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Research Article

An Investigation of Concentration and Health Impacts of Aldehydes Associated with Cooking in 29 Residential Buildings

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Indoor air quality can be influenced by various indoor activities. The indoor air pollutants generated by cooking activities can cause severe risks to occupants' health in residential buildings. The present study conducted field experiments to measure indoor pollutants associated with cooking in 29 residential buildings. Due to an open plan in Korean residential buildings, the emission of indoor pollutants was measured in the kitchen and living room. Focusing on aldehydes, the indoor emission levels for various cooking methods such as grilling, frying, and boiling were analyzed. As a result, the emission of formaldehyde, acetaldehyde, and propionaldehyde was highly increased for all cooking methods. The increase rate of the emission was higher in the kitchen than that in the living room for grilling and frying. In the case of boiling, the highest concentration of aldehydes was observed. Moreover, the indoor level of aldehydes was higher in the living room than that in the kitchen. Moreover, the health risk such as cancer for occupants was assessed based on the measured data for different cooking methods. The assessment results showed that all the emissions of aldehydes for different cooking methods required instant actions to avoid cancer risk for occupants.

1. Introduction

In general, people have spent most of their time in buildings, but it is rapidly increasing, and many were recommended to stay home since the SARS-CoV-2 virus has occurred [1, 2]. Thus, indoor environmental quality in buildings such as indoor air quality and thermal behaviors becomes significantly important, and the role of buildings should maintain healthy physical, mental, and other conditions for occupants [3–5]. Previous studies have shown that improvement of indoor environmental quality can create a comfortable indoor environment as well as assure improved building energy efficiency [6–8]. However, it is challenging to maintain a comfortable indoor environment, particularly thermal parameters because of the various context of climate conditions and associated fluctuations in ambient temperatures [9]. It has then resulted in a large number of studies to investigate the thermal performance of various building materials or systems [6–8, 10–12]. As a matter of fact, indoor air quality is one of the key indoor environmental parameters, which has been of less concern for building users compared with thermal parameters [13]. As with increasing concerns for occupant health, it is necessary to draw significant attention to indoor air quality [13, 14].

Focusing much on indoor sources initiated from building materials, appliances, human activities, etc., previous studies have highlighted that indoor contaminants generated by gas and particulates have harmful effects on indoor air quality [15–17]. In addition, indoor air pollution can be worsened in residential buildings where mechanical ventilation systems are less used than in nonresidential buildings [18]. Pointing out the importance of air pollution in residential buildings, most studies have focused on indoor sources which emit pollutants. Historically, building materials have been a major source of emitting formaldehyde and VOCs which were fatal to occupants' health and productivity [15, 19]. Thus, studies have performed measurements focusing on the particulate matter since it is generally considered that aldehydes are emitted from interior finishes, furniture, and so on in dwellings [20–23]. With the use of improved building materials, indoor aldehyde levels were quite decreased. Meanwhile, people have started to notice the sources generated by cooking as major indoor pollutants in residential buildings. Aldehyde caused by the combustion processes such as heating, cooking, or smoking is difficult to be estimated because of many variables [24]. Besides, indoor aldehyde levels generated by cooking can be varied by cooking types, sources, time, etc. Considering this point, Kabir and Kim observed the emission of aldehydes generated from the cooking in their measurements [25].

Cooking is considered as the main activity for worsening indoor air quality in residential buildings since it particularly generates high concentrations of multiple pollutants such as fine particles ($PM_{2.5}$) [26–29], polycyclic aromatic hydrocarbons (PAHs) [30–32], black carbon (BC) [33–35], carbonyl compounds (formaldehyde, acetaldehyde, acrolein, propionaldehyde, butyraldehyde, and benzaldehyde) [36–39], and nitrogen dioxide (NO_x) [40–42]. Emissions of cooking-generated pollutants vary highly by multiple parameters such as cooking methods, heat sources, cooking materials, and oil types [43–49]. Several studies carried out measurements for cooking-generated air pollutants to characterize emission rates of air pollutants during cooking in residential buildings [38, 50–54]. Lu et al. investigated the health effect of cooking-generated $PM_{2.5}$ in an experimental space [55]. They found that the average of $PM_{2.5}$ concentration generated by eleven Chinese cooking was about eight times higher than the national indoor air standard ($75\,\mu g/m^3$). In addition, O'Leary et al. measured the $PM_{2.5}$ emissions from several cooking methods [48]. As a result, emissions varied from 0.54 to 3.7 mg/min, and decay rates ranged from 4.7 to $6.1\,h^{-1}$. Moreover, Isaxon et al. studied the indoor-generated ultrafine particles and black carbon by several cooking methods such as frying and oven through field measurements [56]. They analyzed the correlation between ultrafine particles and black carbon concentrations. Another study performed by Chen et al. has measured PM and VOCs, formaldehyde emissions by several different cooking conditions including cooking methods, ingredient weights, meat type, the ratio of meat and vegetables, and cooking oils [57]. The result of measurements observed that emissions of $PM_{2.5}$, formaldehyde, and TVOCs were 2.056 mg/min, 1.273 mg/min, and 1.349 mg/min, respectively, and they concluded that the emissions of different indoor air pollutants can be varied by different parameters.

Significantly, exposure to oil fumes generated by cooking activities can cause severe health problems to occupants. For example, high indoor particulate matter concentrations aggravated children's respiratory systems [58, 59]. Carbonyls associated with cooking have been considered as the main cause of lung cancer [45]. Thus, U.S. EPA developed the Integrated Risk Information System to estimate the cancer hazard risk for formaldehyde, acetaldehyde, and benzene [60]. Moreover, indoor NO_x generated during cooking can harm occupants' health regarding inflammatory response and oxidant injury [61]. In addition, Huang et al. characterized and assessed emissions of volatile organic compounds (VOCs) and carbonyls during cooking in two residential buildings by using a gas chromatographic method [45]. In their findings, formaldehyde can cause cancer hazard risks higher than acetaldehyde and benzene. While indoor air pollutants generated by cooking in residential buildings can have a significant impact on occupants' health, a few studies have performed investigations of indoor air pollutants during cooking in residential buildings. In addition, some studies have quantified the emissions of multiple air pollutants during cooking in a few buildings or laboratory facilities such as a chamber.

