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Effects of a Gas-phase Air Cleaner in Removing Human Bioeffluents and Improving Perceived Air Quality

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ABSTRACT

The use of air cleaners to enhance indoor air quality under reduced ventilation for energy conservation has increasingly garnered attention. However, the effects of air cleaners on the removal of gaseous compounds require further research. Reduced ventilation can increase air pollution caused by emissions from humans (bioeffluents); however, little is known about the performance of air cleaners regarding this type of pollution. Thus, this study addressed this gap. Two male participants sitting in a stainless-steel chamber served as a source of bioeffluents at two temperatures (23°C and 28°C), and a gas-phase air cleaner was either operational or idled. Thirteen participants evaluated the air quality, and chemical analyses were performed. The protocols partially followed the ISO Standards 16000-28 and 16000-44. The results indicate that pollutants emitted by humans decreased when the air cleaner was operating. In addition, sensory assessments showed a decrease in odour intensity and percentage of dissatisfaction with the operating air cleaner. The clean air delivery rate was higher at 28°C, and the perceived air freshness also improved at this temperature. Our findings show that air cleaner operations effectively improve the quality of air polluted by human bioeffluents. However, the validation of results in actual environments is recommended.

Keywords: air cleaner, body odour, human bioeffluents, perceived air quality, olfactory threshold

Nomenclature

ACC	average of acceptability responses by panels
ACC_i	acceptability responses by panels
C_0	background concentration, ppm
C_{OFF}	concentration of chemical substances before air cleaner operation, ppm
C_{ON}	concentration of chemical substances after air cleaner operation, ppm
dC / dt	change in the airborne concentration of chemical substances in the chamber, ppm/s
E_{human}	human emission, ppm/s
G	amount of pollutants generated, olf
N	sample size
N_p	number of odour evaluation panels
PAQ_{OFF}	perceived air quality in the non-operating air cleaner condition, decipol
PAQ_{ON}	perceived air quality in the operating air cleaner condition, decipol
Q	ventilation flow rate, m ³ /s
Q_0	ventilation rate in the chamber, L/s
Q_{AC}	air flow rate from the air cleaner, L/s
RR	removal rate, %
T_{sk}	average skin temperature, °C
V	chamber volume, m ³
Z	test statistic

Greek letters

ε	improvement efficiency of PAQ
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1. Introduction

1.1. Background

The recent pandemic of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has drawn attention to air cleaners [1]. Air cleaners remove aerosols, particulate matter, and gaseous pollutants from indoor air, reducing the volume of outdoor air by removing pollutants that would otherwise have to be removed via ventilation. Consequently, air cleaners can reduce the heating and cooling processing loads and save energy. However, when the outdoor air supply decreases, the perceived air quality decreases as well, mainly because of odours originating from pollution sources in the room. This study aimed to examine the effect of gas-phase air cleaners that use activated carbon on perceived air quality with human emissions (bioeffluents) being the indoor sources of pollution.

Human emissions that cause body odours are known sources of indoor air pollution. Bioeffluents that contribute to body odour include dermally emitted pollutants emanating from skin rays and skin surfaces, exhaled bioeffluents, and intestinal gases (flatulence) generated by the digestive system. Body odour is not considered epidemiologically harmful but may cause discomfort with consequences for well-being and other outcomes [2]. Bioeffluents increase diastolic blood pressure and salivary α -amylase levels, which may lead to increased headache, fatigue, and drowsiness [3,4]. In addition, previous studies have shown that exposure to high levels of bioeffluents may adversely affect cognitive function and task performance [3].

Carbon dioxide has been proposed as a proxy for assessing the effects of body odour on human sensory responses [5]. Several other studies have also established this relationship [6,7]. Background carbon dioxide (CO₂) concentrations affect human metabolism and change the concentration of CO₂ released by humans [8] but should not be considered a cause of reduced perceived air quality (CO₂ is odourless at the concentrations measured in commercial and residential buildings) or cognitive

decline; it is only a proxy for bioeffluents that lead to unwanted outcomes[3,4,9–11]. Furthermore, it is odourless at concentrations typically measured indoors. Consequently, air-cleaning countermeasures should not focus on removing CO₂ but on removing bioeffluents.

Indoor pollution can be reduced through source control, ventilation with outdoor air, and air cleaning. Considerable research has been conducted to evaluate the performance of air cleaners in removing chemical substances[12–23]. The source control of human emissions is challenging and probably impossible to implement. Ventilation is adequate but may increase the heating and cooling loads. The use of air cleaners removes air pollutants; therefore, it is energy efficient because there is no extra air-conditioning requirement when the outdoor air supply rate is increased to achieve the same effect on air pollutants. Therefore, the removal of bioeffluents via air cleaning is attractive. However, only a few studies have examined this issue. For instance, Sheng et al. [12] examined the effect of a clean air heat pump system that combined a silica gel rotor with a heat pump to improve indoor air quality. The results showed improved perceived air quality in rooms contaminated with human bioeffluents and building materials. Fang et al. [13] evaluated the performance of a streamer plasma (non-thermal plasma) air cleaner using subjects' sensory evaluation of air quality. No cleaning effects were observed when the cleaner operated in a chamber with people inside. Some studies have reported that the operation of an air cleaner in the presence of bioeffluents reduced air quality [14]. Kolarik et al. [14] examined the effect of photocatalytic air cleaners on the perceived air quality in rooms where humans were the dominant sources of pollution. The authors found that this technology reduced perceived air quality in rooms where humans were present. These effects are attributed to alcohols emitted by humans, which are converted into aldehydes during photooxidation. Other air-cleaning technologies could potentially be used; however, research data on their performance in the presence of bioeffluents are lacking[15,16]. This particularly applies to studies in which the recommendations of ISO 16000-44:2023 [24] and other studies [25] have been followed.

Several studies have examined the performance of activated carbon for single compounds and chemicals derived from building materials. Zhang et al. [16] and Ebrahimifakhar et al. [17] compared the performance of air cleaners based on the clean air delivery rate (CADR). They demonstrated that air cleaners with adsorption mechanisms could effectively remove volatile organic compounds (VOCs). Filters cannot remove VOCs [18], whereas activated carbon can remove them effectively [19]. In addition, they can remove highly volatile substances after additives are added to modify the removal capacity and ability of activated carbon [20,21]. However, studies on the performance of air cleaners using activated carbon to remove bioeffluents have shown meager, very weak, or no effects[22].

1.2. Objective

In this study, chamber experiments were conducted to examine the performance of air cleaners containing activated carbon in removing bioeffluents and improving perceived air quality. The measurements were performed at two temperatures, because the emission rate of the bioeffluents may change with air temperature [25].

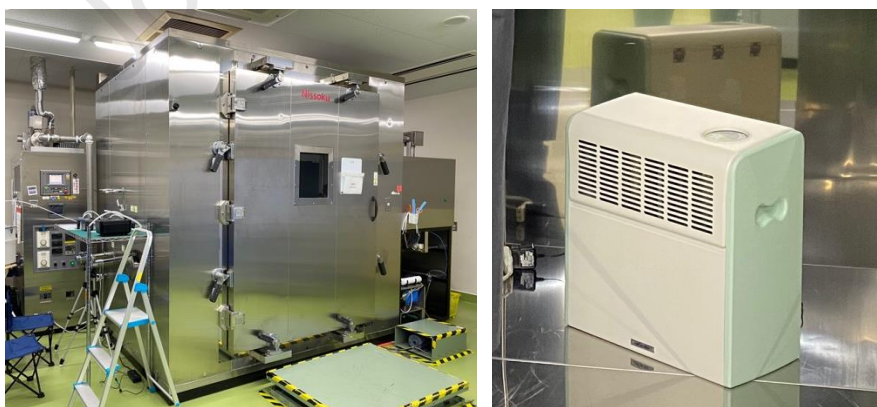
2. Materials and Methods

2.1. Facilities

Fig. 1 (a) shows the exterior of the mid-sized airtight stainless-steel environmental chamber, where the experiments were performed on November 16–17, 2023. The chamber was in compliance with the ISO 16000-9:2006 standard[26]. It had a small window for supervising the interior, simple lighting, two fans for air agitation, and a rack for placing objects. The chairs, air cleaners, and measurement equipment were installed during the experiments. A pedestal fan was used to ensure proper mixing during experiments. The air temperature in the chamber was indirectly controlled by

adjusting it in an air-conditioning bath connected to the chamber. Relative humidity was controlled by mixing humidified air with dry air passing through the chamber air supply duct. The ventilation rate was increased to 2 l/h (11 m³/h). The ozone concentration was lower than 25 ppb and the detection limit of the detector tube (GASTEC Corp., Ayase, Kanagawa, Japan).

Fig. 1 (b) shows the gas-phase air cleaner used in the experiments. This device was developed specifically for chemically sensitive patients. It utilizes an antibacterial enzyme filter for particulate removal and has special activated carbon (Japan patent JP3050139B) [27] to remove gaseous pollutants. Additively modified activated carbon is suitable for adsorbing acidic substances and aldehydes because it is alkaline. Some data exist regarding the single-pass efficiency; for total volatile organic compounds (TVOCs), the removal rates were observed to be approximately 95%[27]. The air cleaner case was made of plastic and partially dismantled during the experiments to minimize the generation of chemical substances from the main body of the equipment. According to the manufacturer, the recommended operating environment is a dust-free room with air temperature <40°C and relative humidity <65%.



