et al. (2013) in rural Ghana of 128.5 μg m^{-3} per day [12]. This marked difference might be attributed to the additional daily activities performed by cooks in the urban city of Bamako, such as commuting, cleaning, and grocery acquisition.
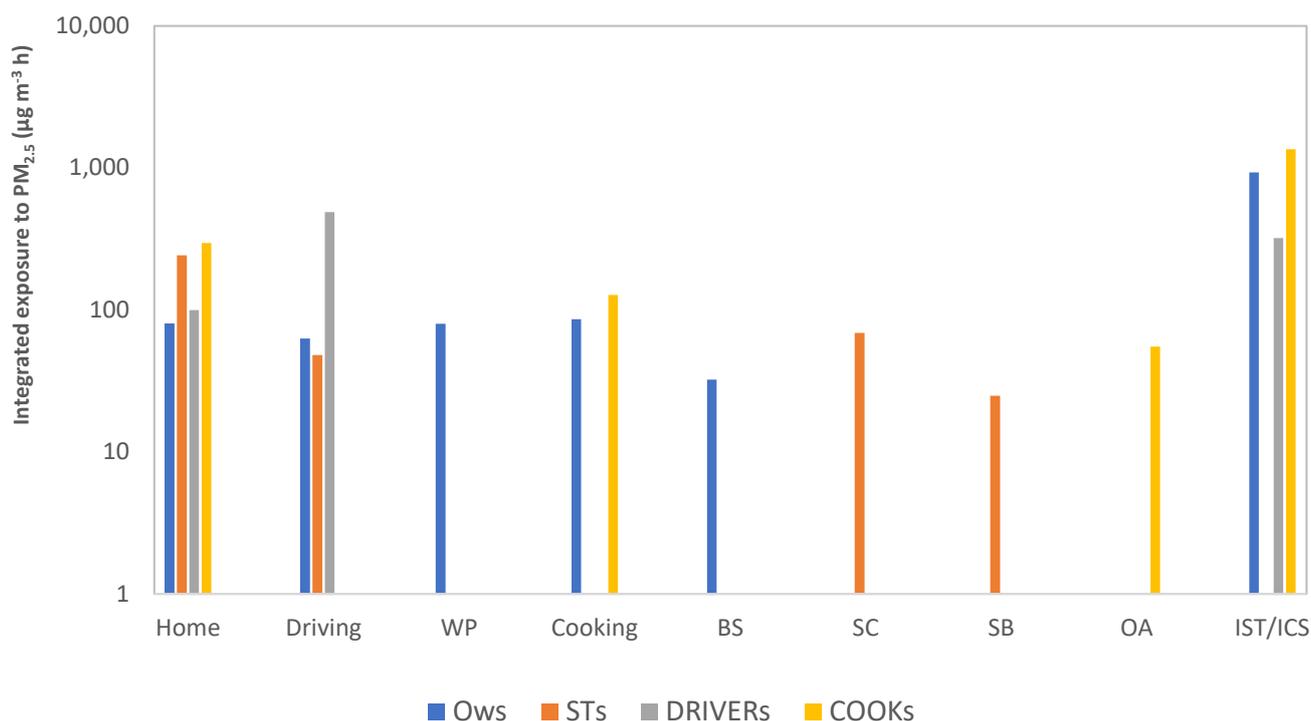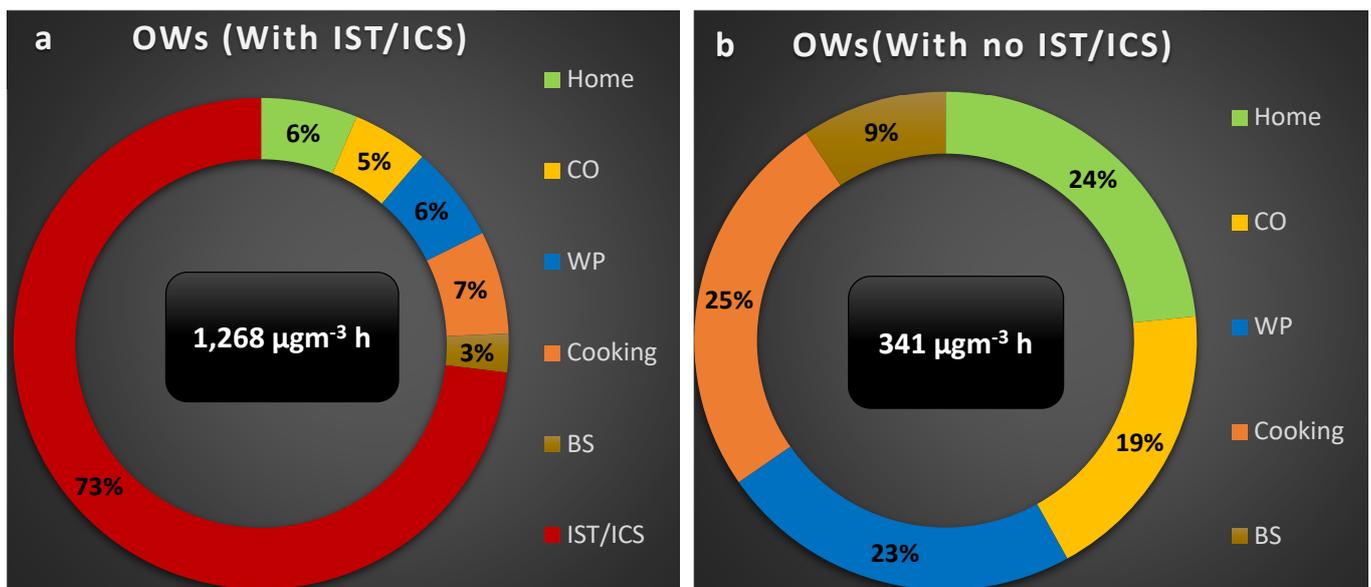
Figure 6. Integrated $PM_{2.5}$ exposure for different activities. IST: Insecticide, ICS: Incense, STs: Students, OWs: Office workers, WP: Workplace, BS: Beauty salon, SC: School (classes), SB: School (break), OA: other activities.

