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$PM_{2.5}$ and ozone in office environments and their potential impact on human health

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ABSTRACT

It is important to have good indoor air quality, especially in indoor office environments, in order to enhance productivity and maintain good work performance. This study investigated the effects of indoor office activities on particulate matter of less than 2.5 μm ($PM_{2.5}$) and ozone (O_3) concentrations, assessing their potential impact on human health. Measurements of indoor $PM_{2.5}$ and O_3 concentrations were taken every 24 h during the working days in five office environments located in a semi-urban area. As a comparison, the outdoor concentrations were derived from the nearest Continuous Air Quality Monitoring Station. The results showed that the average 24 h of indoor and outdoor $PM_{2.5}$ concentrations were 3.24 ± 0.82 μg m^{-3} and 17.4 ± 3.58 μg m^{-3} respectively, while for O_3 they were 4.75 ± 4.52 ppb and 21.5 ± 5.22 ppb respectively. During working hours, the range of $PM_{2.5}$ concentrations were 1.00 μg m^{-3} to 6.10 μg m^{-3} while for O_3 they were 0.10 ppb to 38.0 ppb. The indoor to outdoor ratio (I/O) for $PM_{2.5}$ and O_3 was < 1, thus indicating a low infiltration of outdoor sources. The value of the hazard quotient (HQ) for all sampling buildings was < 1 for both chronic and acute exposures, indicating that the non-carcinogenic risks are negligible. Higher total cancer risk (CR) value for outdoors (2.67E-03) was observed compared to indoors (4.95E-04) under chronic exposure while the CR value for acute exposure exceeded 1.0E-04, thus suggesting a carcinogenic $PM_{2.5}$ risk for both the indoor and outdoor environments. The results of this study suggest that office activities, such as printing and photocopying, affect indoor O_3 concentrations while $PM_{2.5}$ concentrations are impacted by indoor-related contributions.

1. Introduction

The indoor air environment is believed to be more liveable than the outdoor and buildings are thought to provide shelter to human by preventing the exposure to harmful substances present in the ambient air. Detailed studies on the status of indoor air pollution, pollution characteristics and the sources of pollution have been undertaken in a few types of buildings, such as nurseries (Basińska et al., 2019; Branco et al., 2014; Nunes et al., 2015); schools (Alves et al., 2013; Jan et al., 2017; Kishi et al., 2018; Martins and da Graca, 2018; Othman et al., 2019); offices (Al-Hemoud et al., 2018; Nunes et al., 2019; Othman et al., 2016; Wolkoff, 2013); private residences (Ducret-Stich et al., 2012; Kulshrestha et al., 2014; Lee et al., 2012; Massey et al., 2009; Scibor et al., 2019) as well as vehicle interiors (Moreno et al., 2019; Shu et al., 2015; Tartakovsky et al., 2013; Yu et al., 2018). Poor indoor air quality resulting from outdoors infiltration was also observed in urban areas. This was the result of a high level of pollution which was contributed by vehicle emissions and industrial activity (Barraza et al., 2014; Massey et al., 2009; Othman et al., 2019). Office buildings, generally located in urban areas or city centres in order to be more accessible for employees, are considered as the most important type of indoor location (Szigeti et al., 2016).

The office environment itself plays a significant role and is a place where the adult population have been found to spend 30% of their time

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on a working day (Morawska et al., 2017). Activities conducted in offices comprise meetings, discussions and office work performed using computers, printers, photocopier machines and other electronic devices. Computers operating with cathode-ray tube (CRT) monitors and thin-film transistor (TFT) monitors emit a range of volatile organic compounds (VOC) and also semi-volatile organic compounds (SVOC), such as brominated and organophosphate flame retardants which the emission factor has been calculated to be in the 1 ng per hour range (Destaillats et al., 2008). VOCs in the office environment can also be influenced by the entry of air from outside, particularly from fossil fuels through vehicular emissions as is indicated by a high benzene concentration while other sources include cleaning compounds, paints along with furnishing and floor materials (Al-Hemoud et al., 2018; Campagnolo et al., 2017; Nunes et al., 2019). There is also a contaminant called ozone (O_3) which is a reactive gas that is produced with VOCs in the office environment (Kagi et al., 2007). O_3 initiated chemistry reactions with volatile organic compounds have been shown to lead to the formation of secondary organic aerosols and sub-micron particulate matter (PM) in offices, such that these indoor pollutants markedly influence the indoor environment (Szigeti et al., 2016; Weschler and Shields, 1999; Wolkoff, 2013).

PM and O_3 are both pollutants which are usually studied in the office environment through investigation of trends in concentration and emission sources. PM, with diameter less than 2.5 μm ($PM_{2.5}$), originates from both indoors and outdoors where examples for outdoor sources are the infiltration of traffic and industrial activity emissions while laser printers and photocopy machines are known indoor office sources (Szigeti et al., 2014; Zhu et al., 2015). Moreover, the indoor office environment is usually linked to a high utilization of laser printers, which are known to emit O_3 (Salonen et al., 2018). The electrophotographic process in laser printers produces O_3 due to the corona wires that place charges onto photoconductive materials (Guo et al., 2019a; Lee et al., 2001). Printers contribute to significant release of ultrafine particles, especially during the activation and print phases, with maximum values that can reach 202×10^4 cm^{-3} (Koivisto et al., 2010). Other devices linked to indoor O_3 emissions are suggested as wearable air purifiers, ionic air devices, fruit and vegetable washers, refrigerator air purifiers, laundry treatment devices and in duct air cleaners (Guo et al., 2019a). Thus, a far greater understanding of $PM_{2.5}$ and O_3 concentrations is crucial as both pollutants have negative impacts on human health.

$PM_{2.5}$ and O_3 concentrations have also been studied due specifically to their impact on human health in the office environment. As reported by Marlier et al. (2012), human exposure to $PM_{2.5}$ and O_3 is considered to have increased hospital admissions and mortality rates from respiratory and cardiovascular disease. Combined exposure to PM particularly $PM_{2.5}$ and O_3 is also suspected as contributing to asthmatic disease in subgroups (Wolkoff, 2013) and also upper respiratory symptoms as a result of exposure to suspended PM, especially in an office environment (Azuma et al., 2018). Fine PM can reach the lungs far deeper than larger particles and for this reason it posed a greater risk to human health (Fang et al., 2015; Guo et al., 2019b). A study by Othman et al. (2018) found that human health could be significantly affected by office activities where a high level of energy was consumed throughout a building's life cycle. As a result, a reduction in energy consumption and the minimisation of exposure to pollutants was suggested. Moreover, human exposure to O_3 at low concentrations of 10 ppb, was also considered to increase the risk of premature mortality (Bell et al., 2006; Gall and Rim, 2018). Work-related symptoms in offices were noted as mucosal irritation in the eyes and airways, lower respiratory symptoms and those relating to the central nervous system such as headaches and tiredness (fatigue). These work-related illnesses were also associated with climatic, occupational and other risk factors (Wolkoff, 2013). Consequently, office workers should be protected from harmful pollutant either through the ambient sources or indoor generation as a good indoor office environment is desirable for human health.

