

Evaluation of hazardous airborne carbonyls in five urban roadside dwellings: A comprehensive indoor air assessment in Sri Lanka



Chi Sing Chan^a, Ranasinghege Sampath Aravinda Ranasinghe^b, Steven Sai Hang Ho^{c,d,e,*}, Kin Fai Ho^f, Steve Hung Lam Yim^a, A.G.T. Sugathapala^g, Shun Cheng Lee^{h,**}, Wing Tat Hung^h, Yu Huang^{c,d}, Hong Zhangⁱ

^a Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin, Hong Kong, China

^b Air Resource Management Centre (AirMAC), Ministry of Environment, Sri Lanka

^c Key Lab of Aerosol Chemistry & Physics, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, 710061, China

^d The State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, 710061, China

^e Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, 89512, United States

^f The Jockey Club School of Public Health and Primary Care, The Chinese University of Hong Kong, Shatin, Hong Kong, China

^g Department of Mechanical Engineering, University of Moratuwa, Sri Lanka

^h Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China

ⁱ Hong Kong Premium Services and Research Laboratory, Chai Wan, Hong Kong, China

ARTICLE INFO

Keywords:

Carbonyls
Indoor air quality
Carcinogenic
Dwelling
Sri Lanka

ABSTRACT

Indoor hazardous airborne carbonyls were quantified in five natural-ventilated roadside dwellings in Colombo, Sri Lanka. The total concentrations of all targeted carbonyls ranged from 13.6 to 18.6 $\mu\text{g}/\text{m}^3$. Formaldehyde (C1) was the most abundant carbonyl, followed by acetaldehyde (C2) and acetone (C3K). The concentrations of C1 and C2 ranged from 3.3 to 8.5 $\mu\text{g}/\text{m}^3$ and 2.3 to 4.4 $\mu\text{g}/\text{m}^3$, respectively, which accounted for 23 to 42% and 18 to 26% respectively, to the total quantified carbonyls. The highest carbonyls levels were obtained in the dwelling located in an urban district with a mixture of industrial, commercial and residential areas. Much lower concentrations of carbonyls were measured in a light local traffic value was counted. Moderate correlations between individual combustion markers from vehicular emissions suggest the strong impacts from traffics to the indoor airs. The concentrations of C1 and C2 were compared with international indoor guidelines established by different authorities. A health assessment was conducted by estimation of inhalation cancer risk, implementing the inhalation unit risk values provided by Integrated Risk Information System (IRIS), associated with C1 and C2, which were 6.2×10^{-5} and 7.7×10^{-6} , respectively. Even though the risks did not reach the action level (1×10^{-4}), their health impact should not be overlooked. This kick-off indoor monitoring study provides valuable scientific data to the environmental science community since only limit data is available in Sri Lanka.

1. Introduction

Airborne carbonyls are ubiquitous but toxic, and previous studies have shown their presences in the atmosphere are associated to the health impacts on human, such as skin allergy, eye and respiratory irritations while their levels exceed thresholds (Erdem et al., 1996; WHO, 2000, 2010). In urban areas, airborne carbonyls are mainly emitted from anthropogenic sources, including vehicular exhaust and fuel combustions in industries and power plants (Ho et al., 2006; Lui et al., 2017a, 2017b; USEPA, 2000), and they are also originated through

photo-oxidation of hydrocarbons in atmosphere (i.e., alkenes and alkanes) (Atkinson, 2000; Carlier et al., 1986; Lui et al., 2017a).

Exposure to carbonyls in indoor environments is more critical than that in outdoors (WHO, 2010). The United States Environmental Protection Agency (USEPA) reported that people spend > 90% of their time indoors (USEPA, 1989). Among those carbonyls, formaldehyde and acetaldehyde are known probable human carcinogens to human (USEPA, 2017a, b). Epidemiological studies demonstrated significant exposure-response relationship ($p_{\text{trend}} < 0.001$) between peak exposure to formaldehyde and nasopharyngeal cancer incidence (IARC,

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

* Corresponding author. Key Lab of Aerosol Chemistry & Physics, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, 710061, China.

** Corresponding author. Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China.

E-mail addresses: stevengo@hkpsr.org (S.S.H. Ho), shun-cheng.lee@polyu.edu.hk (S.C. Lee).

<http://dx.doi.org/10.1016/j.apr.2017.10.002>

Received 31 May 2017; Received in revised form 22 August 2017; Accepted 4 October 2017

Available online 12 October 2017

1309-1042/ © 2018 Turkish National Committee for Air Pollution Research and Control. Production and hosting by Elsevier B.V.

2006). Acetaldehyde, the most abundant carcinogen in environmental tobacco smoke (ETS), dissolves in saliva during smoking (Salaspuro, 2009; Wang et al., 2012). Microbial or mucosal derived oxidation of acetaldehyde appears to react in the upper digestive tract as a cumulative carcinogen. Apart from carcinogenicity, accumulation of such volatile organic compounds (VOCs) could contribute to “sick building syndrome” (SBS) (Engvall et al., 2001). Residents in “sick buildings” frequently expose to VOCs that are linked with variety of human illness such as eye allergy, acute skin irritation and respiratory disease (Molhave et al., 1986; Yu and Kim, 2010). Relationship between indoor VOCs and SBS has been shown in many cross-sectional investigations on non-industrial workplaces and exposure chamber studies (Andersson et al., 1997; Chang et al., 2015; Norback et al., 1990; Spengler et al., 2001). In indoor environment, carbonyls are released from building materials, furniture, ETS, household heating, and cooking emission (Huang et al., 2011; IARC, 2006; Kabir and Kim, 2011; Mitova et al., 2016; Salthammer et al., 2010; Svendsen et al., 2002).

Comprehensive research and well-developed programmes in air pollution control in Sri Lanka is being sought. Available air pollution studies mainly focus on cooking emissions and few of them demonstrates domestic indoor air quality (IAQ) of dwellings in Sri Lanka. List of policies and actions to improve air quality in indoor environments (CAI-Asia, 2006) were proposed by the Clean Air Action Plan 2015 of the Air Resource Management Centre (AirMAC), Ministry of Environment and Natural Resources, the Government of Sri Lanka. Sustainability contributes to the country's competitiveness because polluted environment not only pose adverse health impacts to human but also affect its productivity (Schwab, 2011). So, this is the first comprehensive indoor air quality study which provides baseline data to forthcoming monitoring and assessment in Sri Lanka. The objective of this study is to evaluate indoor levels of airborne carbonyls in urban dwellings in Sri Lanka, where were all close to roadsides. A comparison was made between formaldehyde and acetaldehyde concentrations of the dwellings and the guidelines established by different countries. The cancer risks regarding to human exposures were also accessed and are worthy of study (Bluyssen et al., 2010; Brown et al., 2010; Yu and Crump, 2010). This study aims to provide valuable scientific data to the environmental science community.