Additionally, the percentages of integrated exposure attributed to different microenvironments were estimated. The value of the integrated exposure for each microenvironment was divided by the sum of the integrated exposure of all the microenvironments in each group. Figure 7 presents the percentages of the integrated exposure for the OW group with and without the use of specific products (a and b, respectively). Percentages for the other groups are given in the Supplementary Materials (Figures S7–S9). For the OW group, the highest percentage of integrated exposure was attributed to the use of IST/ICS (73%, Figure 7a). Without special events, the highest percentage was attributed to cooking (Figure 7b). The data in Figure 7a,b indicate the total integrated exposure decreased by approximately a factor of 4, from 1268 to 341 $\mu g \ m^{-3}$ h, without the combustion of IST/ICS. PM emissions from fossil fuel and biofuel combustion are expected to increase significantly in Africa in the near future [34]. An increase of 10 $\mu g/m^3$ of $PM_{2.5}$ is associated with high respiratory disease mortality and morbidity of 4.6% and 4.5%, respectively [5]. Even though houses in Bamako have natural ventilation systems, the windows and doors are usually kept closed while using products, such as IST and ICS.

In Bamako, occupational gender segregation influences the degree of the integrated exposure. All public transportation drivers are men, and cooks are women. According to the WHO, emissions from road traffic have been linked to a wide range of health effects, including effects on the cardiovascular and respiratory systems [35]. Public transportation drivers spend more than 10 h per day working (Figure 4c). Thus, they are subject to chronic exposure. Moreover, domestic biomass usage for cooking is one of the major $PM_{2.5}$ exposure sources in developing countries [36]. Associated with domestic and forest fires, cooking has generated global concern for its effects on human health and the environment [37]. In 2010, the use of solid fuels for household cooking resulted in 370,000 deaths and 9.9 million disability-adjusted life years on a global scale [38]. In Mali, wood and charcoal represent more than 75 percent of the household energy needs [16]. Solid fuel is usually combusted in inefficient cooking stoves, producing a variety of health-damaging particles [38]. The effects of air pollution can be observed during pregnancy [39]. Chronic exposure to $PM_{2.5}$