(a) Mid-size stainless-steel chamber (b) Gas-phase air cleaner

Fig. 1 Facilities used in the experiment. (a) Exterior of the mid-size stainless-steel chamber used in the experiment (W 1.9 m × D 1.55 m × H 1.9 m, Vol. 5.5 m³) (b) Gas-phase air cleaner used in the experiment (409 mm × 224 mm × 445 mm)

2.2. Participants

Table 1 summarizes the information about the participants, both those who served as sources of pollution and those who performed the sensory assessments.

Two male participants were assigned to each chamber. They were 22 and 23 years old and nonsmokers with no chronic diseases. The clothing insulation was 0.6 clo (disposable underwear, cotton short-sleeved T-shirt washed with unscented detergent, cotton slacks, and cotton socks). They were offered a simple meal (two salted rice balls) 2 hours before the start of the experiment, and they had to refrain from eating or drinking (except plain water) during the experiment. In addition, they were asked not to eat strong-smelling meals the day before the experiment, to take a bath with the provided unscented shampoo and body soap the night before the experiment, and not to use hairdressing or cosmetics on the day of the experiment. The participants were financially compensated for their participation.

Thirteen participants, six males and seven females (21–26 years old), were recruited for sensory evaluations. The participants were Japanese nonsmokers with no chronic diseases. To ensure that participants had a normal olfactory function, they performed screening using five standard dilution liquids called “T&T olfactometer”[28]. All recruited participants passed the test. The participants attended a practice session before the experiments to receive instructions and become acquainted with the procedures and use of measuring scales. They refrained from eating and drinking, except for drinking water, for 1 hour before the start of the sensory evaluations. They also refrained from eating spicy food, smoking, and drinking the day before the experiment to avoid pungent smells. Perfumes, hairdressing materials, and leather products were also not allowed. The participants were financially compensated for their participation.

This study was approved by the Ethics Review Committee on Research with Human Participants of Waseda University (approval no.: 2023-186).

Table 1 Participants serving as the pollution source and participants performing sensory assessments

Characteristic Description	Participants Sitting in the Chamber		Participants Performing Sensory Assessments as Panels
Total		2	13
Sex	Participant A: male	Participant B: male	Male 6, Female 7
Age	Participant A: 22	Participant B: 23	22.8±1.4
Height [cm]	Participant A: 174.8	Participant B: 186.1	-
Weight [kg]	Participant A: 78.1	Participant B: 68.7	-
Estimated body surface area [cm ²]	Participant A: 19010.7	Participant B: 19120.5	-
Smokers	Participant A: no	Participant B: no	0
Participants with allergies, including hay fever		1	10
Participants with rhinitis		2	3
Participants who considered themselves more sensitive to odour and contamination		1	11
Participants who considered themselves more sensitive to physiological reactions (cough, headache, runny nose, etc.) caused by odours and contaminants		1	8
Participants who reported they adapted easily to most odours and contamination		1	8

Note: Estimated body surface area = $53.189 \times \text{weight}^{0.362} \times \text{height}^{0.833}$

2.3. Experimental conditions and procedures

A total of four conditions were tested, with two participants sitting in the chamber with and without air cleaner operating at two temperatures (23°C or 28°C). The chamber was ventilated with outdoor air for 2 l/h. Steady-state conditions were obtained after approximately 90 min; therefore, the sensory evaluations and chemical measurements were performed after 120 and 180 min, respectively. As it has been shown that the adsorption performance of activated carbon decreases as the relative humidity increases [29], the relative humidity was set and controlled at 40%, which is the minimum standard under the Act on Maintenance of Sanitation in Buildings in Japan [30]. All participants entered the chamber simultaneously. The air cleaner operated at an airflow rate of approximately 100 m³/h.

Fig. 2 shows the chamber plan and measurement locations. **Fig. 3** shows the experimental procedure. The measurements were performed daily for 180 min, and the test was conducted each day using a nonoperating air cleaner (for the first 120 min) and an operating air cleaner (for the last 60 min). The measuring equipment and participants were placed in an empty chamber before the 180-minute session for additional measurements. The time at which participants entered the chamber was defined as min 0 (Fig. 3).

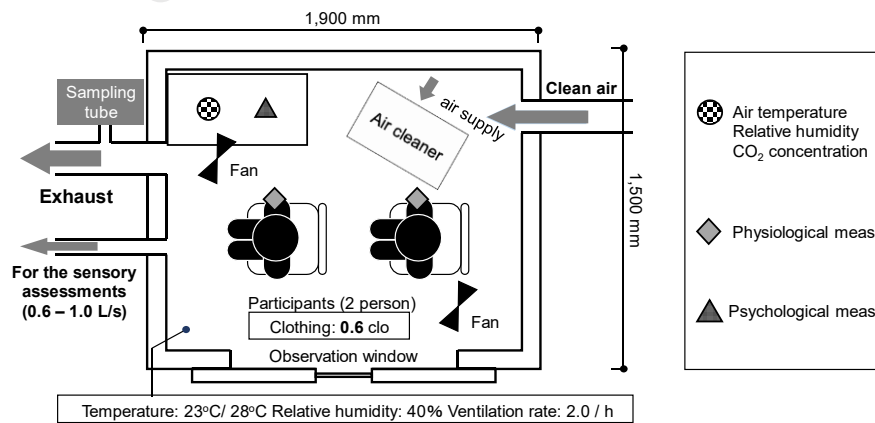


Fig. 2 Chamber plan and the measurement locations

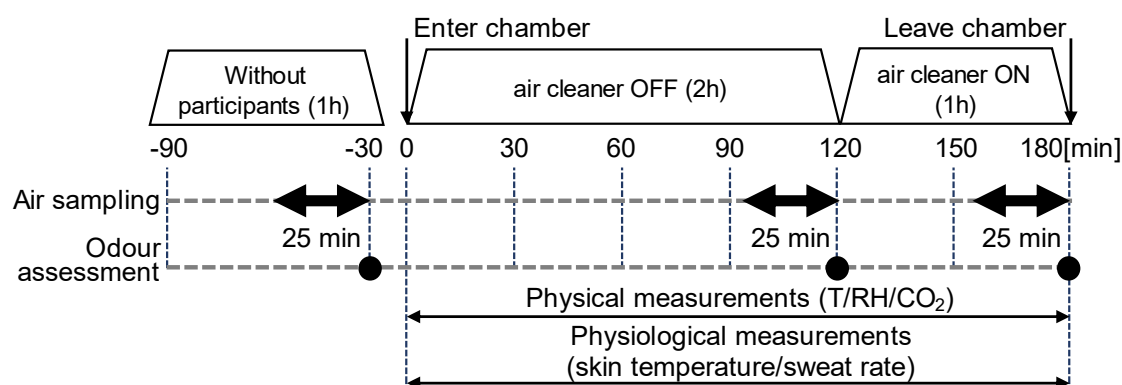


Fig. 3 Timeline of the experimental procedure

2.4. Chemical and physical measurements

Air temperature, relative humidity, and CO₂ concentration were recorded every minute using calibrated sensors and logged inside the chamber using a TR-76Ui (T&D Corp., Matsumoto, Nagano, Japan). The equipment was placed on a rack approximately 1.1 m above the floor.

Table 2 lists the analytical conditions and protocols. The air for the chemical analysis was sampled through a slot located on the side wall of the chambers. The air was collected in a Tenax-TA tube and a DNPH tube for 25 minutes before the end of each measuring cycle (Fig. 3). Calibrated pumps were used for sampling. The sampled volume was 5 and 25 L, and the sampling flow rate was 0.2 and 1.0 L/min, respectively. Sampled air was analyzed using gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC). Ammonia was collected using a liquid collection method parallel to other samples and analyzed using ion chromatography. Calibrated pumps were used for sampling. The sample volume was 250 L, and the sampling flow rate was 10 L/min. No duplicates were made. Analysis was made at MC Evolve Technologies Corporation. Chemical substances to be analyzed were identified using previous studies [25,31,32]; furthermore, substances likely to be detected in this experiment were also selected.

