

# Performance of Air Fresher System for the Removal of Various Odorants Released from Foodstuffs

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## ABSTRACT

The effectiveness of four air fresher (AF) systems was evaluated with respect to their removal efficiencies against offensive odorants. For this purpose, malodorous species were generated by exposing freshly cooked foods emitting odorants with levels moderately above their respective threshold values in a confined room. The deodorization efficiency of the four AF systems was then tested for a period of 30 min by estimating the extent of reduction in odorant levels after the operation of each AF. The removal efficiency of the four AF units against each odorant was evaluated as follows: (1) between AF products from different manufacturers, (2) between odorants and ultrafine particulate matter (PM<sub>2.5</sub>), and (3) between operation and natural degassing. The average sorptive removal of odorants was generally <80% and considered less effective or non-effective relative to PM<sub>2.5</sub>. Further examination of odor reduction, if evaluated in terms of odor indices like odor intensity (OI) and odor activity value (OAV), recorded a mean of 33% and 87%, respectively. The overall results of this study confirmed that all tested AF units were not effective to resolve odor problems created under our testing conditions.

**Key words:** Air fresher, Food odor, Hydrogen sulfide, Ammonia, Fresh food odor

## 1. INTRODUCTION

The demand for clean air is rapidly increasing. In our living environments, various odorants are released

from diverse sources or activities including cooking, use of spray products and cosmetics, or painting (Kim and Kim, 2014; Kim *et al.*, 2013; Lee *et al.*, 2012; Du *et al.*, 2011; Burbank and Qian, 2008; Frauendorfer and Schieberle, 2008; Ahn *et al.*, 2007; Lee *et al.*, 2006; Wettasinghe *et al.*, 2001). Odorants are very diverse and include various volatile species such as reduced sulfur compounds (RSCs), carbonyl compounds (CCs), volatile fatty acids (VFAs), nitrogenous compounds, and volatile organic compounds (VOCs). In fact, several VOCs (e.g., benzene, toluene, ethylbenzene, and the xylene isomers (BTEX)) represent the most commonly cited contaminants. However, there are a variety of VOCs with diverse odor profiles that contribute to odor pollution under various conditions in diverse settings.

The aftermath of active anthropogenic activities generally leads to the significant emission of volatile and odorous pollutants. Because many pollutants are carcinogens and/or allergens, they should be adequately treated to prevent potential health-related problems in many situations. In light of the significant problems associated with indoor pollution, the use of air fresher (AF) systems has become a common trend for the maintenance of air quality in confined environments. The efficiency of AF systems has often been recognized in the control of particulate matter (PM) (Huss *et al.*, 2010); in addition, AFs have been advertised for the removal of odorant substances. However, the reliability of AF systems with respect to odorant species has been poorly validated (Kim *et al.*, 2010; Choi *et al.*, 2002). So far, the most commonly employed means of mitigating odor pollution is decomposition by photocatalysis (Huang *et al.*, 2015; Yu *et al.*, 2013; Mo *et al.*, 2009; Geng *et al.*, 2008; Hodgson *et al.*, 2007; Sakai *et al.*,

2006; Ao and Lee, 2005; Kataoka *et al.*, 2005; Oh, 2003; Zhao and Yang, 2003). However, in light of the inherent shortcomings of AF systems (such as high cost, low availability, lack of portability, eye irritation etc.), many efforts have been put forward to develop efficient AF systems to diminish such issues (Kim, 2006).

In order to learn more about the performance of AFs in odor problem treatment, we investigated the deodorization capacity of four popular AF products commercially available on the Korean market. To examine their deodorization efficiency, we operated the different AF systems under strong malodorous atmospheres using a number of freshly cooked foodstuffs with intrinsic strong odorant properties. The analysis of diverse odorants was conducted both before and after the operation of each AF system and in reference to natural degassing conditions. The results of this study provide valuable insight into the removal characteristics of various odorants by the selected AF systems.

## 2. MATERIALS AND METHODS

In this work, four types of AF instruments (A, B, C, and D) were procured to test their performance against odor pollution originating from diverse foodstuffs and in reference to PM<sub>2.5</sub> (Huss *et al.*, 2010; Zhao *et al.*, 2007). Table 1S provides descriptive information on the AFs and sampling of the odorants. The chosen food samples are known to exhibit pungent smells (Lee *et al.*, 2012; Burbank and Qian, 2008; Wettasinghe *et al.*, 2001). We focused on a list of popular VOCs that are key offensive odorants such as acetaldehyde, hydrogen sulfide, and trimethylamine (KMOE, 2007). The basic physicochemical properties (e.g., chemical formula, structural formula, molecular weight, CAS number, etc.) of all target compounds (n = 24) that are designated as offensive odorants by the KMOE (2007) are summarized in Table 1. The detailed information of analytical procedures used for each air component is described in the supporting information (Table 2S) along with operation conditions for all instrumental systems. The procedures for their quantitation have been described in our recent study (Jo *et al.*, 2013)

### 2.1 Sample Collection

For the purpose of this study, four types of foodstuffs (soy bean soup, steamed egg, kimchi, and fermented skate fish) were purchased from a local market on the day of the AF test. Sampling was conducted in a room (capacity of  $\approx 20 \text{ m}^3$ ) at a mean temperature of  $22 \pm 1^\circ\text{C}$ . All four foodstuffs were placed on a table in the closed room for 10 min to ensure the generation of suf-

ficient odorant levels before air samples were collected using both sorbent tubes and bag samplers. Simultaneously, PM<sub>2.5</sub> was also quantified using a PM sensor. Each AF system was repeatedly operated for 30 min after removing the food samples from the room. Lastly, air samples were again collected and analyzed using each analytical instrument.

### 2.2 Instrumental Set-up for Analysis

In this study, a total of 17 odorous compounds (including two reference compounds) were measured by three different analytical methods: (1) air server (AS)/thermal desorber (TD)/gas chromatography (GC)/pulsed flame photometric detector (PFPD) for five sulfur compounds (hydrogen sulfide, methanethiol, dimethyl sulfide, and dimethyl disulfide), (2) TD/GC/mass spectrometry (MS) for 13 odorants (aldehyde, ketone, ester, alcohol, carboxylic groups, and trimethylamine), and (3) ultraviolet (UV)/visible (Vis) spectrophotometry for ammonia analysis based on the indophenol blue method (Kim and Kim, 2014; Kim and Kim, 2013, 2012). In addition to GC and spectrophotometry-based analysis, air dilution sensory (ADS) tests were performed based on the olfactometry threshold method by diluting odor samples with odorless pure air to determine the dilution-to-threshold ratio (D/T ratio) values (Kim and Park, 2008). Detailed information of these analytical procedures regarding the following targets is available in our previous work (Jo *et al.*, 2013) as well as in the supporting information of the present work (Table 2S).

