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Impact of human activities and building characteristics on indoor air quality in low-income urban settlement

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ABSTRACT

Introduction: Poor Indoor Air Quality (IAQ) in the growing number of low-income urban houses is closely linked to their unstructured neighbourhood development, poor building quality and unique community behaviour. It has been associated with numerous health issues which determine the occupant's quality of life. This study proposed an explanatory model to reveal the interactive effect of building, human, and environment, on IAQ in tropical urban houses.

Materials and methods: Particulate Matter (PM), Carbon dioxide (CO_2), airflow, temperature, and relative humidity were continuously measured using calibrated sensors in two seasons. Data on the active ventilation openings, indoor characteristics (material, volume, layout, and indoor porosity), real-time activity, and occupant's perception were recorded through questionnaire.

Results: The average indoor PM_{10} and $PM_{2.5}$ were 1.8 and 4.8 times higher than World Health Organization (WHO) standard, mostly affected by habitual indoor smoking which increase PM_{10} and $PM_{2.5}$ by 259% and 281%. High cooking intensity increased kitchen CO_2 concentration by 47%. However, 82.75% of the occupants accepted this poor IAQ as neutral, which was correlated to their low education and economic backgrounds. Moreover, regression analysis showed significant effect of house volume, kitchen layout, and roof structure's airtightness, on pollutant concentrations.

Conclusion: Low-income occupants have habits and activities that generate high indoor contaminants, worsen by the confined living space with insufficient ventilation, resulting in poor IAQ. Hence, stakeholders should prioritise educating low-socioeconomic communities about the health risk of high indoor pollution. Beside human activity control, this study offers a new IAQ mitigation perspective on the impact of interior characteristics on pollutant accumulation and dilution inside buildings.

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Introduction

Informal settlements growing in Indonesia's major cities, which house many low-middle-class communities and are often considered slum-like settlements, are called urban kampong [1, 2]. Fig. 1 shows the characteristics of low-income urban kampong elements. Severeal studies around the world have reported that low-income or informal houses are more prone to poor Indoor Air Quality (IAQ) as it is closely related to the poor building and neighbourhood conditions [3]. The most common air pollutants found in houses are Particulate Matter (PM) and Carbon dioxide (CO_2) which usually generated from indoor activities [4]. It has been associated with many health problems, including persistent cough, asthma, allergies, aggravated respiratory infections, and chronic lung disease, particularly in children and women [5]. Many studies have revealed the partial impact of each factor, including human activities, house characteristics [6], meteorological conditions [7] and building settings or outdoor morphology [8] on IAQ. However, the IAQ phenomenon is complex and context-related. Hence, it is crucial to advance our understanding of the overall impact of these factors on the IAQ especially in the growing number of low-income urban households in many developing countries such as Indonesia's urban kampong.

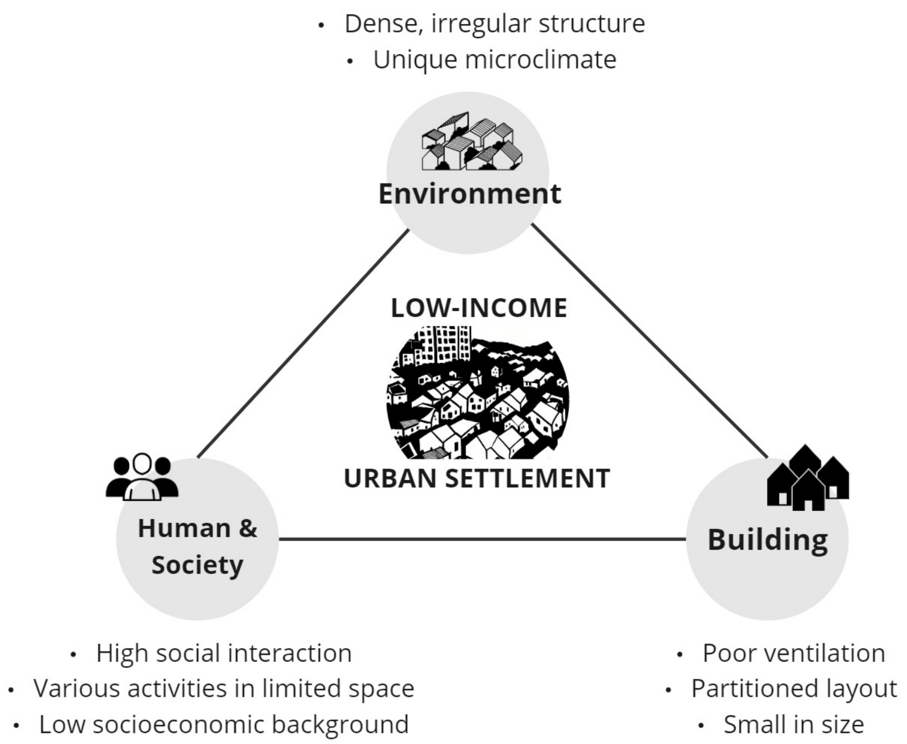


Fig. 1. Characteristics of low-income urban kampong elements

Typically, urban kampong is located directly behind commercial or institutional buildings in urban centres. Therefore, it also poses a high risk of exposure to outdoor pollutants originating predominantly from high-traffic urban activities [9]. High building density and narrow alleys can create their microclimate, causing a lack of air movement that may trap pollutants within the neighbourhood [10]. The buildings are clustered side by side, leaving only a few façades for ventilation; thus, most houses have Single-Sided Natural Ventilation (SSNV) [11]. According to multiple studies, SSNV increases indoor pollutant levels more than cross-ventilation, regardless of external environmental conditions [12, 13]. Among other building variables, building ventilation has been extensively studied with regard to IAQ. Urban kampong houses rely mainly on natural ventilation, which leads to inadequate ventilation [14, 15] and a less-controlled Air Exchange Rate (AER) than housing with advanced mechanical ventilation [16, 17]. A higher AER is beneficial for diluting indoor-generated pollutants, such as VOCs, formaldehyde, particulate matter, and CO_2 [18, 19]. However, a high AER can be a drawback, particularly in naturally ventilated buildings if the outdoor conditions are poor because it promotes the infiltration of PM_{10}, NO_2, and O_3 or cross-transmission between units [20-22]. Because of their affordability, air conditioning, air-cleaning technology, and exhaust fans are rarely used in urban kampong houses. Therefore, the ventilation performance of naturally ventilated houses depends on ventilation opening conditions [13]. The wind direction and source location also affect contaminant transmission and dispersion in and around buildings [23, 24]. In conclusion, the effects of ventilation attributes on IAQ have been reasonably established. However, in low-income urban houses with poor ventilation conditions, the building indoor characteristics may also be crucial in affecting IAQ, yet this has been less studied.

The urban kampong houses are built gradually according to the occupants' needs, with little consideration for comfort or health. Wet areas, such as kitchens and toilets, are common sources of household pollution [25]. Many of these locations were built later and lacked outdoor air [26]. Recent research has revealed that kitchen layouts may influence Particulate Matter (PM), CO, and CO_2 concentrations; however, the impact varies depending on the kitchen ventilation system [27, 28]. The rooms of kampong houses are separated by internal walls, thus lowering the porosity between rooms. Research found that partitioning in a compact house significantly suppressed ventilation and degraded IAQ [14]. In contrast, the high porosity between the kitchen and the adjacent room in an open-plan kitchen promotes pollutant dispersion around the house. Furthermore, building volume may also impact IAQ since it affects the movement and turbulence of airflow in the room. Other researchers showed that the typically small size of low socioeconomic status settlements may have greater $PM_{2.5}$ levels [29]. In addition, it was found in a study, that increasing the kitchen volume increases the ventilation rate and lowers the CO_2 concentration [3]. From the description above, it can be concluded that building indoor characteristics may also influence IAQ; however, no strong conclusions can be drawn from the impact of these variables.

Beside building factors, habits and human activities have been frequently associated with the IAQ condition in the building [30]. Cooking [31], smoking [32], burning wood [33], candle [34], and incense [35] have been identified as significant source of indoor PM. Meanwhile, other activities contribute to the re-suspension of indoor particles such as walking, pets, cleaning or vacuuming, and showering [36]. Specifically for low-income households, the commonly uses of biomass and kerosene fuel for cooking and heating was most often found as the main indoor pollutants source [3, 37, 38]. However, none of them were in the context of tropical climate community. Very few research that focuses on the effect of human activities on indoor pollutions in Indonesia's low-income houses have been conducted. Huboyo

[39] measured the impact of cooking with fuelwood on PM and CO levels, focusing in rural areas. Other research discussed the association of opening window and cleaning with only TVOC and formaldehyde concentrations in urban houses [40]. Meanwhile, a researcher discovered the correlation between solid fuel use and tobacco smoking and the increased risk of children health issues [5]. Nevertheless, the last-mentioned study was based on a demographic health survey that lacked data on actual pollutants.

Overall, unplanned low-income urban houses' conditions lead to a deterioration in physical quality and creates a disaster-prone environment, including the risk of poor air quality [1, 2, 15]. Low socio-economic conditions can also affect daily activities and lifestyles due to their economy limitations and lack of knowledge, thus impacting the indoor pollution exposure in their homes and risking their health [41]. Hence, this paper was aimed to fill the gap of understanding the impact of interaction between building characteristics and human activities on IAQ, especially in the rarely studied context of low-income urban houses in the tropic.

Materials and methods

Description of the case and the occupant

Field measurements and occupant surveys were conducted in a low-income urban kampong in Bandung City to understand the IAQ phenomenon and its influencing factors in urban kampong houses. Real-time indoor and outdoor thermal conditions, particulate matter, and CO_2 concentrations were collected simultaneously via observational monitoring. The corresponding number of indoor occupants, their detailed activities, and Perception of Air Quality (PAQ) were also recorded.

The chosen neighbourhood is a densely populated settlement (136,61 people/km^2) in the city's tourist centre [42]. Its location is strategic, near the main city road, a significant source of environmental pollution (Fig. 2). This region falls under the classification of urban slum neighbourhoods by the local government and was supported by the National Slum Upgrading Program (KOTAKU) in 2015. This area was classified as having a low economic ability, with an income between 37,5–312 USD, dominated by high school graduates [43]. Many residents work in the informal service and economy sectors nearby or inside the area; hence, they usually stay at home or go home at lunch break.

Before conducting field measurements, observations were made to classify the typology of ventilation openings and indoor characteristics of urban kampong houses, as presented in Fig. 3. There were 42 dwellings randomly chosen to represent the population (data confidence level of 90%, based on the Harry King nomogram technique). All the houses had Single-Sided Natural Ventilation (SSNV), which hypothetically had the most unfavourable ventilation performance [44]. The observations showed that the most common typology was a two-bedroom house with a small Ground Floor Area (GFA), below 50 m^2, half of which had a relatively square footprint and contained 2-5 people. They varied from one to two floors with an average ceiling height (FTC) of 2.49 m. Three kitchen layouts were observed: Indoor-Partitioned (IP), Open-plan Indoor (IO), and Outdoor (O). 80% of the Kitchens (K) were located inside a dedicated room with partitions or were connected by a door to the Living Room (LR). This typology aligns with that of urban kampung houses formulated by Funo [26]. All houses had tile floors and brick plastered wall. The roof was constructed of clay tiles, asbestos, or concrete slabs. There are many types of ventilation openings, such as regular awning and casement windows, bovenlicht, rosters, and old-style naco (louvre) windows. The Percentage of Active Ventilation Openings (AVOP) per total floor area, including windows and doors, was 5.8%, which barely met the local requirements of 5% [45]. Fig. 3a shows the mean value of main building characteristics. However, many of the ventilation openings were in poor condition (Fig. 3b.); thus, inhabitants opened doors more often than windows. This habit is preferable because it can serve as an opening for ventilation and human circulation in this dense neighbourhood. Fig. 3c shows the types of kitchen layout.

Fifteen dwellings were chosen for detailed observations with their consent. Table 1 provides information on all the houses. The selected houses exhibit various indoor characteristics and ventilation opening typologies. Observations were performed under occupied conditions, with normal activities and natural ventilation without artificial intervention.