Table 2 Chemical analysis conditions: Tenax-TA, DNPH, and liquid collection method

(A) Tenax-TA	
Equipment	Gas chromatography/mass spectrometry
Thermal desorption unit	TD3.5+ (GERSTEL)
Desorption temperature (time)	280°C (10 min)
Secondary desorption temperature (time)	−150°C → 280°C (10 min)
GC	7890B (Agilent Technologies)
GC/MSD system	5977B (Agilent Technologies)
Trap conditions	Trap temperature: −150°C / Desorption temperature: 280°C / Desorption time: 2 min
Column conditions	Inert Cap-1MS (GL science) 0.25φ × 30 m, f.t.0.25 μm
Temperature conditions	35°C (5 min) → (4°C /min) → 80°C → (10°C /min) → 320°C (3 min)
Carrier gas	He (1mL/min)
Split ratio	30:1
Capture flow (amount)	0.2 L/min (5 L)
The lower limit of quantification	0.5 μg/m ³
Quantitative substance	4-Oxo pentanal, 6-Methyl-5-heptene-2-one, 2-Ethyl-1-hexanol, Octanal, 1-Octanal, (Z)-Geranyl acetone, (E)-Geranyl acetone, Squalene, Nonanal, Decanal, D-limonene, TVOC Octanal equivalent: Hexanal, Heptanal Toluene equivalent: Dimethyl trisulfide, Allyl mercaptan
(B) DNPH	
Equipment	High-performance liquid chromatography Agilent 1260II (Agilent Technologies)
Column	Inertsil ODS-HL (GL science) Inside diameter 4.6 mm, length 250 mm, (5 μm)
Column temperature	40°C
Column flow rate	1.2 mL/min
Mobile phase	Acetonitrile/Water 60:40
Material injection volume	10 μL
Detector wavelength	360 nm
Extended amount	5 mL
Capture flow (amount)	1.0 L/min (25 L)
The lower limit of quantification	1.0 μg/m ³
Quantitative substance	Formaldehyde, Acetaldehyde, Acrolein, Acetone, Propionaldehyde, Crotonaldehyde, Butyraldehyde, Benzaldehyde, iso-Valeraldehyde, Hexanol, 2, 5-dimethyl benzaldehyde
(C) Liquid collection method	
Equipment	Ion chromatography Dionex ICS-1500 (Thermo Fisher Scientific)
Column	CG12A (Thermo Fisher Scientific) 4 × 50mm
Column eluent	20mM Methanesulfonic acid
Column flow rate	1.0 mL/min
Detector	Electrical conductivity detector
Capture flow	10 L/min (250 L)
The lower limit of quantification	10 μg/m ³
Quantitative substance	Ammonia

2.5. Sensory evaluations

Fig. 4 shows the analog scales used for sensory assessment, and **Fig. 5** shows the scale for odour assessment.

Air for the sensory assessments was delivered to a test rig through slots on the sidewalls of the chamber (Fig. 2). This slot was parallel to the slot used to sample air for chemical analysis. A damper was installed in the test rig to set the airflow to approximately 0.6–1.0 L/s [24,28]. This rate was necessary to ensure that the participants inhaled only the air presented for the sensory evaluation, as stipulated in ISO Standards 16000-28 and 16000-44 [24,28].

The area outside the chambers where the sensory assessments were performed was ventilated, and air temperature and relative humidity were measured. The temperature was controlled at $23 \pm 2.0^\circ\text{C}$. The participants assembled and waited for their turn to make the sensory assessments.

The participants assessed the acceptability, odour intensity, and air freshness; the scales were presented in a study in Japanese (Fig. 4). Similar scales have been used previously in Japan in studies examining their effects on perceived air quality [25,31,32]. The following sentence introduced the acceptability scale: “Imagine staying in a room filled with this air for extended periods in your daily life. How do you assess the acceptability of the air quality?” The assessments were performed 120 and 180 min after the participants entered the chamber. Acceptability was assessed first, followed by odour intensity and air freshness [25,31,32]. Before the assessment, the participants sniffed clean air collected in advance in a 10 L Flek-Sampler® (OMI ODOR AIR SERVICE Co., Ltd., Chiyoda, Tokyo, Japan).

The participants completed the sensory assessment scale on three separate occasions to prevent olfactory fatigue. After sniffing the air in the chamber and assessing one scale, they took a 1-minute break before the next assessment.

During the assessments, participants breathed normally and took a maximum of two sniffs of polluted air before recording their ratings on paper. After completing the assessments, the participants returned to the waiting area. These assessments were repeated three times using three different scales.

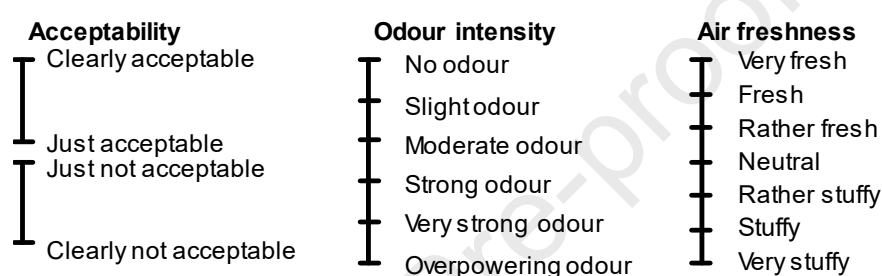


Fig. 4 Visual analog scales used for the odour assessment.

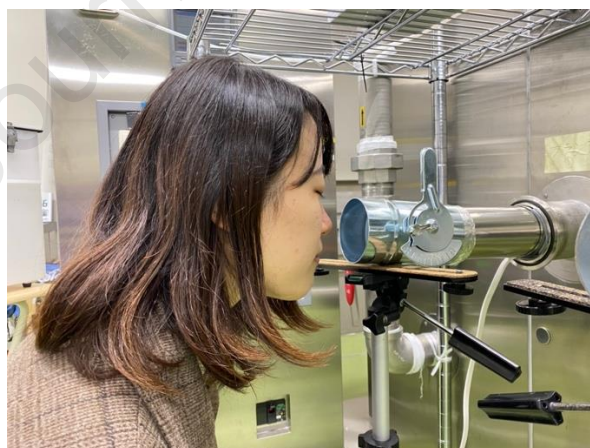


Fig. 5 Sensory evaluations

2.6. Physiological measurements

The skin temperature and sweat rate of the participants sitting in the chamber were measured during the experiment. Equation (1) shows the Hardy and DuBois seven-point method [33] to determine skin temperature measured at the forehead, chest, forearm, hand, thigh, calf, and foot at 5-second intervals using the copper–constantan thermocouple N543R (NIKKISO-THERM CO., LTD., Shibuya, Tokyo, Japan). The average T_{sk} was calculated using Equation (1):

$$T_{sk} = 0.07 \times \text{forehead} + 0.14 \times \text{forearm} + 0.05 \times \text{hand} + 0.35 \times \text{chest} + 0.19 \times \text{thigh} + 0.13 \times \text{calf} + 0.07 \times \text{foot}. \quad (1)$$

Sweat rate was measured every 1 s in the chest to observe the effects of thermogenic sweating using a PPOS-01 (TECHNO NEXT Co., Ltd., Mihama, Chiba, Japan).

2.7 Data treatment and statistical analyses

The sensory ratings were digitized, and the results were manually checked for transcription and other gross errors. The scales were coded as follows: *clearly acceptable* = +1; *just acceptable* = +0; *just not acceptable* = -0; *clearly not acceptable* = -1; *overpowering odour* = +5; *no odour* = 0; *very stuffy* = -3; and *very fresh* = +3.

A non-parametric Wilcoxon's rank test was used to examine the statistical differences in the sensory evaluations between the conditions; 2-Tail p was set at 0.05.

The effect size was calculated using Equation (2) [34] The lower limits of the effect size were set to 0.10, 0.30, and 0.50 for small, medium, and large effects, respectively, following Cohen's decision [34] (1988):

$$r = \frac{z}{\sqrt{N}}. \quad (2)$$

Analyses were performed using IBM SPSS Statistics 29 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. The conditions in the exposure chamber

Fig. 6 shows the CO₂ concentration, air temperature, and relative humidity measured in the stainless-steel chamber with the participants.

The CO₂ concentration in the chamber increased significantly in the first 60 minutes, reaching around 3300 ppm ($SD = 39$) at 28°C and 3240 ppm ($SD = 97$) at 23°C.

The air temperature inside the chamber was unsteady during the first 60 minutes at 28°C and the first 30 minutes at 23°C, probably due to the opening and closing of the chamber door. Afterwards, the air temperature averaged 28.0°C ($SD = 0.2$) in the 28°C condition and 22.8°C ($SD = 0.2$) in the 23°C condition ($SD = 0.2$).

In the first period, at a temperature of 28°C, up until 120 min, the relative humidity in the chamber was unstable and higher than the set value, reaching as high as 49% ($SD = 4$). Door opening and participants' sweating could be the reasons for this. However, this reached 41% ($SD = 1$), deviating slightly from the set value of 40%. The fluctuations in RH were also seen in the 23°C condition; however, after 30 minutes, the relative humidity reached nearly the planned value of 41% ($SD = 0$).

The calculated enthalpy in the 28°C and 23°C conditions was 52.3 kJ/kg and 40.9 kJ/kg, respectively.

These results indicate that the conditions in the chamber reached a steady state during the measurements.

