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Characteristics of Emissions of Volatile Organic Compounds from Smoldering Incense

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Burning incense is a common religious practice in Asia; however, this practice may result in severe adverse health effects (Schoental and Gibbard 1967). Epidemiological investigations also demonstrate the relationship between burning incense and lung cancer (MacLennan et al. 1977), childhood leukemia (Lowergard et al. 1987), brain tumors (Preston-Martin et al. 1982). Cytotoxic studies reveal that incense smoke may cause mutagenic effects and increase sister chromatid exchange (Löfroth et al. 1991; Chen et al. 1996). Moreover, the exact mutagenic effects owing to the smoke from burning Chinese incense are confirmed with the Ames tests (Rasmussen 1987; Sato et al. 1980).

Incense smoke is a complex mixture of gases and particles. The gaseous phase includes volatile organic compounds, aromatic aldehydes, aliphatic aldehydes (Schoental and Gibbard 1967; Lin and Wang 1994; Lin and Tang 1994; Chang et al. 1997; Lee and Wang 2004; Yang et al. 2006), and polycyclic aromatic compounds (PAHs) (Lin and Lee 1998). Gaseous PAHs and aliphatic aldehydes also detrimentally affect health. In addition, the particle phase is mainly submicrometer particles (less than 1 μm) (Yang et al. 2005), whose surface areas embed many organic compounds such as PAHs and aldehydes. Thus, adverse health effects with respect to the exposure to incense smokes may be as a result of the combination of extremely high €number of submicrometer particles and organic compounds occurring in those smokes.

The characteristics of incense smoke may vary with the ingredients of incense (carbon, hydrogen, nitrogen, water, volatility) and its combustion conditions (i.e., airflow, temperature, humidity and oxygen contents). Previous investigations that the reported data do not present the influence of incense composition on the VOCs emission from incense burning (Lee and Wang 2004). These studies could not thoughtfully explain the effects of the volatile organic compound emissions by both incense materials and environmental conditions. Hence, the study aims to elucidate the effects of various incenses with various chemical compositions on the yields of gaseous volatile organic pollutants during the incense combustion.

Materials and Methods

Three types of incense with various incense powders were chosen and tested in this study. They were non-smoke incense (Incense A), reduced-smoke Japanese Incense (Incense B), and standard smoke incense (Incense C, traditional incense). The powder components of Incense A were unknown due to business confidential. Incense B was made of Kataribe (Hinoki) powder, and Incense C was made of dried vegetation *Santalum album* L.. An elemental analyzer (2400 CHN Elemental Analyzer, Perkin–Elmer, USA) was used to measure the carbon, hydrogen, and nitrogen contents. The heating value was measured with an oxygen bomb calorimeter (1271 Oxygen Bomb Calorimeter, Parr Instrument Company, USA).

The testing system was illustrated (Fig. 1) and detailed elsewhere (Yang et al. 2005). The incense was ignited and

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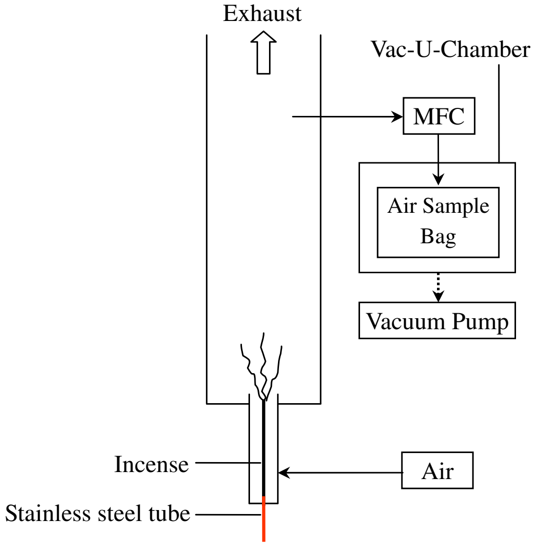

Fig. 1 Incense combustion system set-up

inserted into an incense holder at the bottom of the smoldering chamber. The flow of air (oxygen: 79%, nitrogen: 21%, Chiah Lung Gas Co., Taiwan), which was forced through a high efficiency particle air (HEPA) filter unit prior to be introduced into the gas mixing chamber to ensure complete mixing, was controlled by mass flow controllers. The testing flow rate was determined as 10 L/min based on our previous experiments (Yang et al. 2005) because the emission of total volatile organic compounds would be reaching steady when the airflow rate was higher than 10 L/min. The generated gases and aerosol pollutants were introduced into a 7.8 L test chamber. Before and after burning tests, the joss sticks tested were weighed to determine the net loss of mass, which was further used to calculate the incense-burning rate.