The concentrations of indoor air pollutants in residential buildings have been mainly caused by fuel combustion from cooking, heating, etc. [62]. In South Korea, cooking-appliance types can be categorized into gas and electric cooktops [63, 64]. While there has been a significant increase in the use of electric cooktops because of the issues of indoor air quality caused by gas cooktops during cooking, most housing units still have used gas cooktops in the kitchen [65–67]. Regarding the IAQ issues in the kitchen, most studies have focused on the investigations of indoor air pollution caused by fuel types and ingredients of dishes [45, 66, 68–70]. In their studies, emission rates of particulate matter (PM), volatile organic compounds (VOCs), aldehydes, CO_2, etc. were measured in the kitchen. According to the study of Lai and Chen, the ventilation rates of kitchen hood systems can be an effective solution for reducing the concentration of indoor pollutants [71]. While the capacity of kitchen hood systems can be varied, the indoor air quality in the kitchen caused by cooking activities can be somewhat improved by reducing the concentration of air pollutants. However, some indoor air pollutants in the poorly ventilated kitchen were observed in other areas such as the living room or bedroom [71]. These pollutants can be deposited on surfaces of interior finishes, and in that, they can also harm occupants' health [72, 73].

As one of the main sources of indoor air pollutants, aldehydes are easily found indoors, and their concentrations indoors are usually higher than the outdoors due to the combustion processes involving organic matter such as smoking, cooking, and domestic wood heating and sources such as interior finishes and furnishing products [74, 75]. Among these sources, cooking fumes can contain hazardous pollutants because of the incomplete combustion of carbonaceous components in food materials [76, 77]. Aldehydes are generally generated by a chemical or enzymatic process in food from the lipid oxidation of polyunsaturated fatty acid [78]. Among aldehydes, formaldehyde is one of the most critical air pollutants at high health-related risk according to the guidelines provided by World Health Organization (WHO), which is mainly released from the combustion process during cooking activities [79, 80]. Other high-priority aldehydes include acetaldehydes, acrolein, propanal, butanal, benzaldehyde, and isopentanal.

As can be shown, aldehydes generated during cooking are carcinogenic to humans. To assess the impact of aldehydes on occupants' health effects, it is important to figure out the emission of aldehydes associated with cooking activities as well as assess the relationship between these pollutants with occupants' health. The present study is aimed at measuring aldehyde concentrations during cooking and assessing the health risk of occupants in residential buildings in South Korea.

2. Materials and Methods

Figure 1 presents the research methodology of the present study, consisting of 4 steps. First, 29 residential buildings were selected for field measurements to measure indoor pollutants through cooking activities. To figure out the influence of indoor pollutants from the kitchen, the measuring instruments were located in the kitchen and living room. Focusing on aldehydes, the data were collected before/during cooking through three different cooking activities such as grilling, frying, and boiling in step 2. The measured data were classified into spatial, cooking types as well as analyzed to identify the compounds of aldehydes based on the concentration in step 3. In step 4, the health risk of these aldehydes was assessed.

2.1. Measurement Location. For the present study, on-site measurements were performed in 29 residential buildings from July to December 2015. The average outdoor and indoor air temperatures ranged from 24°C to 32°C and 25°C to 29°C, respectively. Among the selected buildings, 27 buildings were an apartment with total floor areas ranging from 48 m^2 to 157 m^2, and the other buildings were 2 detached houses in which a total floor area ranged from 72 m^2 to 106 m^2. The specification is presented in Table 1. Most buildings were equipped with exhaust hood systems in the kitchen and natural gas cooking burners, while some used electric stoves. Sampling was conducted at two locations in the buildings, which were the kitchen and living room. The height of the sampling points was set to 1.4 m. Most kitchens were directly connected to the living room. While some buildings had doors between the kitchen and living room, these doors were kept open during cooking.

2.2. Sample Collections and Analysis. As can be shown in Table 2, three different cooking methods were performed during the measurement: grilling, frying, and boiling. The dishes prepared in the study covered the major domestic cooking in South Korea. Common local-style dishes were used for the measurements; including (1) pan-baked pork bellies, beef, and fish; (2) fried eggs and frozen food; and (3) miso soup. All ingredients and condiments were purchased from a local market, and the weights of the ingredients used for the measurements ranged from 190 g to 260 g. For the grilling, raw fish and meats were selected. Four eggs were used for the fried egg. These dishes were cooked with the same size of a pan except the frying frozen food which used a deep pan with 500 ml soybean oil. Cooking time was limited to 15 min to prevent overcooking and, the background particle concentrations were measured in the living and kitchen room for 15 min before cooking: specifically, meat grilling: 3 min, fish grilling: 13 min, frying eggs: 4 min, frying frozen meat: 6 min, boiling soup: 6 min, and a decay period. All measurements were performed for 30 min including the time to cook the ingredients. During the measurements, the range hood systems in the kitchen were operated, and either natural or mechanical ventilation systems were used. The capacity of kitchen exhaust hood systems is also presented in Table 2.

Figure 2 and Table 3 present the measuring instruments. For monitoring aldehydes, sampling (0.3 L/min) of carbonyl compounds was carried out in the kitchen and living room in 29 residential buildings by the DNPH-cartridge at 15-minute intervals equally for periods of "before cooking," and "during cooking" including cooking time. The samples were analyzed using high-performance liquid chromatography (HPLC) [81]. In sampling cartridge specimens, an ozone scrubber was mounted at the front of the cartridge to prevent ozone effects on the result. Carbonyl compounds such as formaldehyde, acetaldehyde, acrolein, propionaldehyde, butyraldehyde, and benzaldehyde were analyzed. In addition, the ventilation rates, temperature, and humidity in the kitchen and living room were also measured.

