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The infiltration of wildfire smoke and its potential dose on pregnant women: Lessons learned from Indonesia wildfires in 2019

Vissia Ardiyani [a,b,*], Martin Wooster [c,e], Mark Grosvenor [c,e], Puji Lestari [d], Wiranda Suri [d]

[a] Health Polytechnic of Palangka Raya, 30-32 G. Obos St., Palangka Raya, Central Kalimantan, Indonesia
[b] King's College London, Analytical and Environmental Sciences, 150 Stamford Street, London, UK
[c] King's College London, Department of Geography, King's College London, Aldwych, London, UK
[d] Bandung Institute of Technology, 10 Ganesha St., Bandung, Indonesia
[e] Leverhulme Centre for Wildfires, Environment and Society, Imperial College London, South Kensington, London, UK

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ABSTRACT

The occurrence of wildfires in Indonesia is prevalent during drought seasons. Multiple toxic pollutants emitted from wildfires have deleterious effects on pregnant women. However, the evidence for these on pregnant women was underreported. The study conducted 24-h monitoring of fine particulate matter ($PM_{2.5}$) concentrations indoors and outdoors in 9 low-income homes in Palangka Raya during the 2019 wildfire season and 6 low-income homes during the 2019 non-wildfire season. A hundred and seventy pregnant women had their PM exposure assessed between July and October 2019 using personal monitors. It was observed that outdoor air pollutant levels were greater than those found indoors without indoor sources. The findings indicate that indoor $PM_{2.5}$ concentrations were modestly increased by 1.2 times higher than outdoor, suggesting that buildings only partially protected people from exposure during wildfires. The concentrations of $PM_{2.5}$ were found to be comparatively higher indoors in residential buildings with wood material than in brick houses. The study findings indicate that 8 out of 12 brick houses exhibited a notable $RI/O_{24\ h}$ of less than 1 during the wildfires, whereas all $I/O_{24\ h}$ ratios during the non-wildfire season were >1, suggesting the influence of indoor sources. Based on the estimation of daily $PM_{2.5}$ dose, pregnant women received around 21% of their total daily dose during sedentary activity involving cooking. The present research offers empirical support for the view that indoor air quality in low-income households is affected by a complex combination of factors, including wildfire smoke, air tightness, and occupant behaviour. Also, this situation is more likely a potential risk to pregnant women being exposed to wildfire smoke.

1. Introduction

A type of wetlands called "peatland" stores an immense amount of carbon (C), approximately 105 gigatonnes [1]. The peatlands are formed by decayed organic matter, accumulating layers of peat. In waterlogged conditions, organic matter accumulation requires

* Corresponding author. King's College London, Analytical and Environmental Sciences, 150 Stamford Street, London, UK.
E-mail addresses: vissia.ardiyani@polkesraya.ac.id, vissia.ardiyani@kcl.ac.uk (V. Ardiyani).

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anaerobic processes to partially decompose vegetation, sustaining the C cycle over a thousand years. While the peatlands are crucial in the earth for preventing floods, filtering water, and storing C, a sensitive characteristic of peatlands which depends on the water sustainability, potentially triggers fires during a dry season. Since 1982–1983, Indonesia has encountered devastating fires due to the exploitation of lands for cultivation. It was exacerbated by the drought-induced El Nino -Southern Oscillation (ENSO) [2,3]. During the ENSO period, fires intend to pronounce and contribute more impacts on land loss and degradation [4] and potential adverse health outcomes for humans [5,6].

As humans evolved and developed ways of living globally, dependence on fires to extend their lands for agriculture and build houses increased [7]. It is a fundamental step in accelerating air pollution in a particular area. Rising temperatures and decreased precipitation exacerbate the intensity of fires maximazing pollutants, including greenhouse gas (i.e., CH_4, CO, and N_2O) and particulate matter [8].

The physical properties of particulate matter, which range in size from a few nanometres to tens of micrometers, play a significant role in determining their behaviour both in the atmosphere and within the human respiratory system. However, it should be noted that other factors may also contribute to their behaviour. A fundamental differentiation can be identified based on the size of particles, whereby those measuring less than approximately 2.5 mm are capable of entering the alveoli and terminal bronchioles. Conversely, particles that are larger with the size up to 10 mm, tend to accumulate predominantly in the primary bronchi. Furthermore, particles of much greater size, up to 100 mm, are known to deposit in the nasopharynx. The category of $PM_{2.5}$ encompasses fine particulate matter that ranges in size from 0.1 to 2.5 mm, inclusive of the ultra-fine mode. $PM_{2.5}$ is commonly known as respirable particles due to its capacity to reach the alveolar gas exchange region of the lungs [9]. Particulate matter (PM) comprises heterogeneous chemical substances with different characteristics and toxicities. A chemical substance adsorbed on PM, a product of fires occurring at high temperatures, can modify genetic materials in the human body [10]. For instance, a polycyclic hydrocarbon (i.e., benzo(a)pyrene) is more likely to manifest in the formation of DNA adducts or affecting DNA methylation state prior to the impact on adverse health outcomes such as reduced birth weights [11,12].

Pregnancy might be a potential window of increased susceptibility to DNA adducts formation through placental oxidative stress-induced DNA damage and inflammation because of a wide range of enzyme metabolic functions in the placenta [13,14]. $PM_{2.5}$ – bind PAHs has an aerodynamic diameter of ≤2.5 μm, enabling them to penetrate the placenta. Once they reach the placenta, PAHs are metabolised and generate reactive epoxides, which can bind covalently to DNA, resulting in DNA adducts [15,16]. DNA adducts as a biomarker of exposure reflect individual susceptibility to exposure, absorption, activation, metabolism, and the ability to repair DNA damage [16]. A consequence of DNA adducts in utero is a deficiency in specific hormones, affecting tissue formation and differentiation in a foetus [17,18], leading to reduced birth weight. It, therefore, becomes apparent that the air pollution due to peatland fires contributes to severe health effects in pregnant women.

Assessing chemical substances such as PM is a crucial factor in examining the levels of environmental pollution in particular locations and estimating pollution impact on the population at risk, especially in the sense of intervention evaluation. Ground-based measurements of PM concentrations in Indonesia, which evaluate air quality throughout the year (i.e., non-fires and fires), have yet to be fully represented. Quantifying personal $PM_{2.5}$ concentrations allows us to determine their toxicity in pregnant women.

Further considerations on quantifying personal $PM_{2.5}$ in pregnant women are uncertainty concentrations during their routine activities, both indoor and outdoor environments. During the fires, the affected citizens were urged to stay indoors at all times to minimize exposure to smoke. However, some concerns arise in terms of indoor air quality. The emission from fires degrades air quality in an ambient environment which can penetrate the building envelope and remain suspended in indoor air [19]. These contribute to indoor particle concentrations through air infiltration (i.e., open windows, ventilations, cracks in the barrier of the building envelope). Studies reported that approximately 23%–67% of outdoors polluted air was estimated to contribute to indoor air quality [20,21]. Therefore, assessing indoor and outdoor air quality in pregnant women will measure $PM_{2.5}$ concentrations accurately to reduce exposure misclassification, considering pregnant women's activity patterns. Furthermore, different locations within the city might reflect spatial variability.

A primary objective of this present study is first, to quantify $PM_{2.5}$ concentrations in residential indoor-outdoor sites and personal $PM_{2.5}$ concentrations in pregnant women. We considered the extent of $PM_{2.5}$ in outdoor air infiltrates into buildings through potential entrances at respondents' houses by calculating I/O ratio and F_{inf}. Serial measurements were carried out in residential indoor-outdoor sites, and personal monitoring within an individual's breathing zone. Second, seasonal and daily variability were assessed to estimate the influence of pregnant women's activity in various environments. Third, the serial measurements form the baseline risk assessment of people living in heavily affected fire areas.

2. Material and methods

2.1. Study location and sampling

The location is Palangka Raya, the capital City of Central Kalimantan and home to 291,700 people (93 inhabitants/km [2]). According to BMKG [22], Central Kalimantan has a seasonal climate, with average monthly precipitation ranging from 16.7 mm (July–October) to 200 mm (November–June). Droughts can be brought on by El Nino events [23], and during drought years, precipitation in the July to October period varies between 0 and 50 mm. The mean temperature throughout the year is ∼ 21 °C–36 °C, with the highest temperature during this study found to be 43 °C (derived from our PA network).