2. Experimental section

2.1. Site selection

In accordance with the Census of Population and Housing 2012, Colombo is a western province in Sri Lanka. It has a population of 2.32 millions (11.4% of the total population in the country) with a density of 3438 persons per km². Five roadside dwellings, which were situated in an overpopulated urban areas and suburbs in Colombo, were selected in this study including Kalubowila, Pelawatte, Pitakotte, Battaramulla, and Rajagiriya. The sampling sites were chosen on the basis of (a) districts, (b) zone classes, (c) land use, (d) distance to the main road and traffic condition, and (e) without recent renovation. A brief description of each dwelling is shown as follow (further general information about the sampling sites is shown in Table 1). Fig. 1 shows the locations of

five dwellings. Four of these dwellings were near the heavily trafficked trunks with traffic volumes more than 500 vehicles per hour. H1 was situated in a mixed area of residential, industrial and commercial buildings which was 5 m from a 2-lane carriageway, whereas H2 was situated in an urban residential area and it was close to a 4-lane trunk with only a 1-meter width pedestrian pathway splitting between the sampling site and trunk. H4 and H5 were both located in urban commercial areas, near a 2-lane carriageway. A dwelling, H3, was situated in a sub-urban/rural residential area next to a small local street with fewer than 152 vehicles per hour traffic volume.

2.2. Field sampling

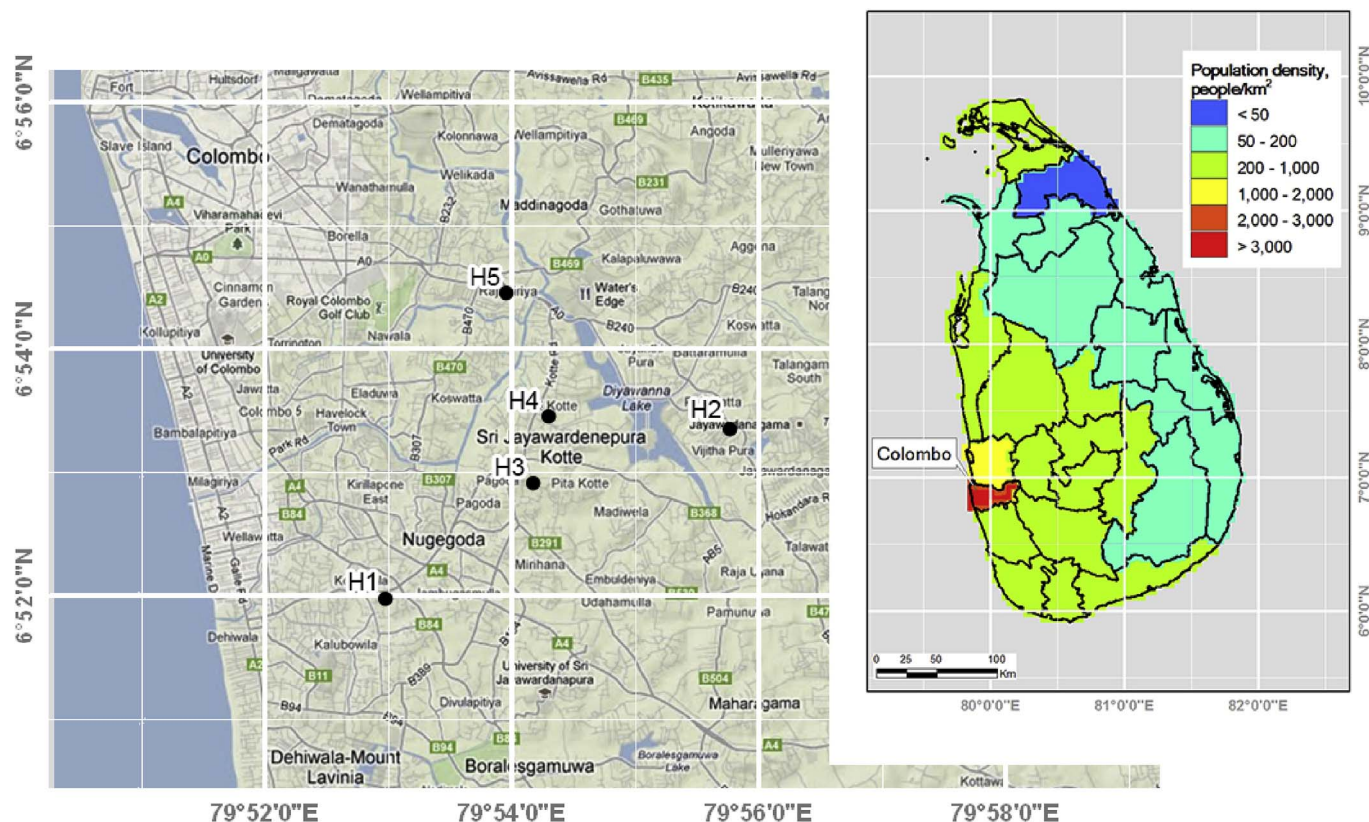
Sampling campaign was held from March 13th to 27th April, 2010. The time selection was due to minimal impact from poor meteorological conditions (i.e., lower rainfall recorded in spring, compared with that in summer). Carbonyl samples were collected for 12 h (from 07:00 to 19:00 local time) in living rooms of five dwellings. Three sampling events were collected in each dwelling and one sample was collected in each event. Two extra sampling events were conducted in H2. The samplers and monitors were situated at least 1 m away from the walls and 1.5 m above ground. No particular indoor pollution source was found in the indoors. The distances between the nearest road and respective sampling sites were recorded. During the sampling events, the airs inside the living rooms were ventilated naturally with open windows and front door. No air-conditioning was operated in all rooms. The living room sizes ranged from 150 to 200 m². No decoration had been done and no new furnishing had been installed at all five sampled dwellings within five years. Any indoor pollution activity (e.g., cooking or other indoor combustions) were prohibited inside the dwellings at least 24 h prior to and during the sampling event. For outdoor, no any commercial restaurant and other obvious pollution sources except traffic emissions were located near the roadside dwellings (< 200 m). In addition, traffic counts were conducted to investigate the relationship between traffic volume and indoor carbonyl levels. Vehicle fleets and traffic volumes were determined by manual counting at the roadsides, at a ten-minute per hour basis. Vehicles were classified into six major categories: (1) bus, (2) dual purpose van, (3) lorry, (4) motor bike, (5) three-wheeler, and (6) private car. A log of occupants' daily activities was remarked at each site.

Carbonyl sampler were used to collect airborne carbonyls by drawing ambient air through an acidified 2,4-di-nitrophenylhydrazine impregnated cartridge (Sep-Pak DNPH-silica, Waters Corporation, Milford, MA, USA). Sampling pump was operated at 0.7 L/min and calibrated by a DryCal[®] gas flow meter (Bios International Corp., Butler, NJ, USA) prior to and after sample collections. No breakthrough was reported at this sampling flow rate and time (Dai et al., 2012; Waters Corporation, 2007). Ozone interference was eliminated by connecting an ozone scrubber (Sep-Pak, Waters Corporation, Milford, MA, USA) in front of the DNPH cartridge. The sampled cartridges were capped and packed, and stored in an ice-box and transported to the laboratory for chemical analysis. The temperature, relative humidity (RH) and carbon dioxide (CO₂) concentration were recorded by Q-Trak[™] indoor air quality monitor (model 8550; TSI, Inc., Shoreview, MN, USA). Air

Table 1
General information of sampling sites in Colombo, Sri Lanka.