2.3. Health Risk Assessment. After the concentrations of aldehydes were obtained, the indoor inhalation cancer risk in the living room was estimated. To calculate the daily inhalation cancer risk (DI) of the occupants during the time they spend in the living room, the equation considering various factors such as exposure frequency, exposure duration, and the body weight of the receptor was used [45, 82]:

$$\mathrm{DI} = \frac{C_a \times \mathrm{IR} \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT} \times 365}, \tag{1}$$

where C_a is the contaminant concentration (mg/m^3) and IR is the inhalation rate (m^3/h). ET is the exposure time (h/day), and EF is the exposure frequency (day/year). In addition, ED is the exposure duration (year), and BW is the body weight (kg). Moreover, AT is the average lifetime (year). According to the standard values provided by the United States Environmental Protection Agency (USEPA), an inhalation rate was assumed as 20 m^3/day [83]. For the body weights for male and female, they were set to 70 kg and 60 kg, respectively. For the exposure days, it was assumed that occupants spend 4 hours per day, which was equal to 92 days per year, and they are exposed to the contaminant for 30 years. The average lifetime for female and male was assumed to be 70 years [84, 85].

For the estimation of lifetime cancer hazard risk (R), the equation below was used:

$$\mathrm{R} = \mathrm{DI} \times \mathrm{PF}, \tag{2}$$

where PF is the cancer potency factor (i.e., cancer slope factor) in the unit of $(\mathrm{mg\,kg^{-1}day^{-1}})^{-1}$ of a specific cancer substance [86, 87]. The values of PF are 0.045 $(\mathrm{mg\,kg^{-1}day^{-1}})^{-1}$ and 0.0077 $(\mathrm{mg\,kg^{-1}day^{-1}})^{-1}$ for formaldehyde and acetaldehyde, respectively.

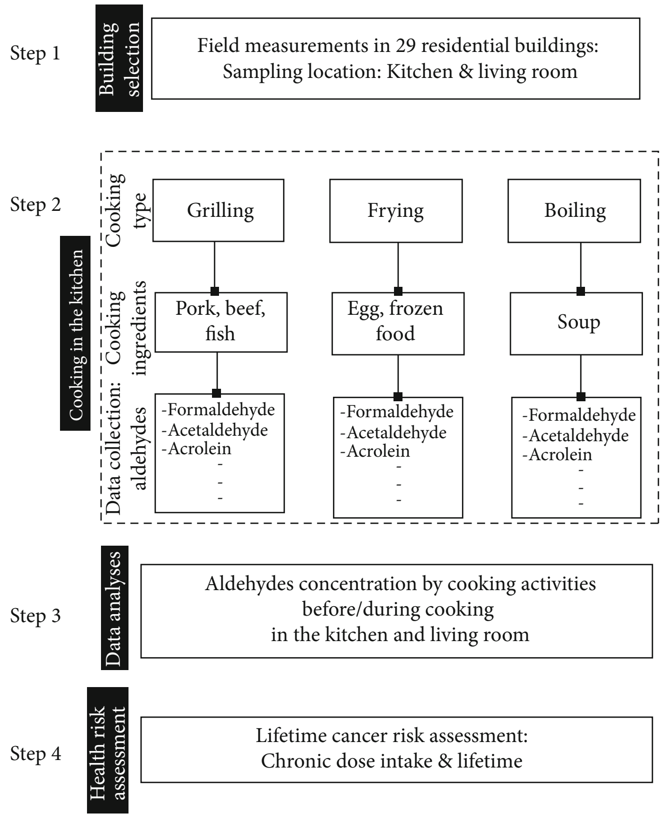


Figure 1: Research methodology.

3. Results

3.1. Overview of IAQ Parameters and Measurement Sites. After the measurements, observations of pollutants in 29 residential buildings and weather data were obtained. Table 4 presents the summary of statistics during cooking in the kitchen and living room. For the weather parameters such as indoor air temperature and relative humidity in the living room, a little difference in the mean values was observed between before and after cooking, while about a 1°C increase in the temperature and a 2% decrease in the relative humidity, a decrease was observed after cooking in the kitchen. For CO_2 concentrations, a slight increase was observed after cooking in the kitchen, while about 9 ppm was decreased in the living room after cooking. Among pollutants, a total of formaldehyde measurements in the kitchen in 29 residential buildings showed that mean and median concentrations were 271.3 and 189 $\mu g/m^3$ before cooking and 280.9 and 207 $\mu g/m^3$ after cooking. In the living room, the mean and median concentrations of formaldehyde were 243 and 159 $\mu g/m^3$ and 258.6 and 159 $\mu g/m^3$, before and after cooking, respectively. Similarly, active sampling of the other aldehydes including acetaldehyde, acrolein, propionaldehyde, butyraldehyde, and benzaldehyde was carried out before and after cooking in two locations in 29 residential buildings. In both locations including the kitchen and living room, the mean concentrations of formaldehyde and benzaldehyde were increased after cooking, while the concentrations of acrolein and propionaldehyde were the same before and after cooking. In the case of acetaldehyde, the mean concentration was increased in only the kitchen after cooking.

3.2. Emission of Aldehydes from Different Cooking Activities. To figure out aldehydes' concentration associated with various cooking activities, the measured data were categorized based on cooking types including grilling, frying, and boiling.