We measured ambient $PM_{2.5}$ concentrations, outdoor-indoor microenvironment $PM_{2.5}$ concentrations, and personal exposure of individual citizens. The targets for the latter were pregnant women located in 10 boroughs of Palangka Raya City, who were each recruited for a study examining the impact of $PM_{2.5}$ exposure on pregnancy outcomes. In total, 170 pregnant women had their $PM_{2.5}$ exposure assessed between July and October 2019 using personal monitoring devices. A subset of people had indoor and outdoor air quality measurements carried out at their homes, nine persons during the 2019 wildfire season (Sept–Oct 2019) and six during the non-wildfire season (May–July 2019).

2.2. Measurements

2.2.1. Ambient $PM_{2.5}$ concentrations across Palangka Raya

A network of ten Purple Air (PA) sensors was used to assess the ambient PM concentration around the city from August to October 2019 (Fig. 1B). During this time, the fire burning in and around the city (Fig. 1A) severely affected the air quality. The locations of the instruments were chosen to broadly represent the home locations of the 170 respondents involved in the study – with an 800 m to 5 km distance separating any respondent's house and 5 km the closest PM reference monitoring site from respondent houses. Despite diverse distances between houses and ambient air sensors, the Pearson Correlation test shows strong agreements (Fig. S2) suggesting that $PM_{2.5}$ concentrations in residential outdoors – representing by 8 houses - were equal to $PM_{2.5}$ concentrations in ambient air where PAs were installed. Thus, ambient $PM_{2.5}$ concentrations were uniformly spread out in outdoor respondents' houses. Due to a technical issue with fixed reference stations in Palangka Raya, we used the PA network to monitor ambient air (Fig. 1D). Fig. 1 shows this network's overall results, which detail is described somewhere else (in prep).

2.2.2. Indoor and outdoor $PM_{2.5}$ concentrations

Indoor $PM_{2.5}$ measurements were conducted inside 19 households, seven during the non-wildfire season (April–July 2019) and twelve during the wildfire season (August–October 2019) [22,24]. Two different instrument types were used for this purpose, with AM520s (Side pack AM520 – personal aerosol monitor, TSI incorporate, Minnesota, USA) used during the non-wildfire season and Purple Air sensors used during the wildfire season. All instruments operate on the principle of laser-backscattering from particulates present within the air sampled by the sensor. Temporal resolution was 15 min, matching the activity diary the householders were asked to keep explaining any noted change in $PM_{2.5}$ concentration (e.g., due to cooking). Following Buonanno, Giovinco, Morawska and Stabile [25], classes were 1. Cooking, 2. Sleeping and resting, 3. Sedentary activities, 4. Non-sedentary activities, 5. Walking, 6. House cleaning, 7. Eating, 8. Entertainment outdoor, 9. Commuting, 10. Sport indoor. Some "eating" time might have been simultaneously classified into the "cooking" category as the cooking activity.

Each instrument was placed 1.0–1.5 m above the ground inside the room (Fig. 1C) where the respondents spent most of their time inside the home (i.e., living room or family room), avoiding the kitchen and away from windows and doors. Outdoor $PM_{2.5}$

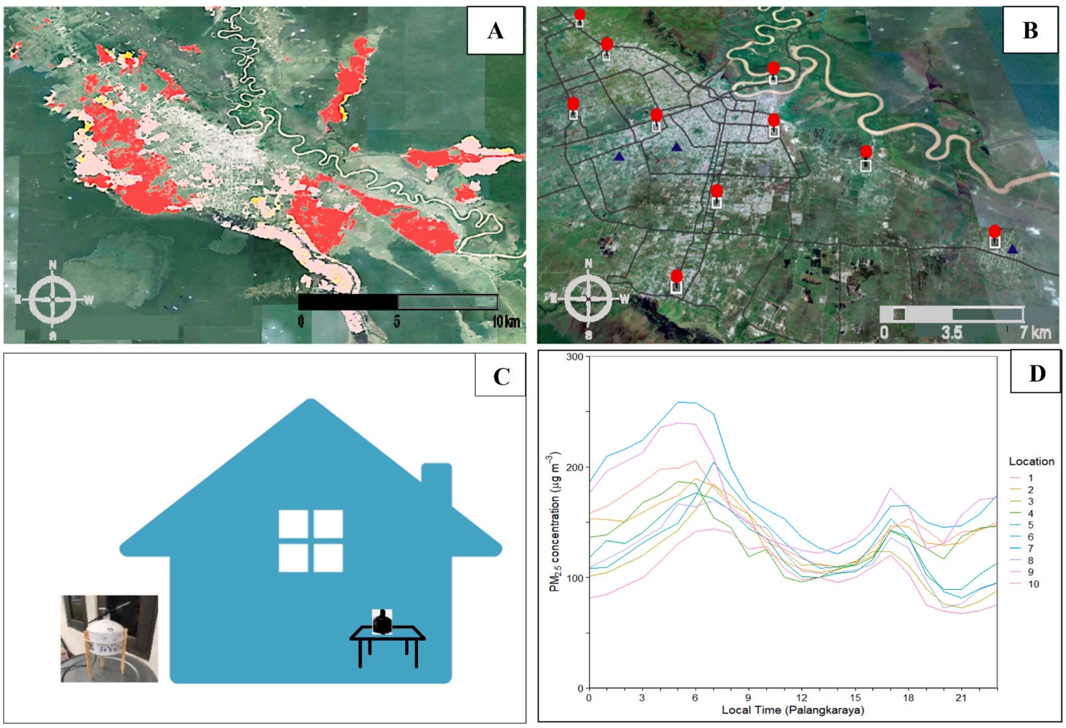

Fig. 1. Study area and our broad results from the Purple Air (PA) Network. (A) Study area in Palangka Raya city. The red colour corresponds to the burned area. (B) The PA network comprises 10 PA sensors installed across the city. (C) A measurement design for residential indoor and outdoor sites which were measured for 24 h. (D) A diurnal cycle according to PA sites.

measurements were taken close to each house during the period the indoor measurements were conducted (Fig. 1C). The sensor used was the same as for the indoor matching measurement, with this typically located on a terrace for 24 h to match the indoor measurements.

2.2.3. Personal exposure monitoring

Personal exposure measurements were conducted on 153 respondents and occurred six days a week except for national holidays and Sunday (in Palangka Raya, Saturday is a weekday). Fifteen minutes of temporal resolution personal exposure measurements were conducted using TSI AM520 (SidePak), which has routinely been used for such studies [26,27]. Each monitored person wore the Sidepack for most of a full day (not including sleep periods), with a record being considered for analysis as long as it was 18 h duration or more. Respondents carried instruments at all times in a bag, with the inlet tube placed in the breathing zone and exposed to the air (Fig. 2). Exceptions were for sleeping, washing, and cooking when the instruments were asked to be placed within 1.0 m (i.e., on the table, hanging on the wall). Seventy-six person-days were assessed during the non-wildfire season and 79 during the wildfire season, with ten percent of data needing to be considered due to instrument faults. Each person's day was a different respondent. The temporal resolution of the data was 1 min, with most measurements conducted during the wildfire season being limited to 18–22 h due to battery issues. Alongside the measures, respondents filled in a diary reporting their activity at 15-min intervals and wore a personal GPS to record their movement.

2.3. Data analysis

2.3.1. Daily integrated exposure and potential dose

We estimate daily integrated exposure and intake dose to quantify a health risk assessment on $PM_{2.5}$. The daily integrated exposure reflects the magnitude of $PM_{2.5}$ in an individual over 24-h. After exposure, there was the amount of $PM_{2.5}$ at the absorption barrier (i.e., lung) available for absorption, in other words, the amount of $PM_{2.5}$ inhaled by pregnant women. In toxicology is called potential dose [28]. Other quantifications on human risk, involving applied and internal doses, are not considered because data availability and animal laboratory were not established in this study. However, a biomarker detection on DNA adducts is being processed. These reflect the internal absorption and bioavailability of $PM_{2.5}$ attached PAHs.