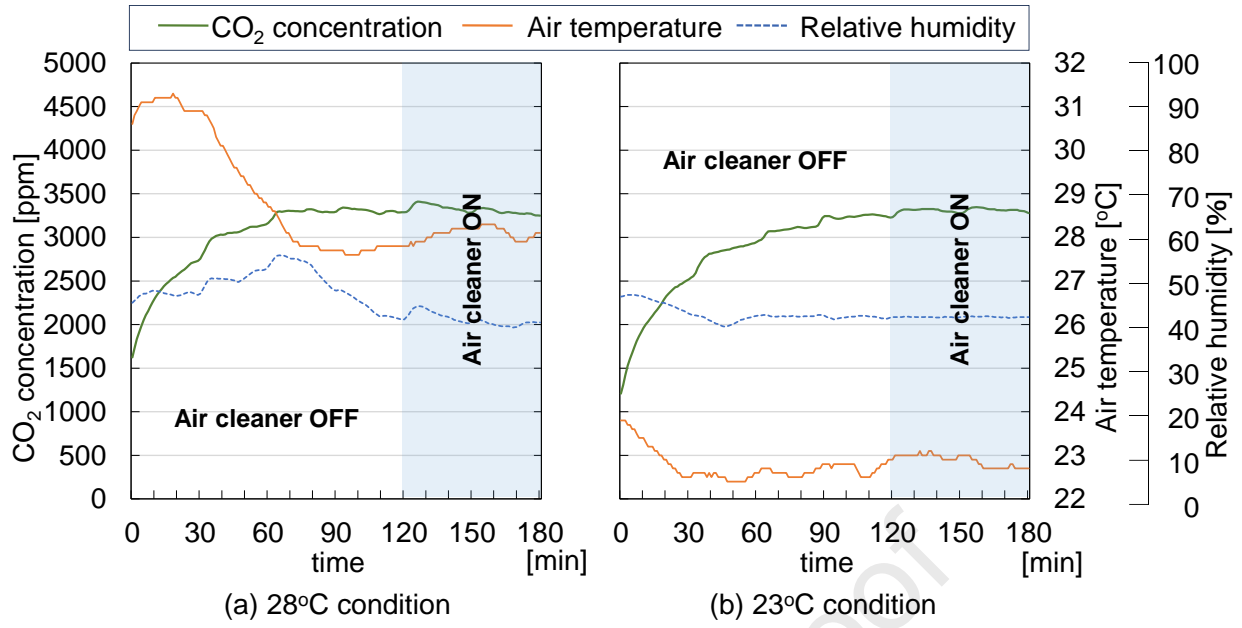


Fig. 6 CO₂ concentration, air temperature, and relative humidity in the chamber with participants; (a) 28°C condition and (b) 23°C condition

Fig. 7 shows the sweat rate and average skin temperature of the participants in the chamber; the sweat rate was measured and corrected for the baseline.

In the 28°C condition, the sweat rate averaged 0.07 mg/cm² ($SD = 0.06$) for Participant A and 0.48 mg/cm² ($SD = 0.19$) for Participant B. There were quite large fluctuations, unlike in the 23°C condition. In the 23°C condition, the sweat rate averaged 0.03 mg/cm² ($SD = 0.03$) for participant A and 0.08 mg/cm² ($SD = 0.19$) for participant B.

In the 28°C condition, the average skin temperature, T_{sk} , averaged 33.9°C ($SD = 0.4$) for Participant A and 33.1°C ($SD = 0.3$) for Participant B. The temperature at which sweating begins is about 34°C [35], consistent with the high sweating rate under 28°C. In this condition, the skin temperature remained nearly unchanged (perhaps falling by about 0.5 K toward the end of the session). In the 23°C condition, the average skin temperature for Participant A was 31.8°C ($SD = 0.6$) and for

Participant B was 32.0°C ($SD = 1.4$). However, the skin temperature decreased considerably (by 2–3°K), suggesting reduced metabolism, although this was not reflected in the significantly lower CO₂. Compared with the 28°C condition, the mean skin temperature T_{sk} was below 34°C, suggesting that no sweating occurred, as shown in Fig. 7.

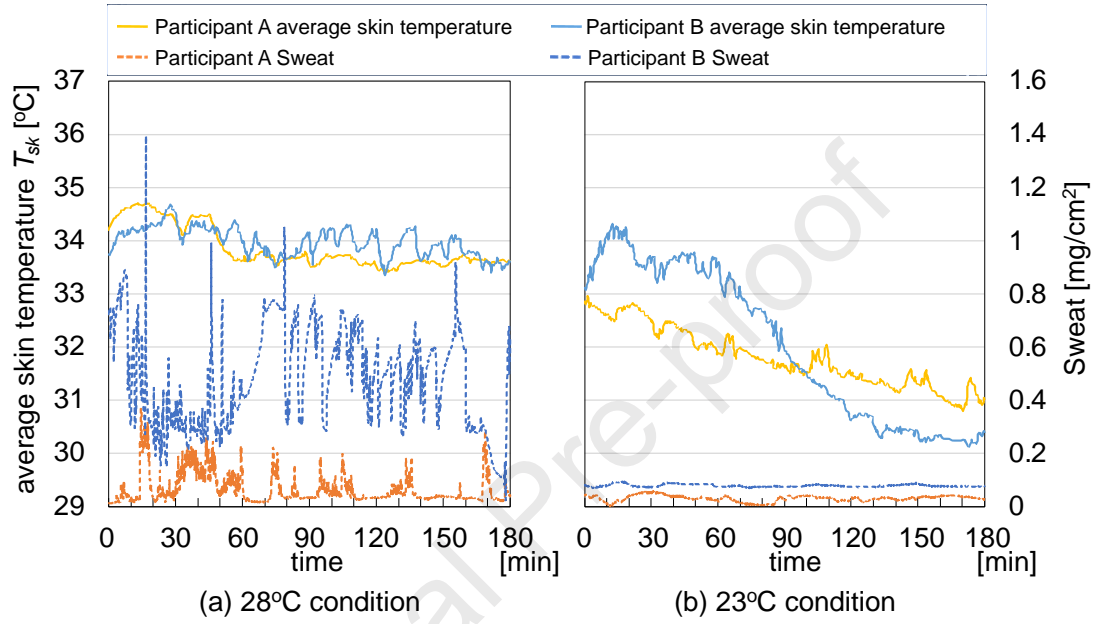


Fig. 7 Sweat rate and average skin temperature of the participants in the chamber: (a) 28°C condition, (b) 23°C condition

3.2. Sensory assessments

3.2.1. Assessments of acceptability and estimation of the percentage of dissatisfied

Fig. 8 shows an evaluation of the acceptability of the air quality. In the 28°C condition, the operation of the air cleaner significantly improved acceptability, which still remained on average on the stuffy side of the scale (medium effect size, $r = 0.44$). There was no significant effect on acceptability when the air cleaner was turned on at 23°C, although the effect size was large ($r = 0.54$).

Using the average ratings of air quality acceptability, the percentage of dissatisfaction was estimated using the following relationship [31]:

$$PD = \frac{\exp(-0.18 - 5.28 \cdot ACC)}{1 + \exp(-0.18 - 5.28 \cdot ACC)} \cdot 100 \quad (3)$$

Fig. 9 shows the results at 23°C. At this temperature, the percentage of dissatisfied (PD) was 26% with air cleaner OFF and 12% with air cleaner ON; at 28°C, acceptability was not significantly different between air cleaner OFF and ON, but PD was 33% and 22%, respectively, tending to decrease at 23°C. The percentage of dissatisfied with the non-operating air cleaner (OFF) was higher than when the cleaner was ON, as expected, and it was also higher at 28°C than at 23°C, as expected, since the enthalpy was higher at the former temperature [36]. Referring to the results of Iwashita et al. [37], the percentage of dissatisfied with air cleaners OFF was used to estimate the ventilation rate, which was 10.4 m³/h/person (2.9 L/s/person) at 28°C and 24.1 m³/h/person (6.7 L/s/person) at 23°C; further details can be found in the Discussion. Using the olf/decipol theory[38], the percentage of dissatisfied with air cleaner ON and OFF were converted into decipols, and the removal rate (RR) was estimated as 43% at the 28°C and 64% at the 23°C conditions.

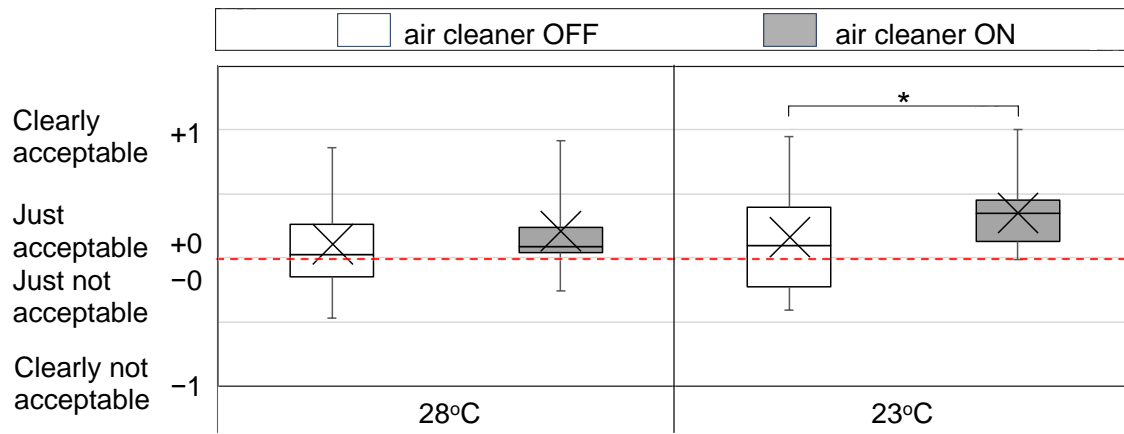


Fig. 8 Acceptability of air quality in the chamber. The boxes and caps indicate the interquartile range and the maximum and minimum ratings, respectively. Means are plotted as black crosses and median as lines ($n = 13$, n.s.: not significant ($p > 0.05$), *: $p < 0.05$, **: $p < 0.01$).