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concentrations exceeding 30 µg/m^3 has been associated with maternal death [9]. Globally, emissions from households' solid fuel burning represented the second largest health risk factor in women, and the third in children on a global scale [12,22]. In Bamako, children spend a considerable amount of time with their mothers during the first few years of their lives. Nevertheless, women are the most exposed to PM from cooking, suggesting that children are subject to PM exposure from cooking. In addition, unlike males, female OWs perform other activities, especially during weekends, exposing them to supplementary sources of PM$_{2.5}$. Figure 8 shows the gender-related integrated exposure for a female OW. In addition to working, female office workers often cook and take care of the house; therefore, they can be exposed to supplementary PM$_{2.5}$ sources.

Figure 7. Percentage of integrated exposure for different activities and microenvironments for office workers including (**a**) and excluding (**b**) the combustion of IST/ICS. OW: Office worker IST: Insecticide, ICS: Incense, CO: Commute, WP: Workplace, BS: Beauty salon.
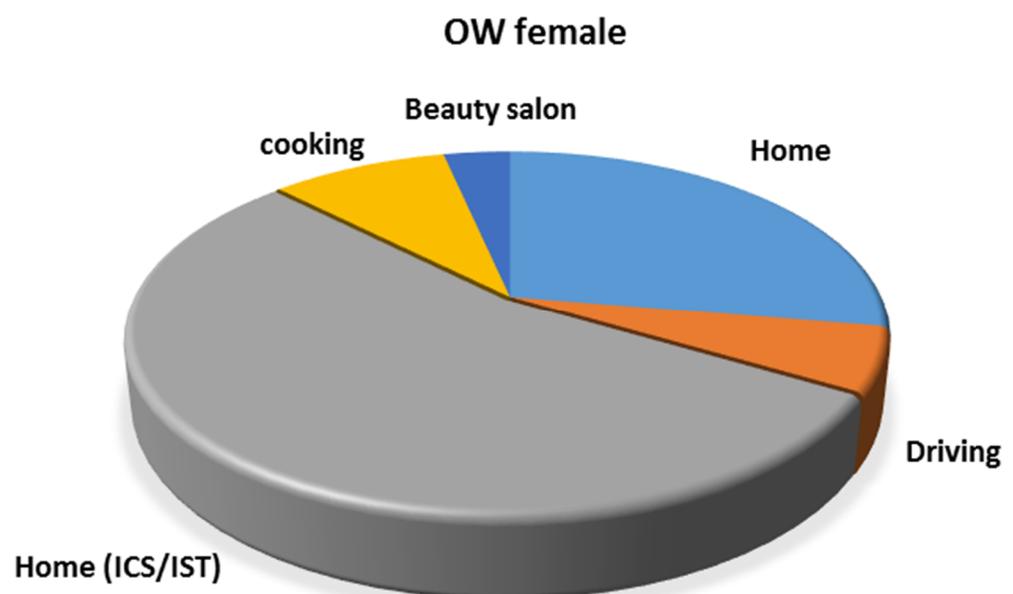
Figure 8. Gender-related integrated exposure to PM$_{2.5}$ adopted from OW5 on 26 and 27 September 2020. OW: Office worker; IST: Insecticide; ICS: Incense.

The findings allowed us to identify three main common daily activities exposing the population to high concentrations of $PM_{2.5}$: combustion of specific products (IST and ICS) in households, traffic, and cooking.