With regards to the personal monitoring data, following [25], each person's exposure to particulate matter was converted to a time-integrated daily $PM_{2.5}$ exposure (μg-h/m^3) using **Equation (1)** [29,30]:

$$E^{daily}_{PM_{2.5}} = \int_0^{24} C^{PM_{2.5}}(t)dt \tag{1}$$

where $E^{daily}_{PM_{2.5}}$ is the daily-integrated exposure, $C^{PM_{2.5}}(t)$ is the real-time exposure concentrations of $PM_{2.5}$ and dt refers to hours in a day

Fig. 2. A respondent carried instruments in a bag, with the inlet tube placed in the breathing zone and exposed to the air.

that was spent in a specific activity. Potential dose (μg/m^3. m^3/min.kg) was calculated using Equation (2) by considering inhalation rate and body weight to assess the dose of $PM_{2.5}$, which is absorbed to the surface barrier (i.e., lung) [28].

$$D_{pot} = \int_{t_1}^{t_2} C(t)\ IR(t)\ W(t)dt \tag{2}$$

where D_{pot} is the potential dose, IR(t) is the inhalation rate, and W = body weight (kg).

2.3.2. The indoor-outdoor ratio (I/O)

We also quantified the effect of outdoor air pollution on indoor air quality using the indoor-outdoor ratio (I/O) and infiltration efficiency (F_{inf}) [19]. The indoor-outdoor ratio (I/O) is defined as in Equation (3).

Table 1
Personal and housing characteristics of the study participants (n = 170).

Characteristics	Mean ± SD or n (%)
Personal	
Age (years)	28 ± 5.4
Educational background, n (%)	
Elementary school	19 (11.2)
Junior high school	38 (22.4)
Senior high school	68 (40)
College	45 (26.5)
Occupation, n (%)	
Housewife	127 (74.7)
Retailer	8 (4.7)
Government employee	12 (7.1)
Private employee	21 (12.4)
Army	2 (1.2)
Housing	
Number of people at home, n (%)	
<4 people	79 (49.5)
4-5 People	58 (34.1)
>5 people	33 (19.4)
Housing density (m^2/person), n (%)	
<8 m^2/person	36 (21.2)
≥8 m^2/person	134 (78.8)
Floor material, n (%)	
Wood/planks	48 (28.2)
Cement	33 (19.4)
Tiles	89 (52.4)
Outerwall, n (%)	
Bamboo	1 (0.6)
Wood	52 (30.6)
Bricks	106 (62.4)
Cement	11 (6.5)
Main roof material	
Wood/sirap	12 (7.1)
Tiles	3 (1.8)
Metal sheets	138 (81.2)
Asbestos/cement sheets	4 (2.4)
Brick stone and lime	2 (1.2)
Stone	2 (1.2)
Other materials	9 (5.3)
Cooking fuel[a]	
Rice cooker & gas & kerosene & wood	3 (1.7)
Rice cooker & gas & wood	4 (2.4)
Rice cooker & gas & kerosene	16 (9.4)
Rice cooker & gas	144 (84.7)
Rice cooker & kerosene	3 (1.7)
Ratio window over the gross floor area	
<10%	40 (23.5)
10%	130 (76.5)
Smokers existence[b]	
Yes	91 (53.5)
No	79 (46.5)

SD: Standard Deviation; [a] more women used wood fuel in non-wildfire season (75%) than in wildfire season (25%) (out of 10% of stove combinations; data not shown); [b] Smokers in the wildfire season group were found quite frequent (50.5%) compared to non-wildfire group (49.5%) (among smokers; data not shown).

$$\frac{I}{O} ratio = \frac{C_{in}}{C_{out}} \tag{3}$$

where C_{in} and C_{out} are the concentrations of indoor and outdoor.

2.3.3. Air infiltration

The quantification of F_{inf} in individual residences holds significant importance in the assessment of PM exposure. The use of F_{inf}, together with temporal and spatial data, enables the distinct estimation of both outdoor-generated and indoor-generated particulate matter exposure, as well as the associated health effects. We performed an alternative method for F_{inf} estimation, approached by using the recursive model (RM), applying hourly indoor and outdoor light scattering data to estimate *P*, *a*, *k*, and F_{inf}. Detail equations are explained in Ref. [31]. Here, the autoregressive distribution lag was applied using STATA (StataCorp 17) to examine the F_{inf}, assuming constant air exchange rates and well-mixed indoor air. Data processing and time series analysis were performed using the R statistical software (v 4.0.1., R Core Team, 2020).

3. Results

3.1. Housing and respondent characteristics

All study participants were non–smokers with an average age of 28 (SD ± 5.4), and most (74.7%) were here housewives without paid employment. All lived in single-story houses, with 62.4% (mainly those from wealthier families) constructed of brick and cement and the others from wood. 83% of participants lived with up to 5 people, and the typical housing layout was a living room, and sometimes a joined 'family room', kitchen, bathroom, and between two and five bedrooms. Nearly 80% of households met or exceeded the Indonesian housing density standard of 8 m^2 per person. No homes had powered ventilation systems, and only 5% had air conditioners. Half of all households included smokers living in the house, but 51.2% of participants reported that smoking was primarily conducted outdoors. Housing and participant characteristics are summarised in Table 1.

The primary source of indoor air pollution in this study was cooking, and the kitchen of each home had at least one external door, a

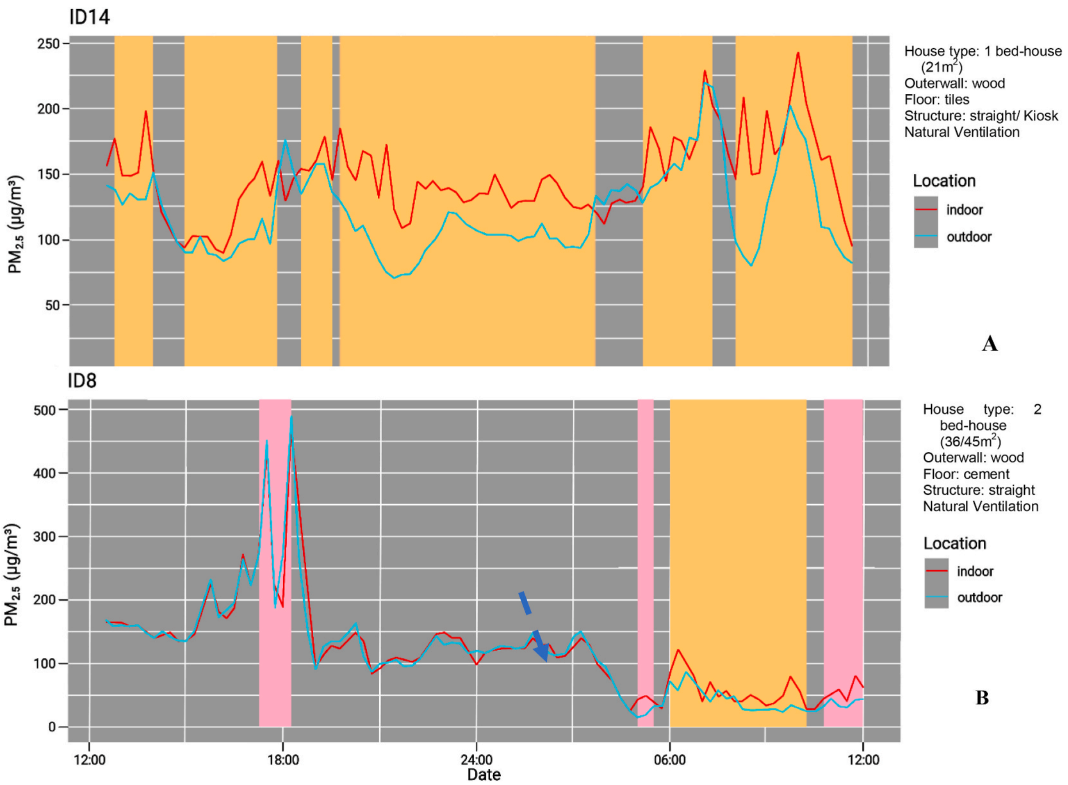

Fig. 3. Time series of $PM_{2.5}$ concentrations (µg/m^3) in four example houses. Indoor (red line) and outdoor $PM_{2.5}$ (green line) concentrations are shown. Picture D is a house with natural ventilations, and it is equipped with AC. As each measurement was conducted at different days with different intensity of smoke, the graphs shown here (A–D) are displayed on different scales of Y-axes. Background shading indicates the time periods when cooking (pink) and smoking (brown) was occurring. The blue arrows show an indoor air pollution source, for instance a cooking activity. During the cooking activity $PM_{2.5}$ went up between 30 and 50 µg/m^3.

