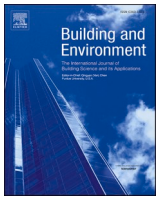
Building and Environment 259 (2024) 111630

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



A method for testing the gas-phase air cleaners using sensory assessments of air quality

Kanta Amada [a,*], Lei Fang [b], Simon Vesth [b], Shin-ichi Tanabe [a], Bjarne W. Olesen [b], Pawel Wargocki [b]

[a] Creative Science and Engineering, Department of Architecture, Waseda University, 55N-701, 3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan
[b] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Nils Koppels Alle, Building 402, DK-2800, Lyngby, Denmark

ARTICLE INFO

Keywords:
Air cleaning
Perceived air quality
VOCs
Activated carbon
Human bioeffluents
Building materials

ABSTRACT

Present standards prescribe chemical analyses for testing the performance of gas-phase air cleaners. As a part of IEA Annex 78, this study examined a prototype method for testing gas-phase air cleaners based on sensory evaluations of air quality. Four common gas-phase air cleaners were tested using the proposed method. The testing consisted of two phases: Phase 1 ensured that air cleaners had no negative effect on air quality, and Phase 2 provided a detailed characterisation of the removal efficiency of air cleaners. Air cleaners were tested in experimental rooms called field laboratories, and pollution sources comprised of building materials and humans. Thirty-one panellists were recruited. They rated the acceptability of air quality and odour intensity immediately upon entering the rooms and of the air extracted from them and presented in diffusers. Chemical measurements were made as well only in Phase 2. The operation of air cleaners reduced concentrations of VOCs regardless of the pollution source; the perceived air quality was only improved when the pollution source was building materials,supporting the necessity of inclusion of sensory ratings. The results also confirmed that comprehensive testing of air cleaners in Phase 2 should only be performed once it is documented that air cleaners positively reduce pollution exposures in Phase 1. The study followed methodologies proposed by the ISO 16000-44 standard, so the results validate and support this standard. The tests of different air cleaner configurations and the round-robin test are recommended to advance the methodology proposed and examined in the present study.

1. Introduction

Building energy use accounts for approximately 40 % of total energy use [1]. Ventilation, heating, and air conditioning use most energy in buildings - 32 % in the residential and 47 % in the tertiary sectors [2]. Thus, reducing energy use for building ventilation is an essential step towards a net-zero society.

People spend 90 % of their lives in buildings [3]. The conditions in buildings that affect indoor environmental quality (IEQ) significantly impact the health, well-being, work performance and learning of building occupants [4–7]. Poor IEQ results in building-related illnesses (BRI) and the symptoms known as sick-building syndrome (SBS) [8]. Air quality is one of the parameters determining the level of IEQ. Ventilation is a method for improving indoor air quality. However, adequate ventilation may result in increased energy use [9].

One of the purposes of ventilation with outdoor air is to dilute and remove pollutants emitted from indoor sources, thereby reducing their concentrations in spaces occupied by people; reduced exposure reduces discomfort and health risks [10]. It is assumed in many ventilation standards that air supplied indoors, primarily outdoor air, is of high quality. However, outdoor air can contain pollutants that are harmful to human health. In some areas, the outdoor air quality is so poor that ventilation could be considered unsuitable unless adequately supplied air is treated correctly [11]. Natural disasters can exacerbate periods of poor outdoor air quality during normal weather conditions and operations, often due to climate changes. In any of the mentioned cases, air cleaning is indispensable to maintain high indoor air quality. Air cleaning can also reduce the concentrations of pollutants emitted indoors, thus supporting ventilation for achieving high indoor air quality.

Supplementing or even substituting ventilation with air cleaning makes it possible to reduce the rate of outdoor air supplied indoors and may consequently provide significant energy benefits [12]. Because

* Corresponding author.
E-mail address: amada@fuji.waseda.jp (K. Amada).

https://doi.org/10.1016/j.buildenv.2024.111630
Received 14 January 2024; Received in revised form 3 May 2024; Accepted 9 May 2024
Available online 10 May 2024

most ventilation standards prescribe ventilation to achieve acceptable air quality based on the sensory perception of air quality defined either by the percentage of people dissatisfied [13,14] or satisfied with air quality [15] and because gases and vapours mainly trigger the sensory perception (odours, freshness, etc.), the use of gas-phase air cleaners can be considered as a method for supplementing or even partially substituting ventilation. In theory, gas-phase air cleaners should remove all gaseous pollutants and/or transform them into inert (benign) species, so their operation should principally bring benefits similar to ventilation with outdoor air. Gas-phase air cleaners can incorporate various technologies, including, among others, adsorption, catalytic oxidation, non-thermal plasma, and even natural plants [16].