4.2. Comparison of $PM_{2.5}$ Concentration with WHO Standards and Health Effects

The 24 h average concentrations with and without the use of the specific products were compared to the WHO standards. With no ISC/ICS, DRIs and COOKs presented very close values to the WHO's guideline for 24 h exposure concentration of 25 $\mu g/m^3$ [33]. However, OWs and STs displayed lower values than the guideline (Table 1). Concentrations were markedly increased in the OW, COOK, and DRI groups with the use of specific products. Concentrations were 2, 1.5, and 3 times higher, respectively, than the recommended daily limit. Diverse health issues from exposure to high $PM_{2.5}$ concentrations have been mentioned in many studies. For example, Li et al. (2013) [40] reported concentrations exceeding 20 $\mu g/m^3$ as the most harmful to human respiratory health. In the present study, all four groups exceeded the yearly limits of 10 $\mu g/m^3$ with no use of IST/ICS. After considering the use of specific products, the ST, DRI, OW, and COOK groups presented values that were 2, 4, 5, and 7.5 times higher, respectively, than the yearly recommended limit of exposure to $PM_{2.5}$. Burning one mosquito coil can release the same amount of $PM_{2.5}$ as burning 75–137 cigarettes [41]. The combustion of IST has been associated with toxicological effects, morphological alterations, and enzyme perturbations [41]. Asthma, lifetime eczema, wheezing, and rhinitis have been associated with the combustion of IST. ICS burning has been found to be associated with wheezing and rhinitis [42]. Furthermore, from previous studies, the combustion of IST/ICS was found to liberate compounds that are carcinogenic to humans [32].

In Bamako, the incidence of acute respiratory disease increased from 282,000 cases in 2001 to more than 1,500,000 in 2016 [18]. An annual concentration of 10 $\mu g/m^3$ is recommended as the long-term exposure limit. However, a recent study pointed out the effects of long exposure to $PM_{2.5}$ concentrations below the recommended limits [43]. Disease from air pollution results in a decrease in life expectancy, similar to those of other high-priority risk factors and diseases [44].

5. Conclusions

Relationships between personal exposure to $PM_{2.5}$ and daily activities were investigated in the city of Bamako using palm-sized optical $PM_{2.5}$ sensors. Sampling was performed indoors and outdoors to determine the exposure level for different activities and microenvironments. The participants were divided into four groups according to their main occupation. Three daily activities that highly expose the population to $PM_{2.5}$ have been identified as the most exposed inhabitants.

The study revealed that Bamako's inhabitants are highly exposed indoors while combusting IST and ICS, where concentrations reached 999 $\mu g/m^3$ on average in a 10 min period. Likewise, participants were least exposed indoors when IST/ICS were not used. Traffic and cooking were identified as high-exposure activities. The concentrations fluctuated among the groups according to their main occupation. Public transportation drivers and cooks were most exposed to $PM_{2.5}$ during their daily activities. Comparisons of our results with the WHO standards indicated that all participants exceeded the yearly exposure limits. Office workers and students presented values within the daily exposure limit without the use of specific products. On the other hand, the group of cooks and drivers exceeded this limit. Although the concentration in students was within the daily limit, the young age makes them more susceptible to air pollution.

Observing the populations actions and avoiding activities that increase pollution could help reduce pollution levels, and consequently, reduce exposure levels. An increase in the level of $PM_{2.5}$ leads to negative effects on health, especially for sensitive people [45]. According to Manigrasso et al. (2017), the impact of particulate matter is higher for sensitive people compared to healthy individuals [46]. Indoor air quality is highly critical for health,

since people typically spend most of their time indoors. The use of specific products indoors greatly increased the concentration of PM$_{2.5}$. Therefore, reducing the use of these products could reduce the exposure at specific locations and reduce the risk level of individual total inhaled doses [47]. Moreover, Vliet et al. (2013) suggested that a change in individual behavior could help reduce exposure to PM$_{2.5}$ [12]. Communities, once aware of the potential health effects from their daily indoor actions, can manage their own exposure by avoiding or reducing activities that emit pollution.

This is the first study assessing personal exposure to PM in the city of Bamako. The results provide valuable information about the level of exposure. The results indicated that the main exposure sources were related to lifestyle, IST/ICS use, driving, and cooking. The exposure levels were acute and, the emission sources were strongly related to daily anthropogenic activities rather than natural emissions. This indicates the advantage of personal exposure monitoring.