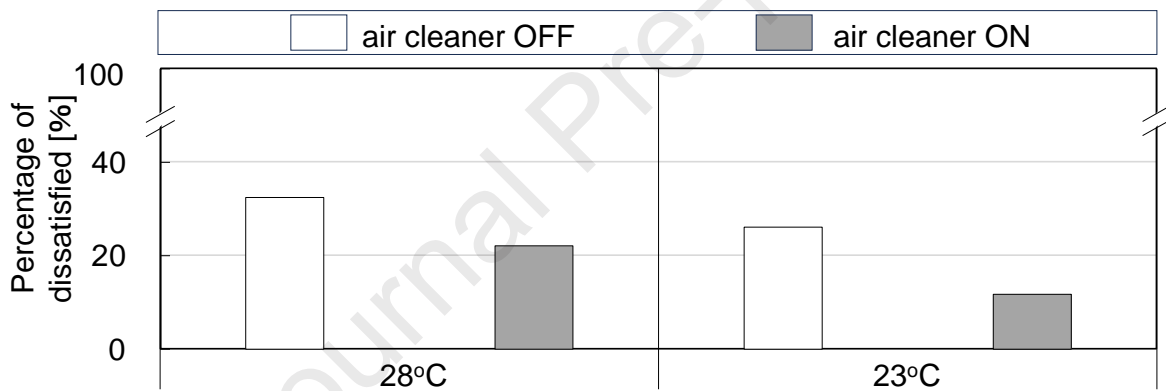


Fig. 9 Percentage of dissatisfied estimated using average ratings of acceptability of air quality

3.2.2. Odour intensity

Fig. 10 shows the results of the odour intensity assessments. Odour intensity was significantly reduced when the air cleaner was ON at 28°C or 23°C. The effect sizes were also large ($r = 0.75$ at 28°C and $r = 0.54$ at 23°C). It is worth noting that on average, odour intensity was similar at 23°C and 28°C, probably because the difference in thermodynamic properties of the air (enthalpy) did not affect the evaluations [32].

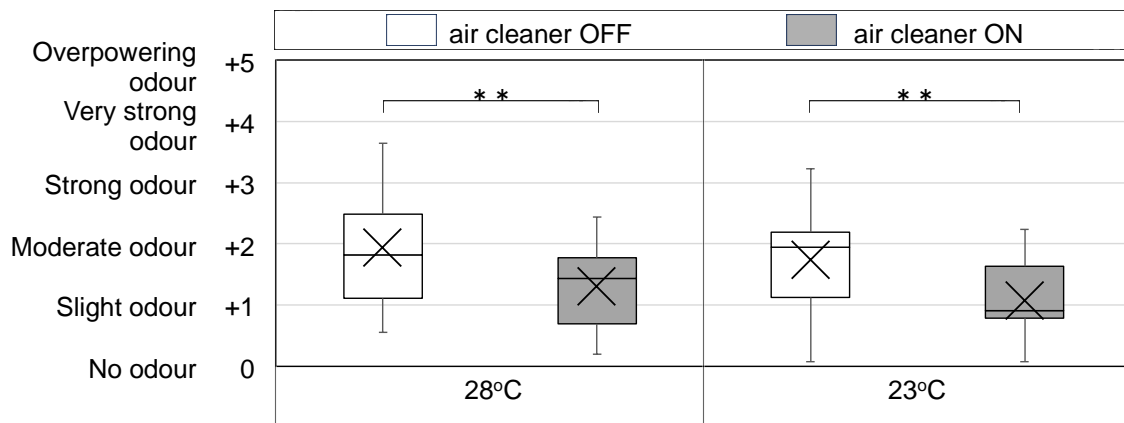


Fig. 10 The ratings of odour intensity. The boxes indicate the interquartile range and the maximum and minimum ratings, respectively. Means are plotted as black crosses and median as lines ($n = 13$, n.s.: not significant ($p > 0.05$), **: $p < 0.01$).

3.2.3. Air Freshness

Fig. 11 shows an evaluation of the freshness of the air in the chamber. In the 28°C condition, the operation of the air cleaner significantly improved freshness, which on average remained on the stuffy side of the scale (large effect size, $r = 0.81$). There was no significant effect on freshness when the air cleaner was turned on at 23°C, although the effect size was medium ($r = 0.44$).

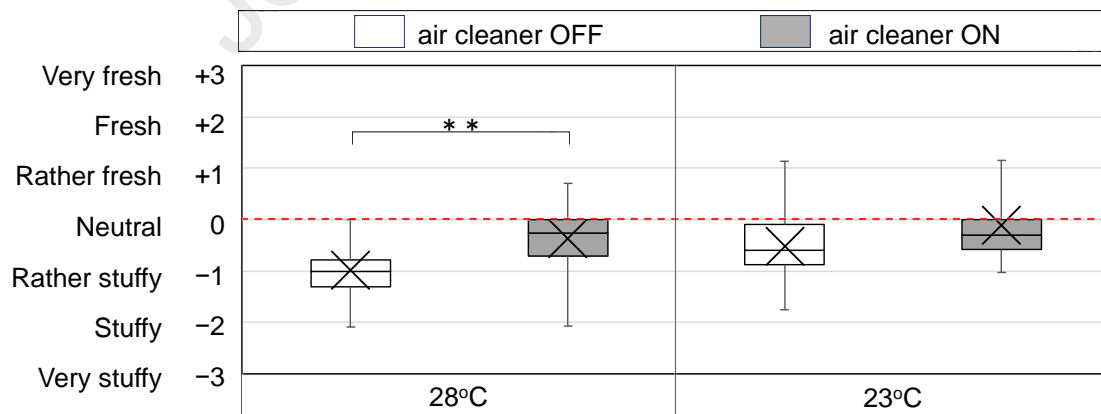


Fig. 11 The ratings of freshness. The boxes indicate the interquartile range and the maximum and minimum ratings, respectively. Means are plotted as black crosses and median as lines ($n = 13$, n.s.: not significant ($p > 0.05$), *: $p < 0.05$, **: $p < 0.01$).

3.3. Results of chemical analyses

Table 3 lists the chemical substance analysis results; values in bold show levels above olfactory thresholds [25,39] the minimum concentration at which odour can be detected. Table 3 shows the results for the airborne concentrations of chemicals measured without participants, with the air cleaner OFF (at 120 min) and the air cleaner ON (at 180 min). **Fig. 12** shows the concentrations of chemical substances.

Ammonia, (E)-geranyl acetone, squalene, toluene, 2-ethyl-1-hexanol (2E1H), d-limonene, nonanal, decanal, hexadecane, formaldehyde, acetaldehyde, and acetone were detected above the limit of using the applied analytical methods. Higher concentrations were seen at the 28°C condition even though the ventilation in the chamber remained the same (2 l/h) and the participants remained seated. However, as shown in Fig. 7, their metabolic rate was higher. The higher concentrations of substances in the air without participants in the chamber may have been caused by chamber contamination when the equipment was installed. In contrast, toluene and hexadecane were detected only when people were absent from the chamber and should not be attributed to human emissions. For nearly all chemical substances, the air-cleaner operation produced a measurable effect: reduced concentration.

Table 3 Results of chemical substance analysis.

Substance	CAS number	28°C Condition [$\mu\text{g}/\text{m}^3$]			23°C Condition [$\mu\text{g}/\text{m}^3$]			Odour Detection Threshold [$\mu\text{g}/\text{m}^3$] [25,39]	Attributed to the Presence of People [25]
		without participants	air cleaner OFF	air cleaner ON	without participants	air cleaner OFF	air cleaner ON		
Ammonia	1336-21-6	<10	328	241	<10	37	26	1.1×10^3	*
Acetone	67-64-1	2.9	78.8	12.0	2.3	55.1	11.9	1.0×10^5	*
Formaldehyde	50-00-0	3.5	6.4	1.7	2.4	3.3	1.2	6.2×10^2	
2-Ethyl-1-hexanol	104-76-7	4.9	4.2	0.6	2.6	2.9	<0.5	7.0×10	
Decanal	112-31-2	1.8	2.8	0.5	1.0	1.0	<0.5	2.8	*
Nonanal	124-19-6	2.3	2.5	<0.5	1.1	0.9	<0.5	2.2	*
Squalene	111-02-4	<0.5	2.4	0.9	<0.5	<0.5	0.8	-	*
Acetaldehyde	75-07-0	2.1	2.0	<1.0	2.1	1.1	<1.0	2.7	
D-limonene	5989-27-5	<0.5	1.8	<0.5	<0.5	0.7	<0.5	2.1×10^2	
(E)-Geranyl acetone	689-67-8	<0.5	1.1	<0.5	<0.5	<0.5	<0.5	-	*
Toluene	108-88-3	1.2	<0.5	<0.5	1.0	<0.5	<0.5	1.25×10^3	*
Hexadecane	544-76-3	1.1	<0.5	<0.5	0.8	<0.5	<0.5	-	
TVOC	-	14.4	25.0	3.8	9.1	16.7	5.9	-	-

Note: Values exceeding the olfactory threshold are shown in bold. The TVOC is the peak in retention from Hexane to Hexadecane, calculated using the toluene response factor.