Gas phase volatile organic compounds were collected by a Tedlar sampling bag (232-03, S.K.C., USA), after the incense smoke particles were removed by quartz filter. These samples were collected at a flow rate of 220 mL/min for 3 min. The sample bag was then connected to an autosampler (ENTECH, 7016CA VOC Autosampler, USA) and an preconcentrator (ENTECH, 7100 Preconcentrator, USA). Finally, the gaseous organic compounds were analyzed by a gas chromatographer (Hewlett Packard, 6890 Gas Chromatograph, USA) equipped with a mass detector (Hewlett Packard, 5973 Mass Selective Detector, USA) following the US EPA TO-14A method (US EPA, 1997). The analytical conditions as follows: (a) an J&W DB-502.2 (60 m × 0.25 mm × 1.4 μm film thickness) column was used with a temperature program of 35°C for 5 min, a 5°C/min ramp to 90°C and 90°C for 2 min, a 7°C/min ramp to 170°C and 170°C for 3.3 min, a 10°C/min ramp to 210°C and 210°C for 5 min; (b) the flow rate for the carrier gas of He was 1.0 mL/min; (c) the injection volume was 5 or 10 mL. (d) the MS detector with scan mode operation was scanned from 45 to 330 amu (3–6 min), 29–330 amu (6–7 min) and 33–330 amu (excess 7 min) with an electron impaction energy of 70 eV.

The organic compounds were identified by comparing the sample mass spectra to the NIST (National of Standards and Technology) mass spectral libraries. Additionally, the standards of 52 volatile organic compounds (Spectra Gases Inc. USA) with 4 internal standard (methane, bromochloro-; benzene, 1, 4-difluoro-; benzene-d5-, chloro-; benzene, 1-bromo-3-fluoro-) were analyzed at the range of 1.42–32.51 ng to establish the standard calibration curves in order to determine the concentrations of volatile organic compounds collected. The correlation coefficients of calibration curves were always greater than 0.980. The method detection limits were determined by threefold standard deviation of seven measurements of the lowest concentration of calibration curve and ranged from 3.6 to 252.2 μg/m^3 (Table 1).

The emission rates and emission factors of gas phase volatile organic compounds were calculated, based on the conservation of mass, as following.

$$V \times \frac{\mathrm{d}C_\mathrm{i}}{\mathrm{d}t} = R \times E_\mathrm{f} - Q \times C_\mathrm{i} \tag{1}$$

where V (m^3) is the volume of the test chamber; C_i (μg/m^3) is the concentration of volatile organic compounds at a given time; R (g/h) is the incense-burning rate; E_f (μg/g) is the emission factor of each pollutant, and Q (10 L/min) is the air flow rate. When the dynamic equilibrium is reached, the $\mathrm{d}C_\mathrm{i}/\mathrm{d}t$ is equal to 0 and then removed. Thus the Eq. 1 is rewritten as following;

$$E_\mathrm{f} = \frac{Q \times C}{R} \tag{2}$$

In Eq. 2, the emission rate was calculated by multiplying the flow rate with the equilibrium concentration of a pollutant. The emission factor, E_f, was the specific emission rate that was normalized to incense burning rate. The expression for the concentrations of volatile organic pollutants was converted from ppb (v/v at 25°C, 1 atm) to μg/m^3 based on the ideal gas law.

