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Improvement of indoor air quality in pet shop using gaseous chlorine dioxide

Ming-Chun Lu · Da-Ji Huang · Ching-Shan Hsu · Chih-Kuo Liang · Geng-Min Chen

Abstract Many studies have shown that pet shops have a high concentration of bioaerosols. Thus, effective disinfection protocols are essential to protect the pet shop staff and visitors to the store. The present study examines the effectiveness of gaseous chlorine dioxide (ClO_2) fogging in minimizing the residual bacteria and fungi levels in a typical pet shop in Taiwan consisting of a commodity area, a lodging area, and a grooming area. This investigation uses three disinfection modes (DMs) according to different disinfection periods, namely once every hour (1DM), once every 2 h (2DM), and once every 3 h (3DM). The bacteria and fungi concentrations are measured before and after disinfection treatment, and the effectiveness of each disinfection mode is evaluated using standard statistical techniques. To assess the effect of the environmental factors on the disinfection efficiency, measurements are taken of temperature, relative humidity, airflow velocity, the carbon dioxide concentration, the PM_1, $PM_{2.5}$, PM_7, PM_{10}, and TSP level at each sampling locations. The results reveal that the effectiveness of the three disinfection modes depends on both the environmental parameters and the use of the three areas (e.g., commodity, lodging, or grooming).

Hence, the choice of disinfection method should be adjusted accordingly. For all three disinfection modes, a faster air velocity is beneficial in spreading the disinfectant throughout the indoor space and improving the disinfection performance. Overall, the results presented in this study confirm that gaseous chlorine dioxide disinfection improves the air quality in the pet shop interior, and thus beneficial in safeguarding the health of the pet shop staff and visitors.

Introduction

The problem of indoor air microbial contamination has attracted significant attention in the literature due to its potentially adverse effects on human health (US EPA 2007; Canter et al. 2005). Microbial pollutants are associated with many medical disorders, such as allergies, asthma, and infectious diseases (Mitchell et al. 2007). Previous studies have shown that the accumulation of microorganisms is particularly severe in indoor environments due to animal housing, treatment, and grooming (Lehtonen et al. 1993; ACGIH 1999). These microorganisms not only jeopardize the health of the workers and customers in the store but may also result in disease outbreak among the pets. Consequently, reducing the airborne bacteria concentration through effective disinfection protocols is essential in ensuring the air quality of the indoor environment.

M.-C. Lu · D.-J. Huang · C.-S. Hsu (✉) · G.-M. Chen
Department of Environmental Resource Management, Chia-Nan University of Pharmacy and Science, Tainan 71710, Taiwan
e-mail: hsuhsu@mail.cnu.edu.tw

C.-K. Liang
Department of Electrical Engineering, National Taitung Junior College, Taitung 95045, Taiwan

In Taiwan, as in many other countries around the world, the relationship between pets and their owners has changed remarkably over the past few decades, with pets now increasingly being regarded as actual family members. Moreover, according to a recent market report, the number of pets and pet products in Taiwan is growing (Euromonitor International 2017). Thus, the number of pet shops in Taiwan is also expected to increase year by year.

A third of pet shop workers in Sweden reported airway symptoms at work or were sensitized, sometimes to unusual pet shop allergens (Renström et al. 2011). Thus, it is essential to raise awareness of potential health risks and effective allergen avoidance measures among pet shop staff and to develop stringent disinfection protocols to promote the general well-being of the staff and customers of the store. The National Institute of Occupational Safety and Health in America and the American Conference of Governmental Industrial Health (ACGIH) have ruled that the total number of bioaerosol particles in indoor environments should not exceed 1000 CFU/m^3, while the total culturable count for bacteria should not be higher than 500 CFU/m^3 (NIOSH 1998; ACGIH 1989; AIHA 1996). In addition, the Taiwan Environmental Protection Administration (TEPA) has stated that for indoor public spaces, the bacteria concentration should not be higher than 1500 CFU/m^3, while the fungi concentration should not exceed 1000 CFU/m^3 (Taiwan EPA 2012).