This study could help increase populations' awareness and should be useful for decision-makers. Consequently, it could help achieve SDG goals, especially regarding health and the environment. For instance, reducing personal exposure to PM$_{2.5}$ through individual daily actions could reduce health impacts and thus contribute to the SDG3 on health and wellbeing. Furthermore, improving the quality of fuel used by strengthening laws on the fuel quality, using catalytic converters to the vehicle exhausts, reinforcing laws on the annual vehicles' technical inspections, promoting teleworking, and the shift in working hours for different institutions and companies could significantly reduce road traffic-induced pollution. Indeed, teleworking can moderate traffic congestion, thus improving air quality and facilitating urban planning and development [48]. Gradually switching from the use of charcoal and wood to the use of cleaner energies, such as solar energy and biogas, could alleviate the exposure to PM$_{2.5}$ from biofuel combustion, as well as pollution from waste incineration. In particular, countries like Mali have high solar potential energy and face waste management issues. These alternatives are economically challenging for developing countries and require time, as proper planning and funds are needed. Therefore, promoting the use of improved cook-stoves with higher combustion efficiency could be practical as a transitional state. Adopting such strategies could help mitigate urban air pollution in Bamako and help achieve SDG7 on affordable and clean energy and SDG13 on climate change at different scales. There is a strong connection between global and local environmental concerns. Although many urban issues are confined within the local scale, many others have regional, or even global consequences. Reducing local emissions has positive repercussions on the mitigation response to regional and global environmental issues, as emissions typically originate from local sources [49].

Our findings demonstrate the need to design appropriate control strategies and continuous monitoring of PM$_{2.5}$, to reduce emissions and protect public health. More work is needed to obtain information on the chemical composition of PM$_{2.5}$, and hence, more information on emission sources and specific health effects in this region.

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grated exposure for different activities and microenvironments for cooks including (a) and excluding (b) the combustion of IST/ICS.