Gas-phase air cleaning is not directly considered in the new ISO standard 17,772–1 concerning indoor environmental quality [13], but the corresponding guideline TR 17772–2 offers the possibility of substituting the part of ventilation air with air cleaning [17]. ASHRAE Standard 62.1 for commercial buildings allows ventilation rate credits for air cleaning using the indoor air quality procedure [15], while the new Addendum AA to this standard provides the list of pollutants that should be removed by an air cleaner to achieve the credit [18]. However, the standards for gas-phase air cleaners do not include the same pollutants for testing their performances [19]. They do not describe the method for testing the performance using sensory evaluation of air quality either; the only exception is Standard 16,000–44 [20], which describes the method of testing gas-phase air cleaners using sensory assessments of air quality, but it was approved as late as in 2023. Even though this standard provides the methodology, it does not describe the performance criteria for testing air cleaners. Since ASHRAE 62–1 [15] prescriptive rates are based on sensory perception of air quality, it would be beneficial that standards for testing air cleaners include this method for evaluating their performance.

Afshari et al. [19] summarised test methods and standards for portable air cleaning devices and showed that existing methods for testing gas-phase air cleaners are generally based on challenging air cleaners with selected contaminants. For example, NF B 44–200, the French national standard for testing methods of air cleaners, requires the measurement of acetone, acetaldehyde, formaldehyde, heptane, and toluene [21]. The standards developed by CEN-ISO and IEC also propose to measure the selected chemical compounds [22]. This methodology may be considered inadequate for evaluating the overall effect of air cleaners on indoor air quality because indoor air contains hundreds of gaseous pollutants [23]. Chemical analysis may not capture all pollutants that air cleaners remove, and thus, the actual removal effect can be underestimated. On the other hand, chemical analyses may not capture all pollutants produced during air cleaning (unwanted products) and thus can overestimate or falsely assess the performance of air cleaners [24]. Guidelines are available for only a few chemicals and only when occurring individually, neglecting the potential interactions [25]. Consequently, other comprehensive methods must be developed to ensure proper measurements of the performance of air cleaners and their effect on indoor quality. Measuring perceived air quality provides such an opportunity. This method is not new: sensory measurements of air quality using humans date back to the 1930s and have been routinely used in air quality investigations since the 1990s [26]. Moreover, they are used in standards for testing emissions from building products [27]. They have also been used to test the performance of air cleaners, as described below.

Iwashita et al. [28] evaluated the efficiency of portable air cleaners challenged with tobacco smoke. They showed that the acceptability of air quality and odour intensity was reduced at lower concentrations of measured particulate matter. Sheng et al. [29] investigated a clean-air heat pump combined with a silica gel rotor and a heat pump. They demonstrated that operating an air cleaner with low ventilation produced a comparable effect on the perceived air quality as a high ventilation rate with no air cleaner. Shaughnessy et al. [30] tested the effectiveness of individual commercially available portable indoor air cleaning units in removing dust particulates, tobacco smoke particulates, vapour-phase constituents, viable and total fungal spores, pollen, and gaseous contaminants in a clean air test chamber. The results indicated that the air cleaner with activated carbon performed the best in terms of perceived air quality. Kolarik and Wargocki [31] showed that the operation of a photocatalytic air cleaner significantly reduced the perceived air quality in rooms with human bioeffluents, probably owing to the incomplete oxidation of alcohols, which are some of the primary pollutants emitted by humans; nevertheless, there was a positive effect for other pollutant types when air cleaners were in operation. Krejcirikova et al. [32] examined the sensory effects of emissions from cement- and cement-ash-based mortar slabs and showed that the odour intensity of the mixture of the slab and linoleum was lower than that produced by any of the two materials when tested individually. Darling et al. [33] studied the sensory impacts of clay plaster as a passive removal material. They showed that adding clay plaster to a chamber with a carpet and ozone improved the perceived air quality. Zhang et al. [34] conducted a subjective experiment to evaluate the effect of a steamer plasma air cleaner on the perceived air quality. They confirmed that the air quality was systematically better when the air cleaner operated. Moya et al. [35] studied the effect of an active plant-based system on perceived air pollution. They demonstrated that the odour intensity was higher and acceptability was lower in a chamber with an active plant-based system than in a chamber without one. Fang et al. [36] examined the performance of a steamer plasma air cleaner using a sensory assessment. They concluded that streamer plasma air cleaners systematically improved the perceived air quality in spaces with typical indoor pollution sources. None of the studies above used standard protocol, and none attempted to convert the method into a standard protocol for testing air cleaners using sensory assessments despite the results showing that the method is valid.