### 2.3 Data Analysis

Apart from the preliminary quantitation of the differences between the input and output odorant concentrations, three analytical parameters, including percent sorptive removal (%SR), odor intensity (OI; (Nagata, 2003)) and odor activity value (OAV; (Qian and Wang, 2005)) were assessed in order to estimate the performance of the different AF units toward all different target odorants. Generally, the SR of an odorant is an indication of adsorption efficiency of the air purifier system. The SR was estimated as the difference in the concentration data for each odorant as given in equation 1:

$$\%SR = \left[ \frac{X_1 - X_2}{X_1} \times 100 \right] \% \quad (1)$$

where  $X_1$  and  $X_2$  represent the concentrations of odorant before (input) and after (output) exposure to the AF system, respectively. Following this simple estimation, the use of Student t-tests was employed to statistically investigate the significant differences between the efficiencies of each pair of treatment conditions (i.e., paired combination among different AF units (A, B, C

**Table 1.** List of the major odorants and volatile organic compounds investigated in this study.

Order	Group	Full name	Short name	CAS No.	Chemical formula	Molecular weight (g/mol)	RF	R <sup>2</sup>	MDL <sup>a</sup> (ng)	RSE <sup>b</sup> (%)	Instrumental analysis method <sup>c</sup>
1		Formaldehyde	FA	50-00-0	CH <sub>2</sub> O	30.0	18,882	0.9956	0.004	0.86	
2		Acetaldehyde	AA	75-07-0	C <sub>2</sub> H <sub>4</sub> O	44.1	14,647	0.9965	0.01	0.27	
3	Aldehyde	Propionaldehyde	PA	123-38-6	C <sub>3</sub> H <sub>6</sub> O	58.1	11,244	0.9968	0.01	0.06	
4		Butyraldehyde	BA	123-72-8	C <sub>4</sub> H <sub>8</sub> O	72.1	8,906	0.9966	0.01	1.27	
5		Isovaleraldehyde	IA	590-86-3	C <sub>5</sub> H <sub>10</sub> O	86.1	7,427	0.9966	0.01	1.52	
6		Valeraldehyde	VA	110-62-3	C <sub>5</sub> H <sub>10</sub> O	86.1	7,162	0.9970	0.01	1.15	DNPH-cartridge/ HPLC/UV
7	Ketone	Acrolein	Acrolein	107-02-8	C <sub>3</sub> H <sub>4</sub> O	56.1	13,511	0.9960	0.01	0.71	
8		Acetone	Acetone	67-64-1	C <sub>3</sub> H <sub>6</sub> O	58.1	9,408	0.9979	0.01	0.29	
9	Aldehyde	Crotonaldehyde	CA	4170-30-3	C <sub>4</sub> H <sub>6</sub> O	70.1	9,519	0.9961	0.01	1.89	
10		Benzaldehyde	BZA	100-52-7	C <sub>7</sub> H <sub>6</sub> O	106	6,211	0.9959	0.01	2.05	
11	Volatile fatty acids	Propionic acid	PPA	79-09-4	C <sub>3</sub> H <sub>6</sub> O <sub>2</sub>	74.1	10,047	0.9949	0.27	0.60	
12		n-Butyric acid	BTA	107-92-6	C <sub>4</sub> H <sub>8</sub> O <sub>2</sub>	88.1	8,604	0.9969	0.16	1.14	
13		i-Valeric acid	IVA	503-74-2	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	102	33,172	0.9987	0.09	0.41	
14		n-Valeric acid	VLA	109-52-4	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	102	28,028	0.9995	0.10	0.49	
15		i-Butyric acid	IBA	79-31-2	C <sub>4</sub> H <sub>8</sub> O <sub>2</sub>	88.1	39,131	0.9994	0.09	2.72	
16		Hexanoic acid	HXA	142-62-1	C <sub>6</sub> H <sub>12</sub> O <sub>2</sub>	116	39,684	0.9985	0.09	0.22	
17		Heptanoic acid	HPA	111-14-8	C <sub>7</sub> H <sub>14</sub> O <sub>2</sub>	130	32,166	0.9991	0.08	0.50	ST/TD/GC/Q-MS
18	Nitrogenous	Trimethylamine	TMA	75-50-3	C <sub>3</sub> H <sub>9</sub> N	59.1	46,196	0.9984	0.05	0.25	
19	Sulfurous	Hydrogen sulfide	H <sub>2</sub> S	7783-06-04	H <sub>2</sub> S	34.1	53.9	0.9992	0.15	3.94	
20		Methanethiol	CH <sub>3</sub> SH	74-93-1	CH <sub>4</sub> S	48.1	38.0	0.9981	0.22	3.46	
21		Dimethyl sulfide	DMS	75-18-3	C <sub>2</sub> H <sub>6</sub> S	62.1	34.5	0.9961	0.24	1.76	AS/TD/GC/SCD
22		Dimethyl disulfide	DMSD	624-92-0	C <sub>2</sub> H <sub>6</sub> S <sub>2</sub>	94.2	37.9	0.9961	0.22	2.19	
23	Nitrogenous	Ammonia	NH <sub>3</sub>	7664-41-7	NH <sub>3</sub>	17.0	18.3	0.9999	0.59	0.41	Sensor
24	Ultrafine dust particles	Particulate Matter Less than 2.5 μm	PM <sub>2.5</sub>	-	-	-	-	-	-	-	90° light-scattering laser photometer

<sup>a</sup>Method detection limit (MDL): The product of the standard deviation of 7 replicate analyses multiplied by the Student's t-test at the 99.9% confidence level (6 df, t = 3.14).

<sup>b</sup>Relative standard error (RSE): Triplicate analyses of the standards at one calibration point.

<sup>c</sup>HPLC = high-performance liquid chromatography, UV = ultraviolet, ST = sorbent tube, TD = thermal desorber, GC = gas chromatography, Q-MS = quadrupole mass spectrometer, AS = air server, SCD = sulfur chemiluminescence detector.

and D) as well as the natural degassing (E) condition). In the case of ultrafine dust removal (DR), %DR was also estimated.