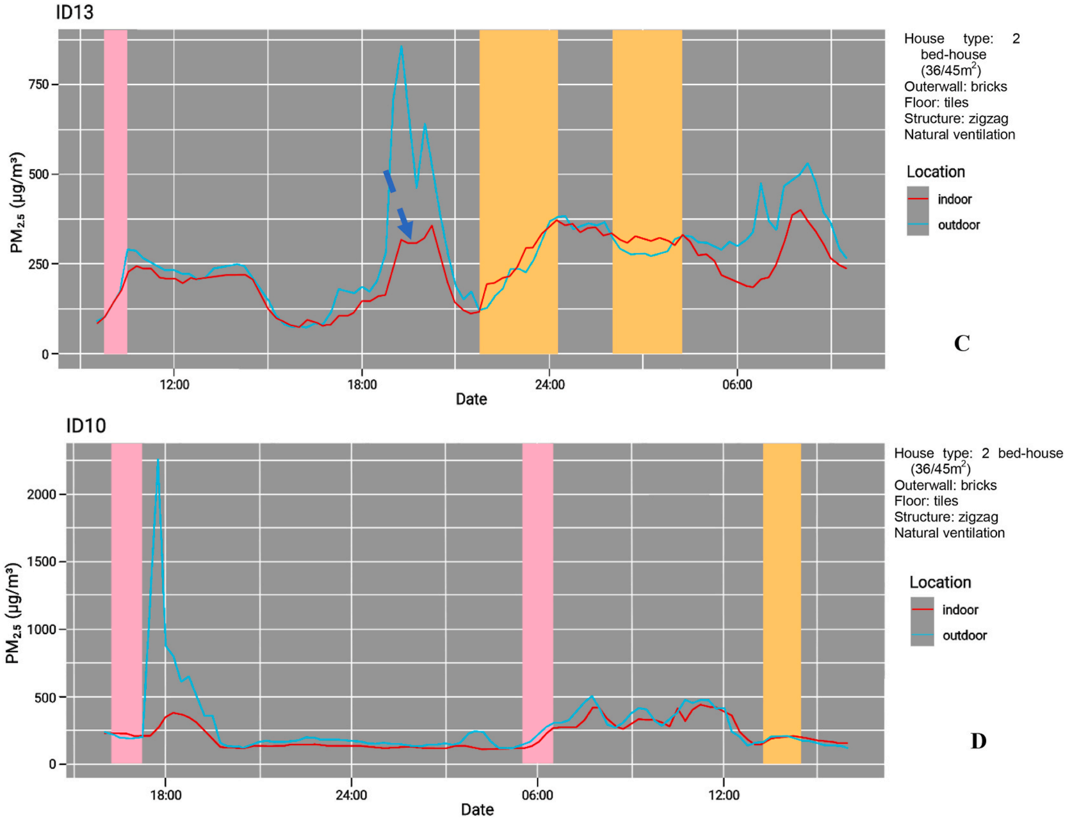

Fig. 3. (*continued*).

set of windows, and/or a passage connected to the living area. The smallest houses (~ 21 m^2) had the kitchen at the side of a bedroom without a partition (Fig. S1). All participants reported using an electric rice cooker in their homes, with nearly 85% using gas as their primary cooking fuel. A few (1.7%) combined rice cookers and gas stoves with wood or kerosene and wood to boil water. Very few (1.7%) used kerosene as a primary fuel.

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Windows are one of the main routes of air exchange between indoors and outdoors [32], so the window to the floor area ratio is essential in controlling air filtration into and out of the home [20]. 76.5% of households had a ratio of window to floor area of 10%, with the remaining households below this. However, windows and doors were shut whenever possible during the wildfire season, so indoor-outdoor air exchange occurred via uncontrolled leakages.

3.2. Ambient $PM_{2.5}$ concentrations

As shown in Fig. 1D, the time series of $PM_{2.5}$ concentrations recorded by the network of Purple Air sensors installed for this study showed that the mean $PM_{2.5}$ concentration measured during the wildfire season studied here was 274 μg/m^3 (standard deviation 261 μg/m^3). These indicate highly polluted air, classed as hazardous to health according to EPA guidelines [33]. Outdoor air temperatures during the same period ranged from a daytime mean of 34.8 °C to a night-time mean of 28.4 °C. Precipitation was 20 mm on average over the period of July–October 2019 [22].

3.3. Indoor and outdoor air concentrations

Examples of matching indoor and outdoor $PM_{2.5}$ concentration data are shown in Fig. 3 for the three primary housing types in Palangka Raya (i.e., 21 m^2, 36/45 m^2, 90/120 m^2). Further details are shown in Fig. S1. One house (ID10; Fig. 3d) is equipped with an air conditioner, whilst the others only have natural ventilation (ID 8, 13, 14).

In the examples shown in Fig. 3, most houses experienced similar indoor air quality to that present outdoor. However, indoor air quality was significantly worse for the house shown in Fig. 3A (ID 14) than outdoor air. These indicate potential indoor sources or the infiltration of polluted outdoor air into the home that diffuses slowly. This house is a typical wooden house in Palangka Raya, with gaps between the wooden boards that form its walls and small open ventilation spaces above the windows (see photos in Fig. S3).

Peaks in Fig. 3B (ID 8) appeared when the cooking activity occurred along with increased residential outdoors at 18:00 h. The other peaks occurred from 05:00 h to 06:00 h. The first peak in the morning was a consequence of cooking activity, while a combined effect of potential indoors and air infiltration outdoors caused the second peak in the morning. The peak continued until 10:00 h. However, the potential indoor source seemed to dominate in this short peak, followed by another cooking activity at 11:00–12:00 h.

Data from another house with natural ventilation is shown in Fig. 3C (ID13); it was a brick house with the windows closed. Here, indoor $PM_{2.5}$ concentrations were lower than matching outdoor concentrations, indicating that the building appears better protected from the infiltration of polluted outdoor air. Despite this, indoor $PM_{2.5}$ concentration peaks did occur late evening, probably due to the highly increased ambient outdoor concentrations after 20:00 h.

The last example shown in Fig. 3D (ID10) represents a brick house equipped with an air conditioner operated throughout the measurement period. Typical houses in Indonesia have small natural ventilations regardless having air conditioner. In non-wildfire season, people do not use AC as frequent as in wildfire season. In contrast, when fires occur, they close all ventilations they have, particularly those who have ACs. While outdoor air increased dramatically, keeping the windows fully closed reduced the impact of outdoor air infiltration. Some peaks might have still appeared but were subtle and occurred during meal preparations. The distance between the kitchen and living room where the residential PA indoor installed is rather far in the house type of >90/12 m^2 (Fig. S1).