3.2.1. Cooking Type: Grilling. Among the cooking activities, the measurements of aldehydes caused by grilling were performed in 8 residential buildings. As shown in Table 5, most pollutants were increased in the kitchen and living room after cooking. Among them, the mean concentration of propionaldehydes was largely increased in both spaces, which was about 86%. In addition, the acetaldehydes and butyraldehyde were also increased in both spaces after cooking. In the case of formaldehyde, about 19% of the mean concentration was increased only in the kitchen, while it was about 4% in the living room. By considering the volume of 8 residential buildings, there was a significant increase in the net weight of the propionaldehydes and acetaldehydes in both spaces, while about 1120 μg of the formaldehyde was increased in the kitchen.

3.2.2. Cooking Type: Frying. In the case of frying, the concentration of aldehydes was measured in 17 residential units in which mostly frozen foods were used for the measurements. The increase in the concentration of aldehydes, formaldehyde,

Table 1: The specification of 29 residential buildings.

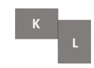
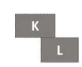
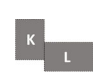
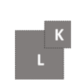
Residential building (#)	Building type	Floor area (m^2)	Volume (m^3)	Number of rooms	Number of occupants	Kitchen ventilation system	Kitchen (K) and living room (L) Shape	Kitchen (K) and living room (L) Area (m^2)
1	APT	74	170.2	3	4	Hood		21.6
2	APT	76	193.2	3	5	Hood		26.8
3	APT	72	253	3	4	Natural ventilation		31.4
4	APT	84	174.8	3	4	Hood		21.2
5	D. house	68	187.2	3	4	Natural ventilation		42.4
6	D. house	152	193.2	3	4	Hood		37.1
7	APT	157	156.4	2	4	Hood		25.4
8	APT	114	349.6	3	4	Natural ventilation		48.6
9	APT	74	361.1	3	4	Hood		46.4
10	APT	102	249.9	3	4	Natural ventilation		38.8
11	APT	106	170.2	3	4	Hood		34.3
12	APT	108	262.2	3	3	Natural ventilation		30.1
13	APT	72	234.6	3	4	Natural ventilation		28.8
14	APT	61	243.8	3	5	Hood		29.3
15	APT	84	234.6	3	4	Natural ventilation		24.7
16	APT	59	152.5	2	6	Hood		22.4
17	APT	116	193.2	3	5	Hood		24.7
18	APT	74	135.7	2	5	Hood		12.6
19	APT	167	266.8	4	5	Hood		22.8
20	APT	48	185	3	5	Natural ventilation		14.6
21	APT	109	384.1	4	5	Natural ventilation		35.6
22	APT	72	174.8	3	5	Hood		27.8
23	APT	59	250.7	3	5	Hood		24.9

Table 1: Continued.

Residential building (#)	Building type	Floor area (m^2)	Volume (m^3)	Number of rooms	Number of occupants	Kitchen ventilation system	Kitchen (K) and living room (L) Shape	Area (m^2)
24	D. house	95	110.4	1	4	Hood		10.4
25	APT	72	165.6	2	6	Natural ventilation		18.9
26	APT	84	135.7	3	4	Hood		16.2
27	APT	110	248.4	3	4	Natural ventilation		29.3
28	APT	76	180	3	5	Hood		19.4
29	APT	102	218.5	3	7	Natural ventilation		23.2

Table 2: Cooking methods and kitchen hood specification in 29 residential buildings.

Building number (#)	Cooking Method	Cooking Ingredient	Cooking appliance types	The airflow rate of the kitchen hood system (m^3/h)
1, 12, 14, 15, 16, 24, 25 11	Grilling	Pork, beef, fish	Natural gas Electricity	210-330
3, 5, 8, 9, 10, 17, 19, 20, 21, 23, 26, 27, 28, 29 2, 18, 22	Frying	Egg, frozen food	Natural gas Electricity	225-345
6, 7, 13 4	Boiling	Soup	Natural gas Electricity	250-320

acetaldehydes, and propionaldehydes was increased and was observed in the kitchen and living room (Table 6). As noticed in the case of grilling, the mean concentration of propionaldehydes was significantly increased. For the net weight change, about 1200 μg and 750 μg of the propionaldehydes were observed after cooking in the kitchen and living room, respectively. For formaldehyde, more than 500 μg of net weight was increased in both the kitchen and living room.

3.2.3. Cooking Type: Boiling. The concentration of aldehydes was measured in four residential units when boiling was applied. As can be seen in Table 7, the mean concentration of most aldehydes except the butyraldehyde was increased in both the kitchen and living room. The biggest increase in the mean concentration was the acetaldehydes. In addition, the increases in the net weight of acetaldehydes were about 2430 μg and 3650 μg in the kitchen and living room, respectively. While the second biggest increase was observed in the concentration of the propionaldehydes, the increase of the net weight of this aldehyde ranged from about 450 μg to 790 μg in the kitchen and living room, which was quite smaller than the net weight increase of formaldehyde.

3.2.4. Summary of the Concentration of Aldehydes in the Kitchen and Living Room. Based on the comparison of the concentration of aldehydes in the kitchen and living room, high concentrations of formaldehyde, acetaldehydes, and propionaldehydes were observed in both spaces. The World Health Organization (WHO) guidelines have provided the recommended pollutant values. For formaldehyde, a short term (i.e., 30 min) of 0.1 mg/m^3 is recommended for preventing sensory irritation, while 0.2 mg/m^3 is used for the evaluation of long-term health effects such as cancer [88]. In general, the short-term value of 0.1 mg/m^3 is used for the prevention of cancer. According to the guidelines of formaldehyde provided by the Korean Ministry of Environment, the level of formaldehyde is set at 210 μg/m^3 [89]. As shown in Figure 3, the concentration of formaldehyde in both the kitchen and living room generated by grilling and boiling was higher than the level set by the Korean Ministry of Environment. In addition, the background level of formaldehyde was initially over 210 μg/m^3. Besides, acetaldehydes are categorized as another group which is uncertain or has insufficient evidence [88]. The International Agency for Research on Cancer (IARC) has pointed out insufficient information that acetaldehyde can cause cancer, even though this is carcinogenic from experiments with animals [90]. According to residential indoor air quality guidelines in Canada, the proposed short-/long-term threshold value of acetaldehyde is 1.42 mg/m^3 and 0.28 mg/m^3, respectively, [91]. In the case of propionaldehyde, only data from the experimental animals were available.