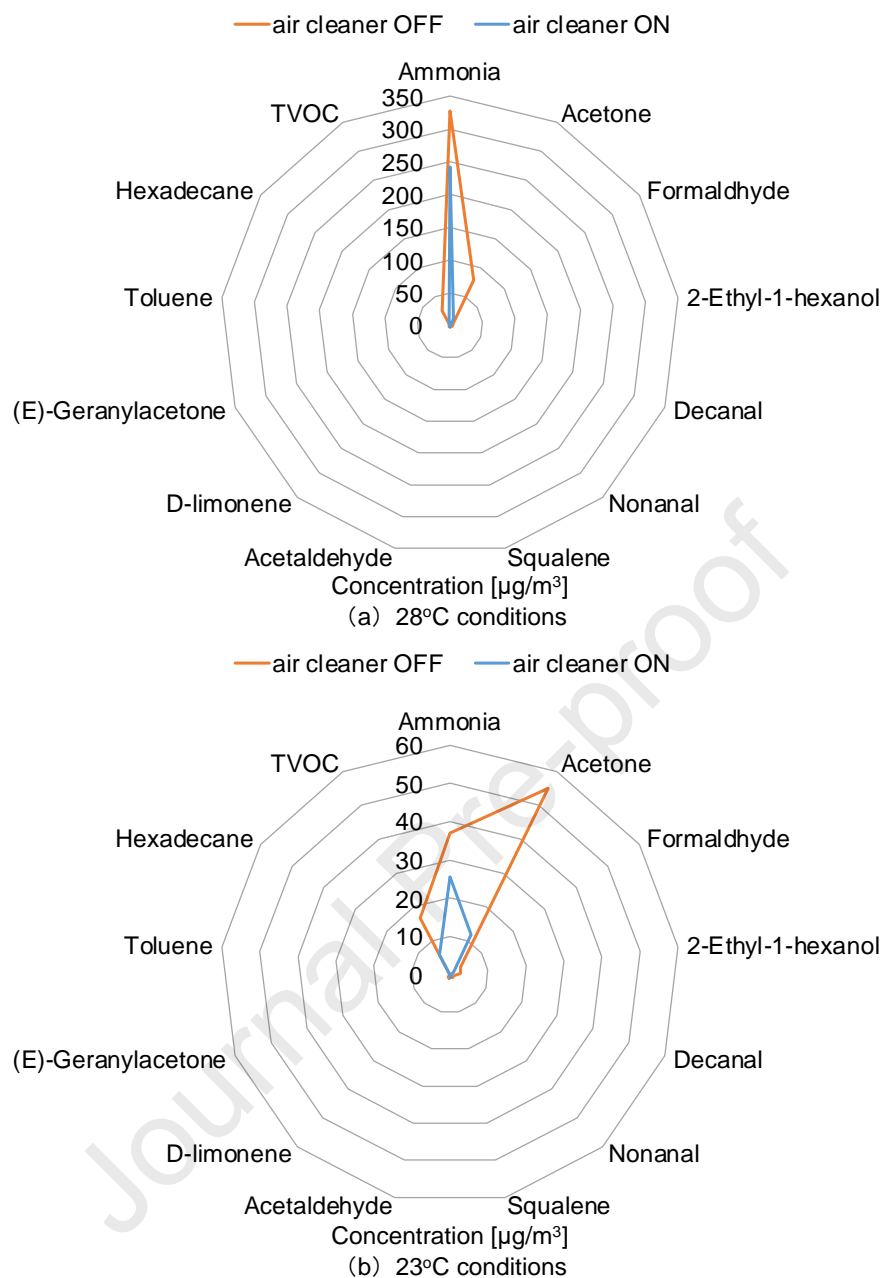


Fig. 12 Concentration of chemical substances: (a) 28°C condition, (b) 23°C condition.

Table 4 presents the RR [%] calculated using Equation (4) [40]. Values below the lower limit of quantification were calculated using concentrations at the lower limit. In addition to ammonia, RR was generally above 50% and higher for some compounds (aldehydes, d-limonene) at 28°C. Using the RR, the clean air delivery rate (CADR) was estimated, and the results are presented in Discussion: CADR for TVOC was 62 m³/h at 28°C (17 L/s) and 20 m³/h (5.6 L/s) at 23°C. CADR was generally higher at 28°C and, for many compounds, higher than the air supply rate to the chamber of 11 m³/h (3.1 L/s):

$$RR = \left(1 - \frac{C_{ON}}{C_{OFF}}\right) \times 100 \quad (4)$$

Table 4 Removal rate (RR) with air cleaners ON.

Substance		Attributed to the Presence of People [25]	28°C Condition	23°C Condition
Inorganic substance	Ammonia	*	26.4%	30.9%
Unsaturated fatty acids	Squalene	*	63.2%	<67.2%
Higher alcohols	2-Ethyl-1-hexanol		84.8%	>82.5%
Terpenoids	D-limonene		>72.8%	>29.8%
Aldehydes	Nonanal	*	>79.7%	>46.7%
	Decanal	*	81.4%	>49.2%
	Formaldehyde		72.9%	64.0%
	Acetaldehyde		>48.9%	>11.8%
Ketones	(E)-Geranyl acetone	*	>56.4%	-
	Acetone	*	84.8%	78.4%
TVOC		-	84.9%	64.8%

Much higher ammonia levels were measured in the 28°C condition than in the 23°C condition and air cleaner OFF. Ammonia emission is related to the metabolic rate of humans [32] and air temperature[41], and emission may have been higher under the 28°C conditions, which thus results in sweating. In addition, the high air temperature in the chamber may have increased the volatilization

of chemicals, resulting in higher airborne concentrations. The ammonia removal rates by the air cleaner were similar, independent of the temperature conditions.

Air cleaner operation reduced formaldehyde concentration. The removal rate was higher at the 28°C condition, in which formaldehyde concentration with the air cleaner not operating was slightly higher than in the 23°C condition. The same was observed for acetaldehyde, nonanal, and decanal, which had concentrations above the odour detection threshold at 28°C when the air cleaner was not operating.

Acetone was higher at 28°C with the air cleaner not operating, but the removal rates were similar independent of the condition. (E)-Geranyl acetone was only detected at 28°C condition and only when the air cleaner was not operating, but the levels were deficient. (E)-Geranylacetone was produced via a squalene/ozone reaction [42–44].

For other compounds such as squalene, 2-ethyl-1-hexanol, and d-limonene, similar tendencies were observed, the concentrations being higher at 28°C than at 23°C with air cleaner OFF. The removal rates of the two former substances were similar under both conditions.

TVOC concentration was higher at the 28°C condition with the air cleaner not operating compared with the 23°C condition. The removal rates were also higher under these conditions, probably because other pollutants were removed in greater amounts. The level of TVOC was much lower than the provisional guideline value in Japan of 400 µg/m³ [45].

4. Discussion

In this study, we examined the performance of an air cleaner containing activated carbon when the source of pollution was human emissions (bioeffluents). Activated carbon was specially manufactured to have high efficiency in removing gaseous pollutants because the air cleaner was intended for use by individuals with multiple chemical sensitivities. We performed sensory tests partly following the protocols prescribed by ISO Standards 16000-28 and 16000-44 [24,28] and used in previous studies [25,31,32] and performed chemical measurements according to the method described by Inasaka et al.[32].

Fig. 13 shows the CADR based on the perceived air quality and chemical concentration. The CADR was calculated to determine air cleaner performance. In this study, the CADR based on the perceived air quality evaluation results was calculated as $CADR_{PAQ}$, and the CADR based on the reduction in chemical concentration was calculated as $CADR_{chemical}$. (Detailed calculations are presented in the Supplementary Material).