The concept of OI and OAV pair can be used to numerically quantify or describe the strength of known odorants emitted from identifiable sources. The full details of these concepts have already been described in our recent work (Adelodun *et al.*, 2015). Therein, we stated that by the use of odorant concentration, the odor intensity (OI, measured in OU m<sup>-3</sup>) of all target compounds is calculated according to Stevens (1960), where psychophysical phenomena (stimuli) such as odor strength follows a power law (Stevens, 1960). The law is expressed as:

$$OI = kX^n \quad (2)$$

where X is the odorant concentration in mg m<sup>-3</sup>, k is the stimulus-dependent constant (Dravnieks *et al.*, 1986), and n is the characteristic constant of each odorant. The relationship between perceived psychological intensity and odorant concentration was later modeled by the Weber-Fechner law (modified from the Steven's law) as:

$$OI = a \log(X) + b \quad (3)$$

where a is the Weber-Fechner coefficient and b is the intercept constant (Jiang *et al.*, 2006). By the calculation of OI, the extent of reduction in odor intensity due to the purifiers could also be assessed in addition to the pattern for their concentration data. OAV (Qian and Wang, 2005), which is a dimensionless expression of odor strength, was obtained by the ratio of the odorant concentration after exposure (to a purifier, X<sub>2</sub>) to the odorant threshold value (Nagata, 2003; Nagata and Takeuchi, 2003). Regardless of the extent by which the odor concentration is reduced after treatment, the odorant removal system is deemed "not environmentally efficient" if OAV > 1, and vice versa. Hence, lower OAV values indicate a more efficient air purifier system in lowering odorant (and dust pollution) menace in the environment. Along with sorptive removal (%SR), these odor indices (OI and OAV) were used to judge the performance of the four commercially available air purifiers. Similarly, we also estimated percent reduction and we made comparisons with data presented in the open literature.

### 3. RESULTS AND DISCUSSION

#### 3.1 Removal of Odorant and Ultrafine Dust Particles by Air Purifiers

Using the analytical procedures described in Table 2S, the reduction in target odorant concentration (in

logarithm form) by the four AFs (A to D) and natural degassing (E) was monitored and recorded (Fig. 1S). The concentrations (in ppb) before (-1) and after (-2) use of each AF are listed in Table 2. We observed that all AFs did not show any significant response to five odorants (PA, IA, VA, CA, and BZA). All the odorants had an unchanged concentration value between initial and final measurements under our experimental conditions (1.59, 0.90, 0.75, 0.94, and 0.97 ppb, respectively) between blanks and samples. Apart from these five targets, ammonia was the only odorant that did not undergo any observable changes from natural degassing conditions (i.e. E1 = E2 = 1,000 ppb). As one of the most influential odorants most commonly encountered, a significant reduction in the concentration levels of ammonia would be an appreciable challenge for AF. However, as there was no detectable change in the concentration of ammonia in natural degassing, the performance of each AF cannot be directly compared relative to such conditions, i.e. below detection limit (BDL) as written in the footnote of Table 2. As the odorants that were BDL were not evaluated further, the total number of targets was reduced to 18 odorants for further statistical analyses.

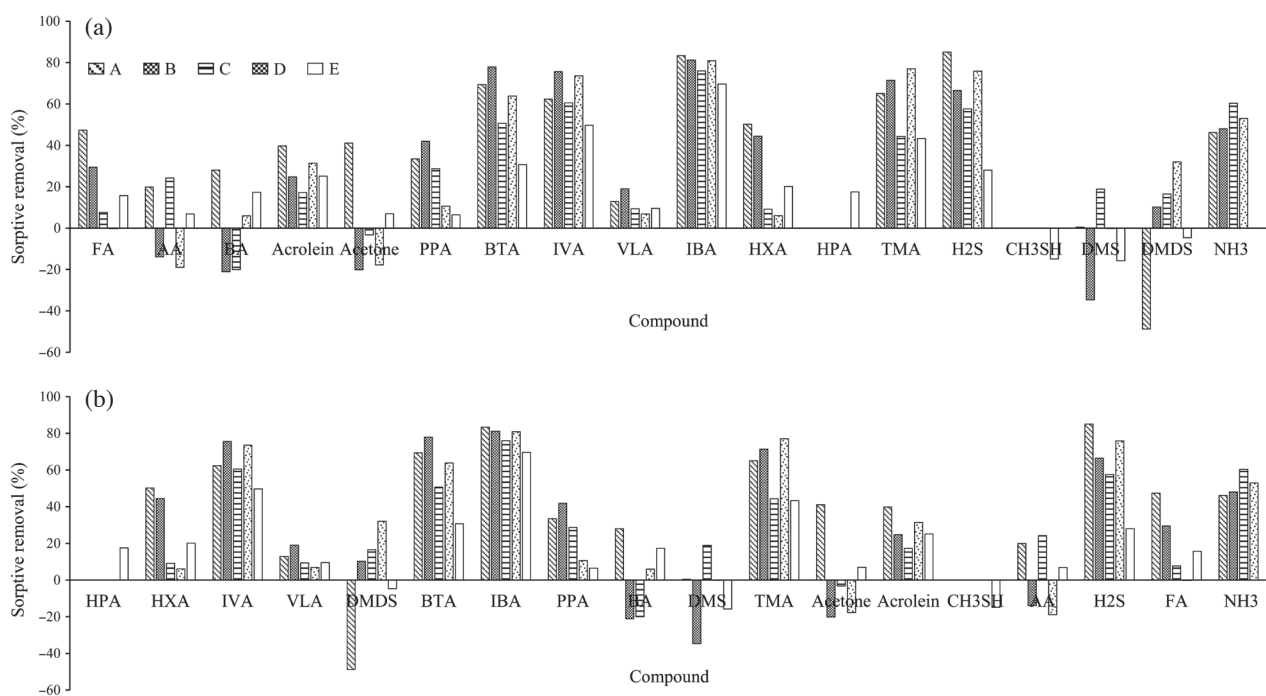
The %SR values were calculated (equation 1) to estimate the extent of reduction in the target odorant levels due to the AF operation (or degassing). The obtained results are provided in Fig. 1 (Table 3S). Because adsorption is known to be influenced by both surface chemical groups and atomic or molecular weights, comparisons among the odorants were made and depicted according to (a) chemical functionalities and (b) decreasing order of molecular weights. It was obvious from the haphazard distribution of %SR that the extent of sorptive removal was neither directly nor solely dependent on such criteria. In certain cases, the AFs lowered the level of odorants relative to those reduced by natural degassing. As such, the results suggest that the effectiveness of AF with respect to odorants is not satisfactory relative to PM. Exceptions to this affirmation were observed where one or two AFs tended to either increase the levels of specific odorants (by emission) or were inefficient (slower scavenging rate) when compared to natural degassing. According to Fig. 1(b), such cases included those of HPA (all AFs), HXA (C & D), DMDS (A), BA (B & C), DMS (B), acetone (B & D) and AA (C & D). Here again, since no AF showed superior preference toward a specific chemical group of odorants, a conclusive remark regarding discrepancies in efficiency and specificity among the AFs toward the various odorant targets could not be drawn. However, when considering differences in their chemical properties (Fig. 1(a)), it was found that all AFs performed very well (between 60% and 80%) against VFAs,