(a) Grilling

(b) Grilling experimental setup in the kitchen

(c) Frying

(d) Frying experimental setup in the kitchen

(e) Boiling

(f) Boiling experimental setup in the kitchen

(g) Experimental setup in the living room

Figure 2: Cooking methods and experimental setup in the kitchen and living room.

Table 3: Measuring instruments.

Measuring target	Measuring instrument	Sampling point
Air exchange rate	Photoacoustic multigas monitor (INNOVA 1412, 1313)	Kitchen, living room
Indoor temperature, humidity	Data logger (SATO SK-L200)	Kitchen, living room
Carbonyl compounds	Dinitrophenylhydrazine (DNPH) silica cartridges (SUPELCO T011/IP-6A aldehyde-DNPH mix)	Kitchen, living room

Table 4: The summary of statistics during cooking in the kitchen and living room.

	Unit	Before cooking						During cooking					
		N	Minimum	Maximum	Mean	Median	SD	*N*	Minimum	Maximum	Mean	Median	SD
Kitchen													
Temperature	(°C)	620	27.4	28.3	27.7	27.7	0.3	576	27.8	29.3	28.4	28.3	0.5
Relative air humidity	(%)	620	46.5	51.4	48.6	48.5	1.4	576	43.9	49.2	46.3	46.3	1.3
Carbon dioxide	(ppm)	620	428.5	916.0	591.1	576.8	182.4	576	427.3	839.5	597.3	600.0	134.6
Formaldehyde	(μg/m^3)	527	66.0	1506.0	271.3	189.0	274.8	485	60.0	1329.0	280.9	207.0	271.7
Acetaldehyde	(μg/m^3)	527	39.0	372.0	101.4	84.0	68.2	485	36.0	543.0	135.0	84.0	114.1
Acrolein	(μg/m^3)	527	108.0	1317.0	292.7	219.0	239.9	485	90.0	981.0	275.6	210.0	193.0
Propionaldehyde	(μg/m^3)	527	0.0	288.0	101.0	105.0	77.5	485	0.0	345.0	100.3	87.0	72.5
Butyraldehyde	(μg/m^3)	527	21.0	270.0	51.7	33.0	54.9	485	0.0	219.0	47.8	27.0	50.4
Benzaldehyde	(μg/m^3)	527	0.0	87.0	20.1	0.0	27.5	485	0.0	141.0	25.9	18.0	36.3
Living room													
Temperature	(°C)	620	27.0	27.7	27.3	27.3	0.2	576	26.9	28.9	27.5	27.5	0.5
Relative air humidity	(%)	620	42.9	47.1	44.9	44.8	1.2	576	42.3	47.0	44.5	44.5	1.2
Carbon dioxide	(ppm)	620	545.4	731.7	627.0	625.8	65.3	576	516.9	800.7	619.1	607.0	90.9
Formaldehyde	(μg/m^3)	527	66.0	1326.0	243.0	159.0	246.9	485	69.00	1335.0	258.6	159.0	268.8
Acetaldehyde	(μg/m^3)	527	36.0	369.0	100.6	84.0	69.5	485	3.0	552.0	84.0	132.1	119.2
Acrolein	(μg/m^3)	527	96.0	1182.0	282.4	204.0	216.3	485	93.0	1002.0	204.0	281.8	206.5
Propionaldehyde	(μg/m^3)	527	0.0	252.0	99.6	90.0	80.3	485	0.0	345.0	91.2	84.0	73.7
Butyraldehyde	(μg/m^3)	527	21.0	243.0	56.7	33.0	57.4	485	21.0	273.0	59.5	27.0	65.3
Benzaldehyde	(μg/m^3)	527	0.0	84.0	18.5	0.0	26.6	485	0.0	129.0	26.9	24.0	35.5

3.3. Health Risk Assessment. Based on the summary, the health risk assessment for occupants in the kitchen and living room was conducted using the mean concentrations of formaldehyde and acetaldehyde. For the carcinogen risk assessment, a few assumptions were taken from the suggestions provided by U.S. EPA [86]. The results of the carcinogen risk assessment were summarized in Table 8.

As can be shown above, formaldehyde has a higher cancer risk to house person than that is associated with acetaldehyde. In addition, the risk associated with formaldehyde and acetaldehyde is higher in the kitchen than that in the living room when food is grilling or frying. When food is boiling, the highest risk associated with formaldehyde was observed. Moreover, the cancer risk associated with these pollutants is higher in the living room than that in the kitchen. The results also demonstrate that the lifetime cancer risks associated with formaldehyde are ranged from 3.1×10^4 to 8.3×10^3, while it ranges from 7.5×10^5 to 8.8×10^4 which is associated with acetaldehyde. According to the study by Lee et al., a cancer risk of less than one in a million (1×10^6) is generally considered under a concerning level, while a risk higher above 100 in a million (1×10^4) can be considered that instant actions or interventions are required to protect human from the cancer risk [82]. Considering these values, all the obtained results of lifetime cancer risks exceed 1×10^4, which represents some actions for house person in both the kitchen and living room.

4. Discussion

According to the measurements performed by Huang et al., the mean concentration of formaldehyde and acetaldehyde was 60.4 μg/m^3-151 μg/m^3 and 4.5 μg/m^3-65.9 μg/m^3, respectively [45]. In their investigation, three different cooking methods with meats, fish, and vegetables were used. Militello-Hourigan and Miller measured the level of formaldehyde generated by an egg frying in 10 residential units [92]. In their measurements, the values ranged from 14 μg/m^3 to 67 μg/m^3. As can be shown, the mean concentration of several aldehydes was presented. Another investigation for measuring indoor pollutants during cooking was performed by Pei et al. [93]. The measured concentration of aldehydes including

TABLE 5: The concentration of aldehydes: grilling.

Chemicals	Residential building (#): 1, 11, 12, 14, 15, 16, 24, 25 Concentration											
	Kitchen						Living room					
	Background ($\mu g/m^3$)		During cooking ($\mu g/m^3$)		Conc. change (%)	Net weight change (μg)	Background ($\mu g/m^3$)		During cooking ($\mu g/m^3$)		Conc. change (%)	Net weight change (μg)
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Formaldehyde	276.4	14.2	339.0	26.7	18.5	1126.3	246.9	15.4	256.7	12.3	3.8	236.6
Acetaldehyde	94.7	4.2	183.4	12.9	48.4	1596.9	104.6	6.3	156.4	8.4	33.2	1244.6
Acrolein	246.4	9.9	249.9	11.2	1.4	61.7	252.0	11.4	238.7	9.2	-5.6	-318.9
Propionaldehyde	13.1	2.6	104.3	10.9	87.4	1640.3	12.0	2.4	85.5	1.9	86.0	1764.0
Butyraldehyde	84.9	5.5	124.7	75.6	32.0	717.4	111.4	5.8	146.6	7.5	24.0	843.4
Benzaldehyde	27.9	6.4	22.7	1.9	-22.6	-92.6	30.0	6.5	27.4	4.4	-9.4	-61.7

Table 6: The concentration of aldehydes: frying.

Chemicals	Residential building (#): 2, 3, 5, 8, 9, 10, 17, 18, 19, 20, 21, 22, 23, 26, 27, 28, 29 Concentration											
	Kitchen						Living room					
	Background ($\mu g/m^3$)		During cooking ($\mu g/m^3$)		Conc. change (%)	Net weight change (μg)	Background ($\mu g/m^3$)		During cooking ($\mu g/m^3$)		Conc. change (%)	Net weight change (μg)
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Formaldehyde	152.3	7.4	178.7	9.2	14.8	555.2	136.9	6.4	156.4	8.1	12.5	565.5
Acetaldehyde	72.6	1.8	114.8	6.6	36.8	885.9	69.9	2.1	83.8	3.1	16.6	402.4
Acrolein	207.2	6.8	223.7	10.7	7.4	346.5	202.1	7.9	203.6	6.3	0.7	43.5
Propionaldehyde	10.2	2.3	67.8	7.6	84.9	1208.1	8.1	2.3	33.9	3.3	76	747.2
Butyraldehyde	136.3	5.3	123.0	7.6	-10.8	-279.6	138.2	6.8	139.3	7.5	0.8	32.6
Benzaldehyde	27.4	4.2	28.7	3.9	4.6	27.6	27.2	4.0	23.4	7.2	-16	-108.8

Table 7: The concentration of aldehydes: boiling.

Chemicals	Residential building (#): 4, 6, 7, 13 — Concentration — Kitchen: Background ($\mu g/m^3$)		Kitchen: During cooking ($\mu g/m^3$)		Kitchen: Conc. change (%)	Kitchen: Net weight change (μg)	Living room: Background ($\mu g/m^3$)		Living room: During cooking ($\mu g/m^3$)		Living room: Conc. change (%)	Living room: Net weight change (μg)
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Formaldehyde	329.0	15.6	452.0	36.4	27.2	2054.1	309.0	16.4	572.0	53.7	46.0	5917.5
Acetaldehyde	103.0	20.0	249.0	15.2	58.6	2438.2	109.0	24.1	271.0	15.6	59.8	3645.0
Acrolein	271.0	12.8	333.0	23.5	18.6	1035.4	284.0	12.4	408.0	35.7	30.4	2790
Propionaldehyde	31.5	3.4	58.5	4.2	46.1	450.9	27.0	3.5	62.3	6.6	56.6	793.1
Butyraldehyde	98.0	2.7	98.0	2.6	0	0.0	84.0	3.2	94.0	3.5	10.6	225
Benzaldehyde	33.0	6.0	34.0	1.2	2.9	16.7	33.0	3.0	39.0	1.2	13.4	135

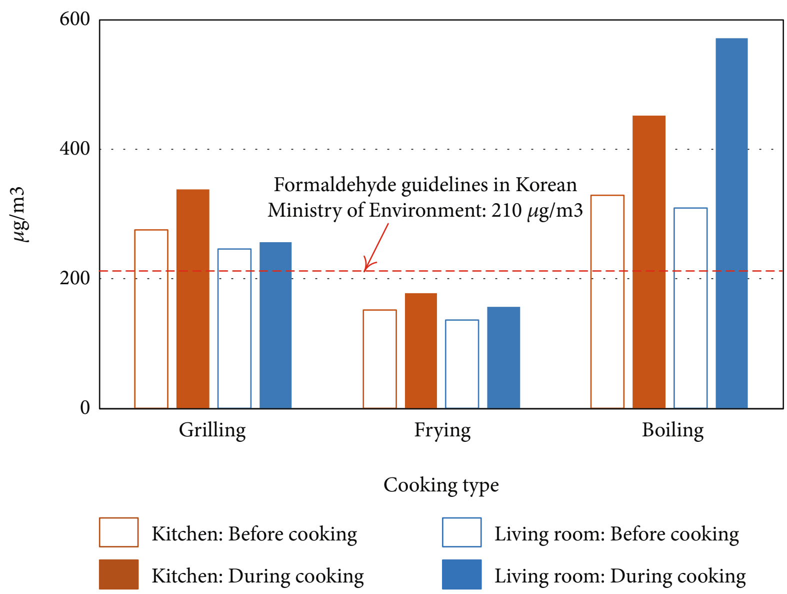


Figure 3: The comparison of formaldehyde between the measured data and the formaldehyde guidelines of the Korean Ministry of Environment.

Table 8: Health risk assessment.

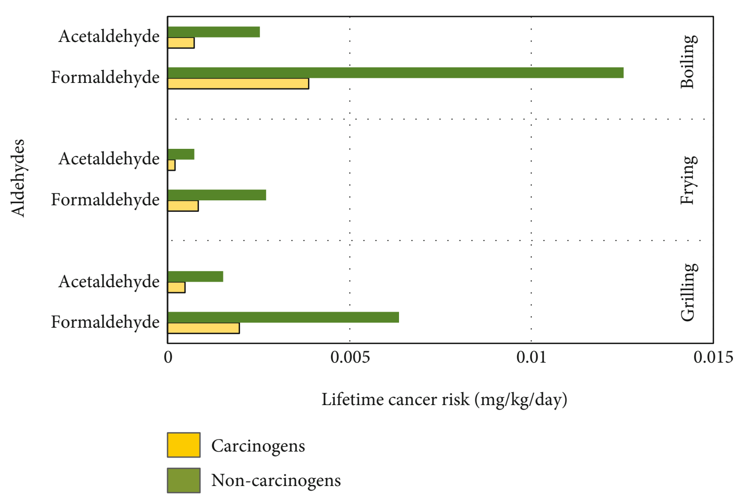
Cooking type	Space	Pollutant	Average concentration (mg/m^3)	Chronic dose intake (mg/kg/day)	Lifetime cancer risk (mg/kg/day)
Grilling	Kitchen	Formaldehyde	0.063	0.044	2.0×10^3
		Acetaldehyde	0.089	0.062	4.8×10^4
	Living room	Formaldehyde	0.01	0.007	3.1×10^4
		Acetaldehyde	0.052	0.036	2.8×10^4
Frying	Kitchen	Formaldehyde	0.026	0.019	8.4×10^4
		Acetaldehyde	0.042	0.03	2.3×10^4
	Living room	Formaldehyde	0.02	0.014	6.2×10^4
		Acetaldehyde	0.014	0.01	7.5×10^5
Boiling	Kitchen	Formaldehyde	0.123	0.087	3.9×10^3
		Acetaldehyde	0.146	0.103	7.9×10^4
	Living room	Formaldehyde	0.263	0.185	8.3×10^3
		Acetaldehyde	0.162	0.114	8.8×10^4

acetaldehyde and benzaldehyde ranged from about 2 $\mu g/m^3$-55 $\mu g/m^3$ by Chinese cooking. They also pointed out that the indoor level of aldehydes can be dependent on seasonal variations. As can be shown, the mean concentration of aldehydes from the previous studies was similar to the minimum concentration obtained in 29 residential buildings, while the maximum concentration was quite higher than those of previous studies. This difference can be caused by spatial scale, cooking types, cooking materials, experimental conditions, etc. Another important point is that the highest increase in the concentration of aldehydes was observed when the food is boiling. This can be seen that the emission of aldehydes is highly affected by high temperatures as well as cooking fuel type [93, 94]. In the present study, 24 residential buildings have used natural gas as cooking fuel. The longest use of natural gas by boiling can cause the highest emission of aldehydes.

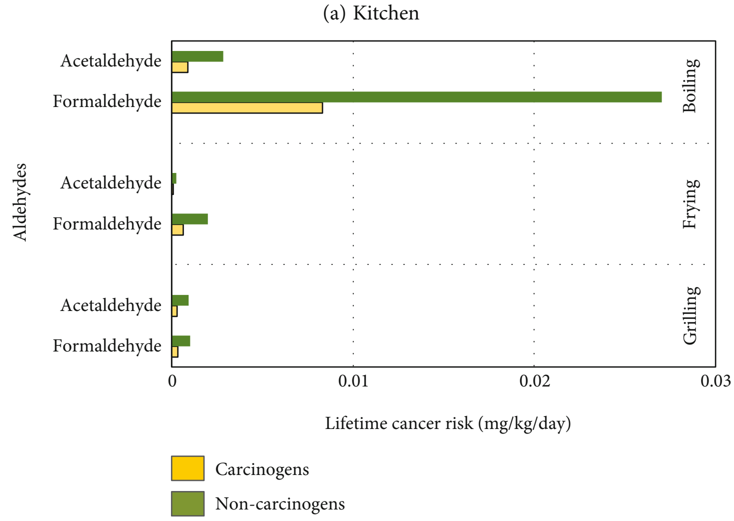
Regarding the health risk assessment associated with aldehydes, most results from the previous studies showed that the indoor levels of aldehydes were at a concerning level, while the obtained results of the current study need instant actions for occupants in both the kitchen and living room. However, this cancer risk assessment only considered the concentration increase by different cooking types. When

Table 9: Health risk assessment based on the concentration of background and increase in cooking methods.

Cooking type	Space	Chemical	Average concentration (mg/m^3)	Chronic dose intake (mg/kg/day)	Lifetime cancer risk (mg/kg/day)
Grilling	Kitchen	Formaldehyde	0.339	0.238	1.1×10^2
		Acetaldehyde	0.183	0.129	9.91×10^4
	Living room	Formaldehyde	0.257	0.181	8.13×10^3
		Acetaldehyde	0.156	0.11	8.45×10^4
Frying	Kitchen	Formaldehyde	0.179	0.126	5.65×10^3
		Acetaldehyde	0.115	0.081	6.21×10^4
	Living room	Formaldehyde	0.156	0.11	4.95×10^3
		Acetaldehyde	0.084	0.059	4.54×10^4
Boiling	Kitchen	Formaldehyde	0.452	0.318	1.4×10^2
		Acetaldehyde	0.249	0.175	1.34×10^3
	Living room	Formaldehyde	0.572	0.402	1.8×10^2
		Acetaldehyde	0.271	0.191	1.47×10^3



(a) Kitchen



(b) Living room

Figure 4: The comparison of lifetime cancer risk between carcinogens and noncarcinogens.

Table 10: The hazard index of noncarcinogenic assessment result.

Cooking type	Chemical	Kitchen HQ Chronic daily intake	Kitchen HQ Lifetime cancer risk	Living room HQ Chronic daily intake	Living room HQ Lifetime cancer risk
Grilling	Formaldehyde	1.5×10^2	6.6×10^4	2.3×10^3	1.0×10^4
	Acetaldehyde	2.2×10^2	1.7×10^4	1.3×10^2	1.0×10^4
	Hazard index	3.7×10^2	8.3×10^4	1.5×10^2	2.1×10^4
Frying	Formaldehyde	6.2×10^3	2.8×10^4	4.5×10^3	2.1×10^4
	Acetaldehyde	1.1×10^2	8.3×10^5	3.5×10^3	2.7×10^5
	Hazard index	1.7×10^2	3.6×10^4	8.1×10^3	2.3×10^4
Boiling	Formaldehyde	2.9×10^2	1.3×10^3	6.1×10^2	2.8×10^3
	Acetaldehyde	3.7×10^2	2.9×10^4	4.1×10^2	3.2×10^4
	Hazard index	6.6×10^2	1.6×10^3	1.1×10^2	3.1×10^3

considering the total concentration of background and increase, the lifetime cancer risk associated with formaldehyde by all cooking types was above 1×10^3, which presents a high cancer potential for occupants (Table 9). In this sense, it is thus required to assess the health risk considering the existing indoor level of aldehydes.

Based on the cancer potency factors provided by USEPA, we have made some assumptions for the calculations of health risk assessment such as body weights of house persons and averaging breathing rates. In addition, a low dose of compounds linearly was assumed for the estimation of lifetime cancer. However, these assumptions may not apply to all compounds. According to the study of Loh et al., they pointed out that short-term exposure to some compounds may be riskier than the linear dose for long term [95]. In this sense, the noncarcinogenic effect of formaldehyde and acetaldehyde was analyzed, which considers dose thresholds, while carcinogenic assessments are based on the linear at low-dose assumption. This can be presented in Equation (3).

$$\mathrm{DI} = \frac{C_a \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{AT} \times 365}, \quad (3)$$

where C_a is the contaminant concentration (mg/m^3) and ET is the exposure time (h/day). EF is the exposure frequency (day/year). In addition, ED is the exposure duration (year). Moreover, AT is the average lifetime (year). This noncarcinogen risk assessment can be evaluated by the hazard index (Equation (4)) [96]. Specifically, the hazard index can be presented as the sum of hazard quotients (Equation (5)).

$$\text{Hazard index} = \sum \mathrm{HQ}i, \quad (4)$$

$$\text{Hazard quotient (HQ)} = \frac{\mathrm{I}}{\mathrm{RfC}}, \quad (5)$$

where HQi is the sum of the hazard quotient for noncarcinogen risk assessment results and I is the inhalation intake (μg/m^3). RfC is the reference concentration of noncarcinogens in which 9.8 μg/m^3 and 9 μg/m^3 were used for formaldehyde and acetaldehyde, respectively [83]. The acceptable level of the hazard index is 1 [87]. The calculation results are shown in Figure 4 and Table 10. As shown in Figure 4, the result of noncarcinogens was about 70% higher than that of carcinogens. Considering the results of the hazard index in Table 10, all the results of the daily intake and lifetime risk for cooking types were less than the acceptable level of the hazard index 1. This shows that the concentration of formaldehyde and acetaldehydes generated by cooking may not cause cancer risk for the house person. The study findings raise a concern about uncertainty regarding cancer risk because of the difference in values used for calculations of carcinogens and noncarcinogens. According to the study of Loh et al., this can be caused by a probable human carcinogen which can cause large uncertainties associated with the interpretation of variables [95].

5. Conclusion

Indoor air quality can be highly affected by various indoor activities. Among these activities, cooking can generate several indoor pollutants which have high risks to occupants' health. In addition, open floor plans in residential buildings in South Korea can spread the emission of indoor pollutants from the kitchen to the living room. The present study measured the indoor level of aldehydes by different cooking methods in 29 residential buildings. With the measured data, the health risk for occupants was assessed. The following conclusion can be made.

Among aldehydes, the indoor level of formaldehyde, acetaldehyde, and benzaldehyde was increased in the kitchen, while there were formaldehyde, butyraldehyde, and benzaldehyde in the living room. To figure out the emission rates of aldehydes by different cooking methods, the measure data were categorized by grilling, frying, and boiling in the kitchen and living room.

For grilling, the emission of formaldehyde, acetaldehyde, and propionaldehyde was highly increased, by which about 20%-80%. The increase rate of the concentration was higher in the kitchen than that in the living room. A similar trend of emission rates for frying was observed. In the case of boiling, the highest concentration of aldehydes was observed. Moreover, the indoor level of aldehydes was higher in the living room than that in the kitchen.

For the health risk assessment, chronic dose intake and lifetime cancer risk were calculated by using the measured data, and the results were also categorized by different cooking types. The results showed that all the cases were above 1×10^4, which requires some actions to avoid cancer risk for occupants. Thus, the current situation in the kitchen and living room requires more air change rates to dilute the emissions of aldehydes generated by cooking. For the present study, a majority of residential units in the study have used natural gas for cooking. Thus, it is considered that different cooking methods may be the only variable to differ in the emission of aldehydes. Because of insufficient information on some aldehydes, it was difficult to assess the health risk. By considering these points, the emission rates of aldehydes by different cooking fuels and other design variables of residential units will be investigated for further study.

Data Availability

The measured data of aldehydes used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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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