Site/district	Class	Area	Distance from main road & traffic condition
H1 (Kalubowila)	Urban	Mix ^a	5 meters from the 2-lane carriageway
H2 (Pelawatte)	Urban	Residential	1 meter from the 4-lane trunk
H3 (Pitakotte)	Suburban/rural	Residential	1 meter from the single lane local road
H4 (Battaramulla)	Urban	Commercial	5 meters from the 2-lane carriageway, close to two main trunk
H5 (Rajagiriya)	Urban	Commercial	15 meters from the 2-lane carriageway

^a Mix: Area consists of residential, commercial and industrial.



Colombo, Sri Lanka

Fig. 1. A map shows the districts and sampled dwellings in Colombo, Sri Lanka. Measurement sites are shown in the figure. H1, H2, H3, H4 and H5 refer to Kalubowila, Pelawatte, Pitakotte, Battaramulla and Rajagiriya, respectively. The general information of each site is provided in Table 1.

exchange rate of each dwelling was determined by the decay rate of CO₂ level in accordance with the American Standard Test Method [ASTM, E741-00(2006)e1] (ASTM International, 2006). Linear portion of decay period was extracted and respective air exchange rate was measured.

2.3. Chemical analysis

A total of 16 carbonyls (14 monocarbonyls and 2 dicarbonyls) were quantified (as listed with abbreviations on Table 2). Similar to our

previous studies, this study will not report the amount and abundances of two unsaturated carbonyls, acrolein and crotonaldehyde because excess derivatization reagent can react with unsaturated carbonyl DNP-hydrazone and produce adducts which gives inaccurate quantification result (Dai et al., 2012; Ho et al., 2011). Further information of the DNP-coated cartridge extraction, instrumental analysis, and quality control and quality assurance (QA/QC) can be referred to Lui et al. (2017b), Dai et al. (2012), and Ho et al. (2014a, 2014b, 2016). A four-point calibration for each target carbonyl over a concentration range of 0.015–3.0 mg/mL from the certified standards (Supelco, Bellefonte, PA) was established, and the correlation coefficients (*r*²) for linear regressions of the calibration curves were at least 0.999. The minimum detection limit (MDL) was done by analyzing at least seven replicates of a standard solution containing the analytes at a concentration of 0.015 µg/mL. The MDL can be estimated by equation (1):

$$MDL = t_{(n-1, 1-\alpha=99\%)} \times S \tag{1}$$

where *t*_(*n*-1, 1- α =99%) is the student's *t*-distribution value at *n*-1 degrees of freedom, and *S* is the standard derivation of the replicates (Meier and Zünd, 2005; Skoog et al., 1998). MDLs of the targeted carbonyls varied between 0.002 and 0.010 µg/mL, which refer to 0.034–0.045 ppbv with 0.72 m³ sample volume.

2.4. Cancer risk calculation

Cancer risk due to chronic inhalation of carbonyls was assessed. Cancer risk estimation is denoted by the likelihood of cancer incidence from a continuous lifetime exposure to a specific carbonyl. The

Table 2
Sixteen targeted carbonyls and their abbreviation in this study.

Pollutants	Acronyms
Formaldehyde	C1
Acetaldehyde	C2
Acetone	C3K
Propionaldehyde	nC3
Methyl-ethyl-ketone	MEK
i-/n-Butylaldehyde	isonC4
Benzaldehyde	Benz
Isovaleraldehyde	isoC5
n-Valeraldehyde	nC5
o-Tolualdehyde	otol
m-Tolualdehyde	mtol
p-Tolualdehyde	ptol
n-Hexaldehyde	C6
2,5-Dimethylbenzaldehyde	2,5-DB
Glyoxal	gly
Methylglyoxal	mgly

Table 3
Physical parameters obtained in the roadside dwellings and estimated hourly traffic volume (derived by 10-minute average).

Dwellings	H1		H2		H3		H4		H5	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
General Information										
Temperature (°C)	32.1	1.8	30.3	1.5	31.9	1.1	30.6	1.3	31.2	1.3
Relative Humidity (%)	71.4	7.9	76.8	4.6	74.8	5.2	79.4	4.9	79.7	2.2
Air Exchange Rate (h ⁻¹)	3.8		4.6		4.6		4.2		3.6	
Area (m ²)	250		170		150		200		200	
Traffic Count										
Bus	98	20	35	12	1	2	30	14	269	41
Dual purpose van	162	42	254	66	14	8	85	32	162	46
Lorry	70	25	141	47	10	9	50	19	109	40
Motor bike	248	57	277	106	61	25	152	48	277	106
Three-wheeler	347	65	241	59	53	22	121	30	267	70
Private car	362	84	635	115	13	9	245	45	273	64
Sum	1,287		1,582		152		683		1,356	

Inhalation Unit Risk (IUR) for formaldehyde and acetaldehyde are 1.3×10^{-5} and 2.2×10^{-6} , respectively. The lifetime cancer risk (R) is determined by following equation (2):

$$R = \text{IUR} \times \text{concentration exposure} \quad (2)$$

3. Results and discussion

3.1. Traffic count and physical conditions

Table 3 lists the traffic volumes and physical parameters measured at the five sampled roadside dwellings. The highest traffic volume of 1582 vehicle/hour was recorded in a 4-lane main trunk outside H2, followed by H5 (1356 vehicle/hour) and H1 (1287 vehicle/hour). The lowest traffic volume of 152 vehicle/hour, only accounting for 10% of the average value of the other sites, was counted in a local road close to H3. The air exchange rates of living rooms ranged from 3.6 to 4.6 h⁻¹. The average temperature and RH ranged from 30.3 to 32.1 °C and 71 to 80%, respectively.

3.2. Carbonyl concentrations

Fig. 2 shows the 12-hr average concentrations of the targeted carbonyls quantified in dwellings (acronyms for carbonyls are shown in Table 2). Formaldehyde (C1), $4.9 \pm 1.6 \mu\text{g}/\text{m}^3$ on average, was the most abundant carbonyl, which accounted for $32 \pm 6.5\%$ of the total

quantified carbonyls on mass base. Acetaldehyde (C2) and acetone (C3K) were the following two abundant carbonyls with average concentrations of $3.5 \pm 0.7 \mu\text{g}/\text{m}^3$ ($23 \pm 2.7\%$) and $2.3 \pm 1.2 \mu\text{g}/\text{m}^3$ ($14 \pm 6.9\%$), respectively. Other carbonyls such as isovaleraldehyde (isoC5) and methylglyoxal (mgly) had lower contributions of 7.1% and 4.8%, respectively.