**Table 2.** Comparison of concentration levels of odorants and VOC measured from air samples.

Order	Group	Short name	Unit	Concentration of test samples								Blank sample		
				A-1	A-2	B-1	B-2	C-1	C-2	D-1	D-2	E1	E2	
1		FA	ppb	207	109	97.3	68.6	80.2	74.1	88.7	88.9	146	123	
2		AA	ppb	86.0	68.9	32.1	36.5	32.9	24.9	36.0	42.8	77.9	72.6	
3	Aldehyde	PA	ppb	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59 <sup>a</sup>	1.59	
4		BA	ppb	3.99	2.87	2.96	3.59	2.76	3.31	2.95	2.77	4.03	3.34	
5		IA	ppb	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	
6		VA	ppb	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	
7		Ketone	Acrolein	ppb	9.80	5.90	2.65	1.99	1.94	1.61	2.65	1.82	7.39	5.53
8			Acetone	ppb	32.6	19.2	15.7	18.8	12.1	12.5	14.4	16.9	50.4	46.9
9	Aldehyde	CA	ppb	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	
10		BZA	ppb	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	
11	Volatile fatty acids	PPA	ppb	2.31	1.54	3.28	1.90	2.40	1.71	2.48	2.22	2.74	2.56	
12		BTA	ppb	0.38	0.12	1.01	0.22	0.46	0.23	0.74	0.27	0.41	0.28	
13		IVA	ppb	1.28	0.48	3.56	0.87	1.30	0.51	2.91	0.77	1.40	0.70	
14		VLA	ppb	0.41	0.35	0.37	0.30	0.28	0.26	0.35	0.33	0.49	0.45	
15		IBA	ppb	9.21	1.53	28.0	5.26	9.81	2.35	21.0	4.02	9.94	3.02	
16		HXA	ppb	0.20	0.10	0.18	0.10	0.14	0.13	0.17	0.16	0.23	0.18	
17		HPA	ppb	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.07	0.06	
18		Nitrogenous	TMA	ppb	87.6	30.6	73.2	20.9	38.5	21.4	80.9	18.6	84.0	47.6
19		Sulfurous	H <sub>2</sub> S	ppb	14.4	2.15	15.3	5.11	17.8	7.56	16.2	3.90	27.9	20.1
20			CH <sub>3</sub> SH	ppb	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.34	1.53
21	DMS		ppb	0.88	0.87	0.53	0.71	0.67	0.54	0.91	0.91	1.27	1.48	
22	DMDS		ppb	1.18	1.75	0.75	0.68	0.85	0.71	0.85	0.58	2.11	2.21	
23	Nitrogenous	NH <sub>3</sub>	ppb	13,000	7,000	8,333	4,333	9,667	3,833	10,333	4,857	1,000	1,000	
24	Ultrafine particles dust	PM <sub>2.5</sub>	mg/m <sup>3</sup>	3.13	0.09	1.66	0.03	1.29	0.06	0.59	0.03	0.62	0.59	

<sup>a</sup>The underlined values imply results that were below the detection limit (BDL) of each sample.





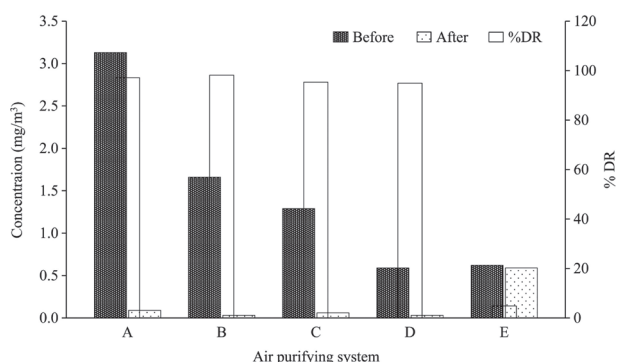
**Fig. 1.** Comparison of odor removal by natural degassing and air fresheners with respect to (a) chemical group and (b) molecular weight.

TMA, H<sub>2</sub>S, and NH<sub>3</sub>. However, in the case of AA, BA, acetone, DMS, and DMDS, a negative %SR was commonly seen. A negative %SR value in this work signifies an occurrence of self-emission of the specific odorant(s) by the AF or a situation whereby the rate of desorption was faster than the adsorption rate. The AF unit B demonstrated the worst performance in this regard. On average (~44% SR), the A product exhibited the highest removal efficiency amongst the different products. Apart from this rough estimation, the other AFs performed similarly well. By general comparison of their %SR, the removal of IBA was moderate (~78% SR) while that of DMS was worst (~23% SR).

Based on random removal efficiencies of the air purifying systems against various target odorants, Student's paired t-tests were used (on the %SR) to determine if significant differences were present between the treatment pairs, i.e. between five sets of data (resulting in 10 pairs: A-B, A-C, A-D, B-C, B-D, C-D, E-A, E-B, E-C, and E-D) by examining the removal efficiency of the odorants after treatment. The results derived from this test on a population or a number of the 18 target compounds ( $df = 17$  and confidence limit of 95%) are listed in Table 4S. Accordingly, significant differences in the performance between each pair ( $t_{cal}$ ) were greater than the tabulated values ( $t_{tab}$ ) (i.e.,  $t_{cal} > t_{tab}$ ) in all cases. Performance-wise, among the AFs (based on the

difference between  $t_{cal}$  and  $t_{tab}$  as well as between each pair of sorption efficiency), those for B and C products were the most closely related, while the highest discrepancy existed between the A and C products. It was also confirmed from this analysis that their correlation with natural degassing (E) was almost non-existent, as in most cases (especially for the E-A pair),  $t_{cal} > t_{tab}$ . Judging from the large differences in the two terms between the pairs of natural degassing and the AFs (relative to the differences between each AF pair), the following conclusions can be drawn. Most importantly, although the odor removal ability of the AFs was higher than that of the natural scavenging process, they were yet ineffective in completely removing or significantly ameliorating the odor that originated from the selected food sources.

The response of the air purifier systems toward ultra-fine particulates was also evaluated in reference to odorant data. From the actual concentration values provided in Table 2, we estimated percent dust removal (%DR) as shown in Fig. 2, and the values were compared along with the concentration values (before and after removal) to assess the relationship between the two conditions. When the extent of reduction was compared in terms of concentration levels amongst the AFs, purifier A was found to show the best removal ability toward ultrafine dust particles compared to oth-



**Fig. 2.** Comparison of PM<sub>2.5</sub> concentrations (before and after treatment) and removal efficiency (%DR) by each air fresher.

ers as it lowered the concentration by  $\sim 3.0$  mg/m<sup>3</sup>. Note that product D exhibited the worst performance in this respect at an  $\sim 0.5$  mg/m<sup>3</sup> reduction of concentration. Despite such differences, product D exhibited approximately the same %DR ( $\sim 95\%$ ; range of  $\sim 90$ - $96\%$ ) as products A, B and C. As such, most of the AFs effectively treated ultrafine dust relative to the odorants tested in this work. In the absence of AFs, the removal of PM<sub>2.5</sub> by natural means was found to be insignificant. We suggest that these particles are extremely fine and lightweight, and therefore tend to exhibit long residence time in the air by remaining suspended unless treated by the AF system.

### 3.2 Evaluation of Odor Intensity and Odor Activity Value

The paired indices of odor strength (OI and OAV) have often been studied in the field of odor chemistry to control and assess the actual effect of odor pollution instead of evaluation based on concentration values (Jiang *et al.*, 2006; Dravnieks *et al.*, 1986; Stevens, 1960b). These calculations enable the quantification of olfactory stimuli strength for easy evaluation of intensity as well as comparison with other odorants.

In this study, OI values were estimated both before and after treatment using equation 3 and the detailed results are described in Table 3. Again, some odorants measured at or below the detection limit were not assessed here. In addition, CH<sub>3</sub>SH and NH<sub>3</sub> were the only undetected odorants when natural degassing and the AF treatments were applied. Since the odorants were initially present at varying concentrations, calculating the percent reduction in terms of OI also quantitated the effect of the AF systems on each odorant. The results are depicted in Fig. 3(a). The odorants are arranged in descending order of %OI reduction to simulate the decreasing order of human tolerance. This comparison was also made along with those derived

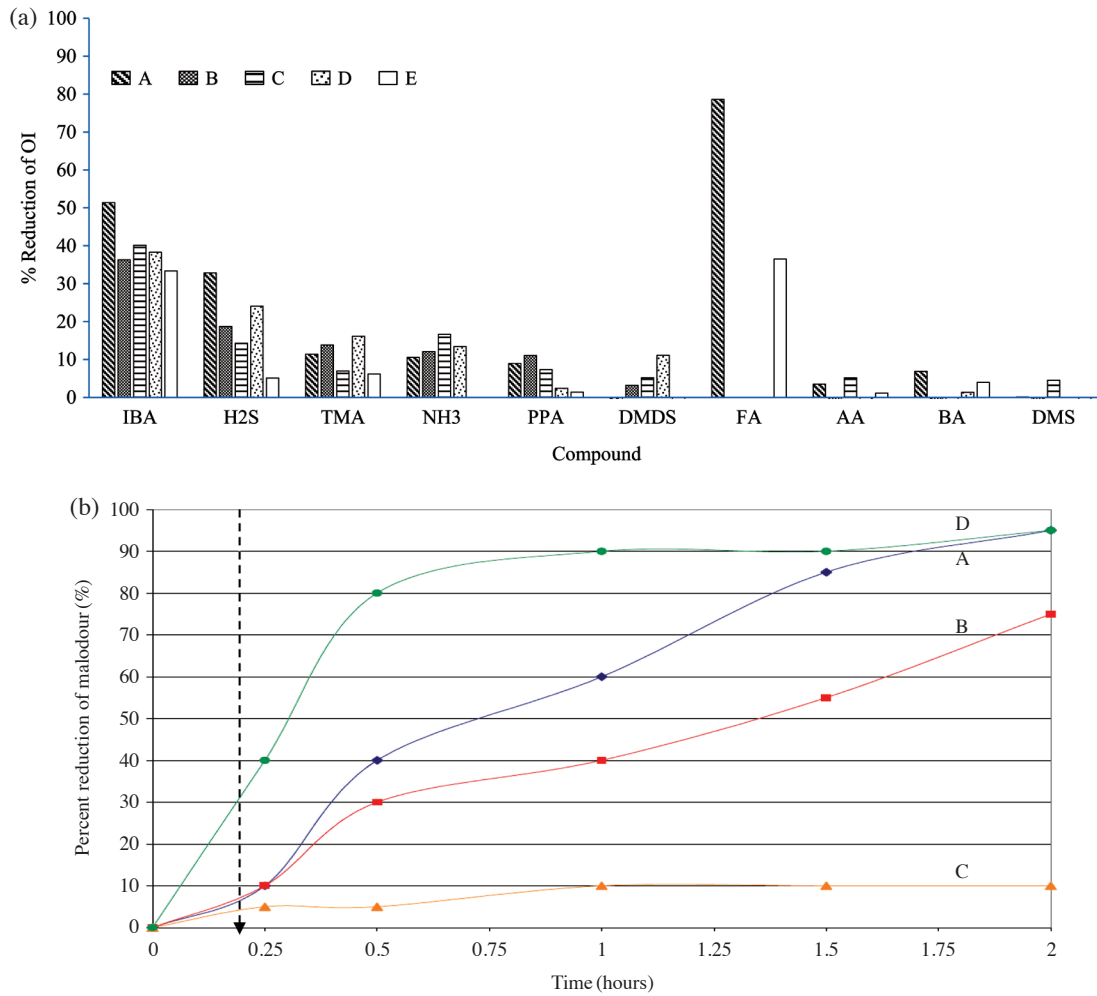
from natural degassing conditions. By virtue of OI values, the effect of the AF on various odorants was found to be random, as no AF showed either a particular preference or deterrent toward/against a particular or group of odorants. The after-treatment intensities (OI<sub>initial</sub>-OI<sub>final</sub>) of IBA, along with the two commonly encountered inorganic odorants (H<sub>2</sub>S and NH<sub>3</sub>), were found to be the highest while those of sulfur-containing compounds (DMDS, CH<sub>3</sub>SH, and DMS) were the lowest (Table 3 and Fig. 3(a)). However, the order of OI reduction was IBA > H<sub>2</sub>S > TMA > NH<sub>3</sub> > PPA, and was found as the all-positive reduction results from the exercise. The increase in OI after treatment was random; consequently, we could infer that the effect of odor reduction in terms of OI-based assessment is not effective to rank the performance between the different AFs. The performance of all the AF units in lowering OIs of target odorants were nonetheless better than those of natural degassing. Such affirmation specifically holds true for IBA, H<sub>2</sub>S, TM, NH<sub>3</sub> and PPA. Also, by comparing the ability of AFs to lower OI values, it was found that on average, purifier A was regarded as the product with the highest performance as it recorded superior values in OI reduction over the other products (Fig. 3(a)).

In a similar work, three air purifiers (A, B, and C) and one fragrance (D) were tested against odors emitted from food samples (McGinley and McGinley, 2006). The effect of the treatment was monitored with respect to the extent of the odorant reduction over a period of 2 h and the reduction in %OI was further computed and plotted (Fig. 3(b)). In the current work, we estimated the percent reduction in OI odors between the four AFs used as well as that of natural degassing. In order to ensure quantitative comparison of our work with the reference (see dotted arrow in Fig. 3(b)), the percent reduction in odor after 20 min (as the period of experimental exposure used in current work) was compared. It was reported that the three (A, B, C) AFs showed an average reduction in OI of 4.6% (range  $\sim 3.1\%$ - $6.7\%$ ) while D exhibited a distinct value of 37.3%. Despite the fact that we selected multiple target compounds for comparison, the AFs used in our study showed on average a comparatively similar percent reduction of OI.

The OAV values were also computed to assess how effectively odor was reduced after treatment (Table 4). More importantly, investigation into how significantly the AFs fared in elevating the sanity of the test atmosphere was conducted. Similar to the assessment based on OI, the results were also compared based on percent reduction in OAV as provided in Fig. 2S. Here, PA, IA, VA, and CH<sub>3</sub>SH were the only inestimable odorants due to aforementioned reasons (under sorptive removal and OI analyses). Unlike the findings







**Fig. 3.** Comparison of % reduction of odor intensity values of target odorants from (a) the current work with (b) similar results in the literature (McGinley and McGinley, 2006) (Note: Situations where the calculated % reduction in OI value is negative are not indicated in this figure).

based on OI analysis, the OAV results showed a more appreciable response of the AFs towards the odorants. A percent reduction as high as 87% was exhibited by most AFs in terms of OAV, and if the results are compared in terms of relative ordering, the most significant reduction in OAV after the treatment was seen from IBA, H<sub>2</sub>S, IVA, BTA, TMA, and NH<sub>3</sub>. At the other extreme, odorants such as DMS, AA, acetone, and BA (in no specific order) demonstrated the least reduction in OAV values, and remain as difficult targets to treat based on this criterion.

#### 4. CONCLUSION

An experimental survey to assess the effectiveness of four commercially available air fresheners against a

list of offensive odorants (and PM<sub>2.5</sub>) commonly emitted from cooking activities was conducted. In each case, performance of the AF units before and after operation was compared with a natural odor scavenging process. With regard to the %SR values, the AFs were helpful to lower the levels of the odorants. All AFs performed moderately (between 60% and 80% SR values) against certain odorants like VFAs, TMA, H<sub>2</sub>S, and NH<sub>3</sub>. In contrast, the AFs showed no reduction or a slight increase in AA, BA, acetone, DMS, and DMDS odors.

The effectiveness of AF operation was also assessed in terms of OAV. All AFs showed positive percent reduction values in OAV against 9 odorants, in descending order: IBA, H<sub>2</sub>S, IVA, BTA, TMA, NH<sub>3</sub>, acrolein, PPA, and VLA. In contrast, some odorants like DMS, acetone, and BA were seen to be the least affected by

**Table 4.** Odor activity values (OAV) for the main odorants emitted from gaseous samples.

Order	Group	Short name	Odor threshold (ppb)	Odor activity values (OAV)											
				A-1	A-2	B-1	B-2	C-1	C-2	D-1	D-2	E-1	E-2		
1	Aldehyde	FA	500	0.41	0.22	0.19	0.14	0.16	0.15	0.18	0.18	0.18	0.29	0.25	
2		AA	1.50	57.3	45.9	21.4	24.4	21.9	16.6	24.0	28.5	51.9	48.4		
3		PA	1.00	—	—	—	—	—	—	—	—	—	—		
4		BA	0.67	5.95	4.29	4.42	5.35	4.12	4.95	4.40	4.13	6.02	4.98		
5		IA	0.1	—	—	—	—	—	—	—	—	—	—		
6		VA	0.41	—	—	—	—	—	—	—	—	—	—		
7	Ketone	Acrolein	3.60	2.72	1.64	0.74	0.55	0.54	0.45	0.74	0.51	2.05	1.54		
8		Acetone	42,000	0.001	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0004	0.001	0.001		
11	Volatile fatty acids	PPA	5.70	0.41	0.27	0.57	0.33	0.42	0.30	0.44	0.39	0.48	0.45		
12		BTA	0.19	2.00	0.61	5.31	1.17	2.44	1.20	3.91	1.42	2.16	1.50		
13		IVA	0.08	16.4	6.18	45.7	11.1	16.7	6.57	37.3	9.87	17.9	9.03		
14		VLA	0.04	11.0	9.59	9.97	8.07	7.65	6.93	9.52	8.87	13.3	12.1		
15		IBA	1.50	6.14	1.02	18.6	3.51	6.54	1.57	14.01	2.68	6.62	2.01		
18	Nitrogenous	TMA	0.032	2,737	956	2,286	654	1,202	670	2,528	580	2,625	1,488		
19	Sulfur	H <sub>2</sub> S	0.41	35.2	5.24	37.3	12.5	43.5	18.4	39.5	9.52	68.1	49.0		
20		CH <sub>3</sub> SH	0.07	—	—	—	—	—	—	—	—	19.1	21.9		
21		DMS	3.00	0.29	0.29	0.18	0.24	0.22	0.18	0.30	0.30	0.42	0.49		
22		DMDS	2.20	0.53	0.80	0.34	0.31	0.39	0.32	0.39	0.26	0.96	1.01		
23	Nitrogenous	NH <sub>3</sub>	1,500	8.67	4.67	5.56	2.89	6.44	2.56	6.89	3.24	—	—		

the operation of AFs. The estimation of OAV is believed to better indicate odor remediation with respect to the usefulness of AFs than that of OI. This assumption is based on the direct relation of the former to the threshold values of human permissible limits. In this case, we suggest that OAV serves as a better indicator of human tolerance levels than OI, a more or less simple chemical index. Consequently, over natural means of degassing emitted odors from selected food materials, the AF systems used in this study were found ineffective in reducing the unpleasant discomfort that arises due to exposure to pungent, strong odors.

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**Table 1S.** Basic information of gaseous samples used for the performance evaluation of air purifiers with respect to the removal efficiency of odorants + PM<sub>2.5</sub>.

Order	Sample code	Manufacturer	Model	Area for exclusive use (m <sup>3</sup> )	Filter type <sup>a</sup>	Sampling point <sup>b</sup>	Date
1	A-1	WINIX	(A) WACU150	20.0	HEPA filter, Prefilter, Antivirus filter	Before operating air purifier	2015-06-23, 24
2	A-2				Carbon filter, Allergy filter	After operating air purifier	"
3	B-1	LG	(B) LA-V079SE	23.0	Prefilter, Deodorization filter	Before operating air purifier	2015-06-23, 24
4	B-2					After operating air purifier	"
5	C-1	Samsung	(C) AX20H5000NDD	22.0	HEPA filter, Prefilter, Deodorization filter	Before operating air purifier	2015-06-23, 24
6	C-2					After operating air purifier	"
7	D-1	Coway	(D) AP-0712FH (TROY)	21.5	Microfiber net-Prefilter, Deodorization filter	Before operating air purifier	2015-06-23, 24
8	D-2				Antivirus-HEPA filter	After operating air purifier	"
9	E-1	–	–	–	–	Before removing naturally	2015-06-22
10	E-2	–	–	–	–	After removing naturally	"

<sup>a</sup>HEPA filter: High efficiency particulate air filter.

<sup>b</sup>"naturally" means the foodstuff was left in closed room conditions in the absence of an AF.

**Table 2S.** Information of the main instrumental setups (HPLC, ST/TD/GC/Q-MS, AS/TD/GC/SCD, sensor and TSI system) used for the analysis of odorants and VOC.

## (A) Laboratory condition

Sample ID	Temp <sup>a</sup> °C	mVol (1 atm) L·mole <sup>-1</sup>
Water-bath	25	24.5

<sup>a</sup>Water bath-controlled temperature for collection with the sampling tube (using the ST/TD/GC/Q-MS system).

## (B) Operational conditions of HPLC system (CC)

Pump (SPECTRA SYSTEM P4000, Thermo Scientific)

Column: Acclaim120 C18 (Dionex)

Mobile phase	70 : 30 (Acetonitrile: H <sub>2</sub> O)
Injection volume:	20 μL
Flow rate:	1.5 mL min <sup>-1</sup>

Detector (SPECTRA SYSTEM UV2000, Thermo Scientific)

Wavelength:	360 nm
Analysis time:	20 min



**Table 2S.** Continued.

## (C) Operational conditions of ST/TD/GC/MS system (VOC)

GC (SHIMADZU GC-2010, JAPAN)/MS (SHIMADZU GCMS-QP2010, JAPAN)

Column: CP Wax (length: 30 m, diameter: 0.25 mm, film thickness: 2.5  $\mu\text{m}$ )

1) Oven setting		2) Detector setting		3) Carrier gas setting	
Temp. (hold time):	40°C (5 min)	Ionization mode:	EI (70 eV)	Gas type:	He (>99.999%)
Heating rate:	24°C min <sup>-1</sup>	Ion source temp:	230°C	Initial gas flow:	1.85 mL min <sup>-1</sup>
Max. temp (hold):	220°C (18 min)	Interface temp:	230°C	Constant gas pressure:	25 psi
Total time:	32 min	TIC scan range:	35-600 m/z		
		Scan speed:	1250 sec <sup>-1</sup>		

Thermal desorber (UNITY II, Markes International, Ltd., UK)

Cold trap sorbent:	Quartz wool + Carbo-pack C + Carbo-pack B (volume ratio = 1 : 1 : 1)		
Split ratio:	0.185	Adsorption temp:	5°C
Split flow:	10 mL min <sup>-1</sup>	Desorption temp:	330°C
Trap hold time:	5 min	Flow path temp:	180°C

Sampling (sorbent) tube

Absorbent:	Carbo-pack C + Carbo-pack B + Carbo-pack X (70, 50, and 50 mg)		
Desorption time:	7 min	Desorption temp:	320°C
Desorption flow:	100 mL min <sup>-1</sup>		

## (D) Operational conditions of AS/TD/GC/SCD system (RSC)

GC (7890A, Agilent Technologies, USA)

SCD (355 Sulfur Chemiluminescence Detector, Agilent Technologies, USA)

Column: HP-1 (length: 60 m, diameter: 0.32 mm, film thickness: 5  $\mu\text{m}$ )

1) Oven setting		2) Detector setting	
Temp. (hold time):	80°C (5 min)	Plasma temp:	800°C
Heating rate:	20°C min <sup>-1</sup>	Detector temp:	250°C
Max temp. (hold):	200°C (5 min)	H <sub>2</sub> flow:	40 mL min <sup>-1</sup>
Total time:	16 min	Air flow:	60 mL min <sup>-1</sup>
Gas type:	N <sub>2</sub> (>99.999%)		

Air server/Thermal desorber (UNITY I, Markes International, Ltd., UK)

Cold trap sorbent:	Carbo-pack B + Silica gel (volume ratio = 1.5 : 2.5)		
Split ratio:	7 : 1	Adsorption temp:	-15°C
Split flow:	10 mL min <sup>-1</sup>	Desorption temp:	275°C
Trap hold time:	5 min	Flow path temp:	80°C

(E) Operational conditions of NH<sub>3</sub> sensor system (NH<sub>3</sub>)

Ibrid MX6 (USA)

1) Sampling (Direct measurement)

Flow rate:	333 mL min <sup>-1</sup>	Interval time	5 min
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## (F) Operational conditions of the TSI system

TSI (Desktop DRX, 8533, USA)

Detector:	90° light-scattering laser photometer
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**Table 3S.** Comparison of the percent sorptive removal of target compounds for each air purifier.

Order	Group	Short name	Sorptive removal (%) <sup>a</sup>				
			A	B	C	D	E
1	Aldehyde	FA	47.4	29.5	7.63	-0.26	15.7
2		AA	19.9	-13.9	24.2	-18.9	6.84
3		BA	28.0	-21.1	-20.1	5.96	17.3
4	Ketone	Acrolein	39.8	24.8	17.2	31.4	25.2
5		Acetone	41.1	-20.2	-3.23	-17.8	6.94
6	Volatile fatty acids	PPA	33.5	41.9	28.7	10.6	6.42
7		BTAA	69.4	77.9	50.6	63.8	30.7
8		IVA	62.4	75.6	60.5	73.5	49.7
9		VLA	12.9	19.0	9.32	6.83	9.54
10		IBA	83.4	81.2	76.0	80.9	69.6
11		HXA	50.2	44.4	9.14	6.06	20.1
12		HPA	-	-	-	-	17.5
13	Nitrogenous	TMA	65.1	71.4	44.3	77.1	43.3
14	Sulfur	H <sub>2</sub> S	85.1	66.5	57.6	75.9	28.0
15		CH <sub>3</sub> SH	-	-	-	-	-14.9
16		DMS	0.47	-34.7	18.9	-0.21	-15.8
17		DMDS	-48.8	10.2	16.5	32.0	-4.70
18	Nitrogenous	NH <sub>3</sub>	46.2	48.0	60.3	53.0	-
19	Ultrafine particles	PM <sub>2.5</sub>	97.1	98.2	95.3	94.9	4.84

<sup>a</sup>Sorptive efficiency (%) = [(Conc. (Sample 1) - Conc. (Sample 2)) / Conc. (Sample 1)] \* 100.

**Table 4S.** Statistical analysis using paired Student t-tests between pairs of odorant removal efficiencies.

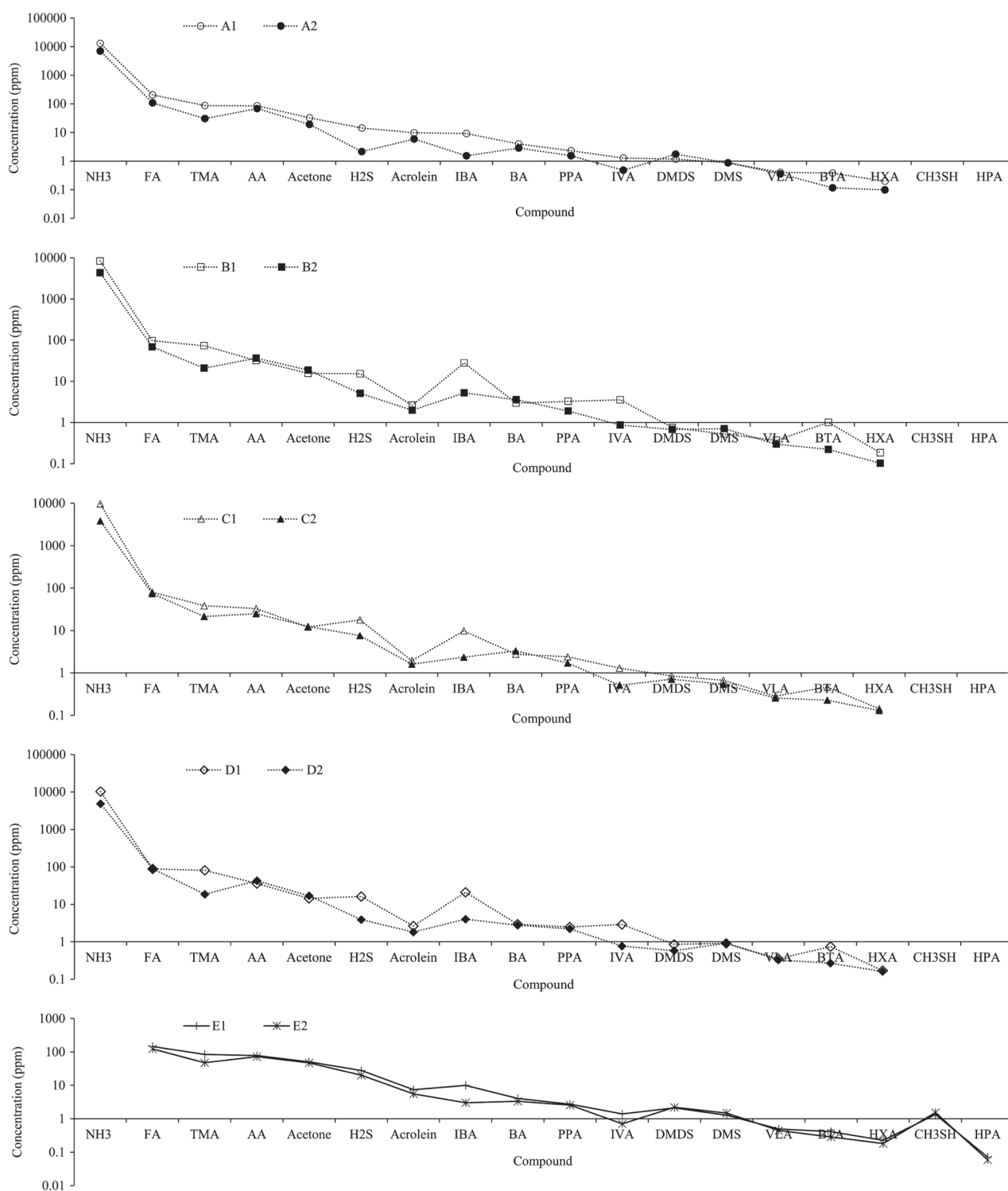
Paired data set	A-B	A-C	A-D	A-E	B-C	B-D	B-E	C-D	C-E	D-E
<i>Parameters</i>	1.1766	1.5580	1.2218	-3.6531	0.4819	0.2854	-2.1272	-0.2882	-1.9550	-2.0330
<sup>a</sup> t <sub>cal</sub>	0.2566	0.1428	0.2402	0.00214	0.6371	0.7790	0.0493	0.7769	0.0683	0.0590
<sup>b</sup> t <sub>tab</sub>	-6.342	-3.825	-0.848	-38.98	-9.190	-8.819	-33.47	-11.06	-29.32	-31.44
95% <sup>c</sup> CI	~22.16	~25.04	~25.41	~10.36	~14.58	~11.56	~0.0577	~8.419	~1.1869	~0.6586
Mean of differences	7.910	10.61	9.282	-24.68	2.696	1.372	-16.77	-1.325	-14.06	-15.39
Conclusion ( <sup>d</sup> sd)	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE

<sup>a</sup>t-cal = calculated student t-value.

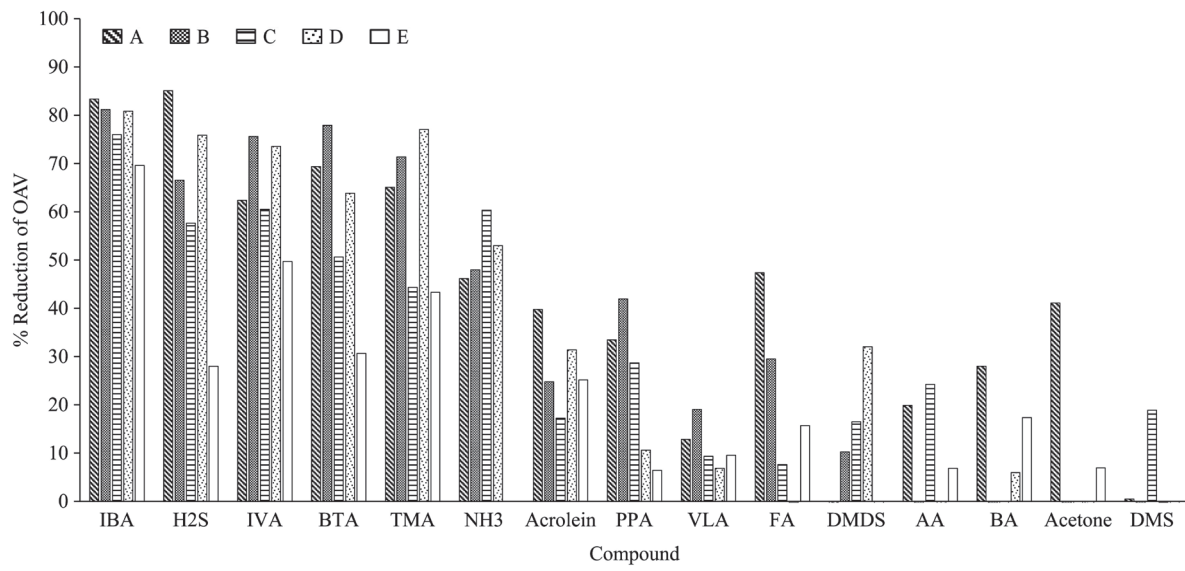
<sup>b</sup>t-tab = theoretical/tabulated student t-value.

<sup>c</sup>CI = confidence interval.

<sup>d</sup>sd = significant difference. If TRUE, it means it does EXIST; if FALSE, it means it does NOT EXIST.



**Fig. 1S.** Comparison of measured concentrations of odorants between the before and after operation of each air fresher.



**Fig. 2S.** Comparison of calculated percent reduction of odor activity values after exposure to air fresher systems.