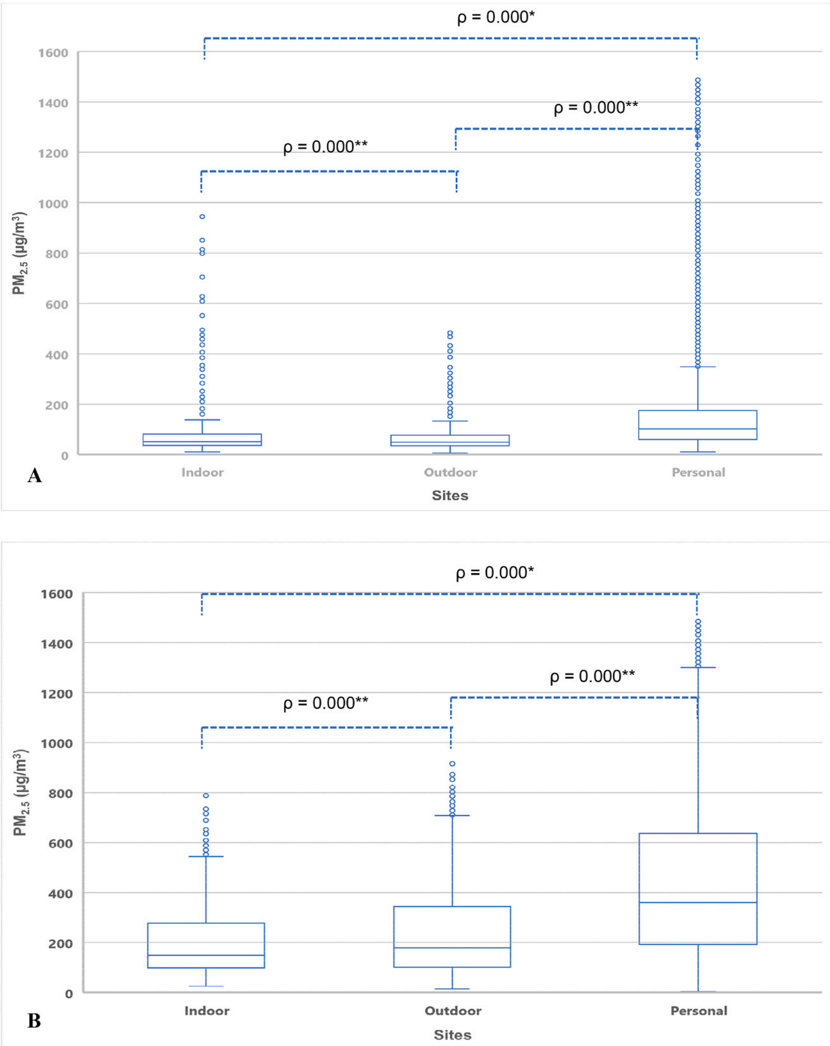

Fig. 4. p.m.$_{2.5}$ concentrations (μg/m^3) measured at different sites across Palangka Raya. Boxplots represent the inter-quartile range (IQR, 25–75 percentile), the horizontal lines represent geometric mean (GM), median values were represented in the middle of the darker grey and the grey whiskers. (A) $PM_{2.5}$ concentrations in non-wildfire season and (B) $PM_{2.5}$ concentrations in wildfire season. *ρ value is significant based on Kruskal Wallis test and **ρ value is significant based on Mann-Whitney tests for the post-hoc tests.

There are three possible reasons which explain the conditions. Firstly, once the $PM_{2.5}$ is emitted from cooking activity, the particles move through the building as a result of the difference in pressure between the kitchen and the other rooms. The heat and humidity from cooking in the kitchen contain denser material than particles. Therefore, the buoyancy effect forces particles to move upward and move to low pressures rooms [34]. Secondly, ventilations in the kitchen also cause naturally produced pressure differences, allowing particles to flow out of the house [35]. Lastly, a similar concept exemplifying the crowd of people in a room in Zheng's experiment [36], partition blocked the airflow and significantly changed the air distribution. For those reasons, air transport reduced $PM_{2.5}$ in the living room significantly.

Overall statistics for the indoor and matching outdoor measurements and the personal monitoring data detailed in section 3.3 are shown in Fig. 4.

During the non-wildfire season, residential indoor $PM_{2.5}$ concentrations were, on average, slightly higher than the outdoor concentrations at 61 and 58 μg/m^3, respectively – most likely due to indoor sources such as cooking. However, during the wildfire season, the average outdoor $PM_{2.5}$ concentration (187 μg/m^3) was moderately higher than the indoor concentration (162 μg/m^3), indicating that indoor environments provided some protection at this time. However, the indoor concentrations are still very high and considered hazardous to health and are analyzed further in the following section.

3.4. Seasonal indoor $PM_{2.5}$ concentrations

The indoor $PM_{2.5}$ concentrations were classified into six severity groups. Group 1 refers to the annual interim target 1 guideline of WHO for indoor air quality related to $PM_{2.5}$ <35 μg/m [37]. Groups 2–6 were classified according to Carter [38], which are 35–100 μg/m^3, 100–250 μg/m^3, 250–500 μg/m^3, 500–1000 μg/m^3, and >1000 μg/m^3. Trends of seasonal indoor $PM_{2.5}$ concentrations are displayed (Fig. 5).

As seen in Fig. 5B, during the non-wildfire season, the majority of the time, indoor air quality fell within the WHO guideline for indoor $PM_{2.5}$ (<35 μg/m^3), whereas this was the case only 5% of the time during the wildfire season. For only a short time, $PM_{2.5}$ >500 μg/m^3 during the non-wildfire season, and this coincided with cooking using a wood stove and use of mosquito coils as recorded in the activity diaries – often between 17:30 h and 18:30 h when house occupants were preparing meals and when mosquitos are typically active between sunset and sunrise [39].

Indoor particle concentrations that met the WHO guideline were only found in 50% of houses from 10:00 a.m. to 12:00 a.m. It could be found nearly 100% early in the morning (i.e., 03:00 a.m., 04:00 a.m., and 07:00 a.m.). Cooking time activity in the afternoon at around 04:00 p.m. was responsible for emitting 250–500 μg/m^3 in more than 60% of houses. Houses at large emitted particles at 35–100 μg/m^3 over time, exceeding the WHO guideline for $PM_{2.5}$ standard [9]. Houses at large (40%) demonstrate 100–250 μg/m^3 over time. In most houses, indoor $PM_{2.5}$ concentrations were highest (250–500 μg/m^3), occurring at around 06:30 a.m.–07:00 a.m., 11:30 a.m.–12:00 a.m., and 05:30 p.m.–07:00 p.m., corresponding to typical meal preparations. In between mealtimes, $PM_{2.5}$ concentrations were around 35–100 μg/m^3 in 25% of houses, while the remaining percentage of houses tended to have 250–500 μg/m^3.

Overall, Fig. 5A confirms that the severity of indoor $PM_{2.5}$ concentrations was very substantially worse during the wildfire season, with the main similarity with the wildfire season measure being a local peak around 17:00 to 18:00 h associated with the indoor sources (cooking primarily). These results confirm that the polluted outdoor air substantially influenced indoor air quality in residential homes during the wildfire season, so they did not protect the occupants from exposure to severe air pollution.

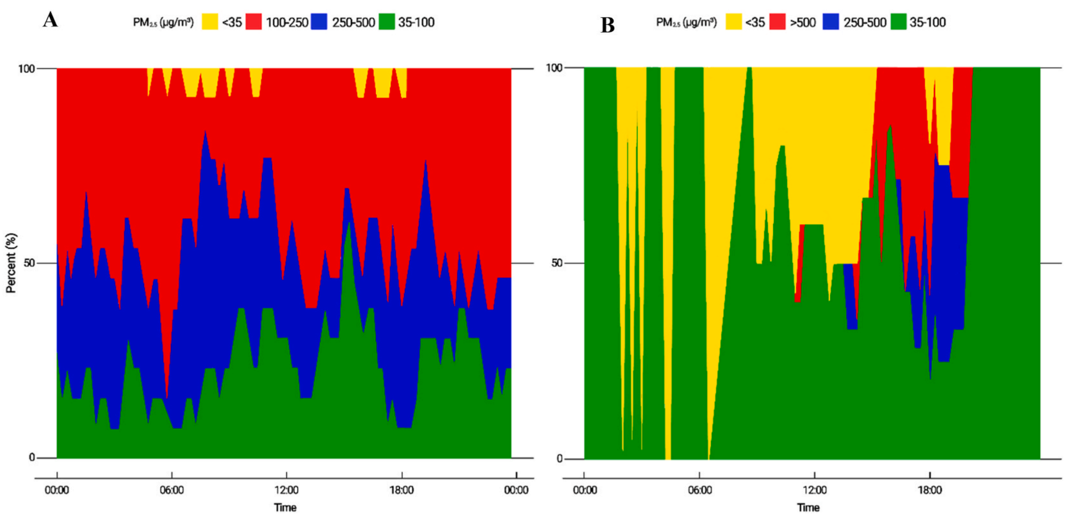

Fig. 5. Distributions of 24-h $PM_{2.5}$ in fire and non-wildfire seasons (in 15 min resolution) measured in 12 houses in wildfire season (panel A) and 7 houses in non-fire season (panel B).

3.5. 24-Hour indoor and outdoor $PM_{2.5}$ patterns

3.5.1. The indoor-outdoor ratio ($R_{I/O}$)

To examine further the relationship between outdoor and indoor air pollution levels and the effectiveness of different housing types in offering protection from the former, we calculated the indoor-outdoor ratio (I/O) to examine levels of air infiltration. The ratio directly represents the relationship between indoor and outdoor PM concentrations [19] and is defined as in **Equation (4)**.

$$R_{I/O} = \frac{C_{in}}{C_{out}} \tag{4}$$

where C_{in} and C_{out} are the indoor and outdoor particle concentrations, respectively. $R_{I/O} > 1.0$ simply means that $PM_{2.5}$ concentration indoors are higher than outdoors, and for $R_{I/O} < 1.0$, vice versa. $R_{I/O}$ can be used to estimate the impact of outdoor air pollution on indoor air quality when there are no indoor air pollution sources [37]. We derived $R_{I/O}$ using both 24-h data and only night-time data from 21:00 p.m. to 04:00 a.m. when we consider indoor sources negligible (confirmed by the activity diaries). Table 2 presents the $R_{I/O}$ data for the wildfire season and during the non-wildfire season. The RI/O is mostly >1.0, indicating that significant indoor sources of $PM_{2.5}$ existed. Overall, a statistically significant difference in $R_{I/O}$ between the 24-h and night-time measurements was observed during the wildfire season ($\rho_{spearman} = 0.05$).

As displayed in Table 1, approximately 10% of respondents used a supplementary stove for cooking, such as wood, kerosene, or a combination of both. It was found that more women used wood fuel in the non-wildfire season (75%) than in the wildfire season (25%) (out of 10% of stove combinations; data not shown). Other possible indoor sources are smoking (Table 1) and mosquito coils, which are common in Indonesian homes [40]. A smoker might have been present for only a small proportion of the entire microenvironment (e.g., a smoker was present for at least 1 min during a 60-min-long microenvironment) [41].

In contrast to the non-wildfire season data, RI/O is < 1 in most houses during the wildfire season when calculated from the 24-h data. However, the ratio exceeds 1 in houses 5, 10, 11, and 12 - indicating that air pollutants predominantly originated indoors. When using night-time data only, $R_{I/O}$ was increased compared to those calculated using the 24-h data measurement (i.e., ID10 and ID11). One possible reason underlying this finding is that a combined effect of $PM_{2.5}$ derived from the presence of a smoker/the usage of mosquito coils [40,42] and the air tightness of the houses [43], which leads to a synergism effect of $PM_{2.5}$ during night-time. Despite the difference between I/O 24-h and I/O night-time, the I/O ratio by materials remained the same ($\rho_{mann\text{-}whitney} = 0.214$). Here, $PM_{2.5}$ from outdoors could infiltrate indoors through any potential cracks regardless of house materials.

3.5.2. The infiltration factor (F_{inf})

To understand the infiltration of outside air indoors, we calculated the Infiltration Factor (F_{inf}), which avoids the influence of indoor particle sources and represents the equilibrium fraction of ambient particles penetrating indoors and remaining suspended [44,45]:

Infiltration of polluted outdoor air can occur via three main mechanisms, (i) through opened windows or doors (natural ventilations), (ii) via cracks and gaps between window frames or other parts of the house construction, and (iii) via an air conditioner that supplies outdoor air into the home [43,45,46].

During the non-wildfire season, F_{inf} shows somewhat random patterns and statistically insignificant relation of indoor-outdoor in houses ID 3,5,6 (Fig. 6B). These implied that some potential indoor sources (i.e., smokers, mosquito coils, cooking activity) were more likely present. Bricks houses demonstrated high F_{inf} because occupants kept their windows open to balance indoor temperature.

During the wildfire season, even though windows were closed to protect indoor air quality, there was a significant correlation between indoor and outdoor $PM_{2.5}$ concentrations – significant at the 0.05 level. Bricks houses demonstrated a lower F_{inf} (0.51–0.69)

Table 2

p.m.$_{2.5}$ I/O ratios in 12 houses, quantified using night-time and day-time averages during the wildfire season in 2019 and the other 7 houses measured during the 2018/2019 non-wildfire season.

	Wildfire season				Non-wildfire season		
ID	Materials	$R_{I/O\ night}$	$R_{I/O\ 24\text{-}h}$	ρ-value	$R_{I/O\ night}$	$R_{I/O\ 24\text{-}h}$	ρ-value
1	Bricks	0.77	0.83	0.174[a]	2	4	0.224[b]
2	Bricks	0.74	0.96	0.002[b]	1.1	1.4	
3	Bricks	0.9	0.92		1.1	1.1	
4	Bricks	0.85	0.94		1	1	
5	Bricks	0.88	1.09		1.5	1.8	
6	Bricks	0.8	0.86		0.7	1.5	
7	Bricks	0.76	0.77		1	1.6	
8	Bricks	0.79	0.9				
9	Wood	0.68	0.76				
10	Wood	1.1	1				
11	Wood	1.33	1.25				
12	Wood	0.98	1.17				

[a] Insignificant at >0.05 perfomed by mann-whitney test for the difference of I/O ratios by materials.
[b] Significant at <0,05 performed by spearman test for the difference between RI/O_{night} and $RI/O_{24\text{-}hour}$.

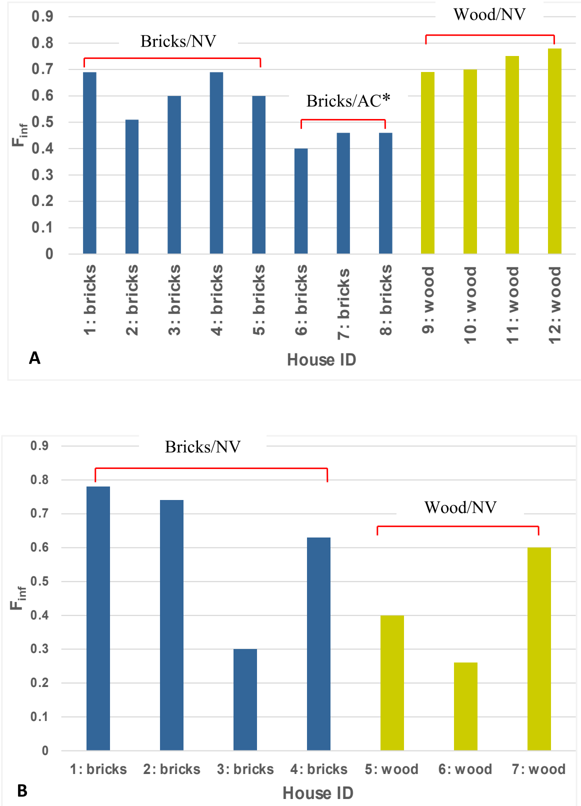

Fig. 6. Air infiltrations (F_{inf}) at observed houses. Picture (a) displays the observed houses during 2019 fire season. According to the Kruskal-Wallis's test, its results show strong evidence of a difference (ρ value < 0.05) between the mean ranks of at least one pair of groups. Furthermore, Mann-Whitney test (the post hoc test) was carried out for the three pairs of groups. There was a difference between the group who had construction materials from bricks with AC and those who had the wood. Picture b shows the observed houses during the 2019 non-fire season with different construction materials and the natural ventilation type. The Kruskal-Wallis's test shows no different values between houses made from bricks and wood (ρ value > 0.05). The abbreviation of NV stands for natural ventilation and AC for air conditioner.

than wooden houses (0.69–0.78) and were decreased further in brick houses equipped with an air conditioner (0.4–0.46) (Fig. 6A). Brick houses with only natural ventilation (NV) were intruded by outdoor air, even with windows closed. Compared to brick houses with AC NV, where F_{inf} decreased by approximately 0.15 (ID 6–8) - implying that enhancing air tightness by installing AC could improve air quality in residential indoor air quality and help control air temperature. In the same construction material as houses with AC, houses ID 1–5 show lower F_{inf} than wood houses because brick partially protects against smoke exposure (Fig. 6A). This result in this observational study is in line with a study by Sharma, who experimented with the building during the smoke period in Singapore. The researcher investigated buildings with some conditions (i.e., keeping windows open, fully closed windows with a fan, and fully closed windows with a fan and air cleaner). The I/O ratio defines air infiltration. Sharma revealed that the experimental case conditioned by a fan and fully closed windows gave better half protection than the building with windows opened. The study concluded that indoor air improved with an air cleaner [47].

3.6. Personal exposure data

The highest GM $PM_{2.5}$ concentrations originated from personal monitoring, as seen in Fig. 4. The highest $PM_{2.5}$ was 378 μg/m^3, approximately 50% higher than residential indoor-outdoor in wildfire season. In contrast, the average $PM_{2.5}$ concentrations during the non-wildfire season were 117.8 μg/m^3 - about 50% lower than in the wildfire season. The variability of $PM_{2.5}$ concentrations was the widest in wildfire and non-wildfire seasons among microenvironment measurements. Its values range from 4.2 to 4934 μg/m^3 (in wildfire season) and 10.9 to 16,304 μg/m^3 (in non-wildfire season). The broadest range of personal exposure corresponds to two factors. Firstly, respondents posed different daily routines according to their occupations. Secondly, house characteristics reflect the level of protection against pollution ingress the houses provide. The highest personal monitoring concentrations in the non-wildfire season were derived mainly from cooking activity, which was found to be emitted from a wood stove and the burning incense. Despite the extremely high concentrations in the non-wildfire season, personal exposure concentrations show a considerable decrease in the non-wildfire season compared to the wildfire season (117.8 μg/m^3 vs. 377.7 μg/m^3).

Respondents had different daily routines according to their occupations and responsibilities. The highest $PM_{2.5}$ concentrations recorded by the personal monitoring devices were those associated with cooking activity. We will discuss this further in the next session. When at the house, as mentioned earlier, the concentration profile was slightly different from residential outdoors during wildfire season. In contrast, indoor concentrations were much higher during the non-wildfire season. Despite the seasonal indoor-outdoor difference, personal exposure concentrations show a slight decrease in the non-wildfire season compared to the wildfire season.

As seen in Fig. 7, there were slight changes in respondents' activity patterns between the non-wildfire and wildfire seasons. Women tended to spend more time indoors (95%) during the wildfire season (i.e., on sedentary and non-sedentary activity, sleeping, and house cleaning) and less on outdoor activities such as commuting, walking, and outdoor gathering. Only 1.9% of women spent time commuting because of either their caring or occupational responsibility. The figures decreased by 10% when they were active during the non-wildfire season, expanded in Fig. 7B. The women spent less time doing activities outdoors (16%) than indoors (84%). Consequently, they were exposed to outdoor air at approximately 21%, higher than during wildfire season (5%). In addition, they were more exposed to indoor air pollution from cooking (10%) during the non-wildfire season.

3.7. *Pregnant women daily integrated exposure and potential dose*

We calculated the potential dose adapted from the US-EPA equation [28], a simple integration of chemical intake rate (concentrations of $PM_{2.5}$ *times* the inhalation rate *times* the duration of exposure). We applied an inhalation rate adapted from Buonanno, Giovinco, Morawska and Stabile [25]. The mean daily-integrated exposure to $PM_{2.5}$ for the 69 respondents in the wildfire season was 1.06×10^4 μg-h/m^3. Its variability was slightly wide (SD = 0.8×10^4 μg-h/m^3; range = 0.1×10^4–3.9×10^4 μg-h/m^3). This value is far much higher compared to the measurement by Zhou et al. [30]. In Zhou's study, female subjects' average daily integrated values during the 2013 light wildfires season in Singapore ranged from 169 to 340 μm^3-h/cm^3 (equal to 70.4–141.7 μg-h/m^3), which were 100s times lower compared to our study in Indonesia. It is worth noting that Zhou's study was conducted in 2013, which had a light magnitude of wildfires.

Comparatively, the mean daily-integrated exposure to $PM_{2.5}$ for the 76 respondents in the non-wildfire season was 0.4×10^4 μg-h/m^3 with the large variability (0.4×10^4 μg-h/m^3; range = 0.07×10^4–2.8×10^4 μg-h/m^3). There is a large variability of daily

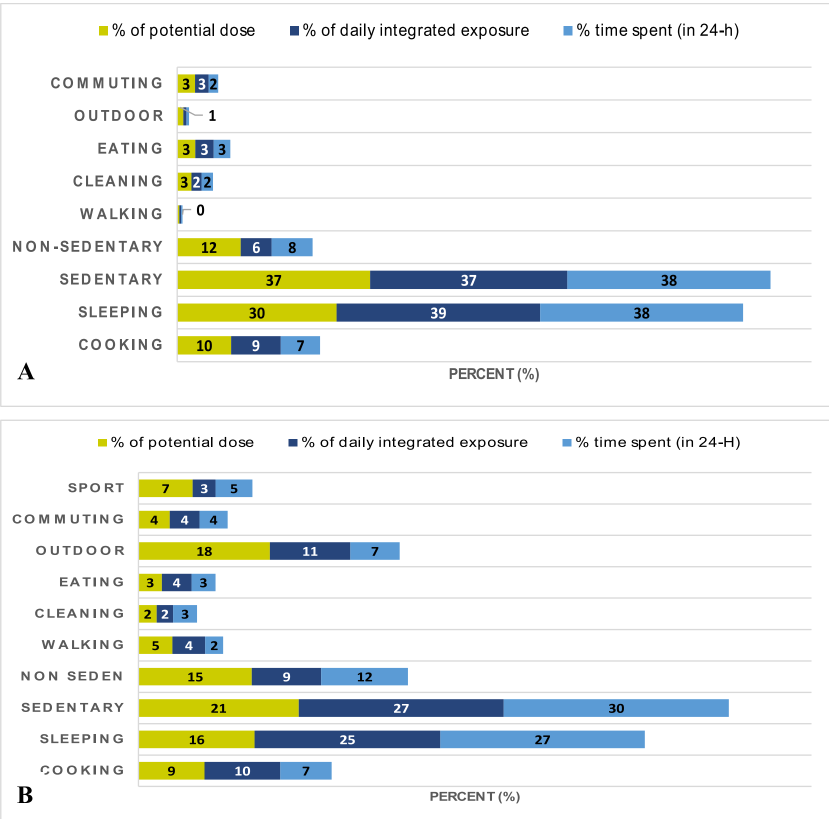

Fig. 7. Mean of percentages relating to daily routines, daily integrated exposure, and potential dose in different microenvironments in the wildfire and non-wildfire seasons; A refers to figures during the wildfire season; B refers to figures during the non-wildfire season. Cooking, sleeping, doing sedentary and non-sedentary activities, eating, and doing sport were classified as indoor activities. Meantime, outdoor activities comprise walking, cleaning, outdoor activities (e.g., shopping, gathering, picking up), and commuting (by car or by motorcycle).

integrated exposure within seasons and interseasonally. The significant difference in combined exposure inter-seasons resulted from the intensity of $PM_{2.5}$ emitted from wildfires. In the meantime, the highest daily integrated exposure was found in the non-wildfire season. The main reasons are that two respondents used wood/kerosene stoves, and the mosquito coils practice was recorded.

With regard to the daily-integrated dose, the mean of the daily-integrated dose accounted for 284 μg/kg day ±68 (range = 72–468 μg/kg day in wildfire season; on the other hand, the values show the opposite in non-wildfire season (28 μg/kg day ± 28; range 6–172 μg/kg of the day). In detail, daily-integrated $PM_{2.5}$ dose according to activities conducted indoors during wildfires is as follows: 1) cooking activity reflects 560.6 μg/day, 2) sleeping is accounted for 1515.1 μg/day, 3) sedentary activities are 1786.6 μg/day, and 4) non-sedentary activities are accounted for 1222.2 μg/day. As seen, pregnant women inhaled 100 times higher $PM_{2.5}$ in the wildfire season (284 μg/kg/day vs. 28 μg/kg/day), which is more likely that they were at risk of experiencing reduced birth weight. In addition, the daily-integrated $PM_{2.5}$ dose varied widely among different activities. From these figures, pregnant women received higher doses from activities which were not very active such as sleeping and sedentary activities. The percentages of daily integrated exposure in Fig. 7 confirm these figures.

4. Discussion

Most previous studies on women's personal exposure to various air pollutants have been conducted in developed and developing countries. However, these studies mainly focused on indoor air pollution derived from energy use and traffic-related air pollution [48]. Limited studies have been observed to assess the population living in heavily affected wildfires, particularly pregnant women. The most recent publications on the impact of outdoor on indoor air quality during wildfire season, which involved ground, were reported in Singapore by Zhou, Chen, Cao, Yang, Chang and Nazaroff [30], by Sharma [47], and Tham, Parshetti, Balasubramanian, Sekhar and Cheong [46], two studies conducted in US by Xiang, Huang, Shirai, Liu, Carmona, Zuidema, Austin, Gould, Larson and Seto [19] and Shrestha, Humphrey, Carlton, Adgate, Barton, Root and Miller [49]. However, these studies did not include pregnant women as observed subjects which might show different activity patterns. Also, the two studies in Singapore focused on assessing air quality during the wildfire season.

According to a study in Singapore [47], $PM_{2.5}$ outdoors was observed at 72–157 μg/m^3. In contrast, $PM_{2.5}$ concentrations in ambient air, recorded from the Colorado air monitoring station, showed 40–70 μg/m^3 during wildfire season [49]. In this case, $PM_{2.5}$ concentrations from Colorado wildfires were slightly lower than the study in Singapore because of short and long-range sources from the western United States and Canada, which are 1000 km away. Another study from Singapore reported that ambient air at the end of June and early July 2013 showed $PM_{2.5}$ concentrations at 18–63 μg/m^3 [30]. Likewise, outdoor air in the western US reached 33–111 μg/m^3, during the wildfire season in 2020 [19]. All these studies reported $PM_{2.5}$ concentrations as many times lower than our 24-h observation (74.8–926.8 μg/m^3) (Table S1), except for a study by Tham, Parshetti, Balasubramanian, Sekhar and Cheong [46] reporting a comparable value of 330 μg/m^3 during 2015 the wildfire season in Singapore. The outdoor concentrations of this current study derived from the air monitoring network indicate that Palangka Raya was affected by the hazardous smoke in August–October 2019.

Controlling wildfire smoke by keeping the windows and doors closed relatively reduces air infiltration from outdoor to indoor houses. However, women spent 95% time indoors (while 39% corresponded to sleeping), inhaling 86% of $PM_{2.5}$ (Fig. 7A). The figures decreased by 10% when they were active during the non-wildfire season, which is expanded in Fig. 7B. The women spent more time doing activities outdoors (18%) than indoors (82%). Consequently, they were exposed to outdoor air at approximately 19%, higher than during wildfire season (11%). In addition, they were more exposed to indoor air pollution from cooking (10%).

It is worth noting that according to our data, spending time indoors contributes to 92% of the potential dose, which is absorbed by a superficial cell membrane, according to a sum of indoor activities recorded in this study: cooking, sleeping, sedentary, non-sedentary, cleaning (see Fig. 7). The percentages of the potential amount are higher in activities such as sleeping, sedentary, non-sedentary, and eating in the span of the wildfire season than in the non-wildfire season. Likewise, outdoor activity was observed to contribute to elevated percentages by potential doses. Despite the elevated percentages, the figures show a lower dose than outdoor activities during non-wildfire season because of limited outdoor activities during the wildfire season. Given those values, the potential highest risk of exposure originated from indoor activities. These results are consistent with Zhou, Chen, Cao, Yang, Chang and Nazaroff [30] and Doubleday, Choe, Busch Isaksen and Errett [50] studies. Zhou, Chen, Cao, Yang, Chang and Nazaroff [30] observed that the highest risk occurred when participants spent time in buildings (i.e., at home and work) during moderate and light haze in Singapore 2013. In the meantime, outdoor activities, in particular, cycling and walking experienced a significant decrease ranging from 14.6% to 36.0% and 31.7%–45.2%, respectively, during the 2018 wildfire smoke event in Seattle, WA, US as reported by Doubleday and colleagues.

Although I observed differences in time spent on daily activities between the wildfire and non-wildfire seasons, the differences were slight. This implies that daily activities during the wildfire and non-wildfire seasons were comparable in that people still performed their routines regardless of exposure to toxic wildfire smoke. Comprehensively, findings give attention to protecting against daily exposure to particles during wildfire season, which should be a priority of Government intervention. For example, informing public on health consequences by organizing campaigns to change behaviour during the wildfire season, modifying microenvironments, evacuating people in vulnerable groups like pregnant women, minor attempts should be taken in to action by providing masks for vulnerable groups such as pregnant women, children, and the elderly.

This work fills the gap between air quality monitoring and health analysis of expectant mothers who live in heavily impacted wildfire areas. It covers both seasons (wildfire and non-wildfire seasons). Some results have limitations due to instrument issues (i.e., number of instruments, technical issues). The indoor and outdoor residential measurements were conducted in only a few houses, and personal exposure was observed for only 24 h.

However, all air quality measurements (i.e., ambient air, microenvironments, and personal monitors) were carried out successfully, covering more than 100 participants in which AM520 characterized air pollution exposure. In a future study, it will be worth conducting observations on personal monitoring for more than 24 h in the fire and non-wildfire seasons, along with improving monitoring of residential indoors and outdoors (observing the accurate air exchange).

The current research aims to update two previous studies on wildfires involving relatively large numbers of respondents being monitored personally. Our results are consistent with other similar topics in Singapore and Colorado. Although those studies were conducted in better-constructed buildings, We found similar observations. This result highlights that the outdoor air impacts indoor air via infiltration, elevating particle concentrations indoors. Furthermore, the highest risk of being exposed to wildfire smoke was when people spent time indoors. It is also confirmed by Zhou et al., Sharma et al., and Shrestha et al. [30,47,49]. Two reasons can explain this. Firstly, potential entrances like gaps and cracks still exist, so outdoor air can infiltrate indoors, particularly for women living in wood houses. However, a study by Sharma and Balasubramanian [47] revealed that keeping all windows closed with an air cleaner could reduce particle concentrations.

The quantification of potential dose on pregnant women showed the highest risk when they spent time indoors, 84% during the wildfire season, corresponding to the exposure of 86% particles. This figure of the potential dose is relatively high compared to a study by Rivas et al. on children of school age in non-fire locations [51], which raises the concern that pregnant women inhaled more toxic air during wildfire smoke. Policies to protect a healthy living environment in Palangka Raya are essential to prevent vulnerable people from being exposed to uncontrolled wildfire smoke annually.

5. Conclusions

A personal monitoring and indoor-outdoor methodologies were performed to assess the daily-integrated levels of PM exposures and the corresponding exposure factors over 24 h amidst the 2019 wildfire season and non-wildfire season in Indonesia. Despite the limited number of subjects and the moderate duration of the study, it is noteworthy that the scale of this monitoring campaign is the first and one of the largest among those employing real-time monitoring equipment. One notable characteristic of this current study is the comprehensive $PM_{2.5}$ monitoring data in both non-wildfire and wildfire seasons with activity diaries, which enables the identification of the specific microenvironments that the study participants occupy and the corresponding contributions to their exposure. While there exists a substantial body of literature on the associations between indoor/outdoor particles and penetration factors, limited research has focused on the specific indoor/outdoor conditions during periods of occupancy, which may differ systematically from the overall average conditions.

The smoke in 2019 significantly impacted the local air quality due to the particles' emissions. Analysis of indoor and outdoor air shows that outdoor $PM_{2.5}$ concentrations influenced indoor concentrations in 2019 wildfires, suggesting that buildings only partially protected people from exposure during wildfires. The conditions were exacerbated by indoor pollution sources such as cooking, smoking, and burning incense. The results are unsurprising as houses in Indonesia typically have ventilations above windows and gaps, particularly in wooden houses.

The I/O ratio confirms the building's partial protection from wildfires, while indoor sources appear to be affecting the non-fire. These facts suggest that exposure to $PM_{2.5}$ may negatively impact health since BaP-$PM_{2.5}$ has relatively higher toxic levels. The highest GM $PM_{2.5}$ concentrations correspond to personal monitoring owing to peak concentration events during cooking times. This is sensible, as most respondents were housewives and spent the most time at home (90%) during the weekdays. The results of this study involve daily potential dose estimations. Based on the analysis of their daily $PM_{2.5}$ dose, they received around 21% of their total daily dose during sedentary activity involving cooking. The dose estimations varied across activities as a function of breathing rates, particularly in indoor environments. Their variation is expected to be significant due to indoor sources (such as fuel stoves, the presence of smokers, and burning incense practices). Considering the time spent indoors, improving buildings' tight ventilation with clean air (for instance, installing integrated trickle ventilation) and providing air purifiers might help reduce exposure to wildfire smoke and thus protect citizens during wildfires. In addition, organizing campaigns to communicate public health risks is required, aiming to modify behaviour during such occurrences.

Author contribution statement

Vissia Didin Ardiyani: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Martin Wooster; Mark Grosvenor: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Puji Lestari; Wiranda Intan Suri: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been published online at [URL].

Informed consent statement

Informed consent was obtained from all respondents who participated in this study in line with Indonesian ethical regulations. We obtained ethical clearance approval from the National Institute of Health Research and Development (HREC-NIHRD) with reference number LB.02.01/2/KE.023/2019.

Declaration of competing interest

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

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Appendix. ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18513.

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