The highest total carbonyl concentration was measured at H1 ($18.6 \mu\text{g}/\text{m}^3$), where also had the highest average concentrations of C1 ($7.6 \mu\text{g}/\text{m}^3$) and C2 ($4.0 \mu\text{g}/\text{m}^3$), accounting for 41% and 21%, respectively, of the total quantified value. The next highest C1 concentration was found in H5 (34% of the total quantified carbonyls), whereas H4 had the next highest C2 concentration (24% of the total quantified carbonyls). Most of the lowest abundances of carbonyls were seen in the H3, where had an average total quantified carbonyl concentration of $13.7 \mu\text{g}/\text{m}^3$, reflecting the significance of traffic emissions influenced to the indoor air quality of other urban roadside dwellings. C1 and C2 are known incomplete combustion products emitted from vehicular engines (Baez et al., 1995; Grosjean, 1982; Viskari et al., 2000). In comparison, similar sum of C1 and C2 concentrations (i.e., C1 + C2) were found in all dwellings, except H1, with averages ranged from 6.9 to $7.5 \mu\text{g}/\text{m}^3$.

3.3. Impact of outdoor sources on indoor airs

High air exchange rates could be resulted from a large number of windows featured in the sampled dwellings. During the sampling periods, as usual as general residential practice in Sri Lanka, the windows and room doors were opened. Therefore, indoor air quality in the dwelling could be significantly affected by the infiltration of the outdoor air. The total carbonyl concentration at H1, where located in an urban residential-commercial-industrial mixed district, was significantly higher than that measured in the H3. This demonstrates that the emissions from various anthropogenic pollution sources could greatly contribute to the carbonyls at the sampling location (Chan et al., 2011; Ho et al., 2002; Wang et al., 2010a). It has been documented that C1 and C2 levels were at least 10% higher at the microenvironment near roadsides than the areas away from traffic emission (Ho et al., 2012; Morknoy et al., 2011). If H1 was removed from the comparison, the carbonyl levels have strong association with the traffic volume near the sites. However, H1 obtained the highest level of carbonyls. This can be attributed to the fact that the background carbonyls from other local anthropogenic activities around the district were also contributed to the elevation of pollutants in the indoor airs. Other factors such as the individual air exchange rate and differences in meteorological parameters could affect the absolute concentrations.

Table 4 lists the C1/C2 ratios in this study and compared with other relevant researches. It was known that C1/C2 ratios vary from 1 to 2 in

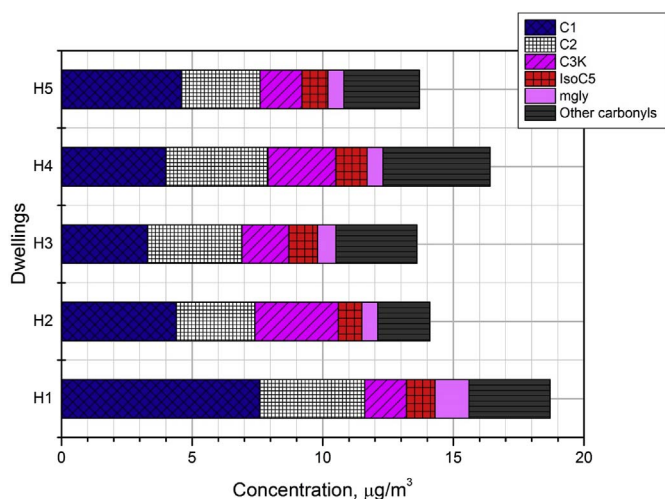


Fig. 2. The 12-hr average carbonyl concentrations ($\mu\text{g}/\text{m}^3$) measured in the sampled dwellings.

Table 4
Comparison of formaldehyde/acetaldehyde (C1/C2) ratio with other studies.

Location	C1/C2	References
Colombo, Sri Lanka	1.4	This study
Kalubowila H1	1.9	
Pelawatte H2	1.5	
Pitakotte H3	0.9	
Battaramulla H4	1.0	
Rajagiriya H5	1.5	
California, U.S.A.		(Bradman et al., 2017)
Indoor	2.2	
Outdoor	1	
Sao Paulo, Brazil	2.1	Nogueira et al. (2014)
Rio de Janeiro, Brazil	1.4	Correa et al. (2010)
Kaohsiung City, Taiwan	1.3	Wang et al. (2010b)
Gyung Gi, South Korea	1.0	Pal et al. (2008)
Strasbourg, France	1.9	Marchand et al. (2006)
Santiago, Chile	0.9	Rubio et al. (2006)
Beirut, Lebanon	1.6	Moussa et al. (2006)
Beijing, China	1.1	Pang and Mu (2006)
New Mexico	2.4	Villanueva-Fierro et al. (2004)
New York, USA	2.3	Sax et al. (2004)
Athens, Greece	1.0	Bakeas et al. (2003)
Xalapa, Mexico	1.3	Baez et al. (2003)
Hong Kong, China	2.2	Ho et al. (2002)
Rio de Janeiro, Brazil	1.0	Grosjean et al. (2002)
Milan, Italy	1.4	Andreini et al. (2000)
Rome, Italy	1.3	Possanzini et al. (1996)
Schauinsland, Germany	1.0	Slemr et al. (1996)
New Jersey, USA	3.2	Zhang et al. (1994)

urban districts and around 10 for sub-urban and rural districts (Wang et al., 2010a). The mean C1/C2 ratio of the five sampled dwellings was 1.4, suggesting that strong impacts of anthropogenic emission on the sites (Wang et al., 2010a). In general, our C1/C2 ratios were within the

Table 5
Comparison of indoor air quality guideline of C1 and C2 established by OEHHA, WHO, JNIHS and CIAQC.

Carbonyls $\mu\text{g}/\text{m}^3$	Standards			
	WHO ^a	OEHHA ^b	JNIHS ^c	CIAQC ^d
C1	100	9	100	100
C2	–	140	48	

^a World Health Organization: Guideline for indoor air quality – selected pollutants (WHO, 2010).

^b Office of Environmental Health Hazard Assessment, CA, US: Chronic reference exposure level (REL) (OEHHA, 2016).

^c Japanese National Institute of Health Sciences (JNIHS, 1997).

^d China Indoor Air Quality Center: Indoor air quality standard GB/T18883-2002 (CIAQC, 2003).

ranges measured in urban areas recorded in other studies. The highest C1/C2 ratio of 1.9 was observed in H1, whereas H3 had the lowest C1/C2 ratio of 0.9. The low ratio at H3 can be ascribed to the real situation that no any biogenic source, other than vehicular emission, was found around the site. Vehicular emission from the local road was the sole anthropogenic pollution source contributing to the carbonyls emission among H2, H3, H4 and H5. Industrial sources in the urban areas might also have various amounts of C1 and C2 emissions which were reflected in the samples collected in H1.