Over the past decades, the office environment has been affected by a variety of outdoor as well as indoor sources, namely gadgets, electronic devices and office equipment. Thus, it is important to understand the impact of pollutants, such as fine particulate and O_3, on office workers' health. In this study, our aim was to investigate the concentrations of $PM_{2.5}$ and O_3 in different office environments. Contribution of indoor activities and other possible sources was also identified. The health risks to office workers from exposure to $PM_{2.5}$ and O_3 in both indoor and outdoor (ambient) environments were estimated to assess the potential health impact using the United States Environmental Protection Agency's (USEPA) Human Health Risk Assessment for inhalation pathways.

2. Materials and method

2.1. Sampling location/office description

Bangi, which is characterised as semi-urban, is a newly developed town in Selangor, in the south of the Malaysian Peninsula. Bangi is located 38 km from the capital city of Kuala Lumpur and is situated between the towns of Kajang and Putrajaya. The towns of Kajang, Putrajaya, Bangi, Cyberjaya, Nilai and Seremban are estimated to form a catchment area of 1.2 million people (New Straits Times, 2017). There are two highways which link Bangi with Kuala Lumpur and there is also a train station for public transportation near-by.

Five different indoor office environments at Universiti Kebangsaan Malaysia (UKM) Bangi were chosen for this study. The site itself is surrounded by residential areas, forest and traffic intensity is about 10,368 vehicles/day. Building 1 (B1) is a new building which was built in 2009 while Building 2 (B2), Building 3 (B3), Building 4 (B4) and Building 5 (B5) are old buildings which were built in 1977. Descriptions of all the sampling locations and buildings are given in Table S1 and their locations shown in Fig. S1. All indoor office spaces were selected based on the location of the building they were in as well as the use of printers and photocopy machines. The buildings for offices B1, B2 and B5 comprised a meeting room and a seminar room for lecturer and student activities while building B3 had a university library that become central area for students. Building B4 was usually utilised for laboratory work and had lecturers' rooms which were occupied by students. All indoor workers, which comprised both male and females, were aged between 25 and 55 years old. In the office areas, smoking was totally prohibited. All of buildings used in this study were mechanically ventilated with centralized air conditioning whereby open windows were not allowed. All air conditioning systems were automatically switched on between 07:30 to 17:30 and switched off out of those hours. During the sampling monitoring, the average temperature and relative humidity was 24.9 °C and 76% respectively for indoors and 31.4 °C and 80% for the ambient air.

2.2. $PM_{2.5}$ and O_3 monitoring

The monitoring of $PM_{2.5}$ and O_3 was carried out at five different office buildings from October 2018 to December 2018. The monitoring undertaken inside of the office buildings was performed simultaneously and continuously for two weeks during the working days of each building. An optical $PM_{2.5}$ sensor, as developed by Nakayama et al. (2018), was used for $PM_{2.5}$ measurements while an ozone analyzer (Tanabyte, USA) was used for O_3 measurements. The optical $PM_{2.5}$ sensor operated based on the relationship of light scattering intensity and particle size (Nakayama et al., 2018) while the ozone analyzer used the photometer method and was equipped with an ozone scrubber and inlet filter (Tanabyte, 2007). The test instruments and accuracy are shown in Table S2. Sampling equipment was placed 1 m above the ground and in the centre of the room, which was 1 m away from the walls, doors and air conditioning units as follows Othman et al. (2019).

The $PM_{2.5}$ and O_3 concentrations were calculated at 1 min data intervals for 9 h (from 08:00 to 17:00) and 24 h (midnight to midnight).

As reported by Ly et al. (2018) and Nakayama et al. (2018), the measurement of $PM_{2.5}$ using optical sensor was calibrated using nearly monodisperse polystyrene latex (PSL) which all $PM_{2.5}$ measurement need to be multiply with correction factor. The calculation of correction factor is highly affected by the differences in refractive index, shape and morphology between PSL and particles size (Ly et al., 2018). For this study, correction factor of 1.3 was used as follows Othman et al. (2019). Correlation analysis of $PM_{2.5}$ concentration in the sampling station with near by air quality stations was suggested for accurate $PM_{2.5}$ concentration (Othman et al., 2019).

At the same time, the continuous ambient $PM_{2.5}$ and O_3 data was used as an outdoor concentration corresponding to each indoor measurement. Both outdoor concentrations were obtained from the nearest Air Quality Monitoring Station which is based in Putrajaya, 17 km from the sampling sites. The data was provided by the Department of Environment, Ministry of Energy, Science, Technology, Environment and Climate Change (Department of Environment, 2019).

2.3. Health risk assessment of $PM_{2.5}$ and O_3 exposure

The possible adverse effects of human exposure to toxic agents are characterised through undertaking a health risk assessment. A health risk assessment is a predictive measurement which takes into account existing exposure data so as to measure the impact of exposure to a particular pollutant on human health (Morakinyo et al., 2017). The health risk assessment of $PM_{2.5}$ and O_3 via the inhalation route was performed using the USEPA recommended method (USEPA, 2009). In this study, both carcinogenic and non-carcinogenic risks were examined for $PM_{2.5}$ exposure while for O_3 exposure, only non-carcinogenic risk was determined. Incremental lifetime cancer is usually calculated to reflect the probability of lifetime cancer or cancer-related illness that represents total exposure (Iwegbue et al., 2018). Exposure to $PM_{2.5}$ and O_3 both in an indoor office and the outdoor (ambient) environment was calculated based on chronic and acute exposure. The chronic exposure concentration (EC) was calculated based on Eq. (1) below:

$$EC = (CA \times ET \times EF \times ED)/AT \quad (1)$$

where CA is the concentration of pollutant ($PM_{2.5}$ or O_3, μg m^{-3}), ET is the exposure time (9 h), EF is the exposure frequency (250 days $year^{-1}$), ED is the exposure duration (25 years) and AT is the averaging time (non-carcinogenic: ED × 365 days year-1 × 24 h $days^{-1}$, carcinogenic: 70 years × 365 days $year^{-1}$ × 24 h $days^{-1}$). Acute exposure was calculated as CA equal to EC. The calculation for the hazard quotient (HQ) for non-carcinogenic risk was estimated based on Eq. (2) using the reference value with terms of reference exposure level (REL) which is a toxic threshold dose as per Matooane and Diab (2003) while the carcinogenic risk (CR) was estimated based on the inhalation unit risk (IUR) as stated in Eq. (3):

$$HQ = EC/REL \quad (2)$$

$$CR = EC \times IUR \quad (3)$$

The value for both REL was 50 μg m^{-3} and 120 μg m^{-3} for $PM_{2.5}$ and O_3 where this value was taken from the New Malaysia Ambient Air Quality Standard for Interim Targets (IT-2 2018) as suggested by Malaysian Department of Environment (Department of Environment, 2019). As reported by Morakinyo et al. (2017), REL is the dose at which adverse health effects can occur in exposed groups compared to unexposed groups. For IUR, due to no specific IUR value for $PM_{2.5}$, the standard value of unit risk of 0.008 per μg m^{-3} was taken from Greene (2006). The Hazard Index (HI) value was calculated as the sum of HQ as HI is used to access overall potential non-carcinogenic effects. As reported by Morakinyo et al. (2017) and Othman et al. (2019), HQ and HI < 1 suggests no significant risk while HQ > 1 suggests the possibility of non-carcinogenic effects. The CR value was suggested to be within an acceptable range being 1.0E-06 to 1.0E-04 (Othman et al., 2018).

2.4. Dosimetry analysis of particle deposition in office workers

Dosimetry analysis is usually performed to calculate the exposure concentration of an inhaled substance in the human respiratory tract. The deposition fraction of inhaled $PM_{2.5}$ particles was calculated using the Multiple-Path Particle Dosimetry Model (MPPD, Version 3.04, ARA Inc) in three regions of the lung, tracheobronchial tract (TB) and pulmonary region (P) with input data for both indoor office and outdoor scenarios. This model calculated the deposition and also clearance of monodisperse and polydisperse aerosols for particles ranging from ultrafine to coarse, based on the single-path and multiple-path methods (ARA, 2019).

In this study, the deposition of $PM_{2.5}$ particulate through nasal breathing in indoor and outdoor scenarios was analysed using the human Yeh/Schum Symmetric model. For the particle properties input, count median diameter (CMD) with a diameter of 2.5 μm and geometric standard deviation (GSD) of 1.0 was used (Othman et al., 2019). The input data for body orientation and breathing frequency in the MPPD model was set to be on back (indoor) and upright (outdoor) with 12 breaths min^{-1} (indoor) and 20 breaths min^{-1} (outdoor) to express the indoor office and outdoor scenarios. The average $PM_{2.5}$ concentrations for all the sampling buildings were used as the concentration for the indoor exposure scenario while the average ambient concentration was set for the outdoor scenario. All input parameters used in both the indoor and outdoor scenarios are listed in Table S3.

2.5. Statistical analysis

Statistical analysis was employed to analyse all the collected data. Several analyses, such as descriptive statistics and one-way ANOVA, were carried out in order to indicate the variations and any significant differences in the data collected from the buildings used in the study. The relationship of indoor and outdoor concentrations of $PM_{2.5}$ and O_3 was investigated using linear regression. All statistical analyses were performed using the Statistical Package for the Social Science (SPSS V.18).

3. Results and discussion

3.1. $PM_{2.5}$ and O_3 concentrations in indoor and outdoor (ambient) environments

The average concentrations of $PM_{2.5}$ and O_3 for the indoor and outdoor (ambient) environments for 24 h and 9 h (working hours) for each sampling building are presented in Table 1. In general, both 24 h and 9 h measurements of $PM_{2.5}$ and O_3 concentrations were higher outdoors (ambient) than indoors for all the sampling buildings ($p < 0.01$). The average $PM_{2.5}$ and O_3 concentrations for 24 h measurements were 3.24 ± 0.82 μg m^{-3} and 4.75 ± 4.52 ppb respectively for indoors, and 17.4 ± 3.58 μg m^{-3} and 21.5 ± 5.22 ppb respectively for outdoors (ambient). Over the entire set of measurements, the highest $PM_{2.5}$ concentration for the 24 h measurement was recorded at B1 for indoors (4.88 ± 0.86 μg m^{-3}) and B5 for outdoors (ambient) (21.1 ± 3.37 μg m^{-3}). The highest 24 h average for O_3 for both indoor and outdoor concentrations was recorded by B5 with concentrations of 9.78 ± 9.07 ppb and 26.5 ± 5.18 ppb respectively. Both indoor and outdoor $PM_{2.5}$ concentrations for all the sampling buildings were far lower than the World Health Organization (WHO) guidelines (25 μg m^{-3}), the National Ambient Air Quality Standard suggested by USEPA (35 μg m^{-3}) and the New Malaysia Ambient Air Quality Standard for 2018 Interim Target-2 (50 μg m^{-3}).

Table 1
$PM_{2.5}$ (μg m^{-3}) and O_3 (ppb) mean concentration (± standard deviation) for 24 h and 9 h (working hours) measurement in the indoor air of offices and in the respective ambient air.

	Indoor				Outdoor (ambient)			
	$PM_{2.5}$		O_3		$PM_{2.5}$		O_3	
	24 h	9 h	24 h	9 h	24 h	9 h	24 h	9 h
B1 (n = 20)	4.88 ± 0.86	4.33 ± 0.62	6.64 ± 6.50	12.4 ± 7.34	15.3 ± 4.30	15.1 ± 5.61	20.6 ± 4.79	32.9 ± 7.90
B2 (n = 20)	3.63 ± 0.71	3.45 ± 0.51	1.83 ± 1.81	3.07 ± 2.13	17.7 ± 3.84	17.9 ± 2.73	21.5 ± 5.43	32.2 ± 9.17
B3 (n = 20)	2.50 ± 0.80	2.10 ± 0.30	3.15 ± 3.10	4.96 ± 3.50	18.6 ± 3.31	21.4 ± 5.72	23.1 ± 8.77	41.1 ± 11.9
B4 (n = 20)	2.28 ± 0.90	2.46 ± 0.97	2.33 ± 2.14	3.76 ± 2.53	14.2 ± 3.10	15.7 ± 3.84	15.9 ± 1.94	28.4 ± 5.27
B5 (n = 20)	2.91 ± 0.82	2.36 ± 0.24	9.78 ± 9.07	15.8 ± 10.6	21.1 ± 3.37	21.5 ± 4.05	26.5 ± 5.18	40.1 ± 5.62
Average	3.24 ± 0.82	2.94 ± 0.53	4.75 ± 4.52	8.03 ± 5.23	17.4 ± 3.58	18.3 ± 4.39	21.5 ± 5.22	34.9 ± 7.99

For 9 h (working hours) measurements for indoors, the $PM_{2.5}$ concentrations were recorded in the sequence of B1 > B2 > B4 > B5 > B3 with an overall average concentration of 2.94 ± 0.53 μg m^{-3} while for outdoors (ambient), the sequence was B5 > B3 > B2 > B4 > B1 with an overall average concentration of 18.3 ± 4.39 μg m^{-3}. The 9 h measurement for O_3 showed the sequence of B5 > B1 > B3 > B4 > B2 (indoor) and the sequence of B3 > B5 > B1 > B2 > B4 (outdoor) with an average concentration of 8.03 ± 5.23 ppb (indoor) and 34.9 ± 7.99 ppb (outdoor). Both indoor and outdoor (ambient) O_3 concentrations for 9 h measurements were lower than the 8 h standard of WHO guideline (100 μg m^{-3} = 50.9 ppb) and the New Malaysia Ambient Air Quality Standard, IT-2 (both with a standard value of 120 μg m^{-3} = 61.1 ppb) for which the 8 h standard was used as a comparison for working hours. The result from the one-way ANOVA showed that there was a significant difference (p < 0.05) between indoor $PM_{2.5}$ and O_3 concentrations from samples from the different sampling buildings.

The highest $PM_{2.5}$ concentration for 24 h (4.88 ± 0.86 μg m^{-3}) and 9 h (4.33 ± 0.62 μg m^{-3}) measurements were recorded at B1, compared to other sampling buildings, indicating that office activities are the main contributors especially regarding the use of paper and photocopiers. B1 is an office which deals with reports and hardbound student theses thus particles and dust from these documents may contribute to the high $PM_{2.5}$ concentrations. Other sampling buildings have similar characteristics regarding the office environment in that they are the offices mainly focusing on administrative work and having minimal visitors comparatively with the office B1, which has high footfall and deals with a large amount of paperwork. The existence of one or more indoor sources, such as smoking particles from a visitor who brings together fine particles as cigarette pollutants which tend to permeate clothing, can also contribute to a higher indoor $PM_{2.5}$ concentration. The main source of indoor $PM_{2.5}$ concentration in office was suggested to be smoking activity. The resuspension from visitor and occupants' movements as well as office equipment emissions in office where smoking is allowed, show that smoking is a main contributor to particulate matter (Saraga et al., 2011). Particle emissions in offices are also suggested to be influenced by the age of printers, print job parameters and room characteristics (Koivisto et al., 2010).

Higher O_3 concentrations were also recorded for B1 and B5 where the use of printers and photocopiers was suggested to contribute to O_3 concentrations. Both B1 and B5 were observed as having a high use of a photocopy machine, which also acts as a printer, while B5 had around 5–10 workers in the same room as a photocopier and printer. Moreover, the type of printer, regarding the type of cartridge and specific mechanism of the printer operation (temperature and electric power), were also found to play an important role in O_3 generation (Lee et al., 2001). Studies on ozone reactions with building materials and indoor furnishings found ozone deposition velocities the highest for drywall office surfaces (Rim et al., 2016) and gypsum wall board and paper facers in an office environment (Poppendieck et al., 2007).

3.2. Indoor-outdoor relationship and effect of building's age

The ratio of indoor to outdoor concentrations is usually used to briefly discuss the I/O relationship of air pollutants (Othman et al., 2016; Zhu et al., 2015). The I/O value > 1 indicates the source is predominantly from indoors while I/O < 1 indicates the pollutants mainly originate from outdoors. The indoor to outdoor relationship was also measured using the correlation coefficient (R^2) to specify the PM species measured indoors originating from outdoors (Zhu et al., 2015).

The indoor $PM_{2.5}$ concentrations were poorly correlated with outdoor (ambient) level while moderately correlation (R^2 = 0.60–0.80) observed for O_3 in all sampling locations. A higher R^2 value for $PM_{2.5}$ was observed for office building in China compared to this study where higher R^2 value was observed for heating season compared to non-heating season which the factor such as temperature, humidity, wind speed and atmospheric pressure play an important role of these R^2 value (Lv et al., 2019). The average I/O ratio ranged between 0.14 and 0.31 for the 24 h measurement while there was a range of 0.10–0.29 for the 9 h measurement of $PM_{2.5}$ (Fig. 1). Overall, a higher I/O value was observed for O_3 compared to $PM_{2.5}$ but with little difference between the I/O values measured for 24 h and 9 h. The range of the I/O ratio value for the 24 h measurement of O_3 was 0.09–0.37 while for the 9 h measurement it was 0.10–0.40. This I/O value clearly indicates that both $PM_{2.5}$ and O_3 concentrations had a minimum penetration from outdoors where indoor concentrations were predominantly driven by outdoor concentrations. A low I/O value suggests minimum penetration of outdoor pollutants into indoor areas where mechanical ventilation and closed windows reduce the degree of particle infiltration. This finding is consistent with previous studies by (Othman et al., 2016; Zhou et al., 2016). The use of mechanical ventilation in the office environment resulted in a smaller outdoor-air exchange which suggests

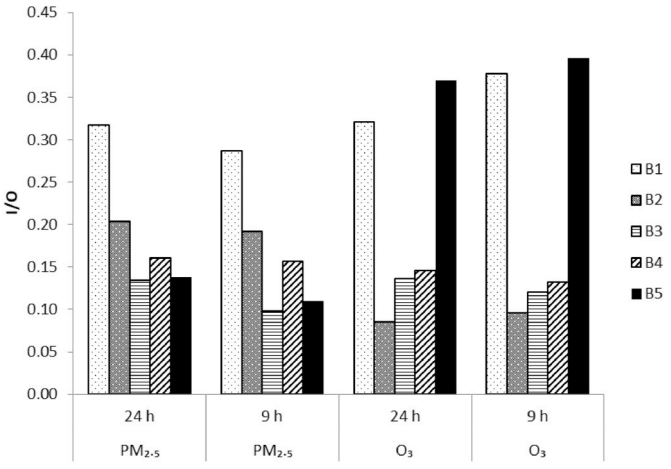

Fig. 1. Average I/O value for $PM_{2.5}$ and O_3 for 24 h and 9 h (working hours).

that the outdoors is the main source of indoor office particles with indoor office sources playing a minor role (Morawska et al., 2017). The highest average of I/O value was recorded by B1 for both 24 h and 9 h measurements of $PM_{2.5,}$ both of which were about twice as high as the other sampling buildings. For O_3, the highest I/O value was recorded by B5 followed by B1 for both 24 h and 9 h measurements. The characteristics of the sampling location can also affect the I/O value as the highest I/O value for $PM_{2.5}$ (recorded by B1) was suggested to be influenced by the main door which was located about 10 m from the sampling instrument, thus allowing the penetration of particles from outdoors. While for O_3, the highest I/O value was recorded by B5 which suggests that this sampling location was influenced by higher indoor contributing sources, such as office activities, compared to the other sampling buildings.

Detailed I/O ratios, based on hourly/diurnal concentrations of indoor and outdoor (ambient) $PM_{2.5}$ and $O_{3,}$ are presented in Fig. S2. For both B1 and B5, the highest I/O value for O_3 was observed during the afternoon at 18:00 (B1) and 16:00 (B5) while for $PM_{2.5}$, the I/O values recorded $<$ 0.4 for B1 and $<$ 0.3 for B5. An increase in I/O values was observed in the early morning for O_3 where a peak value was around 07:00 for all sampling buildings except for B4, which had the highest I/O value at approximately 05:00. This result could be due to a sudden increase in the outdoor O_3 concentration when the sun rises, which in Malaysia is around 07:00, can impact the outdoor O_3 concentration. In this study, O_3 more closely reflected outdoor concentrations which is shown by higher I/O values compared to $PM_{2.5}$. In contrast, a study by Terry et al. (2014) demonstrated $PM_{2.5}$ being more highly affected by the outdoors compared to $O_{3.}$ However, as the ratio value for I/O for both $PM_{2.5}$ and O_3 was still $<$ 1. $PM_{2.5,}$ it closely reflected to outdoor concentration because of lower deposition rates and an absence of chemical sinks where particles could be produced through chemical limonene degradation while O_3 had no chemical production rates without photolysis (Terry et al., 2014). A low I/O value in this study was also suggested to be influenced by the low penetration of outdoor sources where all sampling buildings applied mechanical ventilation system that reduced the outdoor origin of $PM_{2.5}$ and O_3. Studies by Martins and da Graca (2018) found that natural ventilation in office buildings increased cumulative indoor $PM_{2.5}$ exposure fourfold thus the use of electrostatics façade inflow natural ventilation filters was suggested as a way to reduce indoor $PM_{2.5}$ levels.

Comparing the age of the sample buildings, B1 which is a new building with a new type of ventilation system, had the highest I/O value for $PM_{2.5}$ and the second highest value for $O_{3,}$ which shows the age of the building and the new ventilation system may have affected the infiltration of both pollutants. It can be suggested that mechanical ventilation can minimise outside pollutants entering indoor environments where indoor activities are the main indoor source of $PM_{2.5}$ and O_3. Large and coarse particles can be reduced by up to 20% through the use of high efficiency filters in sealed air conditioned offices with low air infiltration rates due to the creation of an air tight building envelope (Fisk et al., 2000). Thus, a good air conditioning system with a building envelope that has a low infiltration of particles from outdoors can significantly reduce the particle concentration indoors. The use of an air filter with a high efficiency filter, coupled with adequate maintenance, may be the most effective and quickest solution to reducing indoor particulate (Azuma et al., 2018; Quang et al., 2013).

3.3. Diurnal $PM_{2.5}$ and O_3 concentrations in indoor offices

The average concentrations for $PM_{2.5}$ and O_3 during working hours and non-working hours are shown in Fig. 2. Non-working hours were observed to be higher compared to working hours for all the sampling buildings except for B4 for $PM_{2.5}$ concentrations. Both working hours and non-working hours for $PM_{2.5}$ concentrations were observed to be the highest for B1 while the lowest working hours and non-working hours concentrations were recorded for B3 and B4 respectively. This

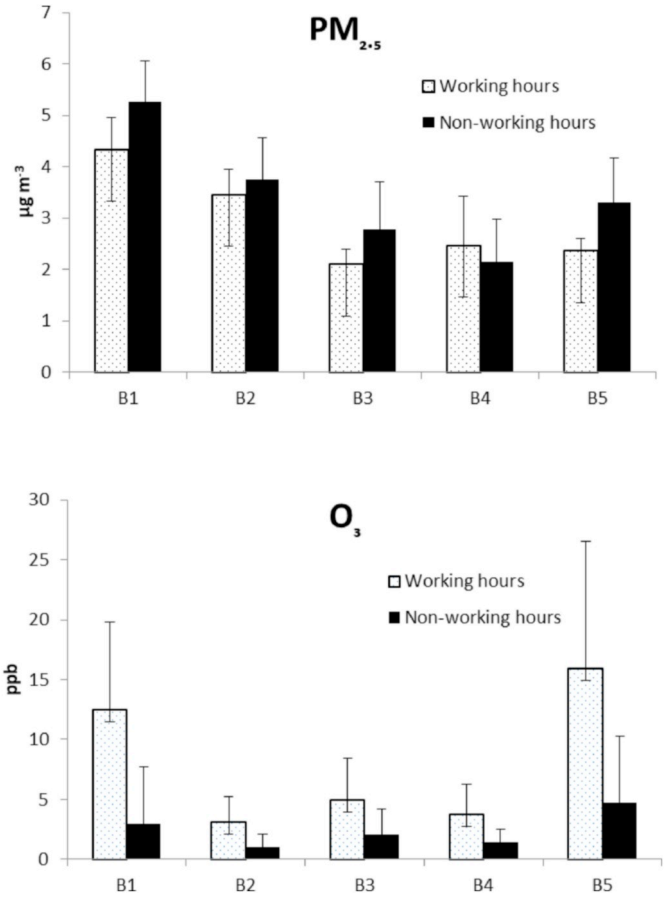

Fig. 2. Average $PM_{2.5}$ and O_3 concentrations during working hours and non-working hours.

result suggests the influence of other indoor sources, which need to be investigated, where activities such as the cleaning function of printers and minimal removal of indoor particle may contribute to higher concentrations during non-working hours. Similar result was recorded by Cheng (2017) where course and $PM_{2.5}$ particulate were suggested not to be efficiently removed through air supply device when mechanical ventilation system was switched off. Meanwhile, the O_3 concentrations during working hours was recorded as being 76%, 65%, 59%, 62% and 70% higher compared to non-working hours for B1, B2, B3, B4 and B5 respectively. B5 was recorded as having the highest O_3 concentrations both during working hours and non-working hours while B2 recorded the lowest. The result from one-way ANOVA confirms that there was significant differences (p $<$ 0.05) of O_3 concentration that monitored during non-working hours and working hours while no significant differences (p $>$ 0.05) was observed for $PM_{2.5}$. It was clear that the highest O_3 concentration was contributed by office activities where the higher working hours concentration were observed compared to non-working hours. The use of printers and a photocopier in the office increased the O_3 concentration due to emissions from this equipment while other office activities, such as cleaning, were also noted to increase the O_3 indoor concentration (Kagi et al., 2007; Terry et al., 2014).

The hourly indoor $PM_{2.5}$ and O_3 concentrations in each sampling building for 24 h measurements are presented in Fig. S3. Diurnal variations in indoor offices can provide useful information about the level and the effect of office activities' real exposure on office workers (Horemans and Van Grieken, 2010). The concentration range for $PM_{2.5}$ in B1, B2, B3, B4 and B5 was 3.1–6.8 µg m^{-3}, 2.0–5.1 µg m^{-3}, 1.2–4.2 µg m^{-3}, 0.4–7.1 µg m^{-3} and 1.6–5.0 µg m^{-3} respectively. There was no clear trend for $PM_{2.5}$ concentrations among the sampling

buildings. The peak $PM_{2.5}$ concentration was observed close to midnight for B1, while the highest/maximum concentration (6.8 μg m^{-3}) was recorded at 16:00 for B4. Moreover, B2, B3 and B5 both showed their highest peak between 04:00 and 06:00 in the morning. A definite explanation of this high concentration in the early morning is still vague but the only possible reason that this can be caused by this result would be due to the settling of $PM_{2.5}$ after office hours. Moreover, as reported by the workers at B2 and B3, printers tend to undertake some cleaning processes where some testing procedures are performed automatically. These may be the causes of the high concentration of $PM_{2.5}$ at certain hours early in the morning. Moreover, outdoor particles were suggested to settle in the office during working hours while minimal movement of office workers suggested a low indoor $PM_{2.5}$ concentration. As reported by Horemans and Van Grieken (2010), most particles have a tendency to settle during the night and have a higher indoor $PM_{2.5}$ and fine PM concentration if smoking is allowed in offices. A study by Ben-David and Waring (2018) on $PM_{2.5}$ concentrations in office buildings found that the ventilation rate was a strong factor in indoor environments and affected $PM_{2.5}$ concentrations, whereby highly efficient filtration could lead to a reduction in the indoor concentration.

No clear trend in $PM_{2.5}$ concentrations was observed during working hours as illustrated in Fig. S4. A single spike was observed at 16:00 for B4 which could be due to the use of office equipment, such as the photocopier which was the only machine used in this office compared to other sampling buildings which also had printers in the office. The trend of $PM_{2.5}$ concentrations observed in B1 clearly shows that the movement/activities in the office contribute to the $PM_{2.5}$ concentration where there is an increment of $PM_{2.5}$ concentrations around 08:00 due to the office working hours where workers started to enter the office. A peak in $PM_{2.5}$ concentrations was observed around 09:30 when workers may have been going out for meetings or to meet visitors. Another peak of concentration was observed at (16:00) which was due to printing and other office activities, as well as cleaning activities which were performed during working hours. A study by Terry et al. (2014) found the concentration of $PM_{2.5}$ notably increased when the air exchange rate was high which suggests that office workers could be significantly affected by exposure to potentially harmful by-products of cleaning.

However, a clear trend for O_3 concentrations was observed for all sampling buildings where the highest peak of concentration was recorded around 14:00–17:00 which significantly denotes a contribution from office activities (Fig. S3). Overall, B5 had the highest O_3 concentration (31.1 ppb) at 15:00 while for B1, the highest O_3 concentration was 21.5 ppb between 14:00 and 15:00 in the afternoon. Even the trend of O_3 concentrations looks similar between sampling buildings, but it clearly shows that the O_3 concentration only starts to increase after 10:00 in the morning and decrease after 17:00. Both B1 and B5 recorded an O_3 concentration of more than 15 ppb during the peak concentration while B2, B3 and B5 recorded one of less than 10 ppb during the peak concentration. A high concentration of O_3 in the afternoon suggests that the origin of O_3 emissions was from office equipment and the reason why certain indoor sampling buildings had a lower O_3 concentration was due to the particular brand of printer and photocopy machines used. The different printing methods employed by printers also influenced O_3 emissions where O_3 was generated as the by-product of the printing process of laser printers and photocopiers (Kagi et al., 2007).

A clear trend in O_3 concentrations was observed at all sampling buildings where it was observed that the highest O_3 concentration started to increase at 10:00 in the morning and steadily rose until 14:00 (Fig. S4). The trend of O_3 concentrations during office hours was clearly indicated with the highest O_3 concentration around 14:00 at B5 where O_3 recorded more than 30 ppb. All sampling buildings showed a decreasing O_3 concentration after 17:00 which suggests a reduction in office activities and emissions thus a low O_3 concentration correlates with the end of the working day.

Table 2
Hazard Quotient (HQ) and Cancer Risk (CR) in indoor and outdoor building.

	Indoor		Outdoor	
	$PM_{2.5}$	O_3	$PM_{2.5}$	O_3
Chronic exposure				
HQ				
B1	2.50E-02	2.80E-02	3.29E-03	8.72E-02
B2	1.86E-02	7.72E-03	3.80E-03	9.07E-02
B3	1.28E-02	1.33E-02	3.99E-03	9.76E-02
B4	1.17E-02	9.81E-03	3.05E-03	6.73E-02
B5	1.50E-02	4.12E-02	4.53E-03	1.12E-01
HI	8.32E-02	1.00E-01	1.87E-02	4.55E-01
CR				
B1	1.49E-04		4.71E-04	
B2	1.11E-04		5.44E-04	
B3	7.64E-05		5.70E-04	
B4	6.97E-05		4.36E-04	
B5	8.91E-05		6.47E-04	
Total	4.95E-04		2.67E-03	
Acute exposure				
HQ				
B1	9.75E-02	1.09E-01	3.08E-01	1.28E-01
B2	7.25E-02	3.01E-02	3.56E-01	1.48E-01
B3	5.00E-02	5.18E-02	3.73E-01	1.55E-01
B4	4.56E-02	3.82E-02	2.85E-01	1.19E-01
B5	5.83E-02	1.61E-01	4.23E-01	1.76E-01
HI	3.24E-01	3.90E-01	1.74 E+00	7.27E-01
CR				
B1	3.90E-02		1.23E-01	
B2	2.90E-02		1.42E-01	
B3	2.00E-02		1.49E-01	
B4	1.82E-02		1.14E-01	
B5	2.33E-02		1.69E-01	
Total	1.30E-01		6.98E-01	

3.4. Health risk assessment of $PM_{2.5}$ and O_3 exposure

3.4.1. Chronic exposure

The non-carcinogenic risk values calculated as HQ and carcinogenic risk values calculated as CR are listed in Table 2. A higher $PM_{2.5}$ HQ value was observed indoors compared to outdoors (ambient) for all sampling locations while the O_3 HQ value was observed to be higher outdoors in most of the sampling buildings compared to indoors. The total HQ value indicated by HI was recorded as 8.32E-02 (indoor) and 1.87E-02 (outdoor) for $PM_{2.5}$ and 1.00E-01 (indoor) and 4.55E-01 (outdoor) for O_3. The results for HQ and HI were lower than the acceptable limit of 1.0 indicating that there is no significant non-carcinogenic risk of $PM_{2.5}$ and O_3 exposure. HQ value was higher for O_3 compared to $PM_{2.5}$, therefore greater non-carcinogenic exposure is posed by O_3. Overall, there was a higher HQ value for all sampling buildings for indoor $PM_{2.5}$ compared to outdoor (ambient) but this reversed for O_3 where a higher outdoor value was observed compared to indoor. The highest non-carcinogenic risk of inhalation of $PM_{2.5}$ appeared to occur for B1 with a value of 2.50E-02 for indoors while for outdoors it occurred for B5 with a value of 4.53E-03. For O_3, the highest indoor HQ recorded was for B4 (9.81E-03) and the highest outdoor HQ recorded for B3 (9.76E-02). Thus, $PM_{2.5}$ and O_3 have negligible non-carcinogenic risks and do not pose a health threat to the workers in sampling building. The CR was only calculated for $PM_{2.5}$ due to the availability of the IUR value which equalled to 0.008 per μg m^{-3}. From the results in Table 2, B1 had the highest CR value indoors and B5 had the highest CR value outdoors. All sampling buildings recorded a CR value higher than the carcinogenic limit of 1.0E-06 but were still within the range 1.0E-04 to 1.0E-06 which indicates an intolerable range. The total CR value indoors was 4.95E-04 and for outdoors was 2.67E-03 which suggests a higher carcinogenic risk outdoors compared to indoors.

A higher HQ value for B1 was suggested to be due to a higher indoor $PM_{2.5}$ concentration resulting from office activities while a higher HQ

for the outdoor concentration could be due to the influence of strong outdoor sources during the sampling campaign. Moreover, this study only measured non-carcinogenic and carcinogenic risks based on atmospheric exposure while previous studied measured the impact of metal exposure on humans (Ali et al., 2017; Kurt-Karakus, 2012; Othman et al., 2016, 2018; Taner et al., 2013). Studies by Morakinyo et al. (2017) had a HQ value of 2.25E+03 for PM_{10} and 9.0E-03 for O_3 under normal chronic exposure where HQ > 1 for infants, children and adults was suggested to pose a risk of developing health-related exposure to coarse particulate. The non-carcinogenic risk for adults in an office environment had a HI of 1.05E-02 and a total carcinogenic risk of 2.48E-09 which indicated no adverse effects relating to human exposure to metals in coarse particulate in the office environment (Iwegbue et al., 2018). Kim et al. (2018) performed a health risk assessment for $PM_{2.5}$ in apartment and had a higher value for carcinogenic risk in the kitchen compared to the living room with a tolerable carcinogenic risk determined.

3.4.2. Acute exposure

In this study, acute exposure was also calculated where acute exposure was defined as that lasting for 24 h (USEPA, 2009). For acute exposure, a 24 h concentration of $PM_{2.5}$ and O_3 was taken for the indoor and outdoor (ambient) environments. No duration time was used for calculations. From the results, a higher HI value, with a definitely higher non-carcinogenic risk, was observed for outdoors compared to indoors (Table 2). The HI value for indoor $PM_{2.5}$ was 3.24E-01 and for outdoor 1.74E+00. For O_3, the HI value was recorded as 3.90E-01 (indoor) and 7.27E-01 (outdoor). All sampling buildings had a HQ value < 1 indicating a very low exposure to non-carcinogenic risks during 24 h exposure to these atmospheric pollutants. The highest HQ value was recorded by B1 for indoor and B5 for outdoor (ambient) $PM_{2.5}$ while B5 also recorded the highest HQ for O_3 indoor and outdoor. The total CR value for acute $PM_{2.5}$ exposure was recorded as 1.30E-01 for indoor and 6.98E-01 for outdoor which show a higher carcinogenic risk outdoors compared to indoors. This result shows that there was a carcinogenic risk for $PM_{2.5}$ exposure in all sampling buildings where the CR value was < 1.0E-04. There were also minimal differences in the value for CR in all the sampling buildings which shows that the office environment had a similar carcinogenic exposure.

Lower HQ and CR values indoors compared to outdoors was due to lower indoor $PM_{2.5}$ concentrations compared to outdoors ones while for O_3, certain sampling buildings had a higher HQ value indoors compared to outdoors for the 24 h concentration. A study by Morakinyo et al. (2017), noted adults experienced acute exposure with a value of 2.2E-02 which was lower than for this study where other exposure groups, such as infants and children, had a much lower HQ value due to a lower ambient concentration. Othman et al. (2016) stated that indoor office workers can be significantly affected by environmental pollutants, such as motor vehicle and industrial emissions, depending on the location of their office.

3.5. Dosimetry analysis of $PM_{2.5}$ deposition in the human respiratory tract

Particle deposition in the respiratory tract of office workers in indoor and outdoor (ambient) scenarios was determined using the MPPD model, particularly for $PM_{2.5}$ (Fig. 3). A higher total deposition fraction was determined for the indoor scenario compared to the outdoor (ambient) one with values of 0.6313 and 0.5487 respectively. For the indoor scenario, the highest deposition fraction was for the head (0.2982) followed by the lungs, which is specifically known as pulmonary, (0.2309) and the trachea and bronchi (0.1021). The same sequence of deposition fractions was observed for the outdoors scenario with values of 0.294, 0.1794 and 0.0753 respectively. Both scenarios had different body orientations and breathing frequencies. Indoor scenarios were related to office activities where office workers tended to sit and have normal breathing frequencies whereas outdoor scenarios were

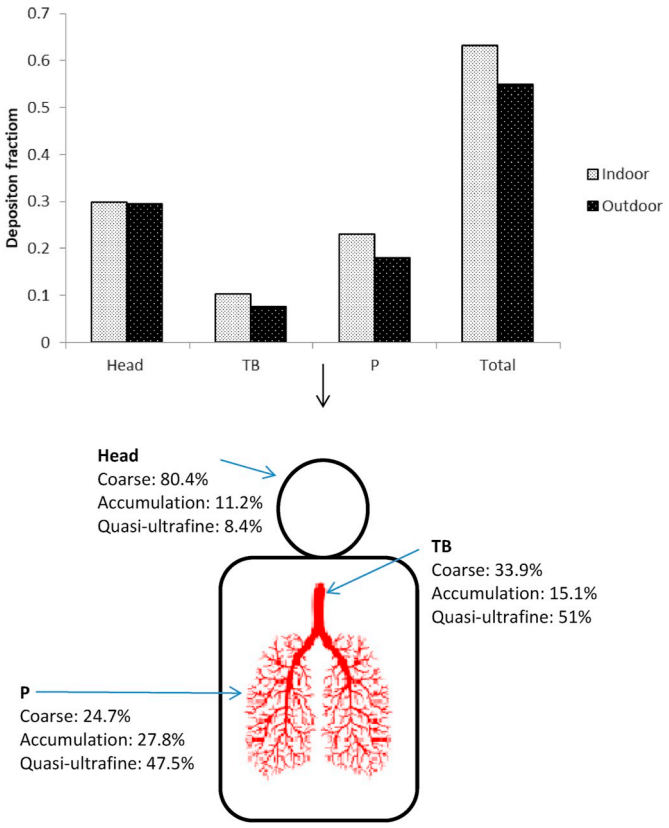

Fig. 3. Deposition fraction of $PM_{2.5}$ in indoor and outdoor scenarios; and percentage of coarse, accumulation and quasi-ultrafine particle in head, TB (tracheobronchial tract) and P (pulmonary region) in human body.

modelled on an upright body orientation and higher breathing frequency. As reported by Othman et al. (2019), a higher deposition fraction in certain scenarios was due to a higher aerosol concentration and also body orientation. Moreover, the head airway region appeared to be the most vulnerable part of the body and was highly exposed to harmful particle compositions. A study in Singapore by Betha et al. (2014), found that the highest level of metals in the head region was observed for Ca with a dominance presence of metals during haze periods compared to non-haze periods. A large proportion of $PM_{2.5}$ that was deposited in the head airways region related to the combination of sedimentation and the impact of particles on the larynx and airway bifurcations (Betha et al., 2014; Zhang and Yu, 1993). Othman et al. (2018) found that the deposition fraction for indoor office PM_{10} was dominant in the head airways region, which produced a higher value for nasal and mouth breathing compared to nasal-only breathing.

The deposition fraction for particulates in the human respiratory system was also integrated within three particle size bins which were coarse (< 10 μm), fine (0.18–2.5 μm) and quasi-ultrafine (< 0.18 μm) as follows Guo et al., 2019b. The results for this multiple particle size range can determine the deposition of each particle size in the human respiratory tract for indoor office workers. The deposition fraction of size-segregated PM in all regions varied where coarse particles were highly deposited in the head region (80.4%), followed by fine size particles (11.2%) and quasi-ultrafine size particles (8.4%). For the TB airway region, the highest deposition fraction was observed for quasi-ultrafine particles (51%) followed by coarse particles (33.9%) and fine size particles (15.1%). The same applied to the P airway region where the highest deposition fraction was observed for quasi-ultrafine particles (47.5%) while this was followed by fine size particles (27.8%) and coarse particles (24.7%). A similar deposition fraction of coarse particulate, which was predominantly deposited in the head, was consistent

with previous studies (Betha et al., 2014; Guo et al., 2019b; Manojkumar et al., 2019).

4. Conclusion

The results from indoor office monitoring of $PM_{2.5}$ and O_3 show an average concentration of 3.24 ± 0.82 μg m^{-3} and 4.75 ± 4.52 ppb respectively for the 24 h averaging time. For working hours with a 9 h measurement, the average indoor $PM_{2.5}$ concentration was 2.94 ± 0.53 μg m^{-3} and average O_3 concentration 8.03 ± 5.23 ppb. All indoor and outdoor $PM_{2.5}$ and O_3 concentrations recorded at all sampling buildings were found to be below the WHO threshold value; the National Ambient Air Quality Standards by USEPA and the New Malaysia Ambient Air Quality Standard for the $PM_{2.5}$ Interim Target (IT-2) for 2018. A higher O_3 concentration during working hours is considered to be influenced by the emissions from printer and photocopying machines. For the office workers, health risk assessment for $PM_{2.5}$ and O_3 exposure, there were no significant non-carcinogenic risks for either pollutant (HQ < 1). The CR value was determined as being within a tolerable range for chronic exposure while a significant cancer risk (CR < 1.0E-04) posed by $PM_{2.5}$ was observed for acute exposure for both the indoor and outdoor (ambient) environments. Reducing $PM_{2.5}$ and O_3 in office were suggested with an alternative of printing room where all printing and photocopy activities were done to reduced air pollutant exposure of this appliance to the office workers. Furthermore, detailed studies on office environment's source of pollutant, ventilation system, office activities and health exposure need to be performed to maintain or improve the indoor air quality in office building.

CRediT authorship contribution statement

Murnira Othman: Conceptualization, Data curation, Formal analysis. **Mohd Talib Latif:** Writing - review & editing. **Chong Zin Yee:** Writing - original draft. **Lina Khalida Norshariffudin:** Investigation. **Azliyana Azhari:** Data curation. **Nor Diana Abdul Halim:** Visualization. **Azwani Alias:** Investigation. **Nurzawani Md Sofwan:** Methodology. **Haris Hafizal Abd Hamid:** Investigation. **Yutaka Matsumi:** Resources.

Declaration of competing interests

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

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Appendix A. Supplementary data

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