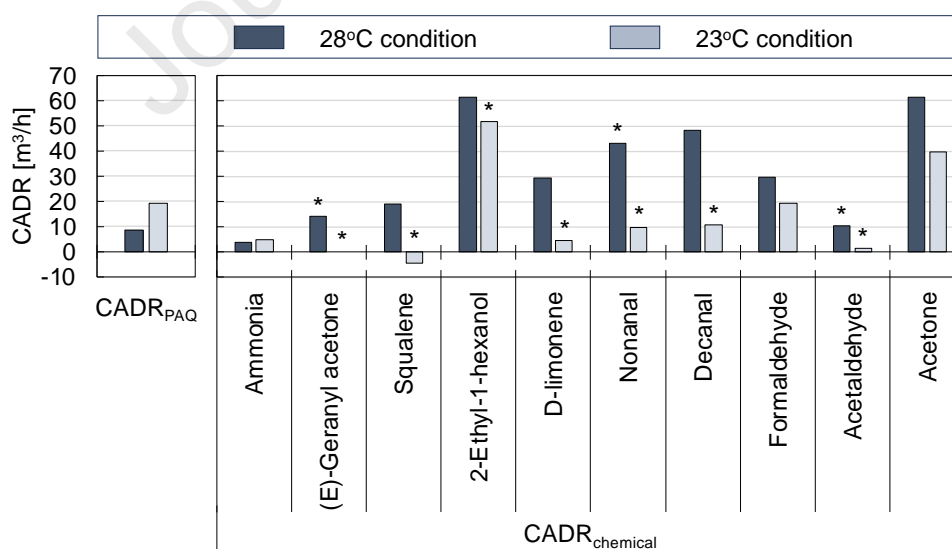


Fig. 13 Calculated CADR based on perceived air quality and chemical concentration. (*: The lower limit was used because the values are below the lower limit of quantification.)

The $CADR_{PAQ}$ was $8.5 \text{ m}^3/\text{h}$ for the 28°C conditions and $19.5 \text{ m}^3/\text{h}$ for the 23°C condition. The 23°C condition showed a $CADR_{PAQ}$ that was 1.8 times higher than the chamber ventilation rate of $11.0 \text{ m}^3/\text{h}$. This value is 77% of the chamber ventilation rate at 28°C . Perceived air quality improvement was achieved under the two temperature conditions.

$CADR_{chemical}$, indicating removal performance based on air concentrations of chemicals, was higher in the 28°C condition than in the 23°C condition. The highest $CADR_{chemical}$ values for 2E1H and acetone for the 28°C condition were $61.3 \text{ m}^3/\text{h}$, that is, 5.6 times the ventilation rate in the chamber of $11 \text{ m}^3/\text{h}$. In physical adsorption by activated carbon, the higher the airborne concentration of the adsorbed object, the greater the amount adsorbed[46]. Therefore, the $CADR_{chemical}$ was higher for the 28°C condition, where the chemical concentration was higher compared to that in the 23°C condition. $CADR_{PAQ}$ based on perceived air quality was higher in the 23°C condition compared to the 28°C condition, a trend different from that of $CADR_{chemical}$.

We showed in the present study that the air cleaner operating at the flow rate of $100 \text{ m}^3/\text{h}$ (27.8 L/s) in a chamber with two people ventilated with outdoor air at 2 l/h , corresponding to $11 \text{ m}^3/\text{h}$ (3.1 L/s) or $5.5 \text{ m}^3/\text{h}$ (1.5 L/s) per person, improved air quality. Perceived air quality improved, as indicated by the higher acceptability of the air quality, lower odour intensity, and less stuffy air. In addition, the concentrations of pollutants measured without the air cleaner during operation were reduced or were below the detection limit when the air cleaner was operated, and the removal rates for many chemicals, besides ammonia, were $> 50\%$. Previous studies have reported mixed results regarding the effectiveness of air cleaners in removing bioeffluents, with some showing no effects, some showing very small effects, and some showing even negative effects; that is, more pollutants were present, and the perceived air quality was reduced [12–14,22]. This study shows that, in spaces polluted by human emissions, passive air cleaners with activated carbon can provide a strong positive effect comparable

to or even higher than ventilation with outdoor air. The airflow through the air cleaner was $100 \text{ m}^3/\text{h}$ (27.8 L/s), that is, $50 \text{ m}^3/\text{h}$ (13.9 L/s) per person; therefore, if the air cleaner was 100% effective, the ventilation would be improved by a factor of 10. However, considering its effect on the acceptability of air quality, the effect expressed as clean air delivery by the air cleaners was lower (between $10 \text{ m}^3/\text{h}$ (2.8 L/s) and $24 \text{ m}^3/\text{h}$ (6.7 L/s)), indicating that the removal efficiency was lower than 100%. This effect should still be considered as it reduces the level of dissatisfaction with air quality to 20% or less, which is recommended by many ventilation standards [47,48]. Adding pollution sources, in addition to humans, could influence the performance of this air cleaner. Further investigation is required to determine whether this is true.

Iwashita et al. [37] investigated the perceived air quality polluted by human bioeffluents in 1990. Fifty-four Japanese students (27 males and 27 females) were divided into six groups to stay in a chamber as an indoor pollution source, and 107 Japanese students (55 males and 52 females) performed sensory evaluations. **Fig. 14** shows the relationship between the percentage of dissatisfaction and the ventilation rate per person in the chamber at a steady state. These results are supported by similar studies conducted in Europe by Fanger et al. [5,49] and in the U.S. by Cain et al. [50]. The results of the present experiments suggest a clean air delivery rate by the air cleaner at $24.1 \text{ m}^3/\text{h}/\text{person}$, that is, 7 L/s per person.

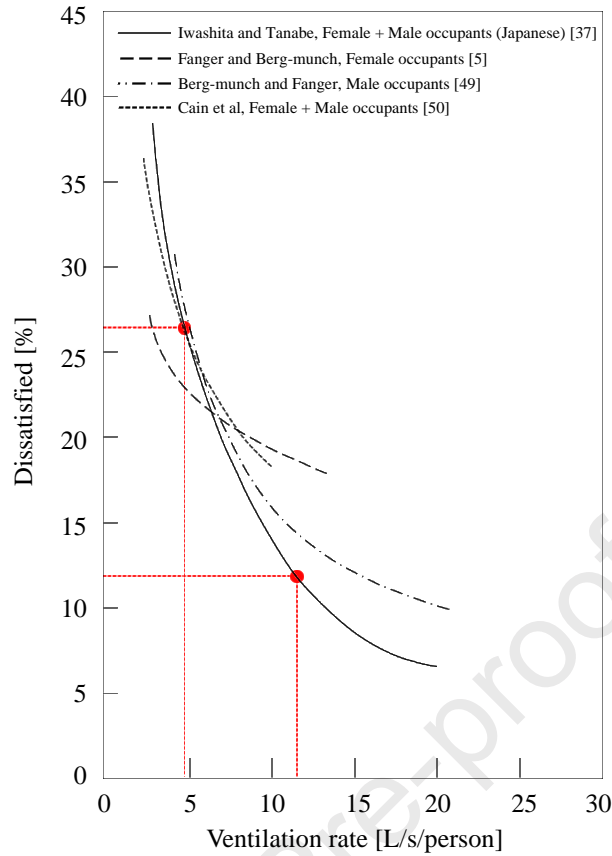


Fig. 14 Percentage of dissatisfied as a function of outdoor air supply rate [5,37,49,50]. The red line plots the 23°C results with (PD=27%) and without (PD=12%) air cleaner of this study.

The removal rate (effectiveness) of the air cleaners differed for different pollutants and perceived air quality. This discrepancy results in a variation in the estimated clean air delivery rate (CADR), which defines the equivalent air rate of clean air delivered by the air cleaner compared to ventilation using outdoor air (assuming that the outdoor air is clean). To account for this discrepancy, a method for measuring the performance and estimating the CADR of the air cleaner should be developed, probably using simpler methods than those applied in the present experiments.

The performance of the air cleaner was examined at two temperatures: 23°C and 28°C. At 28°C, the perceived air quality was different from that at 23°C. This may be because of the effects of elevated temperatures (enthalpy) on sensory perception, as documented in a previous study [30]. These effects

could also be due to the higher emissions of bioeffluents at 28°C, as well as potentially enhanced chemical reactions (if any) at this temperature. Despite the low levels of ozone, ozone/squalene reactions can occur when the products of such reactions, including decanal, are observed during chemical analyses[23]. Even though CO₂ levels were similar under both temperature conditions, the skin temperature was higher at 28°C than at 23°C, which may suggest a higher metabolic rate and thus higher emission rates of bioeffluents. Future studies should investigate this effect further; however, it should be noted that this has already been observed by Tsushima et al.[25]. These results, if confirmed, may indicate the need to revise ventilation standards to account for this effect on the prescribed airflow rates. Indeed, the Australian Standard [51] ventilation rate must be included when the indoor temperature exceeds 27°C.