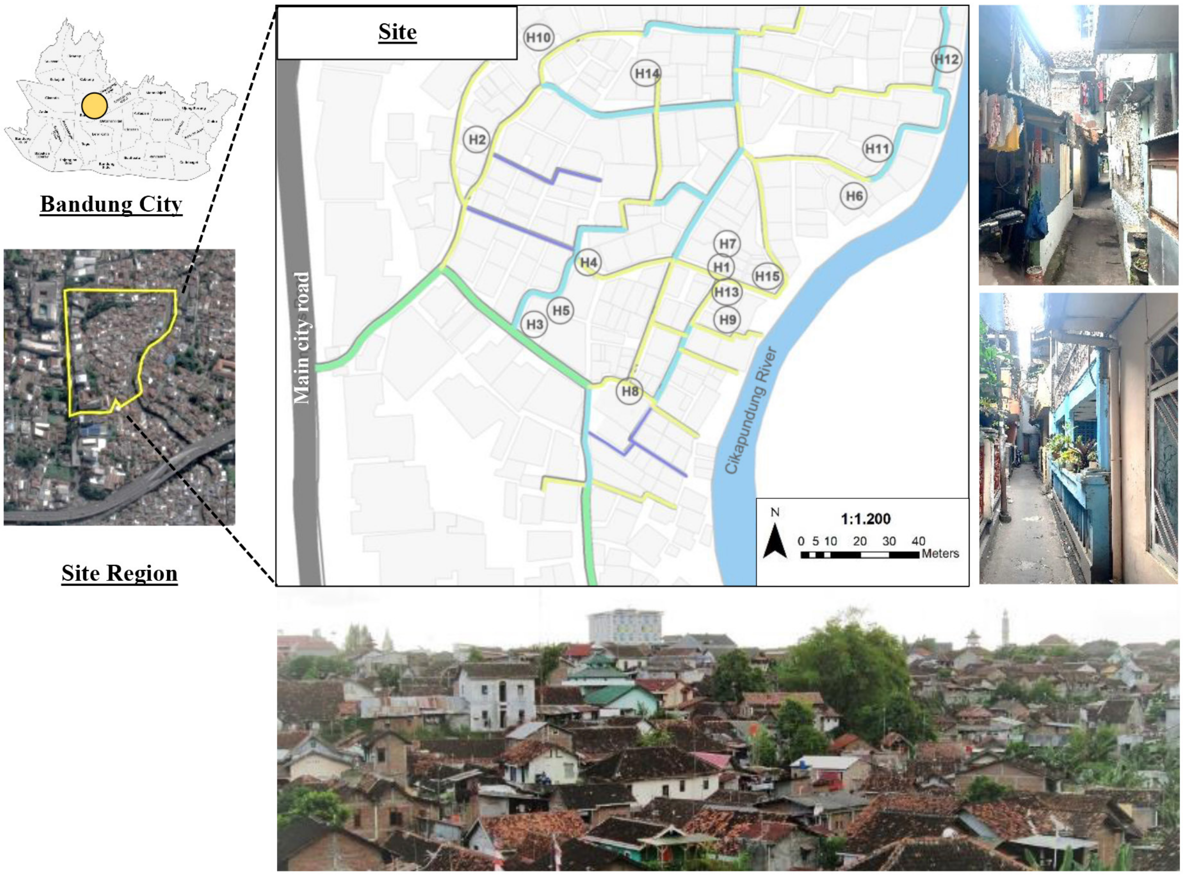


Fig. 2. A geographical map of the dense low-income urban kampong and and the dwelling locations (H=House)

Table 1. Characteristics of the 15 urban kampong houses (Wall material: B=Brick, W=Wood; Roof material: CT=Clay tile, A=Asbestos metal, C=Concrete; Floor material: T=Ceramic tile; E=Exposed concrete; Type of opening: AW=Awning window; CW=Casement window, NW=Naco window, , SW=Sliding window, B=Bovenlicht, R=Roster, S=Skylight, D=Door)

CHARACTERSITICS	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15
Envelope structure															
Wall material	B	B	B	B	B	B	B	B	B	B	B	B	B	B & W	B
Roof material	CT	CT	C	CT & A	CT & A	CT & A	CT	CT	A	A	C & A	CT & A	A	A	A
Floor material	T	T	T	T	T	T	T	T	T	T	T & EC	T	T	T	T
Ventilation Opening (VO)															
AVOP	2.7%	4.3%	5.6%	2.9%	8.7%	4.3%	5.8%	9.5%	12.4%	6.4%	7.0%	7.0%	6.1%	1.2%	3.0%
Type of opening	AW & R	D & B	CW & R	D	D & R	D & NW	D	D, R, AW	D & AW	D, R, AW	D & S	D & S	D & SW	AW & R	D &B
KVOP	2.8%	0.0%	5.4%	0.0%	2.0%	4.2%	0.0%	58.6%	28.1%	0.0%	4.2%	46.0%	0.0%	3.3%	13.7%
Type of opening	R	-	R	-	R	SW	-	AW	AW	-	R	D	-	R	R
Dimension of the house															
GFA (m^2)	26.75	52.7	34.5	27.8	46,00	60.4	22,00	37.8	16.4	29.93	16,00	26.87	29.37	27.87	27.38
No. of floor	1	1	1	2	1	1	1	1	2	2	1	1	2	2	2
FTC	2.7	2.8	2.45	2.5	2.3	2.5	2.3	2.5	2.6	2.8	2.5	2.35	2.78	2.15	2.23
Depth of floor plan	Shallow	Equal	Shallow	Deep	Equal	Shallow	Equal	Equal	Equal	Deep	Deep	Shallow	Equal	Equal	Deep
House Volume (m^3)	72.23	147.56	84.53	69.5	105.8	151.0	50.6	94.5	80.11	160.84	40.0	63.14	125.19	91.47	110.23
Kitchen Volume (m^3)	5.7	7.11	6.37	7.4	12.47	14.3	4.26	2.78	6.27	22.52	4.2	6.23	3.78	13.18	4.03
Other interior characteristics															
Kitchen Layout	IP	IP	IP	IO	IP	IP	IP	IP	IP	IP	IO	IP	O	IP	IP
Horizontal porosity of LR-K (m^2)	1.0	4.9	1.26	8.0	1.84	1.9	1.17	2.13	5.18	1.57	2.2	1.84	1.44	2.27	1.2
Horizontal porosity of LR-K (%)	19.6%	53.3%	24.5%	100.0%	21.9%	22.67%	21.6%	65.1%	71.2%	19.2%	100.0%	30.5%	-	50.3%	30.7%
Activity of occupants															
No. occupant	2	3	5	2	2	4	4	2	3	2	2	3	4	4	4
No. smoker	0	1	0	1	-	1	1	1	1	-	1	1	-	1	1
Cleaning intensity (min)	50	25	55	55	40	50	95	20	30	185	20	30	30	30	40
Smoker intensity (min)	-	25 (After work)	-	45 (After work)	40 (After work)	-	230 (All day)	-	335 (All day)	-	360 (All day)	65 (After work)	-	190 (Half day)	240 (All day)
Cooking intensity (min)	60	35	320 (Food shop)	20	45	45	80	55	65	120	100	90	75	25	130
Heating motorcycle (Y/N)	-	Y	-	-	-	-	-	-	-	-	-	Y	Y	-	Y
VO intensity (h)	12	15,5	13	14	12	11	4	8,5	11,5	9	12,5	7,5	13	17	14

(a) Main building characteristics (average value)

Ground floor area (GFA):	35.36	m^2
Total floor area (TFA):	50.58	m^2
Floor to ceiling height (FTC):	2.49	m
Depth of footrpint (D):	6.13	m
Widht of façade (W):	5.84	m
Active ventilation opening percentage (AVOP):	5.8	%

(b) Ventilation opening type

Awning window + roster

Casement window +roster

Fixed window +Jalousie

Naco window + *Bovenlicht*

(c) Kitchen layout type

Indoor partitioned-kitchen (IP)

Indoor open-kitchen (IO)

Outdoor kitchen (O)

Fig. 3. Building typology in the neighbourhood: a) Mean value of main building characteristics, b) Types of ventilation opening, c) Types of kitchen layout

On-site air quality measurement

Field measurement was done continuously for the 15 homes in two periods which represent two seasons, March 5th – 10th (end of wet season) and July 17th – 29th (dry season) of 2023, following the local [45] and WHO guidelines [46].

Table 2. Specifications of the measurement tools

Measured Variable	Instrument model	Detail
Particulate Matter 1, 2.5, 10 µm	Airlink AQ Monitor 7210, Davis Instrument	Range: 0.3-1.0 µm; 1.0-2.5 µm;. 2.5-10 µm Accuracy: ±10 µg/m^3
Air temperature, relative humidity		Range: -40°C to +60°C, 0.1 to 100 % RH Accuracy: ±0.3°C, ±2% RH
CO_2 gas	CO_2 Meter HT-2000, HTI	Range: 0-9999 Accuracy: ±50 ppm
Air velocity	Hot-Wire Anemometer AM-4234SD, Lutron Instrument	Range: 0.1 m/s to 5 m/s Accuracy: 0.01 m/s, 5% from reading value
Microclimate	Ambient Weather WS-2902	Range: -40°C to +65°C, 10 to 99 % RH, 0 to 44.7 m/s, 0-10x10^3 mm rain Accuracy: ±0.1°C, ±1% RH, 0.6 m/s, 0.25 mm rain

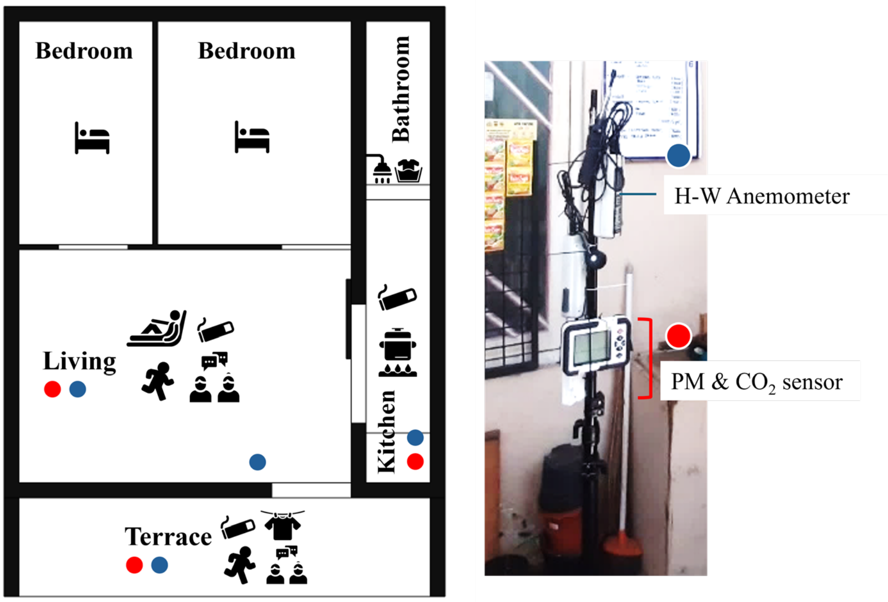


Fig. 4. a) Function of each room and location of the instruments; b) Instalment procedure

All the sensors recorded data at intervals of 300s and had been previously calibrated according to manufacturer's instruction. Table 2 lists the sensors and their specifications. The sensors were located in the living room, kitchen, behind the ventilation opening, and outside the house. The equipment was installed at 1–1.5 m heights, based on the adult breathing zone [47]. The sensors were located around the stove in the kitchen and in the least disturbing area of the living room, where occupants usually perform most of their activities (Fig. 4). Detail indoor airflow condition was measured by placing anemometer in each room and behind the façade. For outdoor air conditions, the equipment was located on the terrace or balcony of each house, with a sampling tube exposed to the outside environment.

Occupant activity and perception survey

All activities that could potentially be household air pollution sources and the following ventilation conditions were recorded, as conducted in other research [47, 48]. To accurately determine the impact of different occupant activities on the production of air pollutants, the participants were requested to complete a questionnaire that meticulously documented the type, timing, and duration of their real-time activities on the measurement days. These activity logs were then temporally analyzed in parallel with the pollutant measurement data to identify the sudden rise in indoor pollutant concentrations which were suspected to be related to the activities taking place at those time. The assumptions were then confirmed through re-interviews with the occupants right after the measurement period. Besides that, developed by researchers, Air Quality Perception (PAQ) of the urban kampong residents was also taken to subjectively assess the impact of pollutant on humans in this area [49]. Table 3 shows the detail questionnaire survey.

Statistical analysis

The data collected from all houses were characterized temporally and spatially. Next, I/O ratios were used to assess the relation between indoor and outdoor pollutants in this urban houses. Correlation between air quality and each of low-income occupant activities and building characteristics were further analysed using actual and 'censored' data, respectively, Finally, the overall impact of all factors on IAQ was formulated using multivariate linear regression. All statistical analysis was conducted using JMP Pro 18. The research framework is illustrated in Fig. 5.

