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Indoor air pollutant exposure and determinant factors controlling household air quality for elderly people in Hong Kong

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Abstract

This study investigated the levels and determinant factors of indoor air pollutants including fine particles ($PM_{2.5}$), nitrogen dioxide (NO_2), and formaldehyde (HCHO) in 55 households exclusively for the elderly in Hong Kong during summer and winter (Jul.–Sep. 2016 and Nov. 2016–Mar. 2017). The average concentrations of $PM_{2.5}$, NO_2, and formaldehyde were 25.3 ± 15.0, 40.5 ± 16.0, and 26.1 ± 22.8 μg/m^3 in summer and 34.2 ± 19.0, 43.5 ± 17.0, and 15.4 ± 4.5 μg/m^3 in winter, respectively. There were ~ 50.3% of households exceeding the World Health Organization indoor air quality standard for $PM_{2.5}$ throughout the study, with ~ 40.6 and ~61.0% of the households in summer and winter, respectively. The determinant factors for indoor $PM_{2.5}$ and NO_2 concentrations were identified as from incense burning and cooking. Cooking with suitable ventilation is an important factor to ease indoor pollutant concentrations. Both of $PM_{2.5}$ and NO_2 indoor concentrations showed good correlations with outdoor concentrations. Winter was observed with higher pollutant concentrations than summer except for formaldehyde concentrations. Major factors controlling indoor formaldehyde concentrations are temperature and humidity. The outcome will be useful for the development of future indoor air quality guidelines for Hong Kong.

Keywords Household air pollutant · Nitrogen dioxide · Fine particulate matter · Formaldehyde · Hong Kong

Introduction

People in urban areas spend majority of their time in various indoor environments. The dwellings are considered to be a dominant micro-indoor environment (Langer et al. 2016). Indoor air quality is closely related to human health outcome and tends to be overlooked by household residents (Rohra and Taneja 2016). According to the Global Burden of Disease Report (Global Burden of Disease Report 2015), household air pollution was ranked the third leading cause of disability-adjusted life years (DALYs) worldwide, suggesting an urgent need to control indoor air quality (Apte and Salvi 2016).

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Particulate matter (PM) is a complex mixture of small liquid droplets and solid particles suspended in the atmosphere. PM consists of various morphologies and chemical constituents that can cause adverse health effects to humans (US EPA 2017a). Previous studies showed the concentrations of fine PM (aerodynamic diameter ≤ 2.5 μm: $PM_{2.5}$) were higher indoors than outdoors due to $PM_{2.5}$ generation in the indoor environment (Wallace 1996; Chao et al. 1998; Jones et al. 2000; Lee et al. 2002; World Health Organization (WHO) 2010; Karakas et al. 2013). The major indoor sources of PM include environmental tobacco smoke (ETS), cooking, fuel combustion for household heating, and incense burning. Formaldehyde can be generated from various indoor combustion processes (IARC 2006; Salthammer et al. 2010). Building materials and consumer products are the major sources for formaldehyde commonly found in non-smoking households under high relative humidity (RH) and temperature (Haghighat and De Bellis 1998; Kelly et al. 1999; World Health Organization (WHO) 2009; Salthammer et al. 2010). Formaldehyde is classified as a carcinogen by the International Agency for Research on Cancer (IARC 2006) (WHO guidelines 2010), and exposure to formaldehyde can cause various short- and long-term adverse health effects (US EPA 2017b). Indoor exposure to formaldehyde is regarded as a dominant contributing pathway to personal exposures via inhalation (WHO guidelines 2010). Nitrogen dioxide (NO_2) is a primary pollutant emitted from combustion processes (WHO guidelines 2010). A previous study showed the average level of NO_2 in homes without combustion appliances was ~ 50% of the outdoor concentration level, whereas in homes with combustion appliances (e.g., gas stoves), the indoor NO_2 levels exceeded outdoor levels (US EPA 2017c). Prolonged exposure to high NO_2 levels can contribute to the development of bronchitis (US EPA 2017c; WHO guidelines 2010).

Building characteristics can be influenced by seasonal factors and further cause variation of air pollutant concentrations. Several indoor gaseous and particulate pollutants can be estimated by occupants' indoor activities and corresponding outdoor concentration levels (Langer et al. 2016). Raw et al. (2004) conducted a survey on indoor air quality in 876 homes in England and showed that concentrations of formaldehyde were higher in new apartments than in occupied households, and the NO_2 concentrations were correlated to the uses of cooking fuel gases. Cooking can lead to an increase of particles and NO_2 concentrations. Outdoor air was the major source of residential indoor pollution in Switzerland (Meier et al. 2015). Azuma et al. (2016) identified aldehydes and NO_2 as the two major types of pollutants in Japanese dwellings during winter and summer.

Hong Kong is under a subtropical climate with high average temperature and RH, and the meteorological conditions favor air pollutant accumulation (WHO guidelines, 2009; Hong Kong Observatory 2017; Hong Kong Census and Statistics Department 2016a). The city is characterized by a dense population and high-rise buildings surrounded by heavy traffic roads, which can cause small per capita living space and high rates of indoor pollutant dispersion, and they are all closely related to indoor air quality (Guo et al. 2009). There are recently over 1.1 million people above 65 years of age accounting for 15% of the total population of Hong Kong (Hong Kong Census and Statistics Department 2016b). Elderly people spend most of their time (> 80%) at home (Karottki et al. 2013). This group of people is particularly vulnerable to indoor air pollution (Tunsaringkarn et al. 2015).

There is currently a lack of studies to investigate determinant factors controlling indoor air quality for domestic households specifically for the elderly in Hong Kong. The aims of this study are to investigate indoor air quality of elderly households in Hong Kong and to further identify sources of air pollutants (PM, formaldehyde, and NO_2).

Materials and method

Selection of subjects

Subjects were selected from Mr. and Ms. Os (Hong Kong) Cohort Study. Four thousand community-dwelling residents (2000 men and 2000 women) (≥ 65 years of age) were recruited for baseline (2001–2003) assessment in Hong Kong (Wang et al. 2013). The year 2017 was the fourth follow-up year for this cohort study. Fifty-five households were randomly selected from the follow-up of the cohort study in order to further participate in this indoor air monitoring study. Among the selected households, 47 were monitored twice (summer and winter), but unfortunately, 8 households withdrew in winter after the entire monitoring period. The summer session started from 4 July 2016 to 29 September 2016, and the winter session started from 14 November 2016 to 6 March 2017. Hong Kong is classified into three territories including New Territories, Kowloon, and Hong Kong Island (The map of Hong Kong can be found at https://en.wikipedia.org/wiki/Districts_of_Hong_Kong#/media/File:Map_of_Hong_Kong_18_Districts_en.svg). The population distribution was ~ 52.6% inhabitants residing in New Territories, ~ 30.2% in Kowloon, and ~ 17.2% in Hong Kong Island (Hong Kong Census and Statistics Department 2016c). According to the Hong Kong Housing Authority (2016), the main types of Hong Kong households are classified as "Public Rental Houses," "The Ownership Scheme Houses," "Private Houses," and "Others." The distribution and characteristics of the sampling households are shown in Fig. 1 and Table S1, respectively.

Sampling

Indoor air pollutants such as $PM_{2.5}$, NO_2, and formaldehyde were measured in this study two times (summer and

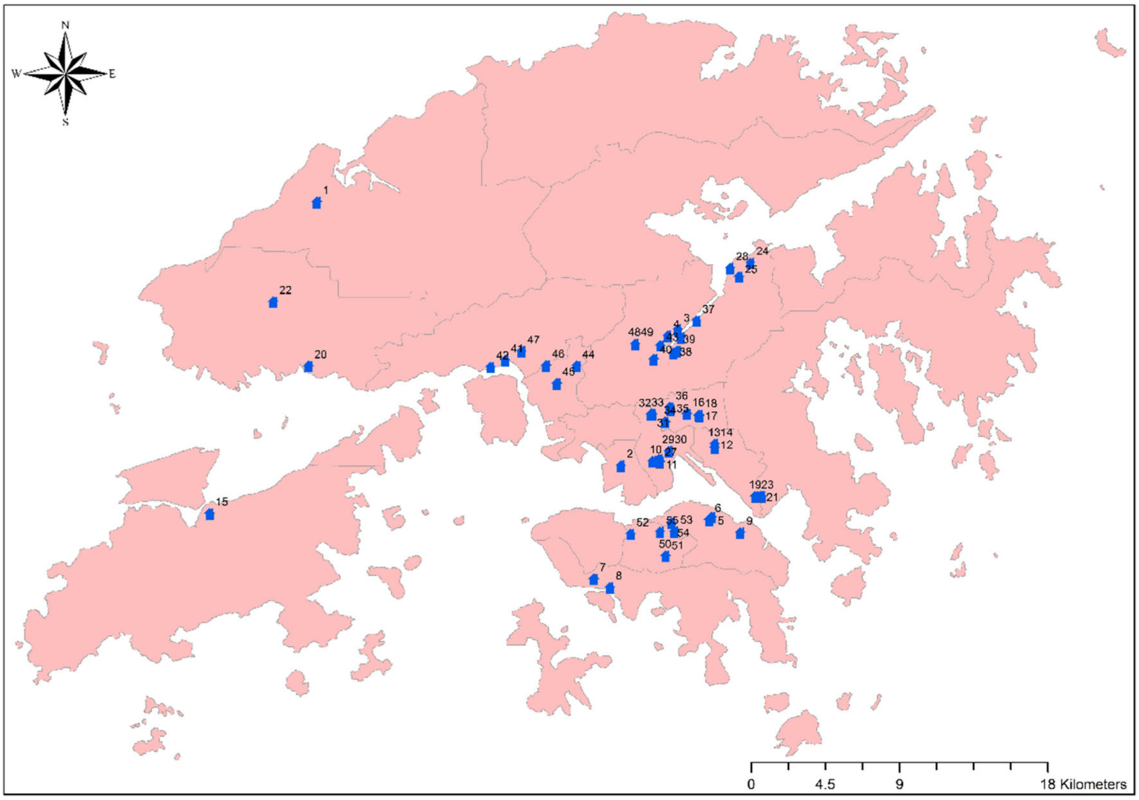

Fig. 1 Map showing sampling households in the campaign

winter) for each household. The sampling duration was assigned for three consecutive sampling days (72 h) in each household to ensure the collected integrated samples (NO_2 and formaldehyde) were above detection limits. All sampling equipment was positioned 1 m above the ground in the household's living room (or similar position if no living room was present). This act was to simulate the height of the breathing zone of inhabitants in the sitting position and to avoid potential interferences from particle re-suspension. All households were asked to follow their usual daily routine during the sampling period in order to ensure representative sampling.

$PM_{2.5}$ was monitored by TSI DustTrak™ Aerosol Monitor (DRX 8533/8534) with 1-min time resolution. Temperature and RH were monitored simultaneously, and data quality was assured by a collocated portable PM sensor. Indoor NO_2 samples were collected using NO_2 diffusion tubes (Gradko International) according to standard procedures (UK Nitrogen Dioxide Diffusion Tube Network Instruction Manual) and the manufacturer's recommendations. Indoor formaldehyde samples were collected in silica cartridges impregnated with acidified 2,4-dinitrophenylhydrazine (Sep-Pak DNPH XpoSure, Waters Corporation, Milford, MA). The detailed sampling method can be found in S2 (sampling method).

Quality control

Relative humidity calibration

The influences of RH can result in significant reading artifacts in light-scattering laser photometer-based aerosol monitors (DustTrak™ Aerosol Monitor) (Day and Malm 2001; Chakrabarti et al. 2004; Wallace et al. 2011; Shi et al. 2016). Equation 1 (Pope et al. 1995; Shi et al. 2016) was used to minimize any errors induced by RH.

$$\text{correction factor} = 1 + 0.25\frac{\mathrm{RH}^2}{(1-\mathrm{RH})} \qquad (1)$$

Calibration of DustTrak™ and portable sensor with filter-based samplers

The equipment was calibrated on a 2-week interval. The temperature and RH of the portable sensor were calibrated with a data logger (HOBO U23 Pro v2). DustTrak™ was calibrated along with filter-based samplers and a personal environmental monitor, together with personal-size air sampling pumps (SKC Ltd.) and a MiniVol portable air sampler (AIR METRICS™) after RH correction. The adjustment factor for the DustTrak™ aerosol monitor was in a range of 0.45–0.53 compared to the filter-based results. The monitored results were multiplied by both the humidity correction factor and filter-based adjustment factor to give the final results.

Calibration of passive samplers

The uptake rate of passive Sep-Pak DNPH XpoSure can be referred to previous studies (Guo et al. 2009; Mullen et al. 2013; Shinohara et al. 2004). The storage requirement and application of passive samplers were strictly in compliance with the sampler's guideline. The passive uptake rate for this study was set as 1.48 ml/min according to a relevant study (Shinohara et al. 2004), and this uptake rate was verified by the active sampling method (Sep-Pak DNPH-Silica cartridges, Waters Corporation, Milford, MA) at four locations for 72 h. The passive and active methods showed good linearity ($R^2 \sim 0.93$) between the formaldehyde collection.

Questionnaire

During the sampling period, each participant was asked to report an indoor activities' diary, stating any possible sources related to the indoor air pollutants (e.g., ventilation method and frequency, types of cooking fuel, smoking, incense burning, household cleaning method, etc.). Details of the questionnaire can be referred to the Supplementary Material. The household information (Raw et al. 2004; Meier et al. 2015; Baxter et al. 2007) such as age of the building, latest renovation period, size of the residential floor area, and number of occupants was recorded before the sampling period.

Statistical analysis

The statistical analysis was conducted by SPSS statistic 21.0 (IBM®, New York, NY) and Microsoft Office Excel 2010 (Microsoft Inc.). A p value of 0.05 was selected for the statistical analysis. The non-parametric Kolmogorov-Smirnov normal test was used to investigate the distribution of the air pollutant concentrations. Mann-Whitney U test, Kruskal-Wallis test, and Dunn test were used for samples not normally distributed. An independent T test was used for samples under normal distribution. Spearman's rho correlation analysis was used to test the relationships between indoor and outdoor air pollutant concentrations. The multivariable linear regression with stepwise regression method (a description of this regression model can be found in S2) was used to investigate the major sources of the air pollutants. Missing data was replaced by the mean of according variables.

Results and discussion

Concentrations of indoor air pollutants

The average concentrations of pollutants are shown in Table 1 and Fig. 2. The 72-h average concentrations of $PM_{2.5}$, NO_2, and formaldehyde with diffusion methods were 25.25 ± 14.99, 40.51 ± 15.96, and 26.10 ± 22.80 μg/m^3 in summer and 34.24 ± 18.98, 43.46 ± 17.02, and 15.36 ± 4.53 μg/m^3 in winter, respectively. The 24-h average concentrations of $PM_{2.5}$ were 25.31 ± 18.82 μg/m^3 in summer and 35.01 ± 23.42 μg/m^3 in winter (Table 1). The large seasonal concentration variations could be due to contribution from different indoor pollution sources. The diurnal change in $PM_{2.5}$ is shown in Fig. S1. The pattern is consistent with that of other studies, demonstrating that the indoor $PM_{2.5}$ could be potentially influenced by subjects' activities, especially by residential cooking (Lai et al. 2006; Lanki et al. 2007; Baxter et al. 2007; Meng et al. 2009). The concentration of $PM_{2.5}$ was shown to increase when inhabitants were more frequently involved in indoor activities (e.g., cooking and having dinner), and the concentration was shown to decrease at night when inhabitants were inactive. Over 50% of the 24-h indoor average concentrations of $PM_{2.5}$ exceed the threshold limit established by the World Health Organization (WHO) (World Health Organization (WHO), Regional Office for Europe 2006, 2010), with ~40.6 and ~61.0% of the households in summer and winter, respectively. The NO_2 concentrations are in accordance with other findings in Asia but higher than the values obtained in Europe (World Health Organization (WHO) 2009; Kotzias et al. 2005). The high indoor NO_2 concentrations could be attributed to the varieties of cooking methods, occurrences of incense burning, and partial air exchange from outdoors at high NO_2 levels. Besides, the formaldehyde concentrations were lower than the values reported in other studies conducted in Asia with the same methodology (Guo et al. 2009). This finding can be potentially due to longer exposure time, variations in ventilation (e.g., windows were open during the sampling period), and lack of potential formaldehyde sources, such as fragrances and consumer products (Steinemann 2016), in targeted elderly residents compared to other age groups.

Relationships between indoor and outdoor concentrations

The results of this study imply the importance between outdoor and indoor pollutant concentrations. The outdoor concentrations of air pollutants (i.e., $PM_{2.5}$ and NO_2) were obtained from air monitoring stations administered by the Hong Kong Environment Protection Department (HKEPD) in proximity to the respective household locations. Formaldehyde was unfortunately not a routinely monitored air pollutant as

Table 1 Concentration of indoor pollutants

		Mean ($\mu g/m^3$)	S.D.	IQR ($\mu g/m^3$)	Mean ($\mu g/m^3$)	S.D.	IQR ($\mu g/m^3$)
		Summer ($N = 55$)			Winter ($N = 47$)		
72-h average	$PM_{2.5}$	25.3	15.0	15.4	34.2	19.0	23.0
	NO_2	40.5	16.0	25.4	43.5	17.0	21.6
	Formaldehyde	26.1	22.8	11.3	15.4	4.5	4.3
		Summer ($N = 165$)			Winter ($N = 141$)		
24-h average	$PM_{2.5}$	25.3	18.8	19.5	35.0	22.4	23.4

S.D. standard deviation, *IQR* interquartile range, *$PM_{2.5}$* particulate matter with aerodynamic diameter < 2.5 μm, *NO_2* nitrogen dioxide

defined by the HKEPD during the sampling period. The correlation coefficients (Table 2) indicate that indoor $PM_{2.5}$ showed significantly positive correlations with outdoor $PM_{2.5}$ in summer ($p < 0.01$) and winter ($p < 0.01$). However, the indoor NO_2 only showed significant positive correlations with outdoor NO_2 in summer ($p < 0.01$), but not in winter ($p = 0.37$). This observation is consistent with the absence of seasonal variation for the indoor NO_2 concentrations. NO_2 can be produced by combustion processes related to traffic emissions. In addition, indoor NO_2 could possibly be influenced by outdoor NO_2 concentrations. We supposed that households near roadsides would have a higher indoor NO_2 concentration than other households (Kimbrough et al. 2013). In this study, three sampling households were located near the roadsides at the districts of Causeway Bay (22° 16′ N, 114° 11′ E), Quarry Bay (22° 17′ N, 114° 13′ E), and Wan Chai (22° 17′ N, 114° 10′ E), respectively, where the downtown business areas are with extremely high daily traffic densities. The average indoor NO_2 concentrations for these roadside households were in a range of 61.84–82.16 $\mu g/m^3$ in summer and 51.96–82.59 $\mu g/m^3$ in winter (the NO_2 concentration at Wan Chai in winter is absent because the participant withdrew for this sampling season), which all exceeded the values obtained in other sampled households. The results indicated that the NO_2 concentration levels at the roadside households can be strongly impacted by the outdoor environment.

Seasonal and spatial variations of indoor air pollutant concentrations

Mann-Whitney *U* test was used to examine seasonal variation of the indoor air pollutant concentrations. Indoor $PM_{2.5}$ ($p < 0.05$) and formaldehyde ($p < 0.001$) showed significant seasonal changes but not NO_2. In Hong Kong, higher pollutant concentrations are usually observed in winter due to meteorological conditions (Hong Kong Environmental Protection Department 2014, 2015). According to the above results ("Relationships between indoor and outdoor concentrations"),

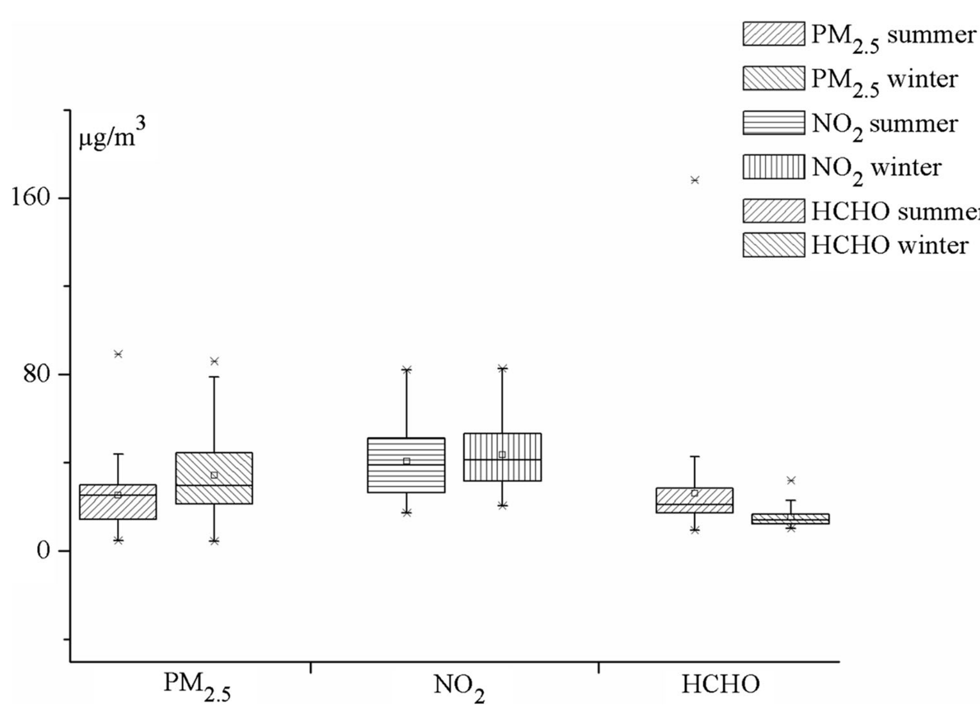

Fig. 2 Boxplot showing 72-h average concentrations of indoor pollutants

Table 2 Spearman's rho correlation coefficients of indoor and outdoor pollutant concentrations in summer and winter

Spearman's rho correlation coefficient	$PM_{2.5}$		$EPDPM_{2.5}$		NO_2		$EPDNO_2$	
	S	W	S	W	S	W	S	W
$PM_{2.5}$	1.00	1.00	.75**	.70**	.36**	.26	.61**	.67**
$EPDPM_{2.5}$	.75**	.70**	1.00	1.00	.31*	.25	.72**	.78**
NO_2	.36**	.26	.31*	.25	1.00	1.00	.42**	.37
$EPDNO_2$	.61**	.67**	.72**	.78**	.42**	.37	1.00	1.00

S summer, *W* winter, *$EPDPM_{2.5}$* concentration of $PM_{2.5}$ from the EPD station, *$EPDNO_2$* concentration of NO_2 from the EPD station

*Correlation is significant at the 0.05 level (two tailed); **correlation is significant at the 0.01 level (two tailed)

indoor $PM_{2.5}$ levels were strongly correlated to outdoor levels. Therefore, the seasonal variation of the indoor $PM_{2.5}$ level can be explained by these ambient $PM_{2.5}$ concentration changes. The higher concentrations of formaldehyde in summer were possibly due to higher indoor source emissions. Previous studies showed that building materials and consumer products were the major sources of formaldehyde in non-smoking households under high temperature and RH (Kelly et al. 1999; Haghighat and De Bellis 1998; World Health Organization (WHO) 2009; Salthammer et al. 2010). In this study, the major sources of residential formaldehyde were released from the household materials, such as wooden furniture and adhesive wallpaper. This source information can be referred to the questionnaires (i.e., question 22 in Supplementary Material). Such emissions are highly sensitive to variation of temperature and RH changes. However, no seasonal variation of the NO_2 level was observed; this could be attributed to more significant indoor than outdoor emissions.

The population distribution showed ~ 52.6% of inhabitants resided in New Territories, ~ 30.2% in Kowloon, and ~ 17.2% in Hong Kong Island (Hong Kong Census and Statistics Department 2016c). The spatial and seasonal distributions of indoor air pollutants were investigated, and the results are shown in Fig. 3a–c. Seasonal variation of $PM_{2.5}$ was observed in New Territories ($p = 0.001$), and spatial variation was further observed between New Territories and Kowloon ($p = 0.014$) in summer. Formaldehyde was observed with significant seasonal variations in New Territories ($p < 0.001$) and Kowloon ($p < 0.001$), but no spatial variation was identified in both seasons. Neither seasonal nor spatial variation was observed for NO_2, which is consistent with our previous findings. To compare with outdoor concentrations, spatial differences were found for both ambient $PM_{2.5}$ and NO_2 in summer, but not in winter. The inconsistent indoor and outdoor spatial variations confirmed the strong impacts of indoor pollution sources to their levels. No statistical spatial variation could be obtained due to uneven distributions of sampling households. In addition, no distinct differences of the indoor sources were observed for the three targeted pollutants (especially for formaldehyde) at different districts.

Multivariable analysis

Due to the small sample size of the NO_2 and formaldehyde dataset, multivariable regression analysis with stepwise method was applied for prediction of $PM_{2.5}$ only. The independent variables were assigned as season; average living area of residents; average temperature and RH during the sampling period; frequency of window opening/use of air-conditioners; cleaning methods (i.e., sweep, swipe, or vacuum cleaner); types of cooking fuels (i.e., Towngas, liquified petroleum gas (LPG), electronic or induction cooker); and mechanical ventilation during cooking, smoking, and incense burning, the sampling data of which were all obtained from the questionnaires in the Supplementary Material section. The ambient concentrations of $PM_{2.5}$ collected from the respective HKEPD stations were also considered as an independent variable. Window opening and use of air-conditioners, temperature and ambient $PM_{2.5}$ concentrations, and RH and ambient $PM_{2.5}$ concentrations were considered as interaction factors. The significance values (Table 3) confirm that the linear relationships are statistically reliable. The results indicate that outdoor $PM_{2.5}$ levels ($p < 0.001$), incense burning ($p < 0.001$), cooking by gas (Towngas) ($p < 0.001$), cooking by induction cooker ($p < 0.001$), and sweep cleaning ($p < 0.001$) can possibly enhance indoor $PM_{2.5}$ concentrations, whereas window opening ($p < 0.001$) and ventilation during cooking ($p < 0.001$) can potentially reduce the concentration levels of the pollutants (Table 3). These findings are consistent with those of other studies (Shinohara et al. 2004; Baxter et al. 2007; Lai et al. 2006). The concentrations of NO_2 and formaldehyde were comparable with those of different sources according to previous studies (World Health Organization (WHO) 2010; Karakas et al. 2013; US EPA 2017c). In this study, NO_2 was only focused on correlations between different types of cooking fuel and the frequency of incense burning; source information about sampling households is shown in Table S2. The results in Fig. S2 illustrate cooking activities with the use of gas fuels (i.e., Towngas or LPG). The figure shows gas fuels can induce higher indoor NO_2 concentrations

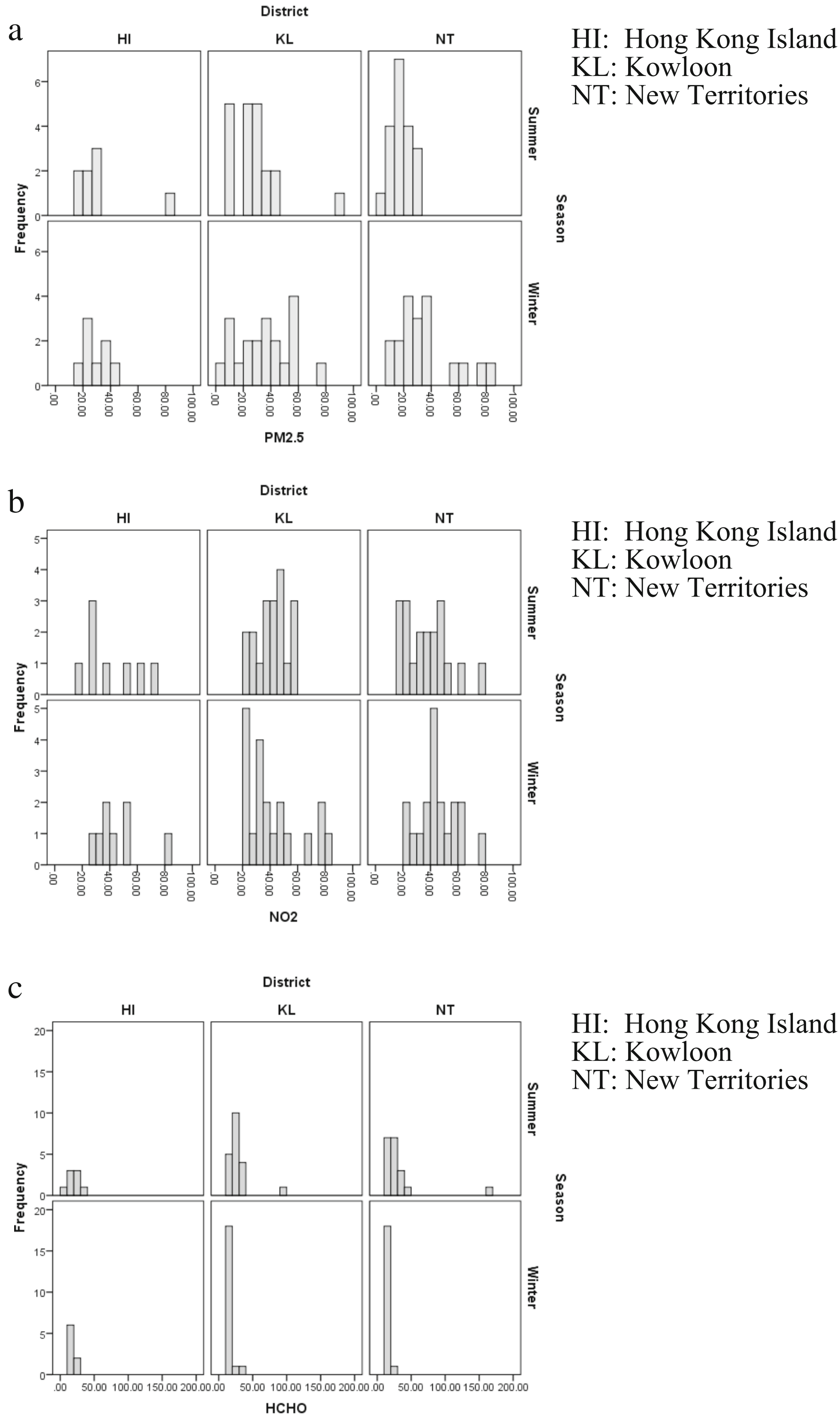

Fig. 3 Spatial and seasonal distributions of **a** $PM_{2.5}$ concentrations, **b** NO_2 concentrations, and **c** formaldehyde concentrations

compared to other cooking fuels/methods. The households which performed incense burning demonstrated higher indoor NO_2 concentrations in summer, but not in winter. Unfortunately, we cannot give a reasonable explanation for this result. A further

Table 3 Coefficient values of indoor sources in stepwise multilinear regression

Model	Unstandardized coefficients		t	Sig.
	B	Std. error		
(Constant)	114.2699	16.0148	7.14	< 0.0001
Season	− 7.3999	3.4492	− 2.15	0.0327
Temperature	− 2.4565	0.4836	− 5.08	< 0.0001
RH	− 0.4419	0.0889	− 4.97	< 0.0001
Ambient originated	− 0.9995	0.2614	− 3.82	0.0002
$WinD_1$[a]	68.7931	16.0564	4.28	< 0.0001
$AirConD_1$[a]	− 14.3253	4.1354	− 3.46	0.0006
$AirConD_2$[a]	− 8.9622	4.2896	− 2.09	0.0375
Cooking ventilation	− 9.7812	3.1861	− 3.07	0.0023
Cooking gas	10.8575	2.7637	3.93	0.0001
Cooking induction	10.9748	2.7789	3.95	< 0.0001
Clean sweep	5.2430	1.8111	2.89	0.0041
Incense burning	15.9741	2.2954	6.96	< 0.0001
$WinD_1$[a] × $AirConD_1$[a]	− 74.1292	17.3095	− 4.28	< 0.0001
$WinD_2$[a] × $AirConD_2$[a]	− 74.0520	17.6439	− 4.20	< 0.0001
Temperature × ambient originated	0.0704	0.0120	5.88	< 0.0001

[a] Dummy code for the frequency of window/air-conditioner opening

Window/air-conditioner $WinD_1/AirConD_1$ $WinD_2/AirConD_2$

Opening hours < 8 h 1 0

8 h < opening hours < 16 h 0 1

Opening hours > 16 h 1 1

study needs to be conducted on how indoor incense burning influences indoor NO_2. The results in Fig. S3 show a comparison between average concentrations of formaldehyde and potential indoor pollution sources in summer and winter. In both seasons, cooking with an induction cooker showed the highest average formaldehyde concentration. A higher average concentration of formaldehyde was observed for households without incense burning activities. This phenomenon could be explained by incense burning not being a dominant factor for indoor formaldehyde among our sampled households. However, further studies on whether incense burning would induce high indoor formaldehyde concentrations still need to be conducted. The lack of a distinct variation of formaldehyde concentrations in the sampling households (except two extreme cases) can be possibly because > 90% of the households are old dwellings with no renovation over the past 5 years. In addition, only few participants (within two households) revealed having smoking habits. The two households with exceptionally high formaldehyde concentrations were observed in summer. One household was re-decorated 2 years ago, and the furniture was mainly purchased from Padauk Classical Furniture (which sells traditional Chinese-style wooden furniture) which caused a higher emission of formaldehyde in summer than in winter. The other household was without re-decoration over the past 10 years and no new furniture purchase in the last 5 years. The high concentration of formaldehyde can be possibly attributed to roasting coffee beans during our sampling period (US EPA report (AP-42) 1995). Further investigation is required in future analysis. In summer, higher temperatures and RH can cause more formaldehyde emissions from furniture and result in higher indoor formaldehyde concentrations.

Study limitation

We used the monitoring data from the nearest Hong Kong EPD monitoring station to represent the outdoor-originated pollutant concentrations at the subjects' households, which did not consider the surrounding environment of the households such as major roads or green space that could influence the levels of air pollutants. This may have influenced the relationship of indoor-outdoor pollutant concentrations. Another limitation of this study is the small sample size. Only 55 households were selected as our sampling subjects, and because we used an integrated measurement method for NO_2 and formaldehyde, the sample sizes for these two pollutants were 55 and 47 in summer and winter, respectively. The small sample size and uneven distribution of indoor pollutant sources can result in unsuitable application of the regression model to these two pollutants. That is why we only investigate the determinant factors for indoor $PM_{2.5}$.

Conclusion

The characteristics of indoor air pollutant exposure and household air quality for elderly people in Hong Kong were investigated. The indoor $PM_{2.5}$ concentration level was higher compared to the WHO indoor air quality standard. Both indoor $PM_{2.5}$ and formaldehyde concentrations were shown with seasonal variations, and a higher $PM_{2.5}$ concentration was observed in winter than in summer, in addition to a higher formaldehyde concentration in summer than in winter. No seasonal variation was identified for indoor NO_2 concentration. The results confirm the variation of indoor air pollutant concentrations is associated with outdoor concentrations, due to the presence of occupants and their activities indoors. These findings also suggest cooking and incense burning can increase indoor concentrations of $PM_{2.5}$ and NO_2, whereas ventilation during cooking can reduce pollutant concentrations. Temperature and relative humidity in the dwellings are the determinant factors for the indoor formaldehyde concentration in households. We suggest the Hong Kong environmental protection department could formulate a guideline for households' indoor air quality.

Future study should be focused on quantifying building characteristics, larger-size sampling locations, and more concise measurement of targeted outdoor pollutant concentrations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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