A limitation of this study was that only two people sat in the chamber, and 13 participants evaluated the air quality. The latter could have resulted in the failure to observe significant differences in perceived air quality when the air cleaner was in operation. We performed a power analysis that showed that approximately 70 participants would be needed to observe statistically significant differences when we did not see them. We believe that these results support the findings of the present study as reliable and robust, and that the air cleaner improved air quality. For the former, the emissions of two people in the chamber could be significantly higher or lower than average human emissions. To examine whether this was the case, we compared the assessments of the percentage of those dissatisfied with air quality and odour intensity with previously reported measurements in which many more people generated emissions [3,5,52] and European participants were taking part. The results shown in **Fig. 15** indicate that the effects of pollutants emitted by the people in the present experiments, with Japanese participants, on perceived air quality were similar to those observed in previous studies. Hence, we can conclude that the application of air cleaners with the activated

charcoal used in the present experiment would produce similar effects if other people were present in the chamber and could, to some extent, be generalized. Nevertheless, additional measurements of the emissions from other individuals must be performed to support this hypothesis. Iwashita et al. [37] compared the effects of human emissions (bioeffluents) on perceived air quality obtained from studies conducted with Japanese participants with the results of studies with Danish participants performed by Fanger et al. [5,49] and U.S. participants conducted by Cain et al. [50] reported no differences in responses that could be attributed to ethnicity. Whether the impact of bioeffluents on sensory evaluation is comparable among other ethnic groups requires verification.

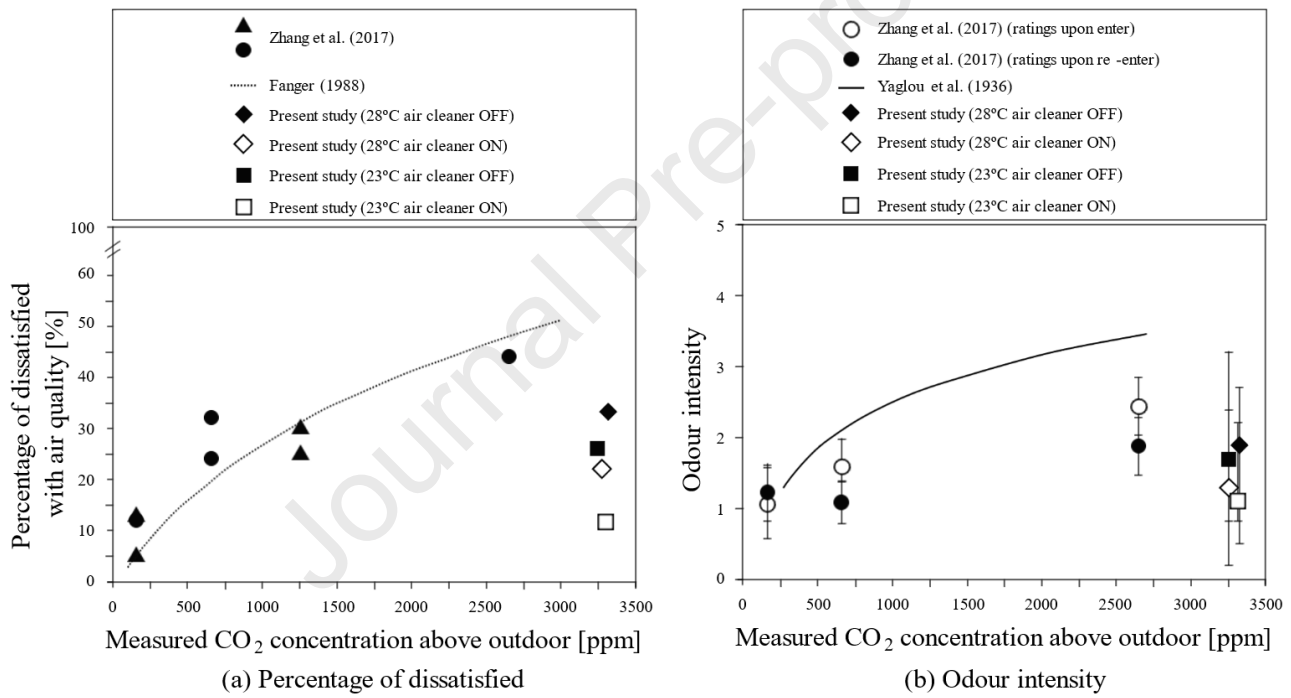


Fig. 15 Relationship between perceived air quality and CO₂ concentration [3,5,52]: (a) percentage of dissatisfied, (b) odour intensity.

Our results show that air cleaners with activated charcoal filters were effective in improving air quality even when the concentration of carbon dioxide (CO₂) in the chamber was higher than 3,000 ppm; CO₂ is a proxy for inadequate ventilation in spaces occupied by people and is non-odorous at

this level. This high level of CO₂ would otherwise trigger an action to improve air quality by increasing ventilation; however, considering chemical measurements and sensory evaluations with the air cleaner during operation, this would not have to be necessary. As discussed earlier, the level of ventilation in the chamber was approximately 5.5 m³/h per person (1.5 L/s per person), and with the air cleaner operating, the percentage of dissatisfaction was lower than 20%. Thus, it can be postulated that, in spaces where the dominant pollution is human emissions and other emissions are considered negligible, the use of an air cleaner with activated carbon, as in the present experiment, would provide measurable benefits. These spaces include bedrooms, classrooms, playrooms in daycare centers, assembly halls, such as theatres and cinemas, and conference and meeting rooms. Studies in spaces with air cleaners, as used in the present experiment, are necessary to support this hypothesis. However, poor ventilation of outdoor air, which results in high levels of CO₂, can create conditions that increase the risk of infection with airborne respiratory viruses. Hence, when an air cleaner is used and the ventilation is low, it must be supplemented with other methods to remove or kill infectious aerosols transmitted through the air. Thus, it would be useful to supplement air cleaners with highly efficient filters, such as HEPA.

The removal rate was higher for some compounds (e.g., aldehydes and d-limonene) at 28°C. At this temperature, the pollutant concentrations were higher. The higher the airborne concentration of the adsorbed object, the greater the pollution [46], which can explain the observed results. As temperature can affect the performance of gas air cleaners using activated charcoal, tests should be performed at different temperatures.

The odour intensity with the air cleaner disabled was the same at 28°C and 23°C. Previously, it was shown that the perception of odour intensity was not affected by air temperature in this range [25]; therefore, this result was as expected. However, as noted above, the concentration of pollutants was

higher at 28°C. It can be postulated that these pollutants evoke different sensory reactions and contribute to changes in the sensory perception of the acceptability of air quality and freshness. Otherwise, it would have been difficult to explain this result. It is also interesting to note that although chemical measurements showed that nearly all pollutants were removed, the sensory evaluations of air quality differed between the conditions with temperatures of 28°C and 23°C when the air cleaner was in operation. As discussed previously, the difference in enthalpy may have contributed to this effect. However, it is possible that some pollutants were not captured by the analytical chemical approach used in our experiments. Interestingly, the concentrations were lower than the odour threshold, yet sensory effects were evoked. This supports the idea that not all pollutants were identified, or that it is a combined effect of many pollutants on sensory responses, even though they are below odour thresholds, as previously speculated [25]. Nevertheless, these results suggest that sensory characterization of the performance of gas-phase air cleaners is necessary; therefore, a new standard ISO 16000-44 was introduced in 2023 to facilitate these measurements [24].

5. Conclusions

In this study, two male participants serving as a source of bioeffluents sat in a stainless-steel chamber at two temperatures (23°C and 28°C) and a gas-phase air cleaner was in operation or idled in either condition. In addition, 13 participants, who were unaware of the source of pollutants, evaluated the perceived quality of the air extracted from the chamber, and chemical analyses were performed.

- The results of this study show that emissions from humans (bioeffluents) can be effectively removed by air cleaners using activated carbon, even when they are at a high concentration, marked by a metabolic CO₂ level above 3,000 ppm. This suggests the potential for using air cleaners in spaces with low ventilation where human pollution is dominant. However, these methods must be supplemented to reduce the risk of airborne viral infection.
- This study showed that even though the concentrations of the measured pollutants were low and below the odour detection threshold, there was a sensory response. This suggests that, if sensory discomfort is a performance metric, sensory evaluations are necessary and cannot be replaced by modeling and prediction using chemical measurements.
- This study showed that increased temperatures could promote the emission of human bioeffluents, probably owing to increased metabolic rates and chemical transformations. Future studies should investigate this result in detail; however, the ventilation standards should be revised to consider this effect.
- Therefore, the observed results must be validated. Future studies should also focus on developing a reliable method for estimating the air-cleaner removal effect using the measured concentrations of chemical substances or sensory evaluations of air quality.
- This study partially followed the protocol suggested by ISO 16000-44 and provides provisional validation of the methodology proposed by the same standard.
- As the present study used an air cleaner specially designed for people with chemical sensitivity, the results showed the potential effects that could be obtained with respect to

removal efficiencies and clean air delivery rates when the source of pollution is human emissions (bioeffluents). They can also guide future developments in air cleaning, and can be used as inputs for simulations.

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Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this paper.

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Highlights

- The removal performance of bioeffluents in gas-phase air cleaners is verified under two different temperature conditions.
- The removal of bioeffluents with high concentrations of CO₂ is possible with gas-phase air cleaners.
- Air cleaners testing requires sensory assessments as well as chemical analysis.
- Increased temperatures accelerate the emission of human bioeffluents.
- Removal of contaminants by air cleaners is effective for acceptability at near-neutral temperatures.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: