

*Case Study*

## Indoor and Outdoor Air Quality in Densely Populated Areas: Case Studies of High-Rise Social Housing in Kuala Lumpur

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### ABSTRACT

Air pollution is one factor that contributes to serious health issues in developing countries. The Malaysian Environmental Department has measured that particulate matter in urban areas is significantly higher than other parts of the country. Thus, this study aims to assess the current level of indoor and outdoor air quality in a tropical city—Kuala Lumpur; and to understand the relationship between these two environments in high-rise buildings. Through a fieldwork study on two typologies of social housing in the city, particulate matters of PM10 and PM2.5 were found to be the most common substances in indoor and outdoor spaces. The first typology, which employs a compact design with light-wells, recorded a decrease in particulate matter concentrations, whereas the second, which

employs atriums in its design, recorded an increase for the same substance. Therefore, a change in the ventilation concept should be implemented to address the problem of indoor air pollution using an integrated hybrid strategy of passive and low energy consumption techniques that should be explored in greater detail in the future.

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## INTRODUCTION

Globally, air pollution caused 3 million premature deaths in 2010, with a total of 6 to 9 million deaths expected by 2060 (OECD, 2016). The World Health Organization (WHO) has identified ten harmful chemicals to public health, including arsenic, asbestos, benzene, cadmium, lead, mercury, and highly hazardous fine particulate matter (WHO, 2010). These toxic substances can be found everywhere in our daily lives, including foods, cosmetics, papers, household equipment, and vehicles (Vogel, 2009), and long-term exposure to these harmful substances may have negative effects on the human body (Reuben, 2010). If these contaminants are allowed to exceed the recommended limits, they can harm human health by causing dizziness, asthma, eczema, lung irritation, and, worst of all, death (Clancy, 2011; WHO, 2010). According to a study, low levels of air pollution, even those below the WHO's recommended limits, can increase mortality (Meng et al., 2021).

Air pollution poses a threat to public health and the economy, where approximately 163 billion euros are spent each year for health costs related to exposure to harmful substances in Europe (European Parliament, 2019). In the global context, health costs are estimated to account for 10% of global GDP (Grandjean & Bellanger, 2017). Furthermore, hospital admissions due to air pollution-related illnesses are expected to triple from 3.6 million in 2010 to 11 million by 2060 (OECD, 2016). Air pollution has also impacted the loss of working days which are projected to be around 3.75 billion days in 2060 (OECD, 2016). WHO has established that 1 in 9 deaths (7 million per annum) is caused by fine particulate air pollution (Osseiran & Lindmeier, 2018), with 92% of the world's population living in cities where pollution levels exceed their guidelines (WHO, 2018a; WHO, 2018b).

South-East Asia (SEA) is a pollution hotspot, with levels frequently exceeding more than five times the WHO annual limits (Osseiran & Lindmeier, 2018), and these levels (20 g/m<sup>3</sup> for PM<sub>10</sub> and 10 g/m<sup>3</sup> for PM<sub>2.5</sub>) are currently increasing at a rate of around 1% per year (WHO, 2018a). In addition, this region is plagued by uncontrollable haze and smog episodes (Payus et al., 2013) caused by high PM<sub>2.5</sub> combustions from a variety of sources, including household equipment, open biomass burning, industrial and transportation-related activities (Shi et al., 2018).

Pollution from motorized vehicles is critical for the outdoor environment in SEA cities (Aung et al., 2019), whereas indoor pollution varies greatly depending on the building design characteristics. However, a few studies conducted in densely populated areas suggest that indoor PM<sub>2.5</sub> and PM<sub>10</sub> levels are related to the outdoor environment (Abdel-Salam, 2021; Tofful et al., 2021). Ścibor et al. (2019) discovered that as the outdoor PM<sub>2.5</sub> and PM<sub>10</sub> concentrations increased, so did the indoor concentrations of the substances. As a result, improving urban air quality can also benefit indoor air quality (Ścibor et al., 2019). Furthermore, it was discovered that the PM<sub>2.5</sub> and CO<sub>2</sub> levels in domestic kitchens are higher than in living areas (Abdel-Salam, 2021). It was also discovered that the majority

of households that use wood-burning stoves are as polluted as or more polluted than the outdoor environment (Hofflinger et al., 2019).

According to a study conducted from 2000 to 2016 in ten SEA cities, air pollution has a possible impact on health and the economy, with CO<sub>2</sub> and PM<sub>2.5</sub> being major risk factors for lung cancer in the region (Taghizadeh-Hesary & Taghizadeh-Hesary, 2020). Another study found that stroke was the most serious disease linked to air pollution (specifically, PM<sub>2.5</sub>), accounting for 40% of 1,256,300 premature deaths in SEA between 1999 and 2014. Meanwhile, ischemic heart disease was the leading cause of death (58%) in relatively cleaner air with PM<sub>2.5</sub> levels of 10 g/m<sup>3</sup> (Meng et al., 2021).

The Malaysian Environmental Department (DOE) found that the concentration of particulate matter less than 10 µ in width (PM<sub>10</sub>) in urban areas was significantly higher than in other parts of Peninsula Malaysia in their environmental reports from 2018 and 2019 (DOE, 2019; DOE, 2020). According to the reports, PM<sub>10</sub> concentrations in Malaysian cities ranged from 44 to 57 µg/m<sup>3</sup> from 2000 to 2019, exceeding the Malaysian Ambient Air Quality Norm of 40 µg/m<sup>3</sup> (DOE, 2014). The reports have also suggested that the daily concentrations of PM<sub>10</sub> for Klang Valley (including Kuala Lumpur) were higher than other stations in suburban and rural areas (DOE, 2019). Another study reported that the concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> in Kuala Lumpur were between 21 to 35 µg/m<sup>3</sup> and 44 to 56 µg/m<sup>3</sup>, respectively (Rahman et al., 2015).

In an analysis of PM concentrations in Kuala Lumpur, the annual average for PM<sub>2.5</sub> and PM<sub>10</sub> from 2002 to 2014 was between 21 and 35 µg/m<sup>3</sup> and 44 to 56 µg/m<sup>3</sup>, respectively (Rahman et al., 2015). This study indicates that air pollution in Kuala Lumpur is primarily caused by the fine particle fraction of PM<sub>2.5</sub>, based on comparisons to the US EPA National Ambient Air Quality Standard in ASHRAE 62.1. According to a study by Khan et al. (2015), PM<sub>10</sub> concentrations in Kuala Lumpur were higher on weekdays than on weekends. It demonstrates that heavy traffic on weekdays has a major effect on PM<sub>10</sub> levels in urban areas (Khan et al., 2015). Based on a dataset collected by DOE since 2000, PM<sub>10</sub> levels in Kuala Lumpur during the dry season (May to August) often exceeded the DOE limit (DOE, 2020).

Research into the application of improved ventilation strategies in buildings, as well as the prevention of hazardous substance emissions into our environment, is critical to regulating environmental and health impacts (Gonzalez-Longo & Sahabuddin, 2019). However, in all of the studies previously mentioned, the measurements were gathered at outdoor locations; thus, a study that measures air quality in both outdoor and indoor environments in high-rise residential buildings in urban areas is crucial to assess the actual conditions of air pollution in indoor and outdoor spaces at various height levels (Sahabuddin & Gonzalez-Longo, 2019).

## CASE STUDIES

People's Housing Program (PPR) is one of Malaysia's social housing projects, developed as a government initiative to address low-income housing issues. Until 2016, over 80,000 PPR units have been built throughout the country (KPKT, 2016; Sahabuddin & Gonzalez-Longo, 2019). The PPR scheme has been divided into two generations since its inception: the first began in 1998 and was followed by the second in 2010. Due to the similar geographical position and the different passive strategies adopted—PPR1 that uses atrium-based design (for the first generation) and PPR2 that uses light-well-based design (for the second generation)—was ultimately chosen for this fieldwork study. These two PPR complexes are in Kepong (Northern part of Kuala Lumpur), with only a 500-metres (0.31 mile) distance between them.

PPR1 is made up of six 18-storey blocks that were constructed on pilotis and feature atriums. All of the housing units are clustered around two large atriums in the centre of each building. The distance between Block A and Block C is approximately 60 m, as shown in Figure 1. There is an open space, a playground, and vehicle parking areas in this housing development. This development's Block A is closest to the main road (Figure 1).

The compact design of PPR2 includes eight light wells for each block, providing daylight and ventilation to the rooms facing the light wells. This development consists of four 20-story buildings, with Block A closest to the main road. As a result, it was chosen as the sample block. An open space with a playground and parking areas is in the middle of the development, similar to the PPR1 (Figure 2). Between the blocks, there is about a 50-meter gap.

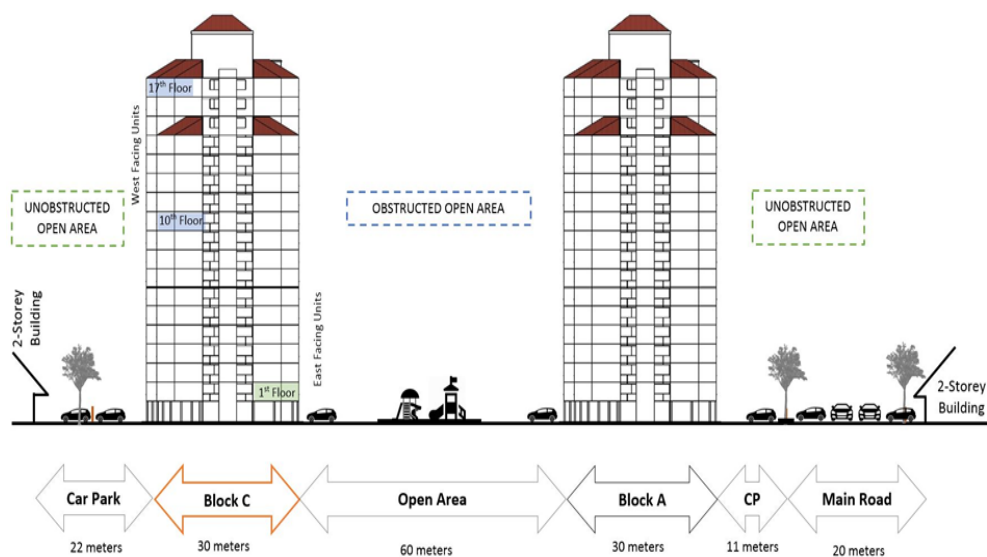


Figure 1. Cross-sections of the site of PPR1



Figure 2. Cross-sections of the site of PPR2

## METHODS

### Instrumentation and Parameters

A few organizations have also identified several hazardous substances in the air, including PM10, PM2.5, carbon dioxide (CO<sub>2</sub>), and carbon monoxide (CO) (ASHRAE, 2010; CIBSE, 2012; DOE, 2019; WHO, 2010). Thus, four substances—PM2.5, PM10, CO<sub>2</sub>, and CO are included in this study. Two types of direct-reading instruments, the Fluke 975 Airmeter, were used to measure CO<sub>2</sub> and CO, and the HoldPeak SD-5800D was used to measure PM10 and PM2.5 levels. The measuring ranges, display resolution, and monitoring system for both pieces of equipment used in this fieldwork analysis are mentioned in Table 1. The Fluke 975 Airmeter tracked CO<sub>2</sub> and CO gas concentrations from 0 to 5000 parts-per-million (ppm) and 0 to 500 ppm, respectively. The concentration levels for both PM10 and PM2.5 monitoring tools are identical, ranging from 0 to 999.9 g/m<sup>3</sup>. During the fieldwork, all equipment used was set to manufacturer calibration data.

Table 1  
Measuring ranges and recording method for the equipment

Equipment	Parameters Measured	Measuring Ranges	Display Resolution
HoldPeak SD-5800D	PM10	0~999.9 µg/m <sup>3</sup>	0.1 ug/m <sup>3</sup>
	PM2.5	0~999.9 µg/m <sup>3</sup>	0.1 ug/m <sup>3</sup>
Fluke 975 Airmeter	CO <sub>2</sub>	0 to 5000 ppm	1 ppm
	CO	0 to 500 ppm	1 ppm

## Limits

As a major global issue that must be addressed, many organizations have developed guidelines and recommendations for measuring and monitoring the limits for various types of airborne pollutants. For example, the WHO has set the PM10 and PM2.5 limits at 20  $\mu\text{g}/\text{m}^3$  and 10  $\mu\text{g}/\text{m}^3$  for one year limit, respectively (WHO, 2006), and the DOSH has set the limit for 24 hours at 150  $\mu\text{g}/\text{m}^3$  (DOSH, 2010), while CIBSE and ASHRAE have proposed 50  $\mu\text{g}/\text{m}^3$  and 15  $\mu\text{g}/\text{m}^3$  for the PM10 and PM2.5 limits, respectively (Table 2).

$\text{CO}_2$  is one of the parameters measured, and the CIBSE KS17 and DOE limits for the gas are 5000 ppm and 1000 ppm, respectively. The DOE's capacity is limited to indicating the adequacy of ventilation in any given room. As a result, readings above this limit indicate insufficient ventilation (DOSH, 2010). CO, another gas measured in this study, has different CIBSE, ASHRAE, and DOSH limits of 26 ppm, 35 ppm, and 10 ppm, respectively (Table 2). All mentioned figures represent the annual mean concentrations.

Table 2

*Parameters, ranges, and limits of several guidelines*

Parameters	WHO <sup>1</sup>		CIBSE KS17 <sup>2</sup>		ASHRAE 62.1 <sup>3</sup>		ICOP IAQ <sup>4</sup>	
	1 year	24hours	1 year	24 hours	1 year	24 hours	1 year	24 hours
	$\mu\text{g}/\text{m}^3$		$\mu\text{g}/\text{m}^3$		$\mu\text{g}/\text{m}^3$		$\mu\text{g}/\text{m}^3$	
PM10	20	50	50	150	50	150	-	150
PM2.5	10	25	-	-	15	65	-	-
	ppm		ppm		ppm		ppm	
$\text{CO}_2$	-	-	-	5000	-	-	-	1000
CO	-	-	-	26	9	35	10	-

*Notes.* <sup>1</sup> WHO Ambient Air Quality Guidelines; <sup>2</sup> Indicated exposure limits for selected airborne pollutants; <sup>3</sup> The concentration of interest for selected contaminants; <sup>4</sup> List of indoor air contaminants and the acceptable limits

## Methods of Assessment

For air quality, the Methods for Monitoring Indoor Air Quality (IAQ) set by WHO was referred for this fieldwork study. Table 3 lists the sampling parameters taken into account for this fieldwork analysis. Gases and particles are the two primary types of samplers (WHO, 2011). According to the WHO, air quality sampling should last at least 48 hours, so that this analysis will take measurements for 54 hours over three days, including weekends and weekdays. The sampling took place only once a day, from 6 a.m. to 12 a.m. (18 hours). Owing to the occupants' safety and privacy concerns, the after-midnight time (12 a.m. to 6 a.m.) could not be measured.

Table 3

*Specific considerations of sampling parameters for the fieldwork study*

Parameters	WHO - Method for Monitoring IAQ
Type of samplers	Selected gases and particles (including temperature and humidity)
Duration of sampling	54 hours (weekend and weekdays)
Sampling time	Every 3 hours (from 6 am to 12 am)
Outdoor air sampling	4 points (at various distances from the main road)
Indoor air sampling locations	2 points (indoor and semi-indoor) at lower, intermediate, and higher levels of the sample block
Potential sources of emission activities	The peak period of vehicular movement (source of outdoor combustion), The peak period of human activities (source of indoor combustion)

In this analysis, two sampling locations were defined: indoor and outdoor areas. There were four outdoor locations chosen: besides the main road (P1), the housing compound or buffer zone fence (P2), the sample block apron (P3), and the open space in between the blocks (P4). In addition, two points were chosen for indoor and semi-indoor locations: near the atrium area (P5) and in the centre of the selected housing units (P6).

Air quality sampling should also identify possible pollution sources – indoors and outdoors (Hess-Kosa, 2018; WHO, 2011). Vehicles are the most significant source of outdoor air pollution (Colls, 1998; Khan et al., 2015; Watkins, 1991), especially in urban areas. Therefore, the sampling cycle was included the peak periods of vehicular movement in the early morning (when people go to work) and late afternoon (back to home). In addition, combustion processes (stoves and heaters), construction materials and furnishings (draperies, rugs, and fabrics), and human activities (smoking and religious ceremonies) all affect indoor air quality (Charles et al., 2005; Tobin et al., 1993). These human activities (outdoor and indoor) are referred to as anthropogenic emissions (Colls, 1998) and taken into consideration when conducting the fieldwork.

## RESULTS

### PM10 Concentration

From 6 a.m. to 6 p.m., nearly all average PM10 readings in PPR1 did not exceed DOE, ASHRAE, or CIBSE limits, except for 6 p.m. to 12 a.m. (outdoor points only) due to human activities (religious practice—burning of joss sticks, thin sticks that burn with an incense-like odour). As a result, during the wet season (September to February), PM10 is not considered a hazard to the inhabitants, but human activities after working hours (6 p.m. to 12 a.m.) are the main contributors to the PM10 level exceeding the limits for several hours.



For PPR2, the average PM10 level in indoor space at level 1 was the highest among the other indoor spaces at levels 10 and 20. In general, average PM10 levels were below the DOE limit of 40  $\mu\text{g}/\text{m}^3$  during the day (9 a.m. to 6 p.m.) but exceeded the limit at night due to human activity. Figure 4 shows the average PM10 concentration in both PPR1 and PPR2, with the light-well-based design building having a higher concentration than the atrium-based design building (Figure 3).

In PPR2, the PM10 level was higher (average 53.5  $\mu\text{g}/\text{m}^3$ ) than in PPR1 (average 29.7  $\mu\text{g}/\text{m}^3$ ). It is due to the PPR2 enclosed atmosphere, which reduces air movement in its semi-indoor and indoor spaces. With an average of 81.4  $\mu\text{g}/\text{m}^3$  for indoor units, PPR2 had the highest PM10 average. The PM10 concentration level in PPR2 was generally significantly high, particularly for level 1. The PM10 level in PPR1 was entirely below the DOE limit, but it was partially exceeded in PPR2, especially during early morning and evening (high traffic volume) in locations near the main road and level 1 (Figure 3).

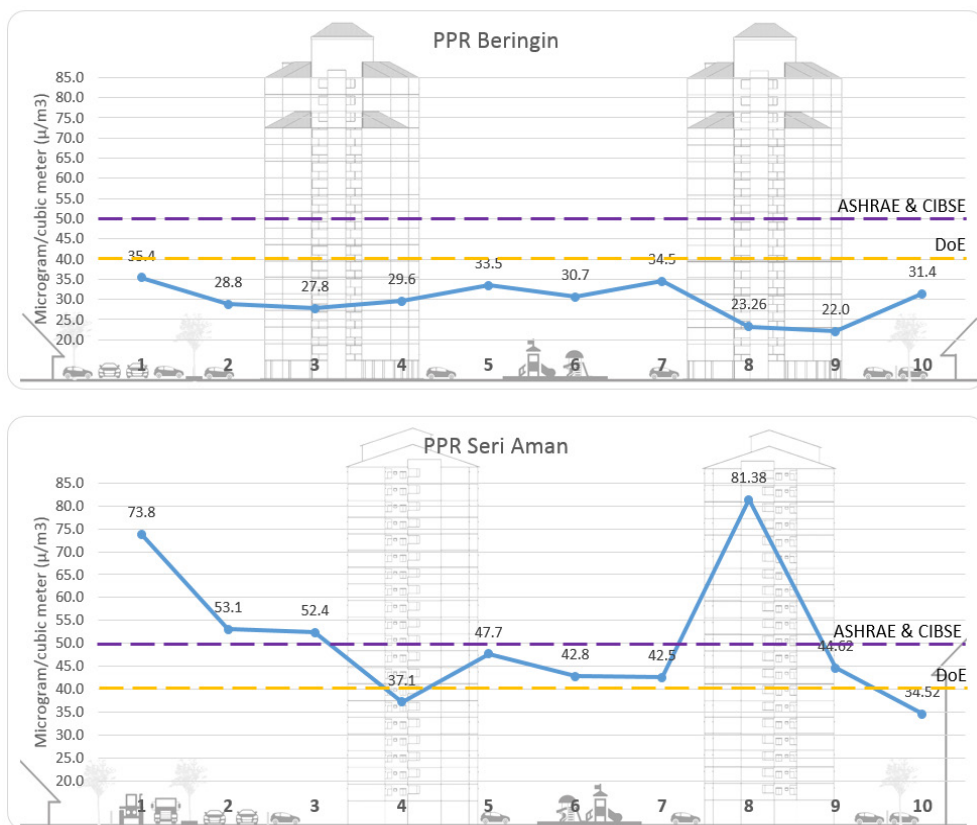


Figure 3. The average PM10 concentrations in PPR1 and PPR2

Note. 1) P1–Main Road; 2) P2–Buffer Zone; 3) P3–Building Apron; 4) P4–Open Space; 5) P5\_L1–Atrium Level 1; 6) P5\_L10–Atrium Level 10; 7) P5\_L17/L20–Atrium Level 17/20; 8) P6\_L1–Indoor Level 1; 9) P6\_L10–Indoor Level 10; 10) P6\_L17/20–Indoor Level 17/20



## PM<sub>2.5</sub> Concentration

In terms of PM<sub>2.5</sub>, average levels in PPR1 always surpassed the ASHRAE and DOE limits (indoor and outdoor) (Figure 4). Since fine particles are so tiny and light, they can remain in the air longer than heavier particles, and this means that PM<sub>2.5</sub> is the main source of air pollution in this atrium-based design building (Payus et al., 2013).

The average PM<sub>2.5</sub> levels in PPR2 surpassed the DOE and ASHRAE limits at outdoor and semi-outdoor points (P1–P5), as well as much of the time in indoor points (P6), apart from 9 a.m. to 6 p.m. in indoor spaces at level 10 and 20 (Figure 4). It demonstrates that PM<sub>2.5</sub> is the primary source of air pollution in indoor and outdoor spaces in this light-well-based design building.

Outdoor PM<sub>2.5</sub> concentrations were typically higher in PPR2 than in PPR1. In addition, PM<sub>2.5</sub> levels in PPR2 were significantly higher than PM<sub>10</sub>, particularly in the indoor unit at level 1. In general, both PPRs observed extremely high PM<sub>2.5</sub> concentrations (average 34.2  $\mu\text{g}/\text{m}^3$  for PPR1 and 44.2  $\mu\text{g}/\text{m}^3$  for PPR2), well exceeding the ASHRAE and DOE limits of 15  $\mu\text{g}/\text{m}^3$  (Figure 4). As a result, PM<sub>2.5</sub> will be the most hazardous material in outdoor and indoor spaces in Kuala Lumpur's urban areas.

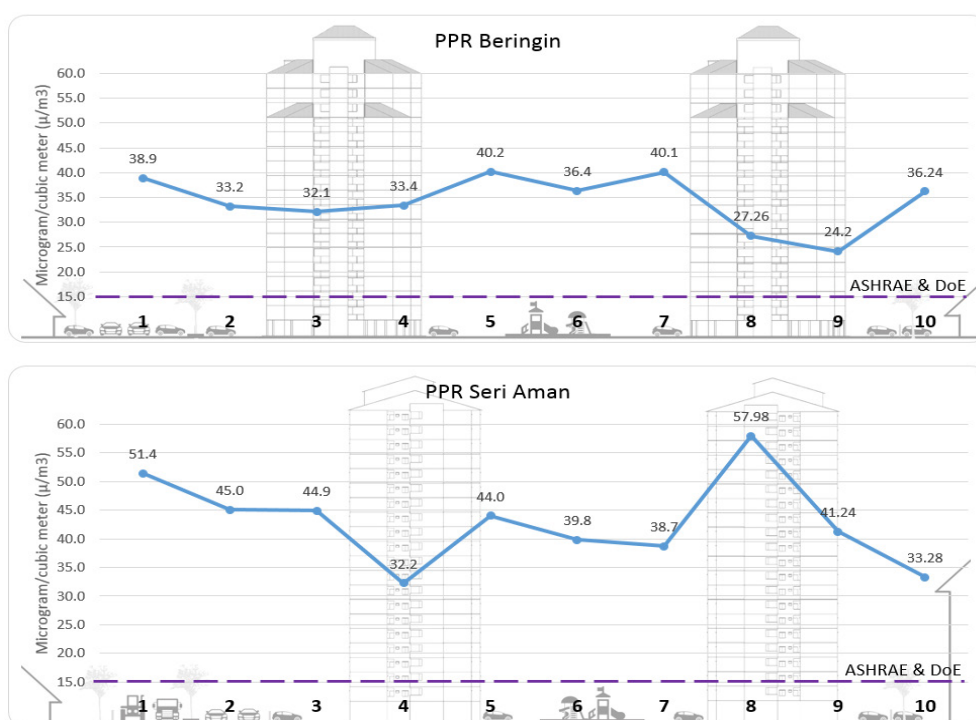


Figure 4. The average PM<sub>2.5</sub> concentrations in PPR1 and PPR2

Note. 1) P1–Main Road; 2) P2–Buffer Zone; 3) P3–Building Apron; 4) P4–Open Space; 5) P5\_L1–Atrium Level 1; 6) P5\_L10–Atrium Level 10; 7) P5\_L17/L20–Atrium Level 17/20; 8) P6\_L1–Indoor Level 1; 9) P6\_L10–Indoor Level 10; 10) P6\_L17/20–Indoor Level 17/20

## CO<sub>2</sub> Concentration

Figure 5 depicts average CO<sub>2</sub> concentrations in PPR1 and PPR2, which were well below the previously proposed standards and guidelines. Due to human appearance and behaviours, indoor CO<sub>2</sub> concentrations in PPR1 were generally higher than outdoor CO<sub>2</sub> concentrations. The concentrations, however, were still well below the required limit.

The average CO<sub>2</sub> concentration in PPR2 indoor space at level 1 was higher than that of indoor spaces at levels 10 and 17. Furthermore, CO<sub>2</sub> levels were typically lower than 500 ppm during the day from 9 a.m. to 6 p.m. and rose above 500 ppm at night due to human activity in indoor space and heavy traffic flow (Figure 5).

For outdoor concentrations, the average CO<sub>2</sub> concentration in PPR2 has been recorded higher than PPR1–530 ppm against 498 ppm. This study has also found that the highest average CO<sub>2</sub> concentrations in indoor spaces were recorded at level 1 for both PPRs. Due to the closed environment set-up, the average CO<sub>2</sub> levels in indoor spaces in both PPRs were recorded higher than in outdoor spaces (Figure 6). Furthermore, the CO<sub>2</sub> concentrations in both PPRs' indoor spaces (averaged 590 ppm for PPR1 and 600 ppm for PPR2) were lower than the DOSH limit of 1000 ppm, indicating CO<sub>2</sub> concentrations in both PPRs' indoor spaces are moderate. Indoor spaces in both developments show signs of insufficient ventilation.

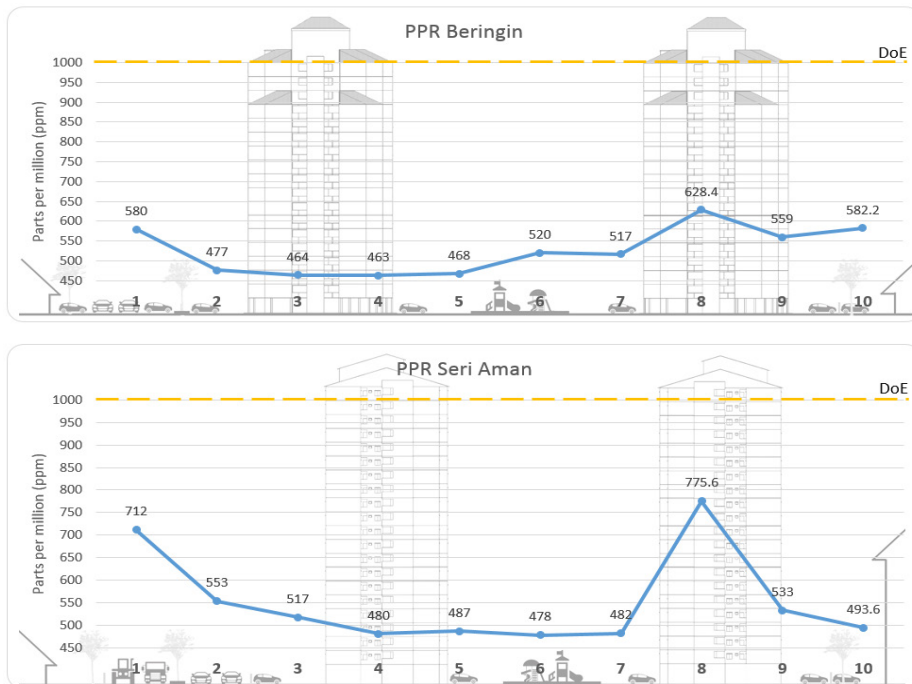


Figure 5. The average CO<sub>2</sub> concentrations in PPR1 and PPR2

Note. 1) P1–Main Road; 2) P2–Buffer Zone; 3) P3–Building Apron; 4) P4–Open Space; 5) P5\_L1–Atrium Level 1; 6) P5\_L10–Atrium Level 10; 7) P5\_L17/L20–Atrium Level 17/20; 8) P6\_L1–Indoor Level 1; 9) P6\_L10–Indoor Level 10; 10) P6\_L17/20–Indoor Level 17/20

## CO Concentration

CO concentrations were low and intangible in PPR1 (indoor and outdoor). The amounts were far below the ASHRAE and DOE's 9 ppm thresholds. As a result, CO is not the primary source of air pollution in this scenario. Similarly, average CO concentrations in indoor spaces at levels 1, 10, and 20 in PPR2 were extremely low and intangible. It means that CO is not a major pollutant in Kuala Lumpur. Furthermore, CO concentrations were very low in both outdoor and indoor locations in both developments (Figure 6). Therefore, it can be deduced that CO levels are very low in both PPRs at all times and locations, implying that this gas is unnoticeable and has no effect on indoor air quality in Kuala Lumpur.

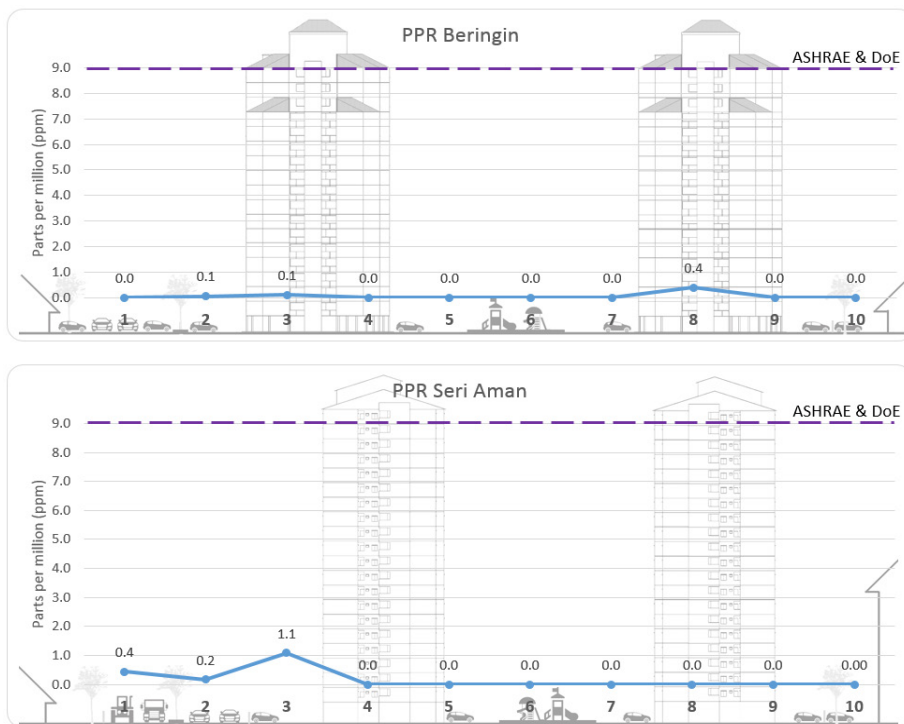


Figure 6. The average CO concentrations in PPR1 and PPR2

## DISCUSSION

Table 4 summarises the fieldwork research findings and is based on a study, and it can be deduced that buildings with atriums have better indoor and outdoor air quality than buildings with light wells (Loo et al., 2021; Sahabuddin & Gonzalez-Longo, 2019). This fieldwork has found that PM10 levels in PPR2 are generally moderate-high, while PM10 levels in PPR1 are moderate-low. PM2.5, for instance, was found to be elevated in both PPRs, regardless of the outdoor or indoor environment. Due to the different layout configurations,

PPR2 (compact light-well), on the other hand, had higher PM2.5 concentrations than PPR1 (open atrium) (Sahabuddin & Howieson, 2020; Wang et al., 2021). Through these fieldwork studies, air pollutants randomly disperse following the air movement and enter a room or space with negative pressure via any opening—vertical or horizontal (Lee et al., 2013).

Following the results from the fieldwork study, CO<sub>2</sub> concentrations in both PPRs were low-moderate and could be worse if the requisite changes in ventilation technique were not factored into building design. CO, a gas released by automobiles, however, did not contribute to air pollution in Kuala Lumpur (Sahabuddin & Gonzalez-Longo, 2018). Therefore, in this study and according to a long-term air quality measurement done by DOE, gas compounds like SO<sub>2</sub>, NO<sub>2</sub>, CO<sub>2</sub>, and CO are not the primary sources of air pollution in Kuala Lumpur (DOE, 2019; DOE, 2020; Binyehmed et al., 2016). Meanwhile, Leh et al. (2012) found that CO and SO<sub>2</sub> concentrations were within reasonable limits on all sampling days and NO<sub>2</sub> concentrations were moderate (Leh et al., 2012).

Considering the scarcity of land in densely populated urban areas where compact design is most advantageous (Sahabuddin & Gonzalez-Longo, 2017), the PPR2 design that incorporates light-wells should be improved in the future. Furthermore, to address the issues of stagnant air and weak stack effect, the light-well (which is currently passive) should incorporate a low-cost active mechanism such as an exhaust fan (Prajongsan & Sharples, 2012).

Table 4  
*Summary of the fieldwork study results*

Parameter	PPR Beringin			PPR Seri Aman		
	Outdoor	P5: Atrium	P6: Indoor	Outdoor	P5: Lightwell	P6: Indoor
<b>PM10</b>						
<b>Level 1</b>	P1: Moderate	Moderate	Low	P1: High	Moderate	High
<b>Level 10</b>	P2: Low	Moderate	Low	P2: Moderate	Moderate	Moderate
<b>Level 17/20</b>	P3: Low	Moderate	Moderate	P3: Moderate	Moderate	Moderate
-	P4: Low	-	-	P4: Moderate	-	-

Table 4 (Continue)

Parameter	PPR Beringin			PPR Seri Aman		
	Outdoor	P5: Atrium	P6: Indoor	Outdoor	P5: Lightwell	P6: Indoor
<b>PM2.5</b>						
Level 1	P1: High	High	High	P1: High	High	High
Level 10	P2: High	High	High	P2: High	High	High
Level 17/20	P3: High	High	High	P3: High	High	High
-	P4: High	-	-	P4: High	-	-
<b>CO2</b>						
Level 1	P1: Moderate	Low	Moderate	P1: Moderate	Low	Moderate
Level 10	P2: Low	Moderate	Moderate	P2: Moderate	Low	Moderate
Level 17/20	P3: Low	Moderate	Moderate	P3: Moderate	Low	Low
-	P4: Low	-	-	P4: Low	-	-
<b>CO</b>						
Level 1	P1: Low	Low	Low	P1: Low	Low	Low
Level 10	P2: Low	Low	Low	P2: Low	Low	Low
Level 17/20	P3: Low	Low	Low	P3: Low	Low	Low
-	P4: Low	-	-	P4: Low	-	-

*Notes.*

PM10	: Low (<30 µg/m <sup>3</sup> )	Moderate (30-50 µg/m <sup>3</sup> )	High (>50 µg/m <sup>3</sup> )
PM2.5	: Low (<10 µg/m <sup>3</sup> )	Moderate (10-15 µg/m <sup>3</sup> )	High (>15 µg/m <sup>3</sup> )
CO <sub>2</sub>	: Low (<499 ppm)	Moderate (500-999 ppm)	High (>1000 ppm)
CO	: Low (<5 ppm)	Moderate (5-9 ppm)	High (>9 ppm)

**CONCLUSION**

PM10 and PM2.5 are two major pollutants that lead to poor air quality in indoor and outdoor spaces in Kuala Lumpur. Human activities and joss stick burning (a thin stick that burns with an incense-like odour) are two of the key factors that contribute to high PM10 and PM2.5 concentrations in both PPRs, particularly after working hours. In addition, construction activity near fieldwork sites and heavy traffic flow in the morning and evening have also led to high PM10 and PM2.5 levels, spreading dust particles to the lower atmosphere.

In buildings with atriums and light-wells, however, there is a substantial difference in PM10 and PM2.5 concentrations. In buildings with atriums, PM10 and PM2.5 concentrations tend to increase, with the highest floor recording the highest concentration, while in buildings with light wells, concentrations tend to decrease from higher to lower

floors. It means that passive methods such as atrium and light-well have resulted in different PM10 and PM2.5 concentration profiles. The study also discovered that lower-level PM10 and PM2.5 concentrations are critical in high-rise buildings with atriums and light-wells. In general, buildings with atriums have better indoor air quality than buildings with light wells. As a result, a new mechanism in the light-well design should be introduced to improve its efficacy in reducing PM10 and PM2.5 concentrations. In high-rise residential buildings, this improvement could also boost air circulation while lowering air temperature and humidity.

This study revealed that PM2.5 is the most common substance found in both indoor and outdoor environments in Kuala Lumpur. This scenario happens due to PM2.5 particles that are lighter and can stay longer in the air than PM10 particles. However, these particles become heavier in high-humidity environments, such as the lower part of light-wells, and if there is not enough air movement, the particles will linger and attract mold. As a result of this research, it is suggested that more comprehensive research on light-well design in high-rise residential buildings be conducted. This feature, which is currently regarded as a passive strategy, has the potential to be enhanced to achieve indoor comfort and ensure health in high-rise residential buildings in urban areas.

A comfortable and healthy living environment could be achieved by architectural designs that could ensure constant air movement in indoor spaces and, at the same time, filtering of external air pollution. Considering that natural ventilation strategies had some limitations, such as allowing outdoor air pollution, an integrated strategy of passive and low energy consumption should be explored in greater detail. This integrated strategy should consider the design of openings and light-wells in more detail to cope with the problems of indoor comfort and health issues in the urban environment.

According to this scenario, Malaysia's current building regulations are unable to provide acceptable indoor air quality in these buildings through natural means. Allowing outdoor air in clearly allows polluted air to enter the internal rooms. As a result, a set of tests involving a scaled model with filtering media and various configurations of ventilation protocols involving passive, hybrid and fully mechanical should be carried out. The investigations' primary goal is to develop a system that can be the optimum solution for providing air filtration for all sources of pollution while meeting the thermal comfort conditions as well as addressing the challenges of modern air pollution.

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