3.4. Correlations between carbonyls

The correlations between C1 and C2, C1 and benzaldehyde (Benz), C1 and *m*-tolualdehyde (mtol), C1 and mgly are shown in Fig. 3. Those are the important components in the exhausts of diesel/gasoline-fueled

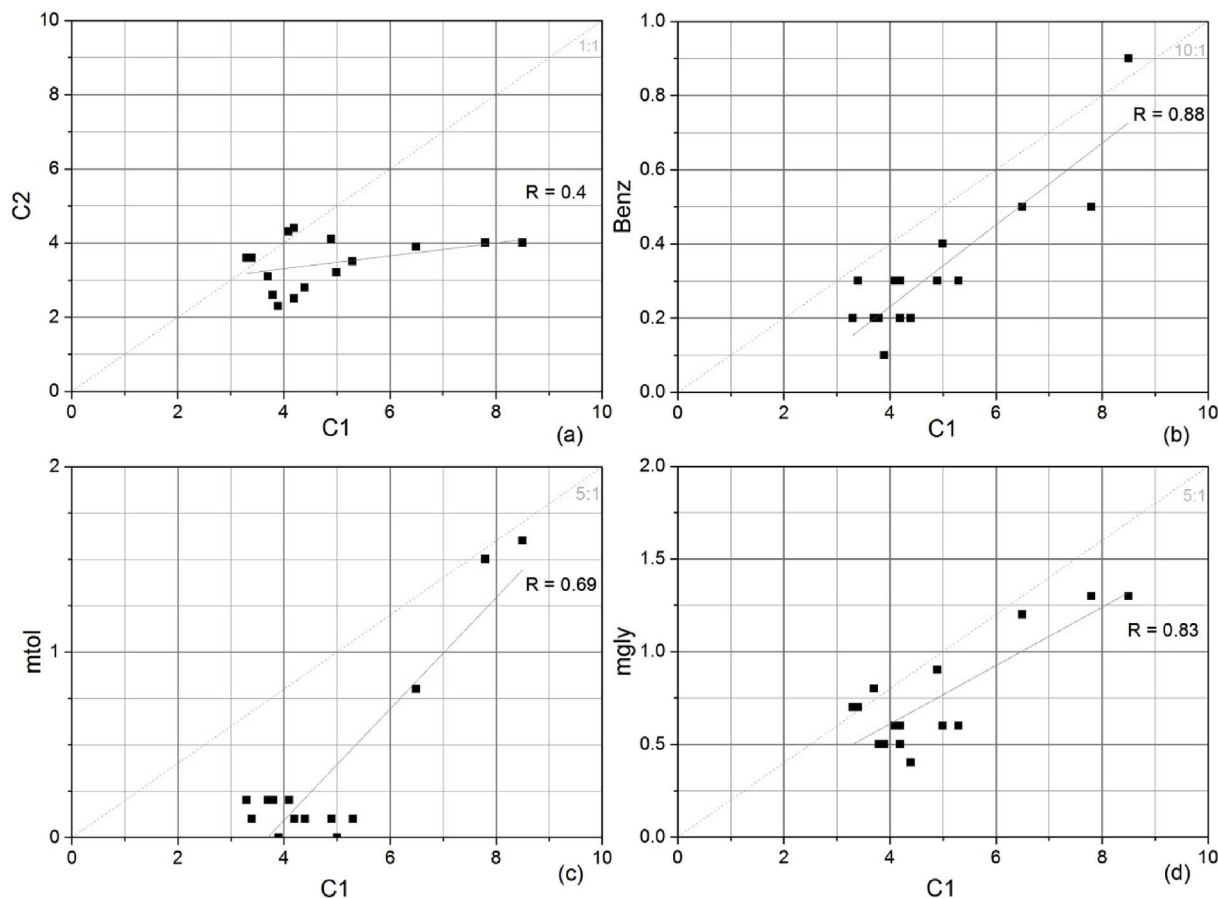


Fig. 3. Scatter plots for concentrations ($\mu\text{g}/\text{m}^3$) of (a) C1 against C2; (b) C1 against Benz; (c) C1 against mtol; and (d) C1 against mgly.

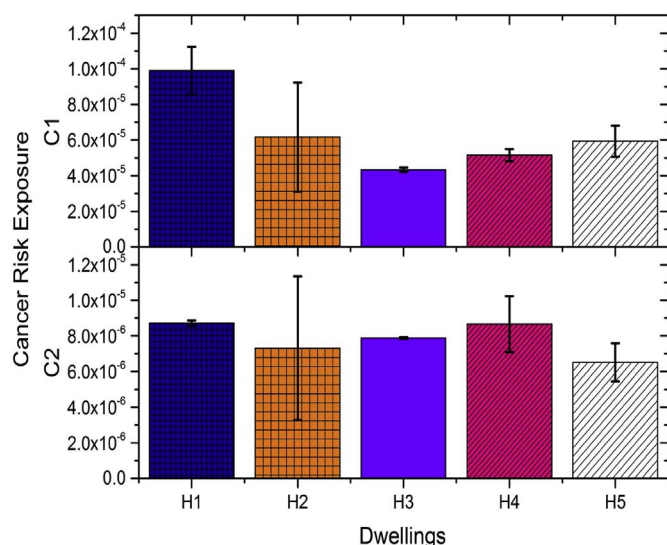


Fig. 4. Chronic cancer risks associated with C1 and C2 estimated in the sampled dwellings.

vehicles (Ban-Weiss et al., 2008; Ho et al., 2006). Weak correlation between C1 and C2 ($R = 0.4$, $p < 0.01$) was observed in this study. However, moderate correlation between C1 and mtol ($R = 0.69$, $p < 0.01$) and strong correlations between C1 and Benz, ($R = 0.88$, $p < 0.01$), and C1 and mgly ($R = 0.83$, $p < 0.01$) were obtained among all of the sampled dwellings. The results evidenced that the carbonyl levels in the indoor airs of the dwellings were attributed to the traffic emissions.

3.5. Health assessment

Table 5 shows the comparison of C1 and C2 concentrations with the indoor air quality guidelines established by World Health Organization (WHO), Office of Environmental Health Hazard Assessment (OEHHA), Japan National Institute of Health Sciences (JNIHS) and China Indoor Air Quality Center (CIAQC). Inhalation is a main exposure pathway for VOCs intakes for human apart from ingestion and dermal absorption. The C1 indoor exposure guideline established by both WHO, JNIHS and CIAQC is $100 \mu\text{g}/\text{m}^3$, while a much stricter chronic C1 reference exposure level was established by the OEHHA ($9 \mu\text{g}/\text{m}^3$). Both C1 and C2 concentrations measured in the sampled dwellings were well below the tolerable levels.

Fig. 4 lists the chronic cancer risks calculated for C1 and C2 in this study. C1, C2 and their potential health risks were determined because

Table 6

Comparison of cancer risks associated with C1 and C2 obtained in other indoor studies.

City, Country	Cancer risk		Indoor type	Estimated exposure period (years)	References
	C1 ($\times 10^{-5}$)	C2 ($\times 10^{-6}$)			
Colombo, Sri Lanka	4.3–9.9	6.5–8.7	Dwellings	70	This study
Fortaleza, Brazil	0.3–3.6	2.3–13	Hospitals	40	Sousa et al. (2011)
Hong Kong, China	1.0–1.6	3.1	Kitchens	70	Huang et al. (2011)
Hangzhou, China ^a	26–130	21–71	Dwellings	70	Weng et al. (2010)
Xalapa, Mexico ^b	49–61	43–59	Dwellings	78	Baez et al. (2003)
Xalapa, Mexico	34–130	42–100	Office	78	Baez et al. (2003)
Fortaleza, Brazil ^c	0.6–2.3	7–23	Office	40	Cavalcante et al. (2006)
Shimizu, Japan ^a	14.2	11	Dwellings	70	Ohura et al. (2006)

^a Geometric means of summer and winter periods.

^b Arithmetic mean values.

^c Values estimated in Pici Campus with a 40 years exposure.

of their high abundances in micro-environments and their carcinogenicity categorized by USEPA (1998). Housewives or maids who often stay in the dwellings were the targeted population for the assessment. Inhalation exposure is linked with the degree of exposure. The lifetime cancer risk for C1, C2 were estimated as shown in Fig. 4. Risk below 1×10^{-6} is usually considered as acceptable risk to a hazard. Risk above 1×10^{-4} is considered as action level, and interventions should be implemented to protect individual who is under particular exposure (Lee et al., 2006). The lifetime cancer risks associated with C1 and C2 among the five sampled dwellings ranged from 4.3×10^{-5} to 9.9×10^{-5} and 6.5×10^{-6} to 8.7×10^{-6} , respectively. Even though the estimated cancer risks for C1 and C2 did not reach the action level, their health impact should not be overlooked. C1 contributes most to lifetime cancer risks, which was eight folds to the lifetime cancer risk raised by C2. Especially for H1, the risk level for C1 exposure was merely below the action level. Table 6 compares the cancer risk on C1 and C2 exposures calculated in other studies. Our inhalation cancer risks associated with both C1 and C2 were lower than those in Hangzhou in China, Xalapa in Mexico and Shimizu in Japan, where those areas were known as heavily polluted cities in the world (Baez et al., 2003; Ohura et al., 2006; Weng et al., 2009).

4. Conclusions

This is the first comprehensive indoor air quality study conducted in Sri Lanka. C1, C2, and C3K were the three most abundant carbonyls quantified in the indoor airs in the roadside dwellings. Their sum of concentrations accounted for 68% of the total quantified carbonyls. The correlation analysis of individual markers proves that traffic emission was the main pollution source contributed to the carbonyl levels in the indoor airs of the dwellings. The C1/C2 ratio was within the range of those reported in other metropolitan cities, suggesting that local anthropogenic activities play an important role on the carbonyls production in Colombo. The indoor C1 and C2 concentrations were all below the tolerated levels established by those international health authorities. Even though the estimated lifetime cancer risks associated with C1 and C2 were also lower than the risk level, the possible health impact should not be overlooked. This study not only evaluated the air pollutant levels, and acted as a kick-off action on the indoor air monitoring and health assessment in Sri Lanka.

Acknowledgements

This project is supported by Clean Air Initiative Asia Center (CAI-Asia), Fredkorpset (FK) Norway, Clean Air Asia, Philippines, Clean Air for Asia (Agreement ID: 121301S3) under Clean Air and Blue Skies Exchange Program - Phase II. The authors would like to express their

heartfelt appreciation to the Hong Kong Polytechnic University, the University of Moratuwa, Sri Lanka, and the Air Resource Management and International Relations Division, Ministry of Environment, Sri Lanka for providing the technical supports, chemical analytical facilities and the logistical arrangements of the study.

References

- Andersson, K., Bakke, J.V., Bjorseth, O., Bornehag, C.G., Clausen, G., Hongslo, J.K., Kjellman, M., Kjaergaard, S., Levy, F., Molhave, L., Skerfving, S., Sundell, J., 1997. TVOC and health in non-industrial indoor environments - report from a Nordic scientific consensus meeting at Langholmen in Stockholm, 1996. *Indoor Air* 7, 78–91.
- Andreini, B.P., Baroni, R., Galimberti, E., Sesana, G., 2000. Aldehydes in the atmospheric environment: evaluation of human exposure in the north-west area of Milan. *Microchem. J.* 67, 11–19.
- ASTM International, 2006. ASTM E741–00(2006)e1, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. ASTM International.
- Atkinson, R., 2000. Atmospheric chemistry of VOCs and NO_x. *Atmos. Environ.* 34, 2063–2101.
- Baez, A., Padilla, H., Garcia, R., Torres Mdel, C., Rosas, I., Belmont, R., 2003. Carbonyl levels in indoor and outdoor air in Mexico City and Xalapa, Mexico. *Sci. Total Environ.* 302, 211–226.
- Baez, A.P., Belmont, R., Padilla, H., 1995. Measurements of formaldehyde and acetaldehyde in the atmosphere of Mexico-City. *Environ. Pollut.* 89, 163–167.
- Bakeas, E.B., Argyris, D.I., Siskos, P.A., 2003. Carbonyl compounds in the urban environment of Athens, Greece. *Chemosphere* 52, 805–813.
- Ban-Weiss, G.A., McLaughlin, J.P., Harley, R.A., Kean, A.J., Grosjean, E., Grosjean, D., 2008. Carbonyl and nitrogen dioxide emissions from gasoline- and diesel-powered motor vehicles. *Environ. Sci. Technol.* 42, 3944–3950.
- Bluyssen, P.M., de Rlichemont, S., Crump, D., Maupetit, F., Witterseh, T., Gajdos, P., 2010. Actions to reduce the impact of construction products on indoor air: outcomes of the European project HealthyAir. *Indoor Built Environ.* 19, 327–339.
- Bradman, A., Gaspar, F., Castorina, R., Williams, J., Hoang, T., Jenkins, P.L., McKone, T.E., Maddalena, R., 2017. Formaldehyde and acetaldehyde exposure and risk characterization in California early childhood education environments. *Indoor Air* 27, 104–113.
- Brown, T., Holmes, P., Harrison, P.T.C., 2010. Review: the applicability of epidemiological methods to the assessment of the risks to human health of indoor air pollution: an overview. *Indoor Built Environ.* 19, 311–326.
- CAI-Asia, 2006. Country Synthesis Report on Urban Air Quality Management. Sri Lanka. http://cleanairinitiative.org/portal/system/files/documents/srilanka_0.pdf, Accessed date: February 2012.
- Carlier, P., Hannachi, H., Mouvrier, G., 1986. The chemistry of carbonyl-compounds in the atmosphere - a review. *Atmos. Environ.* 20, 2079–2099.
- Cavalcante, R.M., Campelo, C.S., Barbosa, M.J., Silveira, E.R., Carvalho, T.V., Nascimento, R.F., 2006. Determination of carbonyl compounds in air and cancer risk assessment in an academic institute in Fortaleza, Brazil. *Atmos. Environ.* 40, 5701–5711.
- Chan, C.S., Lee, S.C., Chan, W.C., Ho, K.F., Tian, L.W., Lai, S.C., Li, Y.S., Huang, Y., 2011. Characterisation of volatile organic compounds at hotels in southern China. *Indoor Built Environ.* 20, 420–429.
- Chang, C.J., Yang, H.H., Wang, Y.F., Li, M.S., 2015. Prevalence of sick building syndrome-related symptoms among hospital workers in confined and open working spaces. *Aerosol air. Qual. Res.* 15, 2378–2384.
- CIAQC, 2003. Indoor Air Quality Standard GB/T18883-2002. China Indoor Air Quality Center (CIAQC).
- Correa, S.M., Arbilla, G., Martins, E.M., Quiterio, S.L., Guimaraes, C.D., Gatti, L.V., 2010. Five years of formaldehyde and acetaldehyde monitoring in the Rio de Janeiro downtown area - Brazil. *Atmos. Environ.* 44, 2302–2308.
- Dai, W.T., Ho, S.S.H., Ho, K.F., Liu, W.D., Cao, J.J., Lee, S.C., 2012. Seasonal and diurnal variations of mono- and di-carbonyls in Xi'an, China. *Atmos. Res.* 113, 102–112.
- Engvall, K., Norrby, C., Norback, D., 2001. Sick building syndrome in relation to building dampness in multi-family residential buildings in Stockholm. *Int. Arch. Occup. Environ. Health* 74, 270–278.
- Erdem, N., Tarhan, U., Bilgic, S., Sabir, H.U., Karakaya, A.E., Sardas, S., 1996. Effect of formaldehyde and wood dust exposure on pulmonary function. *Toxicol. Lett.* 88, 74–74.
- Grosjean, D., 1982. Formaldehyde and other carbonyls in Los-Angeles ambient air. *Environ. Sci. Technol.* 16, 254–262.
- Grosjean, D., Grosjean, E., Moreira, L.F., 2002. Speciated ambient carbonyls in Rio de Janeiro, Brazil. *Environ. Sci. Technol.* 36, 1389–1395.
- Ho, K.F., Ho, S.S.H., Dai, W.T., Cao, J.J., Huang, R.J., Tian, L.W., Deng, W.J., 2014a. Seasonal variations of monocarbonyl and dicarbonyl in urban and sub-urban sites of Xi'an, China. *Environ. Monit. Assess.* 186, 2835–2849.
- Ho, K.F., Lee, S.C., Louie, P.K.K., Zou, S.C., 2002. Seasonal variation of carbonyl compound concentrations in urban area of Hong Kong. *Atmos. Environ.* 36, 1259–1265.
- Ho, K.F., Lee, S.C., Tsai, W.Y., 2006. Carbonyl compounds in the roadside environment of Hong Kong. *J. Hazard. Mater.* 133, 24–29.
- Ho, S.S.H., Ho, K.F., Lee, S.C., Cheng, Y., Yu, J.Z., Lam, K.M., Feng, N.S.Y., Huang, Y., 2012. Carbonyl emissions from vehicular exhausts sources in Hong Kong. *J. Air Waste Manage. Assoc.* 62, 221–234.
- Ho, S.S.H., Ho, K.F., Liu, W.D., Lee, S.C., Dai, W.T., Cao, J.J., Ip, H.S.S., 2011. Unsuitability of using the DNPH-coated solid sorbent cartridge for determination of airborne unsaturated carbonyls. *Atmos. Environ.* 45, 261–265.
- Ho, S.S.H., Ip, H.S.S., Ho, K.F., Ng, L.P.T., Dai, W.T., Cao, J.J., Chan, C.S., Ho, L.B., 2014b. Evaluation of hazardous airborne carbonyls on a university campus in southern China. *J. Air Waste Manage. Assoc.* 64, 903–916.
- Ho, S.S.H., Cheng, Y., Bai, Y., Ho, K.F., Dai, W.T., Cao, J.J., Lee, S.C., Huang, Y., Ho, S.S.L., Deng, W.J., Guo, W., 2016. Risk assessment of indoor formaldehyde and other carbonyls in campus environments in Northwestern China. *AAQR* 16 (8), 1967–1980.
- Huang, Y., Ho, S.S.H., Ho, K.F., Lee, S.C., Yu, J.Z., Louie, P.K.K., 2011. Characteristics and health impacts of VOCs and carbonyls associated with residential cooking activities in Hong Kong. *J. Hazard. Mater.* 186, 344–351.
- IARC, 2006. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans - Formaldehyde, 2-butoxyethanol and 1-tert-butoxypropan-2-ol. World Health Organization, International Agency for Research on Cancer, Lyon, France.
- JNIHS, 1997. <http://www.nihs.gov.jp/mhlw/chemical/situnai/hyou.html>, accessed in May 2017.
- Kabir, E., Kim, K.-H., 2011. An investigation on hazardous and odorous pollutant emission during cooking activities. *J. Hazard. Mater.* 188, 443–454.
- Lee, C.W., Dai, Y.T., Chien, C.H., Hsu, D.J., 2006. Characteristics and health impacts of volatile organic compounds in photocopy centers. *Environ. Res.* 100, 139–149.
- Lui, K.H., Dai, W.T., Chan, C.S., Ho, S.S.H., Cao, J.J., Lee, S.C., Ho, K.F., 2017a. Spatial distributions of airborne di-carbonyls in urban and rural areas in China. *Atmos. Res.* 186, 1–8.
- Lui, K.H., Ho, S.S.H., Louie, P.K.K., Chan, C.S., Lee, S.C., Hu, D., Chan, P.W., Lee, J.C.W., Ho, K.F., 2017b. Seasonal behavior of carbonyls and source characterization of formaldehyde (HCHO) in ambient air. *Atmos. Environ.* 152, 51–60.
- Marchand, C., Buillot, B., Le Calve, S., Mirabel, P., 2006. Aldehyde measurements in indoor environments in Strasbourg (France). *Atmos. Environ.* 40, 1336–1345.
- Meier, P.C., Zünd, R.E., 2005. Limit of Detection, Statistical Methods in Analytical Chemistry, second ed. John Wiley & Sons, Inc., pp. 115–118.
- Mitova, M.I., Campelos, P.B., Goujon-Ginglinger, C.G., Maeder, S., Mottier, N., Rouget, E.G.R., Tharin, M., Tricker, A.R., 2016. Comparison of the impact of the Tobacco Heating System 2.2 and a cigarette on indoor air quality. *Regul. Toxicol. Pharmacol.* 80, 91–101.
- Molhave, L., Bach, B., Pedersen, O.F., 1986. Human reactions to low concentrations of volatile organic compounds. *Environ. Int.* 12, 167–175.
- Morknoy, D., Khummongkol, P., Prueksasit, T., 2011. Seasonal and diurnal concentrations of ambient formaldehyde and acetaldehyde in Bangkok. *Water Air Soil Pollut.* 216, 693–702.
- Moussa, S.G., El-Fadel, M., Saliba, N.A., 2006. Seasonal, diurnal and nocturnal behaviors of lower carbonyl compounds in the urban environment of Beirut, Lebanon. *Atmos. Environ.* 40, 2459–2468.
- Nogueira, T., Dominutti, P.A., de Carvalho, L.R.F., Fornaro, A., Andrade, M.D., 2014. Formaldehyde and acetaldehyde measurements in urban atmosphere impacted by the use of ethanol biofuel: metropolitan Area of Sao Paulo (MASP), 2012–2013. *Fuel* 134, 505–513.
- Norback, D., Torgen, M., Edling, C., 1990. Volatile organic-compounds, respirable dust, and personal factors related to prevalence and incidence of sick building syndrome in primary-schools. *Br. J. Ind. Med.* 47, 733–741.
- OEHHA, 2016. OEHHA Acute, 8-hour and Chronic Reference Exposure Level (REL) Summary. <https://oehha.ca.gov/air/chemicals/formaldehyde>, Accessed date: August 2017.
- Ohura, T., Amagai, T., Senga, Y., Fusaya, M., 2006. Organic air pollutants inside and outside residences in Shimizu, Japan: levels, sources and risks. *Sci. Total Environ.* 366, 485–499.
- Pal, R., Kim, K.H., Hong, Y.J., Jeon, E.C., 2008. The pollution status of atmospheric carbonyls in a highly industrialized area. *J. Hazard. Mater.* 153, 1122–1135.
- Pang, X.B., Mu, Y.J., 2006. Seasonal and diurnal variations of carbonyl compounds in Beijing ambient air. *Atmos. Environ.* 40, 6313–6320.
- Possanzini, M., Dipalo, V., Petricca, M., Fratarcangeli, R., Brocco, D., 1996. Measurements of lower carbonyls in Rome ambient air. *Atmos. Environ.* 30, 3757–3764.
- Rubio, M.A., Zamorano, N., Lissi, E., Rojas, A., Gutierrez, L., von Baer, D., 2006. Volatile carbonylic compounds in downtown Santiago, Chile. *Chemosphere* 62, 1011–1020.
- Salaspuro, M., 2009. Acetaldehyde as a common denominator and cumulative carcinogen in digestive tract cancers. *Scand. J. Gastroenterol.* 44, 912–925.
- Salthammer, T., Mentese, S., Marutzky, R., 2010. Formaldehyde in the indoor environment. *Chem. Rev.* 110, 2536–2572.
- Sax, S.N., Bennett, D.H., Chillrud, S.N., Kinney, P.L., Spengler, J.D., 2004. Differences in source emission rates of volatile organic compounds in inner-city residences of New York City and Los Angeles. *J. Expo. Anal. Environ. Epidemiol.* 14, S95–S109.
- Schwab, K., 2011. The Global Competitiveness Report 2011–2012. pp. 326–327.
- Skoog, D.A., Holler, E.J., Nieman, T.A., 1998. Principles of Instrumental Analysis, fifth ed. Harcourt Brace & Company, Orlando, pp. 13–14.
- Slemr, J., Junkermann, W., VolzThomas, A., 1996. Temporal variations in formaldehyde, acetaldehyde and acetone and budget of formaldehyde at a rural site in southern Germany. *Atmos. Environ.* 30, 3667–3676.
- Sousa, F.W., Caracas, I.B., Nascimento, R.F., Cavalcante, R.M., 2011. Exposure and cancer risk assessment for formaldehyde and acetaldehyde in the hospitals, Fortaleza-Brazil. *Build. Environ.* 46, 2115–2120.
- Spengler, J.D., Samet, J.M., McCarthy, J.F., 2001. Sensory Irritation in Humans Caused by Volatile Organic Compounds (VOCs) as Indoor Air Pollutants: a Summary of 12 Exposure Experiments. *Indoor Air Quality Handbook*. McGraw Hill Professional, Access Engineering.
- Svendsen, K., Jensen, H.N., Sivertsen, I., Sjaastad, K., 2002. Exposure to cooking fumes in restaurant kitchens in Norway. *Ann. Occup. Hyg.* 46, 395–400.
- USEPA, 1989. Report to Congress on Indoor Air Quality, vol. 2 United State

- Environmental Protection Agency (USEPA), Washington, DC.
- USEPA, 1998. Integrated Risk Information System (IRIS). <http://www.epa.gov/iris>, Accessed date: August 2014.
- USEPA, 2000. Air Toxics Web Site: Formaldehyde. <http://www.epa.gov/ttnatw01/hlthef/formalde.html>, Accessed date: August 2014.
- USEPA, 2017a. Integrated Risk Information System (IRIS) - Acetaldehyde. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0290_summary.pdf, Accessed date: August 2017.
- USEPA, 2017b. Integrated Risk Information System (IRIS) - Formaldehyde. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0419_summary.pdf, Accessed date: August 2017.
- Villanueva-Fierro, I., Popp, C.J., Martin, R.S., 2004. Biogenic emissions and ambient concentrations of hydrocarbons, carbonyl compounds and organic acids from ponderosa pine and cottonwood trees at rural and forested sites in Central New Mexico. *Atmos. Environ.* 38, 249–260.
- Viskari, E.L., Vartiainen, M., Pasanen, P., 2000. Seasonal and diurnal variation in formaldehyde and acetaldehyde concentrations along a highway in Eastern Finland. *Atmos. Environ.* 34, 917–923.
- Wang, B., Ho, S.S.H., Ho, K.F., Huang, Y., Chan, C.S., Feng, N.S.Y., Huang, Y., Ip, S.H.S., 2012. An environmental chamber study of the characteristics of air pollutants released from environmental tobacco smoke. *Aerosol Air Qual. Res.* 12 (6), 1269–1281.
- Wang, H.K., Huang, C.H., Chen, K.S., Peng, Y.P., 2010a. Seasonal variation and source apportionment of atmospheric carbonyl compounds in urban Kaohsiung, Taiwan. *Aerosol Air. Qual. Res.* 10, 559–570.
- Wang, H.K., Huang, C.H., Chen, K.S., Peng, Y.P., Lai, C.H., 2010b. Measurement and source characteristics of carbonyl compounds in the atmosphere in Kaohsiung city, Taiwan. *J. Hazard. Mater.* 179, 1115–1121.
- Waters Corporation, 2007. Determination of Formaldehyde in Ambient Air. Milford, MA, 720001988EN MC-CP.
- Weng, M., Zhu, L., Yang, K., Chen, S., 2009. Levels and health risks of carbonyl compounds in selected public places in Hangzhou, China. *J. Hazard. Mater.* 164, 700–706.
- Weng, M.L., Zhu, L.Z., Yang, K., Chen, S.G., 2010. Levels, sources, and health risks of carbonyls in residential indoor air in Hangzhou, China. *Environ. Monit. Assess.* 163, 573–581.
- WHO, 2000. Air Quality Guidelines for Europe. Regional Office for Europe Copenhagen, Denmark, pp. 87–91.
- WHO, 2010. Guideline for Indoor Air Quality - Selected Pollutants. World Health Organization, Regional Office for Europe, Copenhagen, Denmark.
- Yu, C., Crump, D., 2010. Indoor environmental quality - standards for protection of occupants' safety, health and environment. *Indoor Built Environ.* 19, 499–502.
- Yu, C.W.F., Kim, J.T., 2010. Building pathology, investigation of sick buildings - VOC emissions. *Indoor Built Environ.* 19, 30–39.
- Zhang, J.F., He, Q.C., Li, P.J., 1994. Characteristics of aldehydes - concentrations, sources, and exposures for indoor and outdoor residential microenvironments. *Environ. Sci. Technol.* 28, 146–152.