Results and Discussion

The heating values of non-smoke incense (A), reduced-smoke incense (B), and standard smoke incense (C) were 5,060, 4,756, and 4,171 Kcal/Kg, respectively. The carbon, hydrogen, nitrogen and oxygen weight percentages of type A, B and C incenses were 62.0%, 2.6%, 0.70% and 21.6%; 53.4%, 4.7%, 0.5% and 28.8%; 48.4%, 4.9%, 0.8% and

Table 1 Method detection limits and the lowest concentration of calibration curve for individual compounds

ID	Compounds	MDL	R^2	ID	Compounds	MDL	R^2
1	Dichlorodifluoromethane	24.6	0.997	27	Ethylbenzene	22.2	0.981
2	Dichlorotetrafluoroethane	37.7	0.998	28	m/p-Xylene	42.1	0.980
3	Methane, chloro-	12.3	0.997	29	o-Xylene	19.9	0.983
4	Ethene, chloro-	18.6	0.997	30	Styrene	17.7	0.990
5	Methane, bromo-	31.1	0.997	31	Ethane, 1,1,2,2-tetrachloro-	31.8	0.977
6	Ethyl chloride	18.6	0.998	32	Benzene, 1,3,5-trimethyl-	22.0	0.988
7	Trichloromonofluoromethane	50.1	0.998	33	Benzene, 1,2,4-trimethyl-	22.4	0.993
8	Ethane, 1,1,2-trichloro-1,2,2-trifluoro	252.2	0.998	34	Benzene, 1,3-dichloro-	29.6	0.984
9	Ethene, 1,1-dichloro-	60.4	0.998	35	Benzene, 1,4-dichloro-	30.2	0.988
10	Methylene Chloride	16.8	0.985	36	Benzene, 1,2-dichloro-	32.1	0.986
11	Ethane, 1,1-dichloro-	17.5	0.986	37	Benzene, 1,2,4-trichloro-	53.4	0.990
12	Ethene, 1,2-dichloro-, (Z)-	16.8	0.982	38	1,3-Butadiene, 1,1,2,3,4,4-hexachloro-	65.0	0.994
13	Chloroform	22.1	0.993	39	1,3-Butadiene	86.1[a]	0.985
14	Ethane, 1,1,1-trichloro-	21.4	0.991	40	Ethanol	4.1	0.993
15	Carbon tetrachloride	33.2	0.997	41	Isopropyl Alcohol	3.7	0.995
16	Ethane, 1,2-dichloro-	17.8	0.987	42	Acetone	5.0	0.987
17	Benzene	14.4	0.982	43	2-Propenenitrile	88.8[a]	0.999
18	Trichloroethylene	27.9	0.980	44	2-Butanone	3.2[a]	0.997
19	Propane, 1,2-dichloro-	21.8	0.991	45	Ethyl Acetate	3.6	0.998
20	1-Propene, 1,3-dichloro-, (Z)-	19.2	0.980	46	1-Butanol	4.2	0.988
21	Toluene	16.5	0.997	47	2-Propenoic acid, 2-methyl-, methyl ester	110.4[a]	0.999
22	1-Propene, 1,3-dichloro-, (E)-	18.1	0.972	48	Methyl Isobutyl Ketone	6.1	0.986
23	Ethane, 1,1,2-trichloro-	25.3	0.993	49	Acetic acid, butyl ester	73.5[a]	0.998
24	Tetrachloroethylene	36.7	0.975	50	Cyclopentanone	59.1[a]	0.991
25	Ethane, 1,2-dibromo-	38.8	0.983	51	2-Heptanone	56.9[a]	0.998
26	Benzene, chloro-	21.0	0.984	52	Cyclohexanone	58.1[a]	0.991

Unit is μg/m^3

[a] Is the lowest concentration of the standard calibration curve

Table 2 The weight percentages of chemical compositions in elemental phase from non-smoke (A), reduced-smoke (B) and standard smoke (C) incenses

Elemental phase	Incense types		
	A	B	C
C	62.0	53.4	48.4
H	2.6	4.7	4.9
N	0.7	0.5	0.8
O	21.6	28.8	40.4

Unit is %

Table 3 The weight percentages of chemical compositions in molecular phase from non-smoke (A), reduced-smoke (B) and standard smoke (C) incenses

Molecular phase	Incense types		
	A	B	C
Water	5.9	9.6	8.9
Volatile	34.7	27.8	54.4
Ash	12.3	11.4	4.7
Fix. Carbon	47.2	51.3	31.9
Heatig value (Kcal/Kg)	5,060	4,756	4,171

Unit is %

40.4%, respectively (Table 2). In addition, the water, volatile, ash and fixed carbon weight percentages of type A, B and C incense were5.9%, 34.7%, 12.3% and 47.2%; 9.6%, 27.8%, 11.4% and 51.3%; 8.9%, 54.4%, 4.7% and 31.9% (Table 3). The carbon content of non-smoke incense was the highest than reduced-smoke incense and standard smoke incense. The burning rates of incense A, B and C were 2.53 ± 0.09 (average ± SD, $n = 3$), 0.97 ± 0.03 ($n = 3$) and 1.68 ± 0.04 ($n = 3$) g/h, respectively. The burning rate of non-smoke incense was faster than reduced-smoke and standard incense.

The results show the identification and quantification of the volatile organic compounds in the gaseous phase from burning incense A, B, and C. There were 29, 38, and 43 kinds of volatile organic compounds identified by comparing the sample mass spectra to the NIST from smoldering incense A, B, and C, respectively. However, only 14, 15 and 17 kinds of volatile organic compounds were identified in smoldering smokes of incense A, B and C compared with the chromatograph and mass spectra of real standard materials (Table 4). Based on the carcinogen classification by the International Agency for Research on Cancer (IARC), the results show that the benzene (1, human carcinogen) and 1, 3-butadiene (2A, probable human carcinogen) would be produced during the smoldering of Incenses A, B, and C. The acetaldehyde (identified by with NIST database), furan (identified by with NIST database), styrene and chloroform (2B, possible human carcinogen); toluene and xylene (3, not classifiable) also found during incense smoldering. In addition, it is noteworthy that methylchloride, methylene chloride and chloroform, which were reported by Lee et al. (2004), were also confirmed by our experiments. These chemical materials (methylchloride, methylene chloride and chloroform) might be used to dissolve the dyes in order to fabricate the incense colors. Others identified with real standards included ethanol, isopropyl alcohol, acetone, 2-propenenitrile, 2-butanone, cyclopentanone, ethylbenzene, 2-heptanone and 1, 2, 4-trimethylbenzene. The concentrations of total organic compounds (sum of the concentrations identified with real standards) released during the smoldering of non-smoke (A), reduced smoke (B) and standard smoke (C) were 4508.8 ± 472.0 ($n = 2$), 6992.6 ± 1638.8 ($n = 3$) and 18474.0 ± 673.8 ($n = 3$) μg/m^3, respectively. Thus the released amount of the total volatile organic compounds during the smoldering were the non-smoke incense < reduced-smoke < standard smoke incenses. Table 5 shows the emission rates of volatile organic compounds during the smoldering of non-smoke (A), reduced smoke (B) and standard smoke (C) incenses. The emission rates of benzene (1) for incense A, B and C were 1241.5 ± 98.9, 1082.3 ± 153.7 and 2971.2 ± 47.0 μg/h during the smoldering combustion, respectively; those of 1, 3-butadiene (2A) were 119.8 ± 1.5, 518.8 ± 72.8 and 1191.8 ± 26.9 μg/h, respectively; those of styrene (2B) were 134.6 ± 54.6, 294.6 ± 58.3 and 305.4 ± 36.4 μg/h, respectively. Those of toluene (3) were 380.1 ± 78.6, 773.0 ± 181.5 and 2484.7 ± 153.0 μg/h, respectively. Those of m/p/o-xylene (3) were 84.9 ± 19.8, 201.9 ± 53.9 and 244.7 ± 17.5 μg/h, respectively.

Table 4 Identification and quantification of the volatile organic compounds from non-smoke (A), reduced-smoke (B) and standard smoke (C) incense

Compounds	Incense type						Chemical carcinogens (IARC)
	A		B		C		
	Average (μg/m^3)	SD (μg/m^3)	Average (μg/m^3)	SD (μg/m^3)	Average (μg/m^3)	SD (μg/m^3)	
Methane, chloro-	ND	ND	330.08	386.32	736.25	671.07	
1,3-Butadiene	199.54	2.53	864.18	121.19	1985.16	44.80	2A
Ethanol	244.21	10.89	170.11	26.83	874.02	101.42	
Isopropyl Alcohol	71.61	6.61	99.88	20.19	ND	ND	
Acetone	606.71	22.53	1124.47	186.95	2940.67	18.79	
Methylene Chloride	36.28	0.80	39.61	2.37	87.57	9.78	
2-Propenenitrile	28.25	2.52	27.36	8.83	265.64	11.86	
2-Butanone	194.83	22.97	389.87	139.80	984.05	347.25	
Chloroform	ND	ND	ND	ND	163.94	76.23	2B
Benzene	2067.96	164.80	1802.72	256.04	4949.13	78.21	1
Toluene	633.07	130.87	1287.53	302.36	4138.67	254.84	3
Cyclopentanone	ND	ND	ND	ND	9.09	2.26	
Ethylbenzene	41.69	8.37	80.42	21.86	381.90	54.01	
m/p-Xylene	115.61	27.17	272.56	68.05	332.43	23.85	3
2-Heptanone	ND	ND	ND	ND	4.10	0.13	
o-Xylene	25.82	5.77	63.70	21.72	75.07	5.36	3
Styrene	224.13	90.87	415.68	97.12	508.76	60.63	2B
Benzene, 1,2,4-trimethyl-	19.11	1.25	24.39	1.11	37.52	2.88	
Total	4508.83	472.01	6992.57	1638.76	18474.0	673.83	

SD Standard deviation, *ND* not determined, possibly present at low level, *IARC* International Agency for Research on Cancer

Table 5 The emission rates of the volatile organic compounds from non-smoke (A), reduced-smoke (B) and standard smoke (C) incense

Compounds	Incense type						Chemical carcinogens (IARC)
	A		B		C		
	Average (μg/h)	SD (μg/h)	Average (μg/h)	SD (μg/h)	Average (μg/h)	SD (μg/h)	
Methane, chloro-	ND	ND	198.17	231.93	442.01	402.88	
1,3-Butadiene	119.80	1.52	518.82	72.76	1191.80	26.90	2A
Ethanol	146.61	6.54	102.13	16.11	524.72	60.89	
Isopropyl Alcohol	42.99	3.97	59.96	12.12	ND	ND	
Acetone	364.24	13.52	675.08	112.23	1765.45	11.28	
Methylene Chloride	21.78	0.48	23.78	1.42	52.57	5.87	
2-Propenenitrile	16.96	1.52	16.43	5.30	159.48	7.12	
2-Butanone	116.97	13.79	234.06	83.93	590.78	208.48	
Chloroform	ND	ND	ND	ND	98.42	45.76	2B
Benzene	1241.51	98.94	1082.28	153.72	2971.24	46.95	1
Toluene	380.07	78.57	772.98	181.53	2484.68	152.99	3
Cyclopentanone	ND	ND	ND	ND	5.46	1.36	
Ethylbenzene	25.03	5.03	48.28	13.13	229.27	32.43	
m/p-Xylene	69.41	16.31	163.63	40.86	199.58	14.32	3
2-Heptanone	ND	ND	ND	ND	2.46	0.08	
o-Xylene	15.50	3.46	38.24	13.04	45.07	3.22	3
Styrene	134.56	54.55	249.56	58.31	305.44	36.40	2B
Benzene, 1,2,4-trimethyl-	11.47	0.75	14.64	0.66	22.53	1.73	

SD Standard deviation, *ND* not determined, possibly present at low level, *IARC* is International Agency for Research on Cancer

Table 6 The emission factors of the volatile organic compounds from non-smoke (A), reduced-smoke (B) and standard smoke (C) incense

Compounds	Incense type						Chemical carcinogens (IARC)
	A		B		C		
	Average (μg/g)	SD (μg/g)	Average (μg/g)	SD (μg/g)	Average (μg/g)	SD (μg/g)	
Methane, chloro-	ND	ND	205.59	240.84	266.93	247.86	
1,3-Butadiene	47.34	2.10	538.05	79.15	710.35	37.10	2A
Ethanol	57.98	4.49	105.99	17.94	313.19	45.56	
Isopropyl Alcohol	17.02	2.13	61.99	11.66	ND	ND	
Acetone	144.02	9.93	700.62	123.97	1051.81	24.49	
Methylene Chloride	8.61	0.48	24.65	1.56	31.27	2.57	
2-Propenenitrile	6.71	0.79	17.05	5.57	95.09	7.06	
2-Butanone	46.30	6.55	243.04	88.37	350.17	113.77	
Chloroform	ND	ND	ND	ND	58.24	25.53	2B
Benzene	491.07	50.56	1122.28	166.03	1770.78	80.50	1
Toluene	150.66	34.29	801.73	191.81	1481.81	135.08	3
Cyclopentanone	ND	ND	ND	ND	3.26	0.90	
Ethylbenzene	9.89	2.04	50.18	14.19	136.90	23.37	
m/p-Xylene	27.46	6.71	169.89	43.81	118.79	5.00	3
2-Heptanone	N.D.	N.D.	N.D.	N.D.	1.47	0.09	
o-Xylene	6.13	1.40	39.69	13.71	26.82	1.12	3
Styrene	53.28	21.99	258.54	60.26	181.67	16.29	2B
Benzene, 1,2,4-trimethyl-	4.53	0.38	15.18	0.83	13.41	0.63	

SD Standard deviation, *ND* not determined, possibly present at low level, *IARC* is International Agency for Research on Cancer

It is noteworthy, the chloroform (2B) was also found in the smoke of incense C. The chloroform emission rate was 98.4 ± 45.8 μg/h. Conclusively, the increasing order of the emission of detrimental volatile organic compounds during the incense smoldering is the non-smoke < reduced-smoke < standard smoke incenses, with an exception of benzene (reduced-smoke < non-smoke < standard smoke incenses). Table 6 shows the emission factors of volatile organic compounds from smoldering non-smoke (A), reduced smoke (B) and standard smoke (C) incenses. The emission factors of benzene (1) for incense A, B and C were 491.1 ± 50.6, 1122.3 ± 166.0 and 1770.8 ± 80.5 μg/g, respectively; those of 1, 3-butadiene (2A) were 47.3 ± 2.1, 538.1 ± 79.2 and 710.4 ± 37.1 μg/g, respectively; those of styrene (2B) were 53.3 ± 22.0, 258.5 ± 60.3 and 181.7 ± 16.3 μg/g, respectively. The chloroform (2B) emission factor was 58.2 ± 25.5 μg/g for standard smoke incense. The emission factors of toluene (3) for incense A, B and C were 150.7 ± 34.3, 801.7 ± 191.8 and 1481.8 ± 135.1 μg/g, respectively; those of m/p/o-xylene (3) were 33.6 ± 8.1, 209.6 ± 57.5 and 145.6 ± 6.1 μg/g, respectively. According to the characteristics of the emission of volatile organic compounds causing adverse health effects, the emission factors of benzene (1), 1, 3-butadiene (2A) and toluene (3) are in the increasing order as follows: the non-smoke incense < reduced-smoke < standard smoke incenses. However, the emission factors of styrene (2B) and m/p/o-Xylene for reduced smoke incense were the highest among the tested incenses. Löfroth et al. (1991) and Lee et al. (2004) reported that the ranges of the benzene emission factor were 420–440 and 175–1,252 μg/g during incense burning. These values were consistent to the benzene emission from the non-smoke and reduced smoke incense smoldering in our experiments.

Notably, our results indicate much higher benzene emission when traditional incenses were burned. This difference might be due to various environmental combustion conditions and incense composition.

The concentrations of total organic compounds identified with the real standards were 4508.8 ± 472.0 (non-smoke incense), 6992.6 ± 1638.8 (reduced smoke incense) and 18474.0 ± 673.8 (standard smoke incense) μg/m^3. The emission of total volatile organic compounds may be associated with the incense compositions. The estimated molecular ratio of C:H:N:O:H_2O (based on Tables 2, 3) for incenses A, B, and C are approximately (103:39:1:20:6), (111:91:1:32:13), and (67:65:1:34:8), respectively. Based on the compositions of the tested incenses (Tables 2, 3), it implies that incenses with low-volatility materials and high carbon levels may minimize the production of total volatile organic compounds. Additionally, the high ratio of H/C will elevate the emission of total volatile organic compounds.

Smoldering incenses does produce many toxic volatile organic compounds (such as: benzene, 1, 3-butadiene, acetaldehyde, furan, styrene, chloroform, toluene, and xylene) and is an important pollutant source in the indoor environment. Hence, incense burning should be avoided indoors as possible. When one must smolder incenses owing to his/her culture or religion, the study suggests that burning incense with low-volatility materials and high carbon content may minimize the production of total volatile organic compounds, thus the health risk may be therefore significantly reduced.

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