References

1. Seinfeld, J.H.; Pandis, S.N. *Atmospheric Chemistry and Physics from Air Pollution to Climate Change*, 2nd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2006.
2. Jacob, D.J. *Introduction to Atmospheric Chemistry*; Princeton University Press: Chichester, UK, 1999.
3. Penttinen, P.; Timonen, K.L.; Tiittanen, P.; Mirme, A.; Ruuskanen, J.; Pekkanen, J. Number Concentration and Size of Particles in Urban Air: Effects on Spirometric Lung Function in Adult Asthmatic Subjects. *Environ. Health Perspect.* **2001**, *109*, 319–323. [CrossRef] [PubMed]
4. Chowdhury, S.; Dey, S.; Guttikunda, S.; Pillarisetti, A.; Smith, K.R.; Di Girolamo, L. Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 10711–10716. [CrossRef]
5. Miller, L.; Xu, X. Ambient $PM_{2.5}$ Human Health Effects—Findings in China and Research Directions. *Atmosphere* **2018**, *9*, 424. [CrossRef]
6. Sicard, P.; Khaniabadi, Y.O.; Perez, S.; Gualtieri, M.; De Marco, A. Effect of O_3, PM_{10} and $PM_{2.5}$ on cardiovascular and respiratory diseases in cities of France, Iran and Italy. *Environ. Sci. Pollut. Res.* **2019**, *26*, 32645–32665. [CrossRef]
7. Wang, B.; Eum, K.-D.; Kazemiparkouhi, F.; Li, C.; Manjourides, J.; Pavlu, V.; Suh, H. The impact of long-term $PM_{2.5}$ exposure on specific causes of death: Exposure-response curves and effect modification among 53 million U.S. Medicare beneficiaries. *Environ. Health* **2020**, *19*, 20. [CrossRef]
8. Agbo, K.E.; Walgraeve, C.; Eze, J.I.; Ugwoke, P.E.; Ukoha, P.O.; Van Langenhove, H. A review on ambient and indoor air pollution status in Africa. *Atmos. Pollut. Res.* **2020**, *12*, 243–260. [CrossRef]
9. Katoto, P.D.; Byamungu, L.; Brand, A.S.; Mokaya, J.; Strijdom, H.; Goswami, N.; De Boever, P.; Nawrot, T.S.; Nemery, B. Ambient air pollution and health in Sub-Saharan Africa: Current evidence, perspectives and a call to action. *Environ. Res.* **2019**, *173*, 174–188. [CrossRef] [PubMed]
10. Lamri, N.; Hocine, A.K.; Salah, K. Particulate matter from road traffic in Africa. *J. Earth Sci. Geotech. Eng.* **2017**, *7*, 289–304.
11. Bruce, N.; Perez-Padilla, R.; Albalak, R. Indoor air pollution in developing countries: A major environmental and public health challenge. *Bull. World Health Organ.* **2000**, *78*, 1078–1092.
12. Vliet, E.D.S.V.; Asante, K.; Jack, D.W.; Kinney, P.L.; Whyatt, R.M.; Chillrud, S.N.; Abokyi, L.; Zandoh, C.; Owusu-Agyei, S. Personal exposures to fine particulate matter and black carbon in households cooking with biomass fuels in rural Ghana. *Environ. Res.* **2013**, *127*, 40–48. [CrossRef]
13. Lim, S.S.; Vos, T.; Flaxman, A.D.; Danaei, G.; Shibuya, K.; Adair-Rohani, H.; AlMazroa, M.A.; Amann, M.; Anderson, H.R.; Andrews, K.G.; et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **2012**, *380*, 2224–2260. [CrossRef]
14. Tefera, W.; Kumie, A.; Berhane, K.; Gilliland, F.; Lai, A.; Sricharoenvech, P.; Samet, J.; Patz, J.; Schauer, J.J. Chemical Characterization and Seasonality of Ambient Particles ($PM_{2.5}$) in the City Centre of Addis Ababa. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6998. [CrossRef] [PubMed]
15. Togola, M. Pollution de l'air à Bamako: Un seuil (très) critique. *J. Sci. Tech. Du Mali.* **2017**.

16. Ministere De L'environnement, De L'assainissement et Du Developpement Durable (MEADD). Rapport Troisieme Comm-munication Nationale Du Mali A La Convention Cadre Des Nations Unies Sur Les Changements Climatiques. 239. Mali. 2017. Available online: https://chm.cbd.int/api/v2013/documents/7DD41D1F-F5C7-60E6-3987-14624F6A9F90/attachments/RAPPORT_FINAL_TCN_09_01_18.pdf (accessed on 7 June 2021).

17. Dembele, S. Dynamique Socio-Spatiale de la Ville de Bamako et Environs. Normandie Université. 2017. Available online: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers19-04/010075426.pdf (accessed on 6 September 2021).

18. Institut National de la Statistique (INSTAT). *Malikunnafoni, Version 1.0.1*; Mobil Application Software: Bamako, Mali, 2020.

19. Nakayama, T.; Matsumi, Y.; Kawahito, K.; Watabe, Y. Development and evaluation of a palm-sized optical PM2.5 sensor. *Aerosol Sci. Technol.* **2018**, *52*, 2–12. [CrossRef]

20. Population Data.net. 2021. Available online: https://www.populationdata.net/pays/mali/ (accessed on 25 September 2021).

21. Val, S.; Liousse, C.; Doumbia, E.H.T.; Galy-Lacaux, C.; Cachier, H.; Marchand, N.; Badel, A.; Gardrat, E.; Sylvestre, A.; Baeza-Squiban, A. 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*, 10–16. [CrossRef] [PubMed]

22. Panasonic Photo & Lighting Co., Ltd. n.d. Available online: https://industrial.panasonic.com/ww/products/pt/dust-sensor/pm25_led (accessed on 1 September 2021).

23. Li, Z.; Wei, Y.; Zhang, Y.; Xie, Y.; Li, L.; Li, K.; Ma, Y.; Sun, X.; Zhao, W.; Gu, X. Retrieval of Atmospheric Fine Particulate Density Based on Merging Particle Size Distribution Measurements: Multi-instrument Observation and Quality Control at Shouxian. *J. Geophys. Res. Atmos.* **2018**, *123*, 12474–12488. [CrossRef]

24. Lin, Y.; Bahreini, R.; Zimmerman, S.; Fofie, E.A.; Asa-Awuku, A.; Park, K.; Lee, S.-B.; Bae, G.-N.; Jung, H.S. Investigation of ambient aerosol effective density with and without using a catalytic stripper. *Atmos. Environ.* **2018**, *187*, 84–92. [CrossRef]

25. Rissler, J.; Nordin, E.Z.; Eriksson, A.C.; Nilsson, P.T.; Frosch, M.; Sporre, M.K.; Wierzbicka, A.; Svenningsson, B.; Löndahl, J.; Messing, M.E.; et al. Effective Density and Mixing State of Aerosol Particles in a Near-Traffic Urban Environment. *Environ. Sci. Technol.* **2014**, *48*, 6300–6308. [CrossRef]

26. Atmospheric Environmental Regional Observation System: AEROS. 2021. Available online: http://soramame.taiki.go.jp/ (accessed on 26 June 2021).

27. Yoon, S.; Moon, Y.; Jeong, J.; Park, C.-R.; Kang, W. A Network-Based Approach for Reducing Pedestrian Exposure to PM$_{2.5}$ Induced by Road Traffic in Seoul. *Land* **2021**, *10*, 1045. [CrossRef]

28. Kumar, R.; Kumar, D.; Kumar, M.; Mavi, A.K.; Singh, K.; Gupta, N. Monitoring of indoor particulate matter during burning of mosquito coil, incense sticks and dhoop. *Indian J. Allergy Asthma Immunol.* **2014**, *28*, 68. [CrossRef]

29. Abera, A.; Mattisson, K.; Eriksson, A.; Ahlberg, E.; Sahilu, G.; Mengistie, B.; Bayih, A.G.; Aseffaa, A.; Malmqvist, E.; Isaxon, C. Air Pollution Measurements and Land-Use Regression in Urban Sub-Saharan Africa Using Low-Cost Sensors—Possibilities and Pitfalls. *Atmosphere* **2020**, *11*, 1357. [CrossRef]

30. Belarbi, N.; Belamri, M.; Dahmani, B.; Benamar, M.A. Road Traffic and PM10, PM2.5 Emission at an Urban Area in Algeria: Identification and Statistical Analysis. *Pollution* **2020**, *6*, 651–660. [CrossRef]

31. Ariunsaikhan, A.; Chonokhuu, S.; Matsumi, Y. Mobile Measurement of PM$_{2.5}$ Based on an Individual in Ulaanbaatar City. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2701. [CrossRef]

32. Manigrasso, M.; Vitali, M.; Protano, C.; Avino, P. Temporal evolution of ultrafine particles and of alveolar deposited surface area from main indoor combustion and non-combustion sources in a model room. *Sci. Total Environ.* **2017**, *598*, 1015–1026. [CrossRef] [PubMed]

33. World Health Organization (WHO). *Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide Global Update 2005*; WHO: Geneva, Switzerland, 2005.

34. Liousse, C.; Assamoi, E.; Criqui, P.; Granier, C.; Rosset, R. Explosive growth in African combustion emissions from 2005 to 2030. *Environ. Res. Lett.* **2014**, *9*, 035003. [CrossRef]

35. World Health Organization (WHO). *Health Risks of Particulate Matter from Long-Range Transboundary Air Pollution.1-99. Denmark*; WHO: Geneva, Switzerland, 2006.

36. International Institute for Applied Systems Analysis (IIAS). *Sources of Air Pollution in Developing Countries*; IIAS: Laxenburg, Austria, 2016.

37. Mkoma, S.L.; Kawamura, K.; Fu, P.Q. Contributions of biomass/biofuel burning to organic aerosols and particulate matter in Tanzania, East Africa, based on analyses of ionic species, organic and elemental carbon, Levoglucosan and Mannosan. *Atmos. Chem. Phys. Discuss.* **2013**, *13*, 10325–10338. [CrossRef]

38. Chafe, Z.A.; Brauer, M.; Klimont, Z.; Van Dingenen, R.; Mehta, S.; Rao, S.; Riahi, K.; Dentener, F.; Smith, K.R. Household Cooking with Solid Fuels Contributes to Ambient PM2.5 Air Pollution and the Burden of Disease. *Environ. Health Perspect.* **2014**, *122*, 1314–1320. [CrossRef]

39. Dhital, S.; Rupakhet, D. Correction to: Bibliometric analysis of global research on air pollution and human health: 1998–2017. *Environ. Sci. Pollut. Res. Int.* **2019**, *26*, 25386. [CrossRef]

40. Li, P.; Xin, J.; Wang, Y.; Wang, S.; Li, G.; Pan, X.; Liu, Z.; Wang, L. The acute effects of fine particles on respiratory mortality and morbidity in Beijing, 2004–2009. *Environ. Sci. Pollut. Res.* **2013**, *20*, 6433–6444. [CrossRef] [PubMed]

Int. J. Environ. Res. Public Health **2022**, *19*, 611

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41. Liu, W.; Zhang, J.; Hashim, J.H.; Jalaludin, J.; Hashim, Z.; Goldstein, B.D. Mosquito coil emissions and health implications. *Environ. Health Perspect.* **2003**, *111*, 1454–1460. [CrossRef] [PubMed]

42. Norbäcka, D.; Lu, C.; Zhang, Y.; Li, B.; Zhao, Z.; Huang, C.; Zhang, X.; Qian, H.; Sun, Y.; Wang, J.; et al. Sources of indoor particulate matter (PM) and outdoor air pollution in China in relation to asthma, wheeze, rhinitis and eczema among pre-school children: Synergistic effects between antibiotics use and PM10 and second-hand smoke. *Environ. Internet* **2019**, *125*, 252–260. [CrossRef]

43. Yu, W.; Guo, Y.; Shi, L.; Li, S. The association between long-term exposure to low-level PM2.5 and mortality in the state of Queensland, Australia: A modeling study with the difference-in-differences approach. *PLoS Med.* **2020**, *17*, 1003141. [CrossRef] [PubMed]

44. Apte, J.S.; Brauer, M.; Cohen, A.J.; Ezzati, M.; Pope, I.C.A. Ambient PM2.5 Reduces Global and Regional Life Expectancy. *Environ. Sci. Technol. Lett.* **2018**, *5*, 546–551. [CrossRef]

45. Bentayeb, M.; Simoni, M.; Norbäck, D.; Baldacci, S.; Maio, S.; Viegi, G.; Annesi-Maesano, I. Indoor air pollution and respiratory health in the elderly. *J. Environ. Sci. Health* **2013**, *48*, 1783–1789. [CrossRef] [PubMed]

46. Manigrasso, M.; Natale, C.; Vitali, M.; Protano, C.; Avino, P. Pedestrians in Traffic Environments: Ultrafine Particle Respiratory Doses. *Int. J. Environ. Res. Public Health* **2017**, *14*, 288. [CrossRef]

47. Song, J.; Zhou, S.; Xu, J.; Su, L. From PM2.5 exposure to PM2.5 risks of inhaled dose in daily activities: Empirical evidence during workdays from Guangzhou, China. *Atmos. Environ.* **2021**, *249*, 118224. [CrossRef]

48. Giovanis, E. The relationship between teleworking, traffic and air pollution. *Atmos. Pollut. Res.* **2017**, *9*, 1–14. [CrossRef]

49. Bai, X. Integrating Global Environmental Concerns into Urban Management: The Scale and Readiness Arguments. *J. Ind. Ecol.* **2007**, *11*, 15–29. [CrossRef]