Gaseous chlorine dioxide (ClO_2) is one of the most commonly used treatments for the remediation of structures impacted by microbial growth (US EPA 2007) and is recommended as a disinfectant by the World Health Organization (WHO 2003) of the United Nations. ClO_2 can destroy all manner of microorganisms, including bacteria, spores, fungi, viruses, and even protozoans (Ogata and Shibata 2008; Sivaganesan et al. 2003; Loret et al. 2005; Sanekata et al. 2010). Furthermore, it readily dissolves in water and becomes a stable state of small particles. At room temperature conditions, the ClO_2 content within the water evaporates and propagates naturally through the local environment, providing a strong disinfection effect. Since it is in gaseous form, the ClO_2 molecules penetrate deeply into building cavities, wall cavities, and other hard-to-access areas, and therefore provide an extremely thorough disinfection function (Buttner et al. 2004). Additionally, ClO_2 kills microorganisms at low concentrations, even when they are inactive (Lenntech 2014). A past study by the US EPA has shown that ClO_2 results in no physiologically relevant alterations in human or animal health provided that it is present only in low concentrations (US EPA 2000).

This study investigates the effectiveness of gaseous ClO_2 in improving the air quality within a typical pet store in Taiwan. Three different disinfection modes (DMs) are considered, namely once every hour (DM1), once every 2 h (2DM), and once every 3 h (3DM). In every case, the ClO_2 is applied using an ultrasonic aerosol procedure. To investigate the effectiveness of the different DMs, the air quality (i.e., the bacteria and fungi concentration level) is evaluated in three different areas of the pet shop before and after disinfection. Statistical differences in the pre- and post-disinfection colony counts are then identified by means of a post hoc Duncan's multiple-range test.

Material and methods

This work was conducted over a 1-year period from January 2015 to January 2016. Prior to disinfection, air samples were collected and analyzed in order to determine the background concentrations of bacteria and fungi. ClO_2 disinfection was then carried out using the three different application procedures described above. On each sampling day, air samples were collected over a 6-h period in order to evaluate the change in the bacteria and fungi concentration levels over the course of the working day. For each application mode, the ClO_2 disinfection process was performed three times over the 12-month study period. The details of the experimental procedure are described in the sections below.

Study area and sampling time

Figure 1 shows the floor plan of the pet shop considered in the present study. The shop has a total volume of 1051 m^3 and consists of a commodity sales area (815 m^3), a lodging area (18 m^3), and a beauty and grooming area (218 m^3). Disinfection was performed at three different locations in the shop, as indicated by the triangular symbols in Fig. 1. By contrast, sampling was conducted at four locations, namely three locations within the store (i.e., in the commodity area, lodging area, and beauty area) and one location outside the store. Air samples were collected in accordance with the NIEA (National Institute of Environmental Analysis) guidelines specified by the TEPA (Taiwan EPA 2012). On each
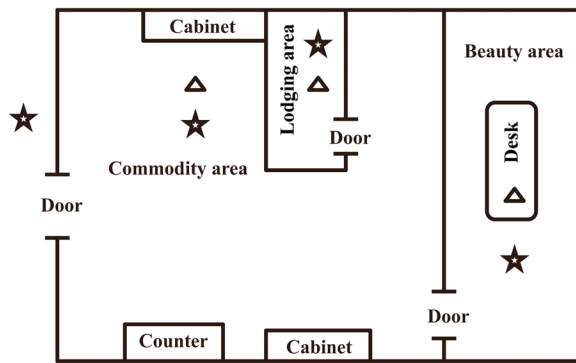
Fig. 1 Floor plan of pet shop (sample collection location (★); disinfection location (△))

sampling day, indoor air samples were collected at hourly intervals between 10:00 a.m. and 4:00 p.m. The samples were analyzed in order to determine the concentrations of the various biological (i.e., bacteria and fungi) and non-biological (i.e., suspended particle) components. The particulate matter concentrations (PM_1, $PM_{2.5}$, PM_7, and PM_{10}) and total number of suspended particles (TSP) were measured using an Aerocet-531 Mass Particle Counter (Met One Instruments, Inc., USA). To ensure the reliability of the analytic results, each sample was tested in triplicate. To investigate the effects of environmental factors on the ClO_2 disinfection efficiency, the relative humidity and temperature were measured each time a sample was collected using a TES-1364 Humidity Temperature Meter (TES, Taiwan). In addition, the air-flow velocity and CO_2 concentration were measured using a Q-TRAK IAQ meter (Model 7565, TSI, USA).

Disinfection methods

According to the literature, the permissible exposure limits (PELs) for ClO_2 are as follows: (a) general industry 0.1 ppm and 0.3 mg/m³; (b) construction industry 0.1 ppm and 0.3 mg/m³ time-weighted average (TWA); (c) American Conference of Governmental Industrial Hygienists 0.1 ppm and 0.28 mg/m³ TWA; 0.3 ppm and 0.83 mg/m³ short-term exposure limit (STEL); and (d) National Institute for Occupational Safety and Health 0.1 ppm TWA; 0.3 ppm STEL (US OSHA 2006). As described above, the commodity area, lodging area, and beauty area of the pet shop had cubic volumes of 815, 18, and 218 m³, respectively. Thus, to satisfy the 8-h TWA maximum exposure limit of 0.3 mg/m³ for ClO_2 (US OSHA 2006), ClO_2

disinfection in the commodity area, lodging area, and beauty area was performed using 0.987, 0.022, and 0.262 L ClO_2 solutions (250 mg/L), respectively. The ClO_2 solution was applied using ultrasonic aerosol devices (Model EP606, Great Long Co., Ltd., Taiwan) placed at three locations in the pet shop. In general, ClO_2 exists in gaseous form at temperatures higher than 11 °C (Hsu et al. 2015). In the present study, the average temperature within the pet shop was consistently higher than 11 °C throughout the entire study period, and hence, the ClO_2 solution evaporated upon application, resulting in the gradual release and propagation of ClO_2 molecules throughout the pet shop environment.

One each sampling day, an initial sampling process was performed at 9:00 a.m. in order to obtain the background colony counts of bacteria and fungi. Air samples were then collected on an hourly basis until 4:00 p.m. As described above, three different disinfection modes (DMs) were implemented namely, once every hour (1DM), once every 2 h (2DM), and once every 3 h (3DM). In the 1DM method, the ClO_2 solution was applied at 10:00 a.m. and replenished every 1 h. In the 2DM method, the ClO_2 solution was applied at 10:00 a.m. and replenished every 2 h. In the 3DM method, the ClO_2 solution was applied at 10:00 a.m. and replenished every 3 h. Thus, the overall ClO_2 dosage of 1DM, 2DM, and 3DM was different. For each disinfection mode, the disinfection/sampling process was limited to a single day.

Air sample collection

Air samples with a volume of 1000 L were collected in accordance with the relevant Taiwan NIEA guidelines (i.e., NIEA E301.12C for bacteria and E401.12C for fungus (Taiwan EPA 2008). The samples were collected using a MAS-100 Eco Microbial Air Sampler (Merck, Germany, 100 L/min) containing petri dishes with tryptic soy agar (TSA) plates and malt extract agar (MEA) plates. Following a 10-min collection period, the petri dishes were removed from the sampler in order to cultivate the bioaerosols. For the bacteria bioaerosols, the TSA plates were incubated at a temperature of 30 ± 1 °C for 48 ± 2 h. For the fungi bioaerosols, the MEA plates were incubated at 25 ± 1 °C for 4 ± 1 day. Following the respective incubation periods, the bacteria and fungi levels were evaluated by counting the number of colonies formed on the agar surfaces.

Statistical analyses

The collected data were analyzed statistically using commercial SPSS software (SPSS, 2003; Version 12.0). Colony-time curves showing the variations in the residual bacteria and fungi concentration levels over the course of the sampling day were estimated using a regression analysis technique based on the logistic curve mode in Organ 8 software. MANOVA tests were performed to evaluate the relative effects of the environmental factors on the disinfection performance in the three different areas ($p = 0.05$; SPSS Inc., USA 2003). A post hoc Duncan's multiple-range test was used to evaluate the disinfection efficiencies of the three disinfection methods. Finally, the Spearman's rank correlation coefficient test was used to assess the relationships among the colony counts and environmental parameters after disinfection.

Results and discussion

As described above, the pet shop consisted of three main areas, namely a commodity area (selling pet food and other pet-related articles), a lodging area (providing short-term accommodation for pets), and a beauty area (providing washing and grooming services). Indoor environments potentially pose a far greater risk to human health than outdoor environments since the enclosed space can lead to a dangerously high accumulation of bioparticles and other harmful contaminants (CEC 1993). In fact, a third of pet shop workers have reported the occurrence of airway symptoms while at work (Renström et al. 2011). This study performed an experimental investigation into the disinfection efficiency of gaseous ClO_2 in the three areas of the pet shop over a 1-year period extending from January 2015 to January 2016.

Figures 2 and 3 show the experimental results obtained for the residual bacteria and fungi colony-time curves, respectively. According to the Taiwan EPA guidelines, the indoor bioaerosol concentration should be lower than the equivalent outdoor concentration. Furthermore, the indoor bacteria and fungus colony counts should be less than 1500 and 1000 CFU/m^3, respectively (Taiwan EPA 2012). However, when the indoor/outdoor fungus concentration ratio is less than or equal to 1.3, the fungus concentration limit of < 1000 CFU/m^3 does not apply. An inspection of Fig. 3 shows that the fungus concentration ratio is indeed less than 1.3 in all three areas of the pet shop. Thus, the limit of 1000 CFU/m^3 need not be

considered in the present case, and it is sufficient to infer simply that the indoor fungus concentration is not adversely affected by the outdoor concentration.

Figure 2 shows that when disinfection is not performed, the background (BG) concentration of bacteria tends to increase with an increasing store opening time. Furthermore, in some areas of the store (e.g., the commodity area and the lodging area), the bacteria concentration exceeded the maximum permissible concentration level prescribed by the EPA (i.e., 1500 CFU/m^3). Therefore, applying some form of indoor disinfection process is essential in protecting the health of the store occupants and pets. Comparing the results obtained for the three different disinfection methods, it was found that the disinfection efficiency of the 1DM protocol was generally better than that of the 2DM method, while the disinfection efficiency of the 2DM method was better than that of the 3DM method. A detailed inspection of the results obtained in the commodity area of the store revealed that for the 1DM and 2DM disinfection protocols, the number of bacteria decreases with an increasing post-disinfection time. However, for the 3DM treatment mode, the number of bacteria started to increase 2 h after the application of ClO_2. This suggests that the large volume of the commodity area, together with its close proximity to the entrance of the store, resulted in a more rapid dilution of the ClO_2 concentration and a corresponding reduction in the disinfection efficiency. However, the residual bacteria concentration is still less than 1500 CFU/m^3 and thus conforms to health guidelines. In the lodging area, all three disinfection methods had reasonable performances. However, the bacteria concentration nevertheless tends to increase with an increasing store opening time. Given the use of the 1DM and 2DM treatment protocols, the bacteria concentration fell to less than 1000 CFU/m^3 within 2 h. By contrast, for the 3DM method, the bacteria concentration fell to less than 1000 CFU/m^3 more slowly (i.e., after around 4 h). In the beauty area of the store, the 1DM method resulted in the best disinfection performance of the three methods. For the 3DM method, the bacteria concentration once again decreased relatively slow, which suggested that the average disinfection dose was insufficient. Nonetheless, the background bacteria concentration in the beauty area was lower than that in the lodging area, and hence, the bacteria concentration was lower than the recommended guideline of 1500 CFU/m^3 for all three disinfection protocols at all six sampling times.

As shown in Fig. 3, the background fungi concentration in the commodity area reduced from an initial value
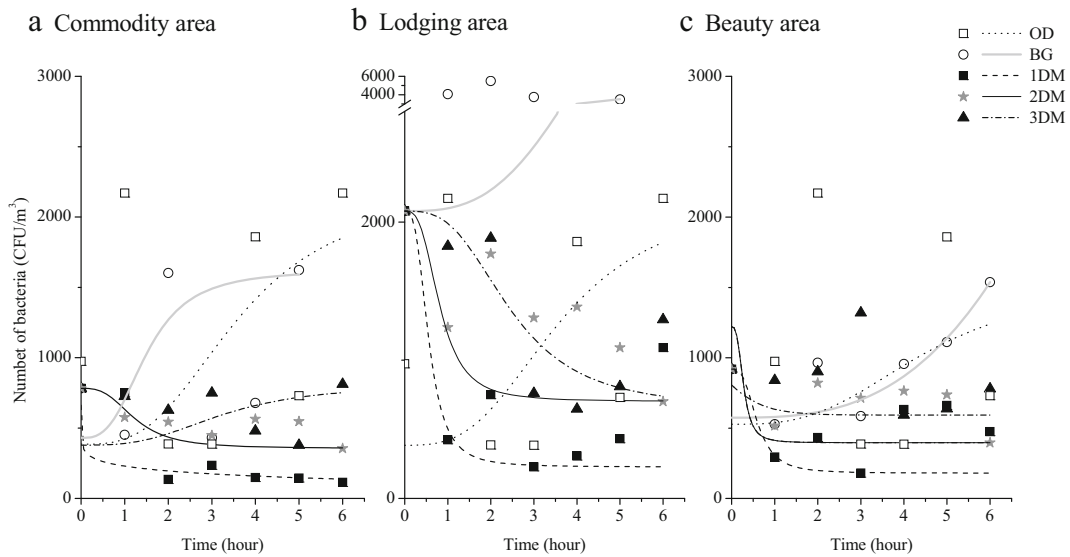
Fig. 2 Variation of residual bacteria colonies at three indoor sampling points (**a** commodity area, **b** lodging area, **c** beauty area) following disinfection using three disinfection modes (1DM, 2DM, and 3DM). Note that outdoor (OD) and background (BG) bacteria colony counts are also provided for reference purposes

of approximately 1000 CFU/m³ as the store opening time first increases. However, after approximately 3 h, the concentration level started to increase once again. For all three disinfection protocols, the fungi concentration generally reduces with an increasing post-disinfection time. However, the rate of reduction was relatively slower for the 1DM treatment mode. For the lodging area, all three disinfection methods showed a

reasonable performance, and no obvious difference in the disinfection efficiency was observed. However, in the beauty area, the 3DM method had a notably lower disinfection efficiency than the 1DM or 2DM method due to the longer disinfection interval.

Table 1 shows the experimental values (mean ± SD) of the environmental parameters in the three investigation areas of the store. It is seen that of the three sampling areas,
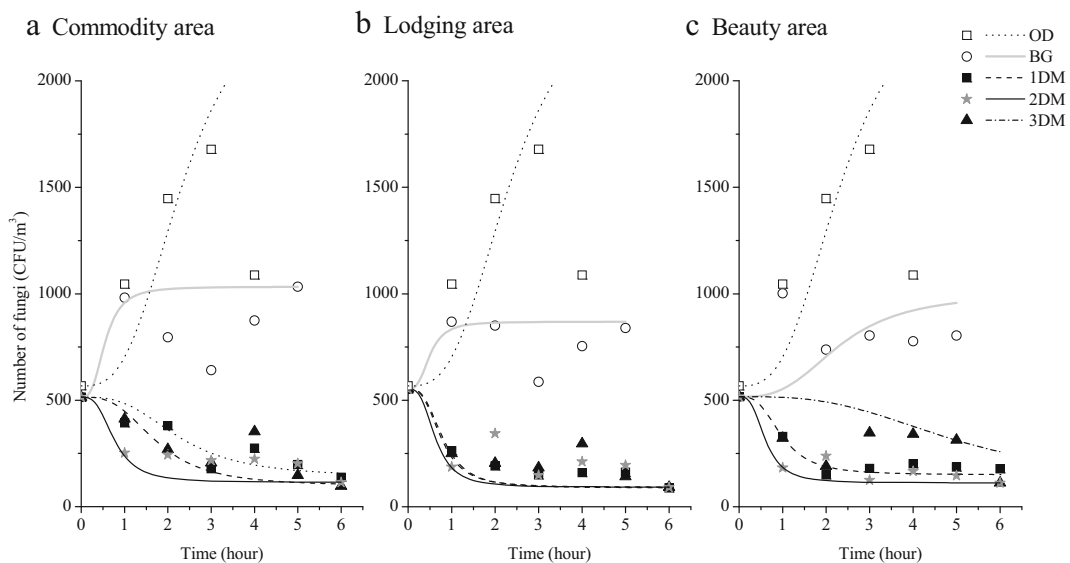

Fig. 3 Variation of residual fungus colonies at three indoor sampling points (**a** commodity area, **b** lodging area, **c** beauty area) following disinfection using three disinfection modes (1DM, 2DM, and 3DM). Note that outdoor (OD) and background (BG) fungus colony counts are also provided for reference purposes

Table 1 Experimental conditions in three areas of pet shop (mean ± SD)

Items	Commodity area	Lodging area	Beauty area
Area (m^3)	815	18	218
No. of samples	249	249	246
Temperature (°C)	24.78 ± 4.37	24.9 ± 4.2	23.96 ± 3.75
Relative humidity (%)	66.99 ± 9.73	69.93 ± 10.08	66.44 ± 10.05
Airflow velocity (ft/min)	1.42 ± 1.85	0.51 ± 0.74	1.12 ± 1.05
Carbon dioxide (ppm)	514.12 ± 55.33a	689.16 ± 123.89b	519.5 ± 58.02a
PM_1 (mg/m^3)	0.02 ± 0.02a	0.01 ± 0.01b	0.01 ± 0.01b
$PM_{2.5}$ (mg/m^3)	0.08 ± 0.17a	0.04 ± 0.07b	0.02 ± 0.01c
PM_7 (mg/m^3)	0.20 ± 0.46a	0.09 ± 0.13b	0.04 ± 0.02c
PM_{10} (mg/m^3)	0.22 ± 0.50a	0.10 ± 0.13b	0.04 ± 0.02c
TSP (mg/m^3)	0.25 ± 0.62	0.12 ± 0.14	0.05 ± 0.02

Within the same column, entries annotated with different letters (a–c) exhibit a statistical difference according to Duncan's test ($p < 0.05$)

the highest carbon dioxide concentration occurred in the lodging area due to its small volume (18 m^3). Furthermore, the average $PM_{2.5}$ concentrations in the commodity area, lodging area, and beauty area are 0.08 ± 0.17, 0.04 ± 0.07, and 0.02 ± 0.01 mg/m^3, respectively, while the average PM_{10} concentrations are 0.22 ± 0.50, 0.10 ± 0.13, and 0.04 ± 0.02 mg/m^3, respectively. In other words, the average $PM_{2.5}$ and PM_{10} concentration levels in all three areas exceeded the Taiwan EPA guidelines (i.e., 0.035 and 0.075 mg/m^3, respectively) (Taiwan EPA 2012). Moreover, the commodity area has a higher level of indoor airborne pollution than the lodging or beauty area. This finding is reasonable since the commodity area is close to the entrance of the shop, and hence whenever the door opens, outdoor pollutants tend to flow into the indoor area.

Table 2 shows the bacteria and fungi disinfection efficiencies (per hour) of the three treatment protocols in the three different areas of the shop. Note that the disinfection efficiency is computed as follows: (starting number of bioaerosols − final number of bioaerosols) / starting number of bioaerosols / (total sampling hours × 100%). As shown, the background values of bacteria and fungi are negative for all three investigation areas since for both contaminants, the bioaerosol concentration increases with an increasing store opening time (as shown in Figs. 2 and 3). For all three disinfection methods, the disinfected bacteria and fungi per hour (%) have positive values which meant that the disinfection was effective. In other words, all three methods reduced the bioaerosol concentration in the commodity area, lodging area, and beauty area of the store. Observing the results for the bacteria disinfection efficiency, no

significant difference ($p > 0.05$) is found between the 1DM, 2DM, and 3DM methods in the commodity area ($p > 0.05$). A similar result is observed in the lodging area ($p > 0.05$). However, in the beauty area, the 3DM method had a significantly poorer disinfection efficiency than the 1DM or 2DM method. The results obtained for the fungi disinfection efficiencies of the three methods are similar to those obtained for the bacteria disinfection efficiency. Thus, overall, the results show that the 1DM, 2DM, and 3DM methods all provide an effective disinfection function in the commodity area and lodging area of the store, whereas in the beauty area, only the 1DM and 2DM methods yield a significant reduction in the bioaerosol concentration. Pets are a well-known source of indoor bioaerosols (ACGIH 1999). Consequently, it is reasonable to assume that the pet density has a direct effect on the microbial level within the store. Since the commodity area only sells pet food and other pet-related articles (no animals for sale), the post-disinfection bioaerosol levels are comfortably lower than the respective maximum permissible concentration levels prescribed by the EPA (i.e., bacteria 1500 CFU/m^3; fungi 1000 CFU/m^3), as shown in Figs. 2a and 3a. Moreover, the bacteria and fungi disinfection efficiencies of the three methods are all higher than 9.23%, as shown in Table 2. The lodging area, with a volume of 18 m^3, is the smallest of the three considered areas. The lodging area has a consistently high pet density since the pets generally spend most of their time indoors when lodging at the store. Consequently, the lodging area has an extremely high background bacteria concentration, as shown in Fig. 2b. Nonetheless, the

Table 2 Disinfection efficiencies of three treatment methods for bacteria and fungi bioaerosols

Items Area (m^3)		Commodity area 815	Lodging area 18	Beauty area 218
Disinfected bacteria per hour (%)	Background value	-20.81 ± 7.01	-13.51 ± 2.49	-11.22 ± 7.16
	1 DM	14.29 ± 11.36	7.91 ± 8.00	8.06 ± 9.45^a
	2 DM	9.23 ± 9.73	7.92 ± 8.35	9.49 ± 8.71^a
	3 DM	10.48 ± 9.82	6.3 ± 7.78	2.54 ± 7.97^b
Disinfected fungi per hour (%)	Background value	-20.13 ± 0.25	-10.33 ± 0.98	-11.1 ± 1.47
	1 DM	12.19 ± 10.60	11.57 ± 10.27	10.07 ± 9.96^a
	2 DM	12.97 ± 10.97	10.46 ± 7.97	11.3 ± 9.16^a
	3 DM	13.54 ± 10.84	10.53 ± 8.57	7.55 ± 6.13^b

[a-b] Within the same column, entries annotated with different superscripts exhibit a statistical difference according to Duncan's ANOVA test ($p < 0.05$)

three disinfection methods still achieved bacteria and fungi disinfection efficiencies of more than 6.3%, as shown in Table 2. In other words, the atomized disinfectant is present in a sufficient quantity to penetrate every corner of the lodging area and achieve a good disinfection performance. The beauty area of the store has a far larger volume (218 m^3) than the lodging area. Moreover, the area is used primarily for bathing, hair grooming, and nail trimming. Consequently, the residence time of the pets in the beauty area is shorter than that in the lodging area. As a result, the 3DM disinfection method has only a limited effectiveness (see Fig. 2a and Table 2) since the area has only a low background bacteria concentration, has a larger volume, and the residence time of the pets is typically far lower than the disinfection interval (3 h).

Thus, while the 3DM method provided an effective disinfection performance in the commodity and lodging areas of the store, the 2DM method is preferred in the beauty area (see Table 2). The results therefore show that the optimal disinfection method in each area of the store depended on the particular application performed in that area (i.e., sales, lodging, or grooming).

The correlation between the bacteria and fungi colony counts and the disinfection efficiencies of the three disinfection protocols was investigated by means of a MANOVA test. The results showed that all three disinfection methods led to a significant ($p < 0.05$) reduction in the colony count in the commodity and lodging areas. The 1DM and 2DM methods also had a significant ($p < 0.05$) effect on the colony count in the beauty area.

Table 3 Spearman rank order correlation values among colony counts and environmental parameters (after disinfection treatment)

Items	Residual bacteria	Residual fungi	Temperature	Relative humidity	Airflow velocity	Carbon dioxide	PM$_1$	PM$_{2.5}$	PM$_7$	PM$_{10}$
Residual fungi	.169**									
Temperature	$-$.109**	$-$.229**								
Relative humidity	.047	.252**	.456**							
Airflow velocity	$-$.350**	.012	$-$.030	$-$.169**						
Carbon dioxide	.356**	.100**	.043	.302**	$-$.627**					
PM$_1$	.226**	.122**	$-$.486**	$-$.279**	$-$.188**	.173**				
PM$_{2.5}$	.225**	.152**	$-$.489**	$-$.228**	$-$.196**	.158**	.972**			
PM$_7$	.176**	.116**	$-$.464**	$-$.268**	$-$.148**	.077*	.887**	.928**		
PM$_{10}$	.207**	.095**	$-$.440**	$-$.267**	$-$.159**	.110**	.841**	.877**	.946**	
TSP	.310**	.170**	$-$.430**	$-$.150**	$-$.203**	.271**	.782**	.804**	.839**	.884**

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

Table 3 shows the Spearman rank order correlations among the colony counts (following disinfection treatment) and environmental factors. As shown, significant positive correlations exist between the disinfected volume and the residual fungi concentration (volume $r = 0.070$, $p < 0.05$), carbon dioxide concentration (volume $r = 0.150$, $p < 0.01$), PM_1 concentration (volume $r = 0.124$, $p < 0.01$), and $PM_{2.5}$ concentration (volume $r = 0.100$, $p < 0.01$). In addition, significant positive correlations also exist between the residual bacteria concentration and the residual fungi concentration (bacteria $r = 0.169$, $p < 0.01$), carbon dioxide concentration (bacteria $r = 0.356$, $p < 0.01$), PM_1 concentration (bacteria $r = 0.226$, $p < 0.01$), $PM_{2.5}$ concentration (bacteria $r = 0.225$, $p < 0.01$), PM_7 concentration (bacteria $r = 0.176$, $p < 0.01$), PM_{10} concentration (bacteria $r = 0.207$, $p < 0.01$), and TSP concentration (bacteria $r = 0.310$, $p < 0.01$). Similarly, significant positive correlations exist between the residual fungi concentration and the relative humidity (fungi $r = 0.252$, $p < 0.01$), carbon dioxide concentration (fungi $r = 0.100$, $p < 0.01$), PM_1 concentration (fungi $r = 0.122$, $p < 0.01$), $PM_{2.5}$ concentration (fungi $r = 0.152$, $p < 0.01$), PM_7 concentration (fungi $r = 0.116$, $p < 0.01$), PM_{10} concentration (fungi $r = 0.095$, $p < 0.01$), and TSP concentration (fungi $r = 0.170$, $p < 0.01$). By contrast, a significant negative correlation exists between the disinfected volume and the airflow velocity (volume $r = -0.329$, $p < 0.01$). Significant negative correlations exist between the residual bacteria concentration and the temperature (bacteria $r = -0.109$, $p < 0.01$) and airflow velocity (bacteria $r = -0.350$, $p < 0.01$). Similarly, a significant negative correlation also exists between the residual fungi concentration and the temperature (fungi $r = -0.229$, $p < 0.01$). In other words, the residual bacteria concentration increases with an increasing residual fungi concentration, carbon dioxide concentration, PM_1 concentration, $PM_{2.5}$ concentration, PM_7 concentration, PM_{10} concentration, and TSP concentration, but decreases with an increasing temperature and airflow velocity. Similarly, the residual fungi concentration increases with an increasing relative humidity, carbon dioxide concentration, PM_1 concentration, $PM_{2.5}$ concentration, PM_7 concentration, PM_{10} concentration, and TSP concentration, but decreases with an increasing temperature.

In general, the results presented in this study confirm the effectiveness of the ClO_2 fogging treatment in reducing not only the bioaerosol (residual bacteria and fungi) concentration in the considered pet shop but also the dust and other fine particulate matter airborne concentrations. Furthermore, the negative correlation between the

airflow velocity and the residual bacteria concentration indicates that the movement of air within the indoor space is beneficial in distributing the evaporated disinfectant particles and improving the disinfection effect as a result. Overall, the results confirm that ClO_2 fogging disinfection improves the indoor air quality of the pet shop, and therefore safeguards the health of both the store occupants (staff and customers) and the pets themselves.

Conclusions

This study performed an experimental investigation into the effectiveness of gaseous ClO_2 in reducing the bacteria and fungi levels in the commodity area, lodging area, and beauty area of a pet shop in Taiwan. Three different ClO_2 disinfectant modes were considered, namely once every hour (1DM), once every 2 h (2DM), and once every 3 h (3DM). The results have shown that in the commodity area (given over to the selling of pet food and pet-related articles), all three disinfection methods provided an effective means of reducing the indoor bioaerosol concentration. The lodging area of the store has a higher pet density and a longer residence time. Consequently, the background bacteria and fungi levels are much higher than those in the commodity area. However, the lodging area has only a small volume (18 m^3). Thus, the 1DM, 2DM, and 3DM disinfection methods all proved effective in reducing the bioaerosol concentration. However, the beauty area of the store has a large volume (218 m^3), and hence, the 3DM method has only a limited disinfection performance. Accordingly, for the pet store considered in this study, the results suggest the use of the 3DM disinfection method in the commodity and lodging areas, but the 2DM method in the beauty area.

In general terms, the results indicated that for any pet shop, the ClO_2 disinfection method used in different areas of the store should be tailored in accordance with the particular function performed in each area. A strong negative correlation has been found between the airflow velocity and the residual bacteria concentration. In other words, a faster air velocity is beneficial in spreading the gaseous ClO_2 disinfectant through the indoor space and improving the disinfection performance as a result. Overall, the present results confirmed that ClO_2 fogging disinfection is an effective means of satisfying the Taiwan EPA guidelines for the air quality in indoor

environments, and hence improves the health and well-being of both pet store occupants and the animals themselves.

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