Table 3. Detail questionnaire survey

Category	Factors	Detail
Respondent's info	Background	Age, sex, stay duration, education, household income, smoking habit
	PAQ	Perception of temperature, smell, airflow, freshness, humidity, cleanliness, overall AQ
Real-time activity	Ventilation	Close-open time, duration for: main door, window, & other ventilation systems
	Occupant's Activity Log	Start-stop time, duration, no. of occupancy and location for: cleaning house (sweeping, mopping, or moving furniture), cleaning toilet, drying clothes, cooking, having a pet, warming motorcycle, and smoking

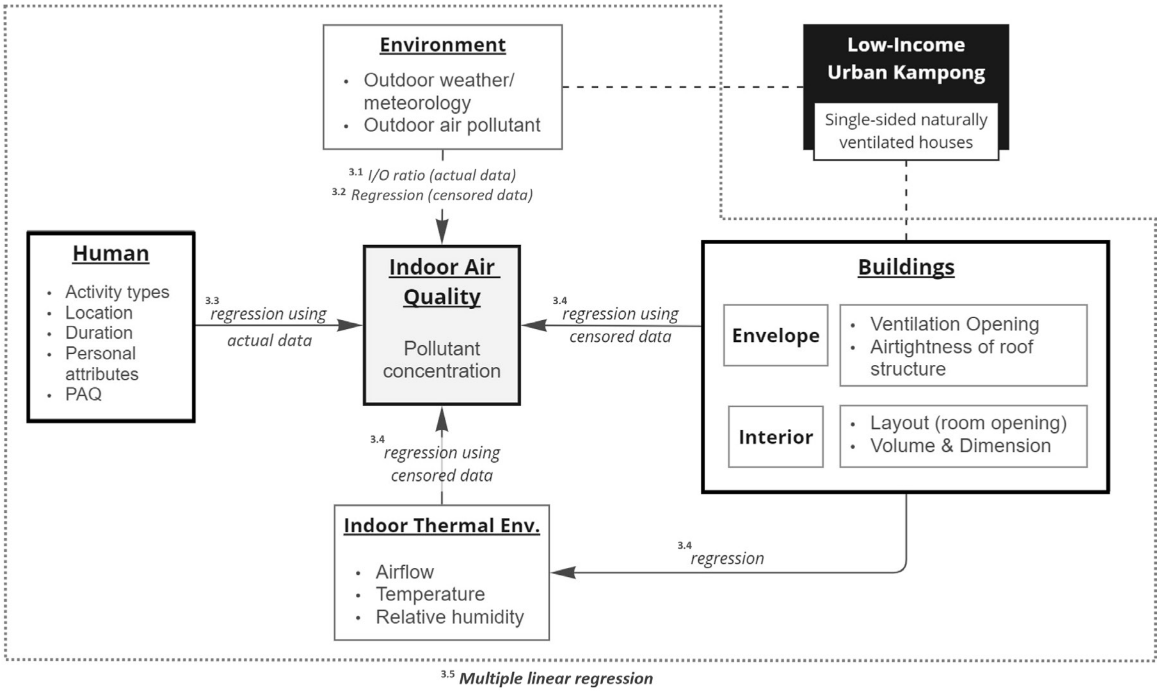


Fig. 5. Research framework and variables

Indoor peak censored

Field measurements were carried out in occupied conditions. However, with detailed recording of occupant activities log inside and in the front of the house, it was possible to predict pollutant data in the buildings without the influence of human activities. This was done through an indoor-peak censoring process, using the algorithm developed by researchers resulting in a 'censored' pollutant concentration data [50, 51]. This process was important because several field-measurement-based studies on IAQ had tried to formulate the impact of building factors on IAQ without thoroughly examining the impact of real-time activity data on indoor pollutant fluctuations. Consequently, when attempting to comprehend the influence of other factors on IAQ, it is possible that human activities influenced the observed associations.

The indoor and outdoor pollutants concentration, detailed activity, and ventilation log were aligned and visually inspected. Then, censoring process was meticulously done in the Excel software with the following algorithm. The indoor peak event was characterised by a distinct, sharp rise in the indoor pollutant concentration from the previous timestamp, either the indoor concentration increase outpaced a simultaneous outdoor concentration increase, or the inside concentration was higher than the outdoor concentration. The peak ended when the concentration had reached the previous timestamp value. All data within the peak was given a censored value equivalent to the previous timestamp concentration. In order to avoid miss interpretation and validate the identified peak events, re-interview to the occupants were conducted, immediately after the measurement period finished.

I/O ratio

The I/O ratio was used to generally understand the influence of human activities compared to infiltration of outdoor pollutants on IAQ, by examining the relationship between indoor (C_{in})

and outdoor (C_{out}) particle concentrations, as described in Eq. 1.

$$I/O = \frac{C_{in}}{C_{out}} \quad (1)$$

An I/O ratio of below one signifies that the impact of external pollutant was not quite significant on indoor levels. It can be attributed to the low outdoor infiltration and ventilation or else, indicating the effectiveness of air filtration system if any [52]. Conversely, a ratio more than 1 indicates the presence of strong indoor-generated pollutants [53]. Even though this metric has been widely used for decades [54], it's important to note that I/O ratios can be influenced by various factors such as indoor emission rates, ventilation rates, and specific building characteristics, which may limit their effectiveness as a sole metric for understanding IAQ [55]. Moreover, this ratio is mostly measured through passive sampling (unoccupied condition) only to reveal the performance of building envelope. Acknowledging these limitations, our study employs a multi-faceted approach to address these constraints. We used dynamic I/O ratios, in conjunction to detailed activity logging, building characteristic analysis, and indoor peak censoring, as explained before. These approaches align with Stamp's findings that dynamic I/O ratios (measured under occupied condition continuously) reveal the strong influence of occupancy and activities within a building [56]. The method captures temporal variations and allows for a better interpretation of the I/O ratio, representing the effect of human variables as much as physical building metrics, which is very much in line with the objectives of this study.

Model development for identifying key predictors of PM and CO_2 concentrations

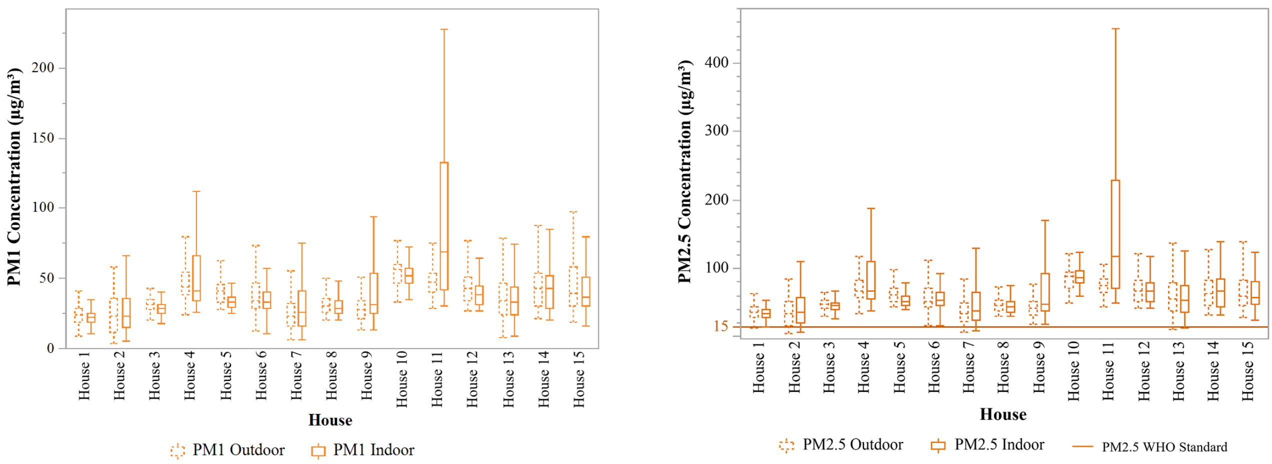
The candidate predictor variables were obtained from the literature review. They were outdoor pollutants concentration and indoor thermal conditions (temperature, RH, and airflow) to represent the environment, activities frequency to represent humans, also ventilation opening, roof structure's airtightness, volume, and layout to reflect building factors. Stepwise multiple linear regression with bidirectional (forward and backward) elimination approaches was employed. In order to avoid overfitting and carefully identify the most important variables that affect PM and CO_2 concentration in this context, the predictors were added or eliminated in a stepwise manner based on their statistical significance, making sure that each variable was added with a clear justification [57]. In the forward selection process, we started with no variables in the model, then predictors were added one at a time, if their inclusion resulted in a p-value < 0.05. For the backward selection, we began with all candidate variables in the model and iteratively removed the least significant variable (highest p-value) until all remaining variables had a p-value<0.05. The ultimate models were selected based on the minimum Bayesian Information Criterion (BIC); therefore, only significant predictors (p-value<0.05) were retained in the model. BIC was chosen for its ability to balance model fit and complexity, given the multiple potential predictors [58]. This approach also favored more streamlined models compared to other criteria, aligning with our goal of identifying the most influential factors while maintaining model simplicity and interpretability in the context of low-income urban housing [59]. To assess multicollinearity among the variables, the Variance Inflation Factor (VIF) was calculated, with a threshold of VIF$\geq$3 indicating potential multicollinearity [60]. Hence, variables exhibiting VIF$\geq$3 were excluded. This step was crucial as multicollinearity can significantly impact model interpretation. When predictor variables are highly correlated, it becomes difficult to distinguish their individual effects on the dependent variable. Multicollinearity can inflate standard errors of the coefficients, potentially leading to incorrect conclusions about which predictors are significant [61]. By addressing multicollinearity, we ensure more accurate and reliable interpretations of the relationships between our predictors (environmental, human, and building factors) and the outcome variables (PM and CO_2 concentrations).

10-fold Cross-Validation (CV) was used to assess the model's performance [62]. Ten subsets of almost comparable size were randomly selected from the data set. The model was fitted using data from nine subgroups, and the selected pollutants concentration in the excluded subset were predicted using the model's coefficients. This procedure was repeated ten times to ensure robustness in the evaluation. To evaluate the model, coefficient of determination (R^2) and p-value were assessed.

Results and discussion

Outdoor pollutant and the relation to IAQ

The average outdoor and indoor pollutant levels of selected pollutants parameters are listed in Fig. 6. The results show that the average outdoor PM_{10}, $PM_{2.5}$, and PM_1 concentrations were 69.43 µg/m³, 59.72 µg/m³, and 39.07 µg/m³. The average indoor PM_{10}, $PM_{2.5}$, and PM_1 concentrations were 82.25 µg/m³, 72.33 µg/m³, and 43.13 µg/m³. Maximum PM_{10} and $PM_{2.5}$ concentration for 24 h is 45 µg/m³ and 15 µg/m³ by WHO 2021 standard. Compared to that, the outdoor PM_{10} and $PM_{2.5}$ values are 1.5 and 4 times higher, while indoor PM_{10} and $PM_{2.5}$ values were 1.8 and 4.8 times higher. Meanwhile, the average outdoor and indoor CO_2 was 466.19 ppm and 569.49 ppm, which was still within the threshold of 1000 ppm by ANSI/ASHRAE Standard 62.1. House 11 had the highest and widest range of indoor PM level. Houses 2, 4, 7, and 9 also had a noticeably higher indoor PM level than the outdoor. Meanwhile, for CO_2, most of the houses had a higher indoor CO_2 level than the outdoor. These results proved that the outdoor air quality in urban kampongs was unacceptable, but the indoor conditions were even worse. These variations of indoor and outdoor pollutants level were linked to several factors, including the human activity and building characteristics.



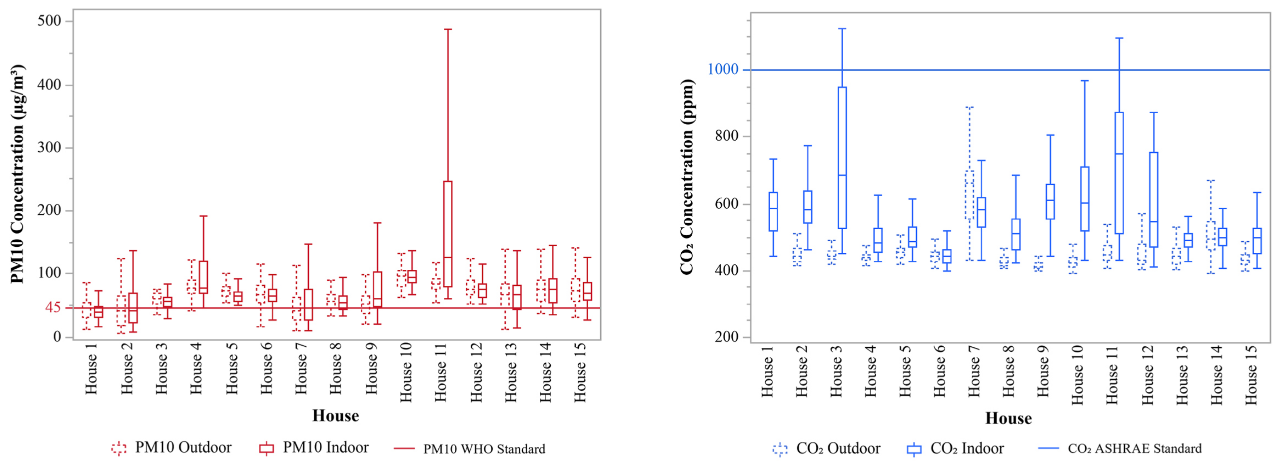


Fig. 6. Pollutant concentrations variation of all houses

High levels of indoor contaminants can originate from both indoor and outdoor sources, especially for naturally ventilated houses in urban area. Previous research had used I/O to generally understand the contribution of indoor and outdoor particles on IAQ. In this paper, we specifically employed dynamic I/O ratio where measurement was conducted under occupied condition. Fig. 7 shows the I/O ratios for all the pollutants in the houses.

The mean I/O ratio for PM_{10}, $PM_{2.5}$, and PM_1 are 1.17±0.33, 1.20±0.35, and 1.10±0.26, respectively. As stated by many researchers [53, 56], I/O ratio above 1 in 8 houses indicated the strong contribution of indoor-source pollutant that need to be examined further. Although urban kampong houses rely only on natural ventilation and were located near high-traffic road, the association between indoor and outdoor dust particles exhibited only moderate correlations (Table 4). This indicated that the infiltration of outdoor air pollutants was not strong [60], probably because of low ventilation performance. PM_1 had a slightly larger indoor-to-outdoor correlation than that of the other particles. Finer particles are easier to transport by wind. Hence, the dispersion of PM_1 between indoor and outdoor area was more prominent than that of coarse particles [22]. Meanwhile, the PM_{10} deposition rate was higher; therefore, it settled more easily on the ground, resulting in a lower indoor-to-outdoor correlation [55, 63].

As for CO_2, 13 houses had higher CO_2 level than the outdoor level (see Fig. 6). Additionally, the indoor-to-outdoor CO_2 level correlation was very low (r = 0.0643, p<0.001), but the living room and kitchen CO_2 correlations were strong (r = 0.64, p<0.001). These data confirmed that CO_2 was primarily generated inside buildings and many studies linked the high indoor CO_2 level to combustion activities and human respiration [64].

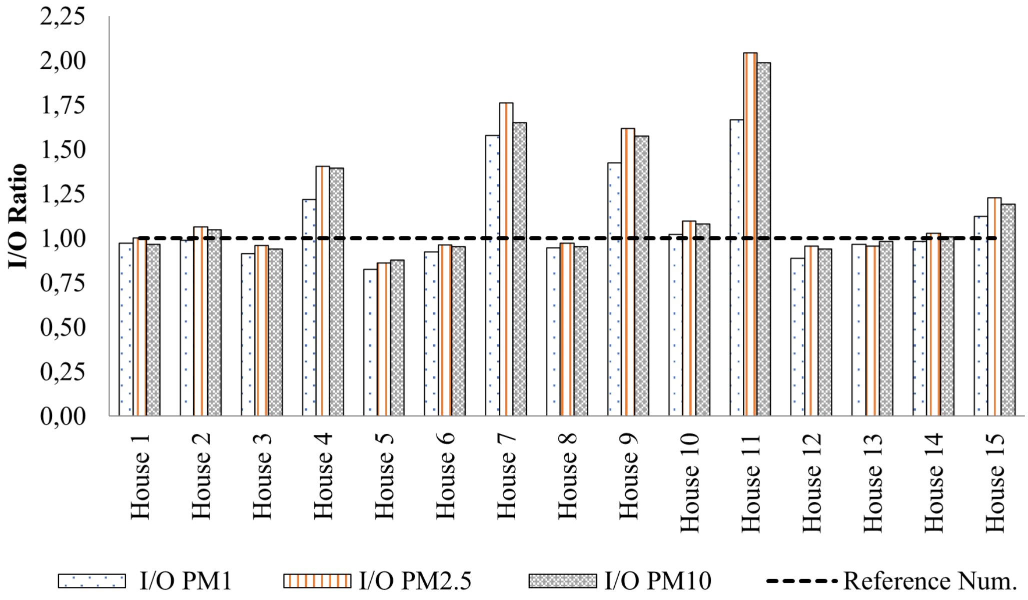


Fig. 7. I/O ratio of particulate matter in the houses

Table 4. Pearson correlation between indoor and outdoor air contaminants (**p-value < 0.001)

Pollutant	PM_1 Outdoor	$PM_{2.5}$ Outdoor	PM_{10} Outdoor	CO_2 Outdoor
PM1 Indoor	0.4971**	0.4912**	0.4851**	0.0207
PM2.5 Indoor	0.4353**	0.4325**	0.4254**	0.0061
PM10 Indoor	0.4256**	0.4228**	0.4185**	-0.0014
CO_2 Indoor	-0.0367	-0.0308	-0.0341	0.0643**

Overall, the air quality in low-income urban houses was inevitably impacted by outdoor pollutants due to uncontrolled natural ventilation [65]. However, the indoor conditions were worse. The results indicated that IAQ was affected by indoor sources, presumably human activities, rather than by the infiltration of outdoor pollutants. This also denoted the ineffectiveness of ventilation openings in supplying air exchange in these houses; hence, contaminants were high and retained inside [66]. This result contradicted other research on urban houses [67, 68] in which outdoor pollutants were usually higher than indoor pollutants because of their location and proximity to major roads. The morphology of this kampong, which was located on a slope and surrounded by mid-rise building, may create unique wind turbulence and local pollutant distribution patterns [69].

Moreover, the IAQ was affected by meteorological conditions, behavioural factors, and architectural characteristics [70]. In order to understand the sole influence of each variable, the fluctuations originating from indoor sources need to be removed or 'censored', as explained in the previous section.

Local meteorological variables and the impact on outdoor pollution

Measurements were taken during two different periods with different local meteorological patterns (Table 5). Comparing the outdoor meteorological and particulate matter data of both seasons, significant difference was found (p-value <0.0001). The first period (end of the rainy season) had higher temperature, relative humidity, and wind speed but lower particulate matter levels than the second period (dry season). The higher outdoor pollutants in dry season were also found by other studies of ambient air quality in Jakarta, Indonesia [71, 72]. Understanding the relationship between meteorological variables and air pollutants is complicated, affected by geographical factors, and requires a prolonged observation period to make general conclusions [73]. The following findings are categorised by measurement period and cannot be extrapolated to represent annual correlation trends.

As shown in Fig. 8, in March, the increased in relative humidity and ambient wind speed positively correlated with the rise of outdoor PM and CO_2 levels. In contrast, as the outdoor air temperature increased, pollutant levels in the area decreased. In July, increasing relative humidity correlated with increasing outdoor PM and CO_2 concentrations, similar to the pattern observed in March. Temperature showed the most significant correlation among the other two variables in July; an increase in temperature was positively related to an increase in PM and negatively associated with a decrease in CO_2. Lower wind speeds in July have an insignificant correlation to PM and CO_2.

Table 5. Local meteorological and outdoor air quality conditions in kampong

Period (2023)	T (°C)[a]	RH (%)[a]	Outdoor airflow (m/s)[a]	Wind speed (m/s)[b]	Wind direction[b]	PM_{10} Outdoor (μg/m^3)[a]	$PM_{2.5}$ Outdoor (μg/m^3)[a]	PM_1 Outdoor (μg/m^3)[a]	CO_2 Outdoor (ppm)[a]
5/3 - 10/3 (End wet season)	26.46	70.2	0.16	0.42	W-NW	55.86	47.08	31.59	336.77
17/7 - 29/7 (Dry season)	24.88	68.83	0.11	0.3	E-SE	68.20	58.52	38.19	459.61
Statistics of ANOVA between both season									
F ratio	364.02	23.516	123.88	-	-	227.53	219.092	189.905	890.503
P-value	<.0001	<.0001	<.0001	-	-	<.0001	<.0001	<.0001	<.0001

[a] Data were taken from the outdoor sensors of the homes

[b] Data were taken from the Weather Station (WS)

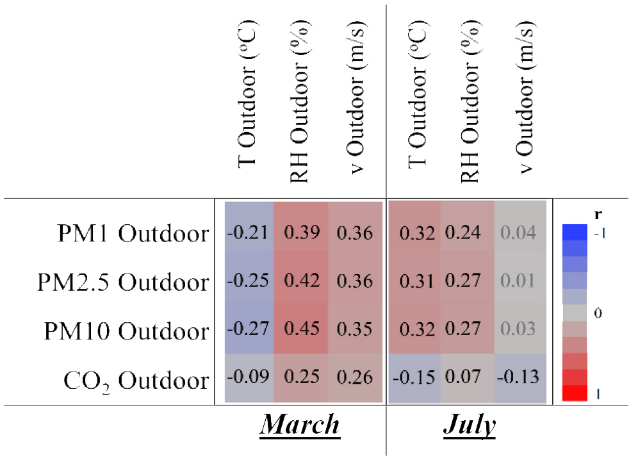


Fig. 8. Colour map on Pearson correlation value between local meteorological conditions and outdoor air contaminants per period (black fonts indicate $**p < 0.001$)

These findings imply that meteorological variables affect outdoor air pollution concentrations differently. Humidity around 70% consistently exerted a positive correlation on outdoor levels of PM and CO_2, as found in previous research [74, 75]. A researcher [76] explained that in low to mid humidity condition (45-70%), the growing RH accelerated secondary pollutant formation and hygroscopic particle growth; hence, high accumulation of particle in the air [77]. The temperature was positively and negatively associated with particulate matter levels. An elevated earth surface temperature generates convection, which increases the mixing height and further disperses contaminants. Thus, pollutant concentrations near the Earth's surface have decreased [78]. The temperature also affects particle formation [79]. High temperatures enhance photochemical processes and increase the levels of $PM_{2.5}$, precursors, and secondary pollutants [80]. Wind speed is positively correlated with pollutants, diluting and reducing local air pollutant levels [81, 9]. However, a negative association was observed between the CO_2 levels in July. Suppose the wind is strong and originates from a polluted area. In this case, contaminants can be transported across considerable distances, increasing pollutant concentrations [77]. Alternatively, low wind speeds cause minimal turbulence and weak horizontal air movement and are dominated by a sinking motion at the top layer of the atmosphere. This wind movement pattern restricts upward pollutant dispersal and increases surface pollutant concentrations [82].

Moreover, the outdoor sensors measured lower ground-level airflow than roof-level wind speed data from a weather station. This proves that high building density and low neighbourhood porosity hinder ground-level airflow, as mentioned in previous research [10, 83]. This urban kampong exhibits a dense, irregular building arrangement in a sloped terrain surrounded by middle-rise public buildings and rivers. Different directions of incoming wind between the two periods, in combination with this unique morphological condition, create a localised meteorological phenomenon that impacts neighbourhood pollutant dispersion [84, 85].

Effects of human on IAQ and PAQ in urban kampong

Effect of occupant activities on pollutant concentration

As mentioned in the I/O ratio analysis, it was suspected that there was a strong impact of indoor pollutant source originating from human activities. Therefore, more discussion was required to determine how the distinct activity context affects lower-class groups in tropical urban homes. Fig. 9-a illustrates the distribution of average particle and CO_2 concentrations in the houses during each indoor activity. Smoking resulted in the most PM_{10}, $PM_{2.5}$, and PM_1 with the average of 239.17 μg/m³, 219.36 μg/m³, and 116.35 μg/m³ respectively. Meanwhile, the most CO_2 (as much as 767.4 ppm on average) was gained through cooking activities. The only available mode of transportation in this area was motorcycles. However, the effect of the heating motor on the pollutant levels was not significant (p-value > 0.1 for PM and CO_2) because it was performed in a short time. The floor was manually broomed daily. Cleaning with a broom and moving objects around were found to contribute to the instant fluctuations of PM_{10}, $PM_{2.5}$, and PM_1 by 33%, 34%, and 34%, respectively (Fig. 9-b). Housekeeping such as brooming or vacuuming can cause deposited particulates to be quickly resuspended in the air [86, 87].

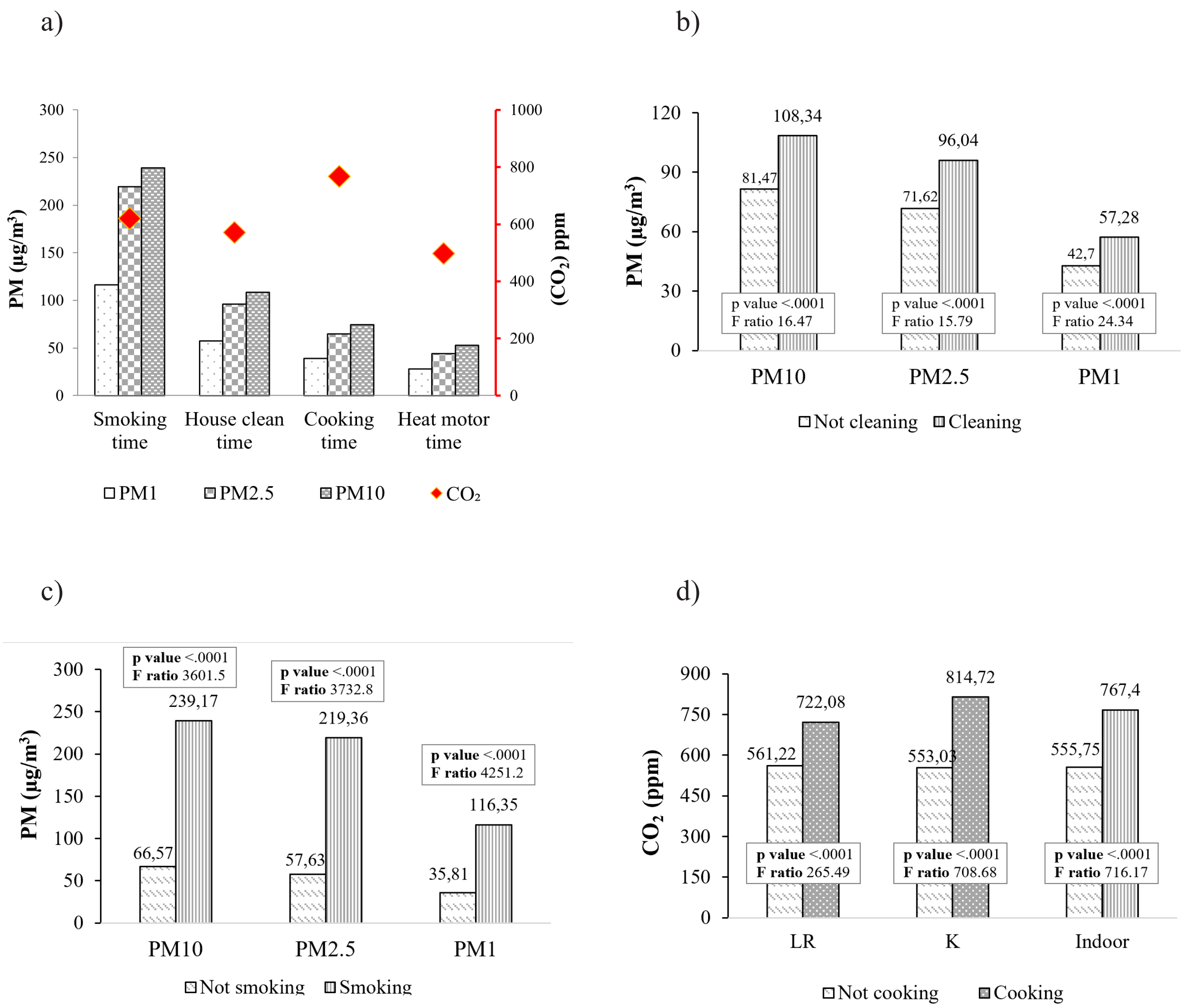


Fig. 9. Statistics on the effect of activities: (a) Distribution of mean indoor PM and CO_2 levels during each activity, (b) ANOVA of indoor PM levels by cleaning events, (c) ANOVA of indoor PM levels by smoking events, (d) ANOVA of indoor CO_2 levels by cooking events in the living room (LR), kitchen (kitchen), and indoor average

Sixty percent of the houses had a smoker with various smoking intensities anywhere in the house, mainly in the living room, kitchen, and terrace. Fluctuations in PM_{10}, $PM_{2.5}$, and PM_1 during smoking were considerably higher than those in the absence of smoking by 259%, 281%, and 225%, respectively, as shown in Fig. 9-c. Smoking frequency was also strongly correlated with PM_{10}, $PM_{2.5}$, and PM_1 levels in homes ($r = 0.67$, 0.68, and 0.7, respectively; $p<0.05$). This correlation was also found in previous studies [29, 32, 88]. Meanwhile, the correlation towards CO_2 level was low, despite its significance ($r=0.12$, $p<0.05$).

The CO_2 peaks during cooking were found to be the highest among the activities in the kitchen and living room at 47% and 29%, respectively (Fig. 9-d). A significant correlation was found between the cooking frequency and CO_2 levels ($r= 0.38$, $p<0.05$). Unlike low-income households in rural areas, where many kitchens remained outdoors [27], people in this urban kampong (93%, n=14) cooked inside a small kitchen using a gas cooker without an exhaust fan or cooker hood. Moreover, from the recorded data of cooking events in the detailed activity logs, it was found that the average duration of cooking activity in this research was 84 min/day, similar to the finding reported in Kuehls' report (2024) [89]. Houses with cooking activity duration over 84 min daily were considered to have high cooking activity. This occured in some home-based food shops (warung) found in this kampong. Fig. 10 shows the pattern of pollutant levels, activity intensity, and occupancy rate/h. For example, in House 3, long duration simmering was done overnight to prepare half-cooked dishes, ready to be sold the next day (Fig. 11-b).

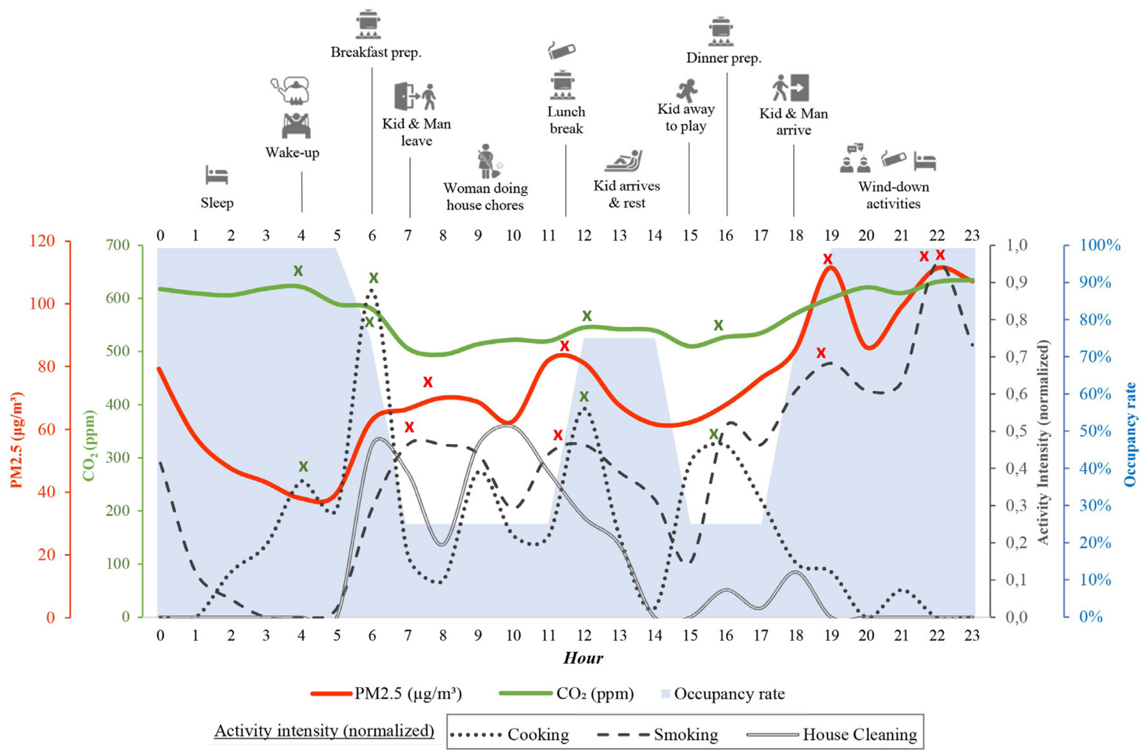


Fig. 10. Pattern of pollutant levels, activity intensity, and occupancy rate/h

Fig. 10 concludes the hourly pattern of pollutant concentrations which aligned with the intensity of significant activities in low-income urban households. Due to limited indoor and outdoor spaces, the rooms became multi-functional. Living room and kitchen as the only common space functioned as room for gathering, eating, smoking, playing, and even sleeping. Hence, during full occupancy, regardless of asleep or awake, the CO_2 was at the highest level and the lowest during less-occupancy. Cooking activities, which occur three times a day (including the early morning time to boil water for bath or drink), led to increase of CO_2 levels. Habitual smoking was done as a means of relaxation, before work, during afternoon break, and most intense during the night before sleep, resulting in the highest PM levels. In conclusion, low-income residents had distinct habits and activities closely related to their circumstances. The confined living space was unable to accommodate the various pollutant-generating activities, resulting in the buildup of pollutants throughout the houses.

Effect of occupant activities on the pollutant's dilution and dispersion

In addition to the impact of activities on pollutants generation at home, the dispersion patterns of pollutants can also be examined by analysing the peak fluctuations of each pollutant in several rooms, as demonstrated in several prior studies [90, 91]. Due to the high intensity of indoor activities, every house experiences many peak indoor events. Houses 9 and 3 illustrate the intense indoor peaks of $PM_{2.5}$ and CO_2 (Fig. 11). The highest peaks of $PM_{2.5}$, occurred during smoking. Wherever smoking took place, the $PM_{2.5}$, concentration in the rest of the house followed. However, the differences in $PM_{2.5}$ concentrations between floors ($\Delta|C2^{nd}$ - $C1^{st}|$) were higher when occupants smoked on the 2nd floor, whereas they were smaller when smoking occured on the 1st floor. This indirectly indicates that PM generated on the upper floor was contained, while PM coming from ground level was quickly dispersed upward and affected the concentration on the 2nd floor. Similarly, the CO_2 emissions from cooking in the kitchen is quickly dispersed and accumulated on the 2nd floor. These results were also confirmed for the other two-storey houses. The air temperature difference caused by the indoor burning activities (cooking and smoking) produces density variation that induces buoyancy flow, encouraging air to move upward and gather pollutants near the roof/ceiling surface. A CFD simulation also revealed this CO_2 vertical stratification pattern caused by the temperature and density gradient in a room with low airflow speeds [92]. Furthermore, these findings highlight the importance of source location in determining the dispersion route of pollutants, which aligns with the results from CFD simulation [84] and wind-tunnel experiment [93] of other research.

In addition to the pollutant dispersion behaviour, peak event analysis allowed us to qualitatively observe the impact of ventilation openings on pollutant concentration dilution. Reserchers reported that natural ventilation alone was not practical for removing indoor pollutants [31, 28]. However, in urban kampong houses, opening windows or doors while smoking or cooking was the only ventilation option to accelerate the dilution of PM and CO_2. When windows were closed, a time lag occurred before pollutant concentration returned to its original value. Each peak in Fig. 11-a represents one cigarette, typically lasting 4-5 min [86]. When the window were opened, it took 20-35 min for dust particle dilution to occur, until it returned to its initial concentration. Meanwhile, with the closed window, it took up to ≥50 min; the same was valid for cooking. This was observed in House 3 as an example (Fig. 11b). The effect of ventilation operation on indoor-generated pollutant dilution aligns with CFD simulation conducted by Ma and Sun [94]. Their study concluded that in a no-ventilation scenario, dust particles from smoking concentrated at chest-level in the breathing zone, far exceeding the WHO threshold.

When cooking with closed windows, the CO_2 concentration in the living room mirrored those in the kitchen. Conversely, the CO_2 concentration in the living room remained slow when the windows were opened. This demonstrates that even a weak breeze through open windows can reduce the CO_2 levels in the house. Meanwhile, when cooking with windows closed, the absence of proper ventilation prevents fresh air exchange, causing pollutants to become trapped and subsequently disperse throughout the house. CFD experiment conducted by Rahman et.al [88] also showed that cooking with closed window resulted in the most severe distribution of CO_2 around the cook, compared to cooking with open window and forced ventilation.

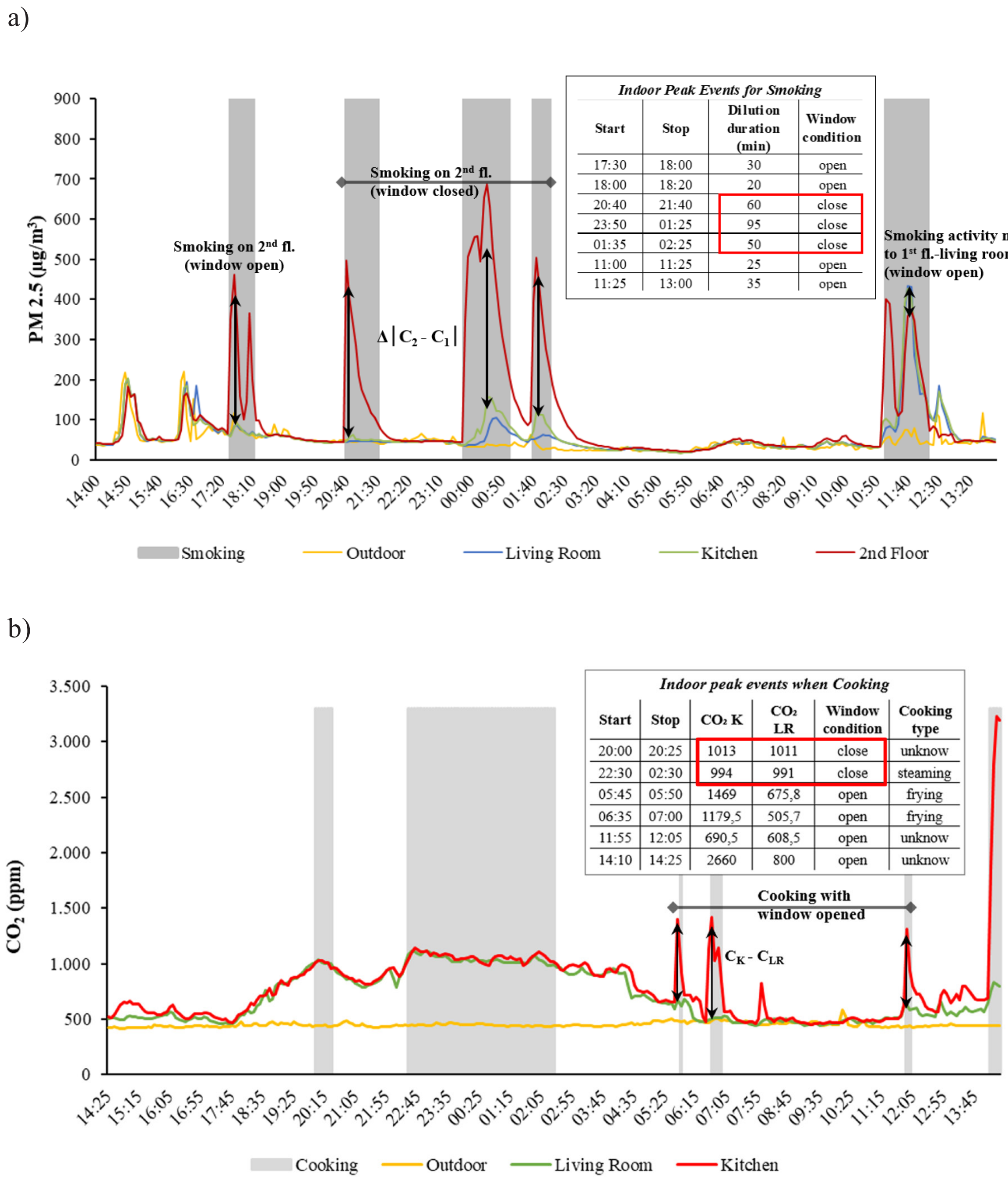


Fig. 11. Indoor peak of (a) $PM_{2.5}$ when smoking in House 9, (b) CO_2 when cooking in House 3

Low-income occupants' perception of air quality

Long-term exposure to pollutants can have an impact on residents' quality of life. Occupants' Perceptions of Air Quality (PAQ) have been used as subjective assessment of existing air quality conditions. Personal attributes, environmental conditions and pollution exposure are the main factors that influence PAQ [95]. Personal attributes include knowledge and self-efficacy (ability to improve condition) that links to the economy condition [96].

In this study, overall satisfaction mostly correlated with the perception of air cleanliness ($r= 0.564$, $p< 0.001$). However, this perception was not significantly correlated with PM levels, even though the concentration is quite alarming, especially in smoker houses. This indicated the resident's insensitivity to dust. The same was true for humidity perception, which was not correlated with relative humidity despite its high value. This was aligned with the results of previous research [97, 98] who stated that the PAQ was related to personal attributes rather than pollutant exposure itself. In contrast, occupants were sensitive to airflow because airflow perception was significantly correlated with indoor airflow, although the velocity was very low ($r= 0.382$, $p< 0.05$). Airflow helps with sweat evaporation, lowers the mean skin temperature, and alleviates thermal dissatisfaction [99]. Moreover, the response to the questionnaire also showed that people in this neighbourhood have a neutral opinion (scale value ±3) about air quality, where they feel neither content nor dissatisfied (Table 6).

Table 7 explains more about the relationship between personal attributes and IAQ towards PAQ in this low-income neighbourhood. It was new found that the duration respondents had lived in the house had a significant negative correlation with overall air quality satisfaction ($r= -0.4252$, $p< 0.05$). As they lived longer in the house, they became accustomed and more acceptable to the house condition. The lack of resource encouraged them to be satisfied and adaptable with the existing condition. Other research also found this adaptability driven by socioeconomic condition was higher in low-income communities [100-102]. Additionally, we found that this acceptance of poor air quality was also inversely correlated with the education rank and monthly income ($r= -0.4248$ and $r= -0.3001$, $p< 0.05$). Even though the existing air pollutant levels were high in these low-income urban houses, residents tended to perceive air as "good" (scale 2) or "regular" (scale 3). As mentioned by previous research, group with lower socioeconomic status was exposed to higher indoor air pollution [103, 104]. Economy condition influenced a person's lifestyle, including daily habit, type and condition of the house, and availability for home improvement [105-107]. Furthermore, study showed a correlation between lower monthly income and lower parental education level, which in turn leads to higher pollutant concentrations due to a lack of understanding and access to air quality information [108]. Residents' unawareness of the danger of poor air quality is concerning, as some studies have already proven the health risk of pollutant exposure, especially in low-income communities [109, 110].

Table 6. Average occupants' PAQ in low-income urban kampong (on Likert scale of 1-5)

PAQ	Hot-Cold (Temp)	No-Strong (Odour)	Still-draughty (Airflow)	Fresh-stuffy (Freshness)	Dry-humid (Humidity)	Clean-dusty (cleanliness)	Satisfied – No (Overall AQ)
Average	3.3	2.3	3.3	2.2	3.4	2.1	2.5
Meaning	Just right	Just a bit	Just right	Quite fresh	Just right	Quite clean	Quite satisfied

Effect of building characteristics

In addition to identifying and limiting outdoor and indoor pollutant sources, building factors have been studied to control IAQ because they are highly related to the ventilation and circulation of indoor air. The characteristics of a typical house typology are explained in previous section. Indoor activity-generated pollutants were 'censored' to resemble IAQ conditions without human intervention and to solely understand building characteristics' impact, as explained before.

Effect of ventilation opening

Many studies have used the tracer-gas method to calculate the air exchange rate in buildings. However, this technique was inappropriate in this case because of its affordability and the presence of an occupant. Hence, we used an index similar to a study [111], Active Ventilation Opening Percentage (AVOP) to assess the effectiveness of ventilation. Table 8 shows the correlation coefficients from the multivariate analysis of most building variables toward the IAQ parameter. It was found that the indoor airflow increased with AVOP. Although significant, the correlations were very low, indicating the inefficiency of the SSNV in bringing outdoor airflow into buildings [112, 113]. Nevertheless, this ventilation can reduce indoor pollutant concentrations despite its inefficiency because there were very weak but significant negative correlations between AVOP, air velocity, and PM_{10}, $PM_{2.5}$, PM_1, and CO_2. This was reasonable because, in this case, indoor pollutants were more dominant than outdoor pollutants. Previous studies found that opening windows increases the infiltration of outdoor pollutants into buildings [87]. However, it had the reverse effect, which was beneficial for reducing indoor pollutants [51]. The dilution effect of the airflow was more pronounced for CO_2 than for dust particles, which may be attributed to the disparity in pollutant density. Specifically, the density of CO_2 is significantly lower, around 1.98×10^{-3} g/cm^3, while the density of PM is between 0.8–2.5 g/cm^3 [114, 115]. Kitchen ventilation also accounted for the IAQ of residential kitchens [3]. A higher kitchen ventilation opening percentage (KVOP) increased kitchen airflow ($r=0.13$, $p<0.001$), thereby lowering the PM_{10}, $PM_{2.5}$, PM_1, and CO_2 concentrations in the kitchen ($r=-0.06$, $r=-0.072$, $r=-0.073$, and $r=-0.22$, respectively, $p<0.001$). This evidence confirmed the cooking-induced CO_2 dilution behaviour between window open and closed conditions, as revealed in earlier section.

Table 7. Correlation between PAQ to IAQ and personal attributes (*$p<0.05$)

	Hot-Cold	No-strong Odour	Still-draughty	Fresh-stuffy	Dry-humid	Dusty-clean	Overall AQ Satisfaction
IAQ & Thermal							
PM_1 Indoor	-0.1665	-0.0343	-0.0021	-0.0573	-0.0460	-0.0548	0.1687
$PM_{2.5}$ Indoor	-0.1587	-0.0269	-0.0329	-0.0594	-0.0562	-0.0497	0.1318
PM_{10} Indoor	-0.1627	-0.0543	-0.0423	-0.0761	-0.0808	-0.0583	0.1138
CO_2 Indoor	-0.0136	0.0411	0.1088	-0.0655	0.4229	-0.1997	-0.2622
T Indoor	-0.3474	-0.2487	-0.0127	0.0384	-0.1790	0.0593	-0.1124
Rh Indoor	0.3077	-0.0326	-0.0527	-0.2461	0.1996	-0.2665	-0.3966*
v Indoor	-0.2350	0.2922	0.3827*	0.0807	-0.1981	-0.0079	-0.2039
Personal Attributes							
Age	-0.2502	0.0441	0.3041	0.0514	0.3436	-0.0996	-0.2268
Duration inside the house in 24 h	-0.2293	0.1611	-0.2022	0.2033	-0.1251	0.2013	0.0418
Duration living in the house	-0.2713	-0.1641	0.2632	-0.1343	-0.0220	-0.0411	-0.4252*
Education rank	-0.2152	0.2911	0.0827	-0.0013	-0.1091	-0.1869	-0.4248*
Monthly income	-0.1443	0.3384	-0.1019	0.0169	0.0308	-0.1914	-0.3001*

Table 8. Results of $PM_{2.5}$, CO_2, and other thermal variables correlation analysis

	PM_1	$PM_{2.5}$	PM_{10}	CO_2	T	RH	Air v
Building Characteristics							
AVOP [a]	-0.1095**	-0.0988**	-0.0823**	-0.1345**	0.1659**	-0.2667**	0.0365*
Roof structure's airtightness [b]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
House volume [a]	0.1394**	0.1198**	0.1228**	-0.3206**	-0.2589**	0.1777**	-0.0114
No. floors [a]	0.2984**	0.2789**	0.2818**	-0.2183**	0.0622**	-0.0962**	-0.1763**
Kitchen layout [b]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Horizontal porosity [a]	0,2630**	0,2745**	0,2756**	0,1536**	0,3441**	-0,0228	-0,2994**
IAQ							
PM1 [a]	1.0000**	0.9921**	0.9845**	0.0034	0.2515**	0.1545**	-0.0391*
PM2.5 [a]	0.9921**	1.0000**	0.9925**	0.0273	0.2763**	0.1707**	-0.0277
PM10 [a]	0.9845**	0.9925**	1.0000**	0.0001	0.2700**	0.1545**	-0.0197
CO_2 [a]	0.0034	0.0273	0.0001	1.0000**	0.2841**	0.3583**	-0.1915**

[a] correlation value of Pearson test *p-value <0.05; ** p-value <0.001, [b] p-value of ANOVA test

Effect of roof structures' airtightness

Beside air exchange from ventilation openings, unintentional infiltration from the building envelope can also affect IAQ [60]. There were many unpredicted infiltration pathways in naturally ventilated houses, such as wall cavities, ventilation opening gaps, and roof gaps [116]. As described in Table 1, materials and construction methods of the wall, floor, and ventilation opening in these urban houses were quite similar; however, there was a distinct difference in roof structures' tightness of roof covering materials. Less airtight roofing materials were more commonly used in low-income neighbourhoods because of their affordability and ease of construction. We found that houses with concrete roofs had significantly higher CO_2 but lower PM concentrations ($p<0.0001$) than those with clay tile and asbestos roofs (Fig. 12.a-b).

Roofs with clay tile and asbestos covering had many cracks and gaps between the structures (purlins, rafters, and battens), as well as a larger space in the roof cavity because of the tilted shape (Fig. 12.c). The roof gaps increased air exchange, which was beneficial to dilute indoor-generated CO_2; however, it resulted in higher particulate matter due to a more pathways of outdoor pollutant infiltration [117]. A similar result was found, where less airtight informal houses in South Africa a had higher PM level than airtight formally constructed houses [5]. Meanwhile, a flat concrete roof created a smaller space and more airtight environment below the roof due to the monolithic structure (Fig. 12.c). The airtight structure limited the amount of air exchange, which prevented the infiltration of outdoor dust particles, but also led to the buildup of CO_2 because of fewer pathways for it to be diluted [118]. In conclusion, this phenomenon can be attributed to the trade-off between ventilation and airtightness. Houses with better natural ventilation may unintentionally allow more infiltration of particulate matter, whereas more airtight houses tend to trap indoor-generated pollutants such as CO_2.

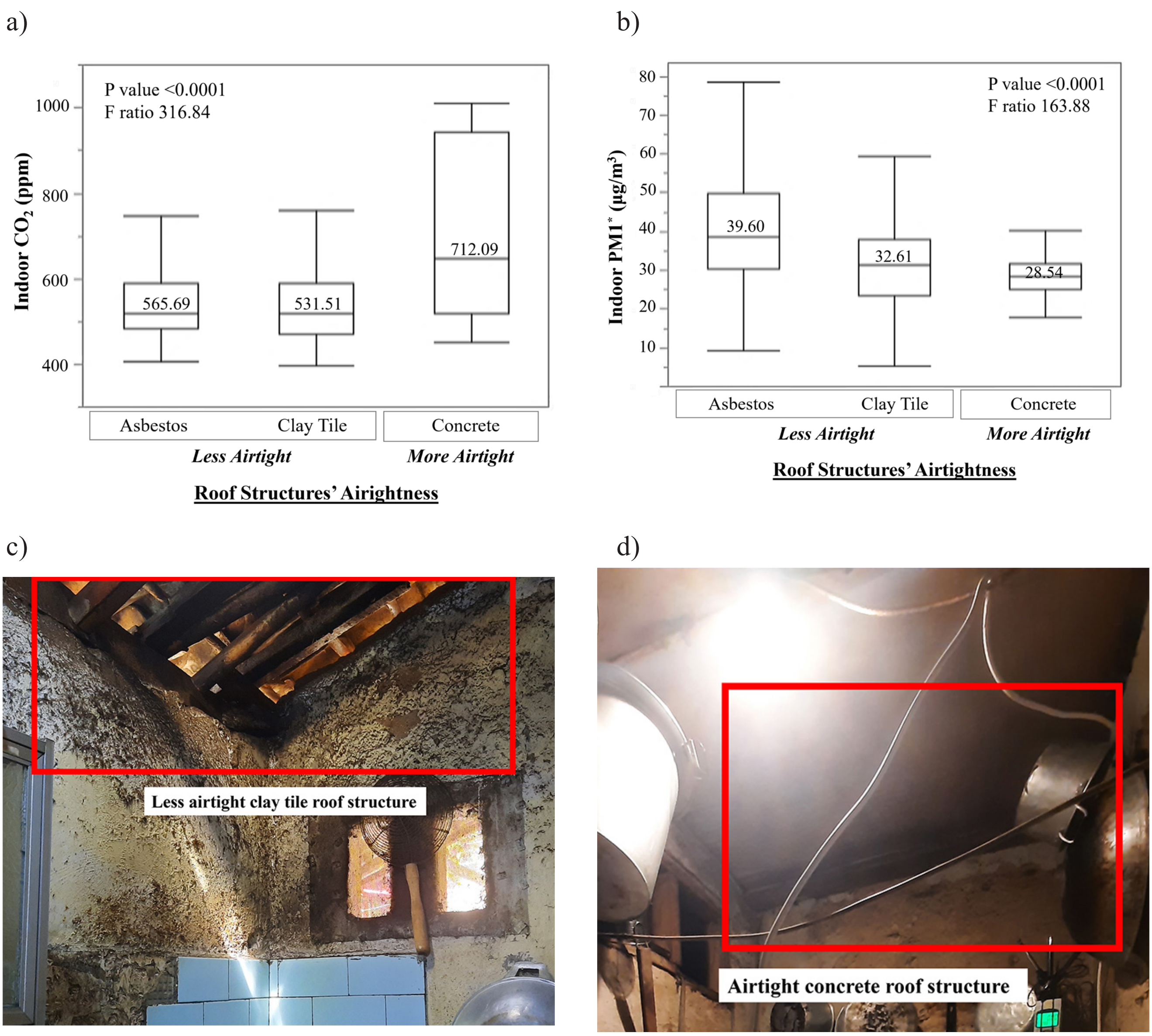


Fig. 12. Effect of roof structures' airtightness of different covering materials on (a) ANOVA for indoor CO_2 and (b) ANOVA for indoor PM_1 level, and illustration of house structure with (c) clay tile and (d) concrete covering material

Effect of housing dimensions

Although few, some studies have shown the impact of building dimensions on IAQ. We found that building volume and number of floors had significant influence on the pollutants level. We found that a higher total PM concentration was linked to a larger house (Fig. 13). Other research also pointed to house volume as a predictor of high PM resuspension [119, 120]. This relationship may be due to the increasing number of belongings, furniture, and surfaces where dust particles have accumulated as the house got bigger. In contrast, a larger house had an inverse correlation with CO_2 levels. Likewise, a larger kitchen volume tended to have a lower CO_2 concentration in the kitchen and average indoors ($r= -0.21$, $r=0.176$, $p<.001$). The correlation between house volume and CO_2 was similar to the findings of other studies [121, 122]. Bigger space provides larger mixing space for gas pollutant dilution, hence, lower CO_2 concentration.

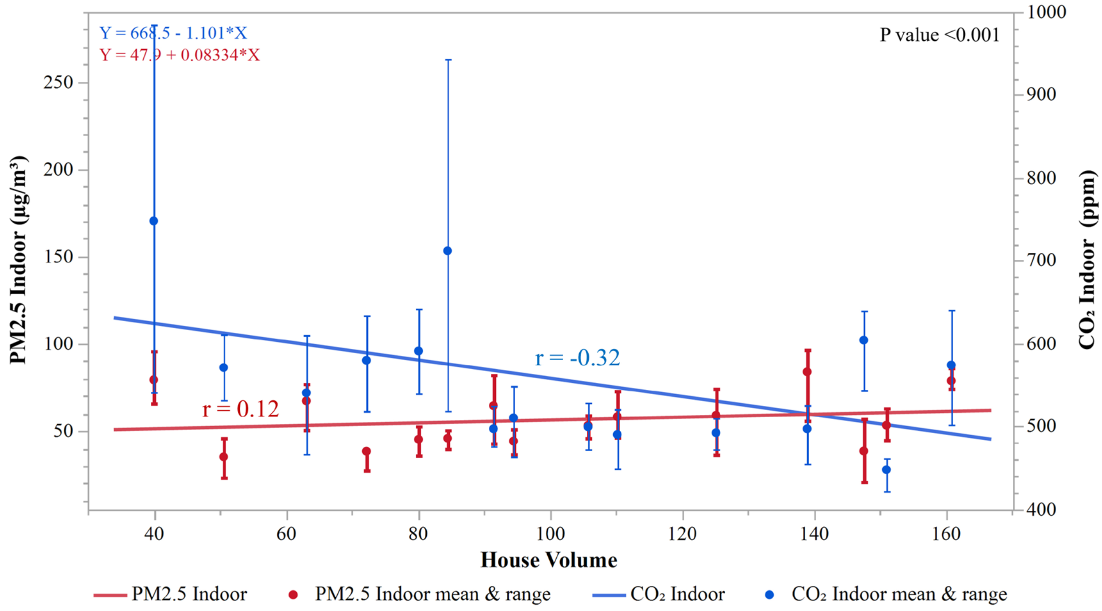


Fig. 13. Correlation between house volume and pollutants concentrations

Effect of other interior characteristics

Considering that kitchens were one of the primary sources of domestic pollutants, some studies had been conducted concerning the impact of kitchen layouts on IAQ. As revealed in other studies [119, 27], a significantly (p-value <0.0001) higher mean indoor PM and CO_2 levels were found in open-plan (IO) compared to separated Indoor (IP) and Outdoor kitchens (O) (Fig. 14.a-b). Kitchens were always located next to living rooms in these kampong houses. Therefore, in this study we quantified the connectivity between living and kitchen by measuring the indoor horizontal porosity (percentage degree of room opening area per wall partition area, between rooms). Open-plan kitchen had a 100% horizontal porosity while partitioned kitchen had smaller porosity between living and kitchen. We found that higher porosity between living and kitchen led to higher indoor PM and CO_2 levels (Fig. 14.c). The open-concept layout, worsened by the absence of mechanical kitchen ventilation, could facilitate the spread of kitchen pollutants. Fortunately, most houses in this neighbourhood had partitioned kitchens. Cheung [14] found a similar result where partitioned kitchen was preferable in a small house since it helps prevent particles from spreading over the entire house. However, the effect of horizontal porosity on CO_2 was contradictory to the finding of other researcher [27] which stated that gas pollutants were lower in an open-plan kitchen.

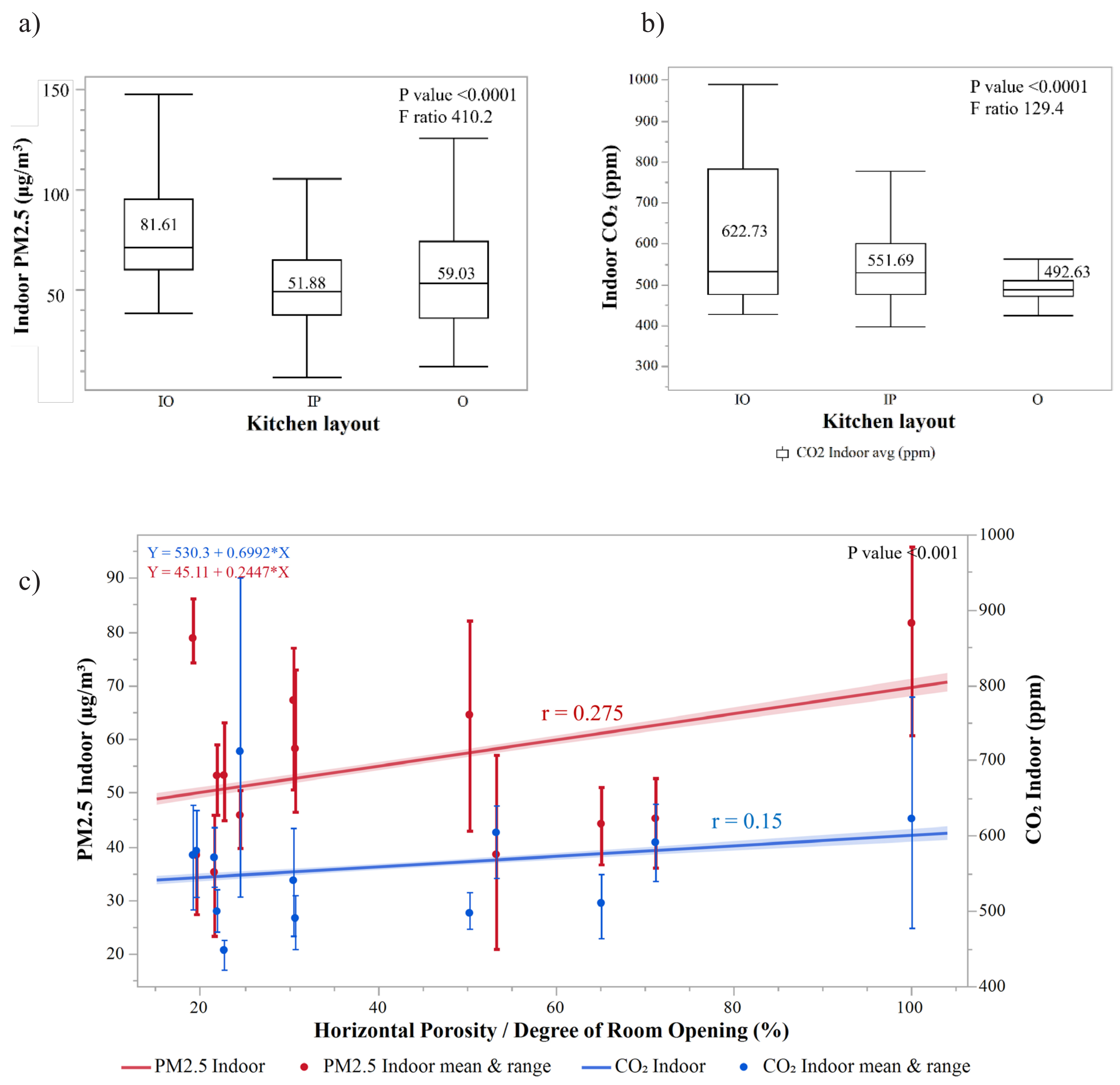


Fig. 14. Effect of kitchen layout on (a) ANOVA for indoor $PM_{2.5}$ level, (b) ANOVA for indoor CO_2 level; and (c) Correlation between horizontal porosity and indoor $PM_{2.5}$ and CO_2 levels

Horizontal porosity between rooms has a complex impact on air circulation and pollutant dispersion inside houses; however, it has been less studied. In a study it was demonstrated that the location of the pollutant source and the measurement point strongly influenced the impact of partitioning [123]. In general, higher porosity accelerates pollutant dispersion between rooms to a certain extent, resulting in higher pollutant concentrations. However, there are many other factors that may contribute to the dispersion of pollutants, such as pollutant source location and ventilation scenario of the rooms; hence, full experiments through computational simulation or controlled laboratory are recommended in the future.

Revealing the interactive impact of human, environment, and building on PM & CO_2

After understanding the detail relationship between each variable on PM and CO_2 and its underlying physical reasoning, explanatory models using stepwise linear regression was developed to identify the most significant variables that can explain the PM and CO_2 concentration and understand the relative effect of the predictor variables. As written on Table 9, the key predictors of $PM_{2.5}$ explained 56% of the variability in $PM_{2.5}$ concentration. Smoking had the most significant effect on indoor PM generation (β: 0.574), while house cleaning also increased indoor PM concentration because they resuspend particles into the air (β: 0.056). Beside indoor source, particles may also be originated from outside, hence outdoor PM had positive effect on indoor PM concentration (β: 0.156). Indoor temperature and relative humidity had positive impact on PM concentration (β: 0.046 and 0.037 respectively). Moreover, kitchen layout with higher porosity had the strongest significant influence on PM among other building factors (β: 0.19), followed by less airtight roof structure and building volume (β: 0.061 and 0.037 respectively). Low ventilation performance in these low-income urban houses was insignificant for PM dilution, therefore, it was excluded from the model.

The regression model showed that 42% of the indoor CO_2 level variability can be explained by the predictors. Occupants in this urban kampong contributed to the increase of indoor CO_2 through cooking and smoking activity (β: 0.318 and 0.103 respectively). Meanwhile, outdoor CO_2 did not affect indoor CO_2 significantly, hence it was not included in the model, confirming that most CO_2 was generated indoors. Furthermore, higher indoor relative humidity and temperature contributed to the increase of CO_2 concentration (β: 0.389 and 0.145 respectively), while indoor airflow reduced CO_2 concentration (β: -0.065). Moreover, building factors affected the indoor CO_2 concentration differently. Higher airtightness of the roof structure raised indoor CO_2 concentration (β: 0.162), whereas conversely, greater building volume and ventilation decreased CO_2 concentration (β: -0.159 and -0.188 respectively). Interestingly, we found that roof structures' tightness and building volume had contradictory effects on PM and CO_2 concentrations. An airtight roof structure, such as concrete roof, prevented CO_2 from being diluted into the outside air, while also limiting outdoor particles from entering the house. On the other hand, large building volumes offered more room for CO_2 to be diluted, even though they often permitted more furniture and other belongings that may raise the concentration of particles.

From all the discussion above, this study reveals a complex interaction among environmental, human, and building variables that collectively influence IAQ. Outdoor pollutants and human activities serve as source variables that directly increase pollution concentrations indoors through processes of emission and infiltration. Human activities can also affect indoor thermal conditions; for instance, cooking activities release water vapor into the air, and window operations can influence airflow, humidity, and room temperature [124, 25, 125]. Therefore, controlling IAQ through occupant behavioral interventions is crucial. Meanwhile, indoor thermal conditions, such as temperature, relative humidity, and air velocity, function as environmental mediator variables that affect the emission, dispersion, and dilution of pollutants. Increases in relative humidity and temperature can promote pollutants emission from building materials and the formation of secondary pollutants [77, 79], while an increase in air velocity can influence the dispersion and dilution of pollutants within the space [51].

On the other hand, building characteristics (volume, layout, ventilation, and roof structure airtightness) act as physical mediator variables that determine how pollutants are dispersed, diluted, and accumulated within the space. In addition to directly impacting pollutant concentrations, building physical characteristics—especially ventilation and roof structure airtightness—also have indirect effects on IAQ. These two variables can control the exchange and flow of air within the building, thereby influencing indoor thermal conditions that subsequently affect pollutant concentrations in the space. This has been explained in more detail in previous section.

Overall, this research indicates that buildings are not merely passive containers but active mediators that influence the interaction between pollutant sources and thermal environmental conditions within spaces. In buildings with poor ventilation conditions, such as those found in low-income urban settlements, other variables like roof structure airtightness, house volume, and interior layout can shape thermal responses by regulating airflow and air exchange, which then directly impacts pollutant concentrations. These findings provide a new perspective for developing more holistic indoor air quality management strategies, where the interactions between humans, thermal environments, and building design interventions must be considered to create healthy and comfortable living spaces.

Table 9. Regression for average $PM_{2.5}$ and CO_2 concentration

Pollutants	Variables	Estimate (B)	Std Error	t Ratio	p-Value	Standarized estimate (β)	VIF (Collinearity)
$PM_{2.5}$	Intercept	-72.659	19.473	-3.73	0.0002*	.	.
$R^2 = 0.56$	House Volume	0.075	0.023	3.28	0.0010*	0.037	1.210
R^2 K-Fold = 0.55 P-Value <.0001*	Kitchen layout (IO)	38.186	2.235	17.08	<.0001*	0.190	1.208
	Roof structure's tightness (Asbestos)	8.559	1.559	5.49	<.0001*	0.061	1.220
	Smoking frequency	136.526	2.733	49.96	<.0001*	0.574	1.291
	House clean frequency	22.886	4.113	5.56	<.0001*	0.056	1.007
	PM2.5 Outdoor	0.335	0.025	13.51	<.0001*	0.156	1.300
	T Indoor	2.665	0.644	4.14	<.0001*	0.046	1.232
	RH Indoor	0.373	0.112	3.33	0.0009*	0.037	1.178
CO_2	Intercept	-432.064	44.709	-9.66	<.0001*	.	.
$R^2 = 0.42$	House Volume	-0.661	0.052	-12.65	<.0001*	-0.159	1.182
R^2 K-Fold = 0.43	AVOP	9.173	0.601	15.26	<.0001*	-0.188	1.133
P-Value <.0001*	Roof structure's tightness (Concrete)	90.052	7.084	12.71	<.0001*	0.162	1.219
	Cooking frequency	178.767	6.620	27.01	<.0001*	0.318	1.037
	Smoking frequency	49.809	5.775	8.62	<.0001*	0.103	1.076
	T Indoor	16.840	1.429	11.79	<.0001*	0.145	1.132
	RH Indoor	8.043	0.275	29.27	<.0001*	0.389	1.319
	Air velocity Indoor	-245.012	46.019	-5.32	<.0001*	-0.065	1.114

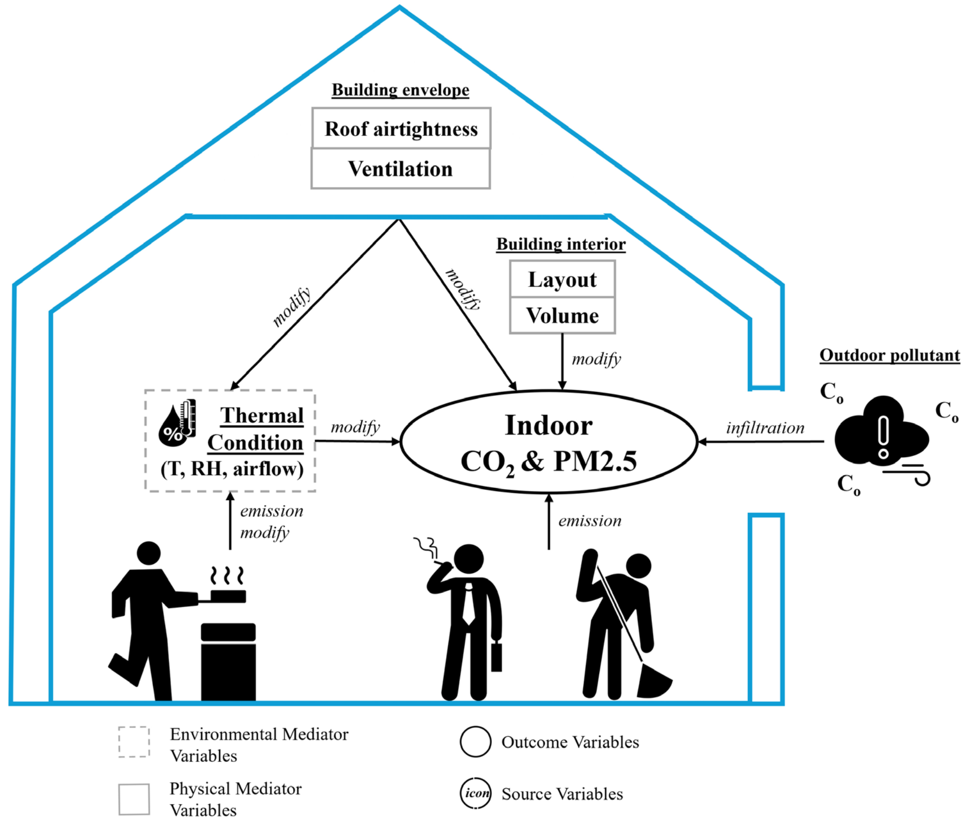


Fig. 15. Interactive relationship between human, building, and environment in influencing $PM_{2.5}$ and CO_2 in low-income urban houses

Fig. 15 shows the interactive relationship between human, building, and environment in influencing $PM_{2.5}$ and CO_2 in low-income urban houses.

Limitation and future directions

Based on the previously discussed results, it is important to note that the number of cases is still limited. For future studies, expanding the number of data units over a longer measurement period is recommended to better reflect IAQ under a wider variety of low-income urban houses conditions. The results found correlations between various indoor characteristics and pollutant concentration but the effect on pollutant dispersion is harder to confirm from field measurement. Hence, a computational pollutant simulation will be conducted in the future. Knowledge of the impact of outdoor morphological characteristics on local outdoor air quality is also valuable, however it is not discussed since the study was conducted only in one region. Therefore, measurement in multiple study areas should be considered for further studies to represent diverse urban settlement contexts. On the building scale, future studies should focus on the development of affordable air exchange and air filtration technologies for IAQ mitigation in low-income houses.

Conclusion

Field measurements and thorough questionnaires were completed to understand the relationship between building characteristics and human factors in affecting indoor air quality in poorly ventilated low-income urban houses. The following conclusions were drawn.

Even though the low-income kampong settlement was located in the city centre, indoor $PM_{2.5}$, and CO_2 were 22.5% and 23.4% higher than outdoor conditions, respectively. This was because high indoor activities have the most significant impact among other factors. Smoking indoors was still a habit for lower-class people, which increased $PM_{2.5}$, rapidly up to 281%. Local home-based enterprises, such as food stalls were often found in front of the low-income houses. The high cooking intensity contributed to the rise of CO_2 level by 47% in the kitchen. Besides, rooms in the low-income houses became multi-functional due to the limited space; hence, during full occupancy period, CO_2 reached the highest level. Moreover, the location of activities also influenced the dispersion of pollutants in different areas of the house.

Despite the poor IAQ conditions, 82.75% of the residents perceived this poor IAQ in the range of ‘neutral’ up to ‘satisfying’. Their acceptance rate increased with long stay, low monthly income, and low education level. These low socioeconomic conditions limited their knowledge of air quality, restricted the housing designs, and hindered them from making home improvements. Densely built neighbourhoods combined with poor single-sided ventilation resulted in low outdoor and indoor airflow; hence, indoor contaminants were trapped inside. Opening windows or doors can help alleviated the pollutant dilution time; however, the performance remained insignificant. The dilution effect was more prominent for CO_2 because of its lower density. Another type of unpredictable air exchange occurred through building gaps in the roof structure, which depend on the roof covering material. Asbestos and clay-tile roofs were often used for low-cost reasons. Compared with these types, a concrete roof with tighter structure traped 29.8% more CO_2 inside but reduced PM_1 infiltration by 20.9 %.

In addition to the building envelope elements, this study found that a larger house volume and more stories led to an increased accumulation of indoor particles within the house but, conversely, facilitated gas dispersion and, hence, lower CO_2 levels. It was also found that houses with open-plan kitchens (IO) had greater $PM_{2.5}$, and CO_2 concentrations by 57.3% and 48%, respectively, when cooking. This occurs because of the high porosity of the kitchen with no mechanical ventilation, which facilitates the faster dispersion of cooking pollutants to the rest of the house.

Overall, low-income residents have distinct habits and activities which generated high indoor contaminant; hence, it has the most significant impact on the poor IAQ conditions. Therefore, limiting pollution sources should be the primary IAQ control strategy. The unawareness of residents is a concern; hence, stakeholders and policymakers should prioritise educating low-socioeconomic societies about the risk of high indoor pollution. The confined living space with insufficient ventilation is unable to accommodate the various pollutant-generating activities, worsens these conditions. Therefore, this research highlights a new IAQ mitigation perspective regarding the importance of the interior characteristics on air circulation that could affect pollutant accumulation and dilution inside the buildings. In addition, efforts should be made to improve air exchange and filter indoor air affordably.

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Competing interests

The authors declare that they have no known potential conflict of interest that could have appeared to influence the work reported in this paper.

Authors’ contributions

Fathina I. Nugrahanti: Writing – review & editing, Writing – original draft, Methodology, Investigation, Project administration, Data curation, Conceptualization. Mochamad D. Koerniawan: Writing – review, Supervision, Project administration, Funding acquisition. Dewi Larasati: Writing – review, Supervision. Agustinus A. Abadi: Writing – review, Supervision. Müslüm Arıcı: Writing – review & editing. Surjamanto Wonorahardjo: Writing – review & editing, Methodology, Conceptualization, Project administration, Funding acquisition.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc) have been completely observed by the authors.

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