The actual performance of air cleaners can only be assessed if the testing method includes identifying their potential negative effects on air quality. Some air cleaners use technologies that may produce unwanted by-products during the air cleaning process; these by-products can be more harmful than processed pollutants. An example is air cleaning using photocatalytic oxidation. In this case, incomplete air cleaning can transform even relatively inert pollutants such as toluene into hazardous species [37]. Also, ozone generation during the air cleaning process should be considered unwanted because ozone can participate in chemical reactions resulting in harmful and unwanted species [38]. Traditional chemical analytical measurements may not always identify all potentially hazardous by-products resulting from the operation of air cleaners. Evaluating by-products is also complicated because no standards currently define which pollutants could be produced and which are unwanted. The potential negative effects of air cleaner operation on air quality can be identified using sensory measurements of air quality, as shown in the study by Kolarik and Wargocki [31], thus providing an additional argument regarding the attractiveness of this approach. IEA Annex 78 on Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications (https://annex78.iea-ebc.org/) was proposed to investigate the possible energy benefits by using gas phase air cleaners (partial substitute for ventilation) and establish procedures for improving indoor air quality or reduced amount of ventilation by gas phase air cleaning. One objective was to develop a test method for air cleaners using sensory evaluation of air quality. As part of IEA Annex 78, the objective of the present study was to examine a prototype for such a method, which is comparable to the method included in Standard 16,000–44 [20]. Different air cleaners using various technologies were tested; they were challenged with various pollutants, and different methods of presenting the air for sensory evaluations were examined as well. Furthermore, the sensory evaluations were compared against the results of chemical analyses.

2. Methods

2.1. Approach

Air cleaners with different operational principles were challenged with pollutants emitted from building materials and humans. The performance of air cleaners was examined using sensory ratings of air quality and chemical measurements and compared with the effect obtained by increasing the ventilation rate. The testing was performed in two phases. In Phase 1, whether air cleaners had positive, benign, or negative effects on air quality was examined. In Phase 2, the air cleaners were further examined by comparing their performance against the effect on air quality obtained by changing outdoor air supply rates. Chemical measurements were only performed for selected conditions in Phase 2. We used two types of air cleaners: subtractive, which removed gas-phase chemicals from the air stream by adsorption or sorption, and additive, which decomposed gas-phase chemicals into different molecules by adding components initiating active chemical decomposition. Similar nomenclature was proposed by [39].

2.2. Facilities

The experiments were performed in the field laboratories at the International Centre for Indoor Environment and Energy, Technical University of Denmark [40]. Fig. 1 shows the sketch, and Fig. 2 shows a view from inside and outside of the experimental rooms. The volume of each room was 55.7 m^3 (width 2.9 *m*, length 6.0 *m*, height 3.2 *m*). The rooms were separated by a well-sealed partition, and the air did not move between the rooms. The windows from the rooms faced west and were closed during the experiments. Rooms were ventilated with outdoor air (no recirculation) using a mechanical ventilation system with filtration and heating [40]. The air supply was installed in the ceiling, while the exhaust was located above the door. Each room was kept under slight overpressure towards surrounding spaces.

The outdoor air supply rate, temperature, and relative humidity in the rooms were controlled by the specially designed control system; the latter was achieved by ultrasonic humidifiers installed in the rooms. Pedestal fans were installed in the room to ensure good mixing. Partitions with a height of 1.5 *m* were placed in each room to hide air cleaners and people sitting inside the rooms so that the panellists performing sensory evaluations could not see them under various exposure scenarios. Other pollution sources (building materials) were placed in the ventilated cabinets called 'pollution boxes'; a fan installed on the top of each cabinet and operated at a sufficient speed ensured that cabinets were adequately ventilated [40]. The pollution sources, pedestal fans and air cleaners could not be seen when performing these measurements. A small fan extracted the air from each room through a hose duct to the corridor; this air was presented for sensory evaluation via a diffuser at a flow rate of 1.0 L/s [41] (Fig. 1). Three diffusers were installed to extract air from the three rooms, and the diffusers' arrangement was made so that the panellists performing sensory assessments could not identify which diffuser extracted the air from which room and even whether the air in the diffuser was extracted from the rooms. Two crosses were marked on the floor before the partition to indicate where the sensory evaluations had to be performed upon entering the room.

2.3. Participants

The participants performing sensory evaluations, called panellists, and participants serving as sources of human emissions (bioeffluents), called occupants, were recruited. All participants were students. We collected information about the participants, presented in Table 1; all information was self-reported by the participants. The participants were financially compensated for their participation in the experiments.

Thirty panellists were recruited in Phase 1, and thirty-one in Phase 2; some participating in Phase 1 participated also in Phase 2. To characterise the sensory abilities of panellists, we calculated a chemical sensitivity scale (CSS) score [42] but did not perform any medical examination or tests examining the ability to perceive odours; the average CSS score was typical for the general population and suggested no specific sensitivity for the selected panellists.

Eight occupants were recruited. During the experiments, three occupants sat quietly behind a partition (Fig. 1). One person in Phase 1 was a smoker (smoking was not allowed during the experiments), but no other smokers or people with allergies or chronic diseases were recruited.

All recruited participants were requested not to consume alcohol, garlic, or spicy foods in the evening and night before the experimental day and on the day of the experiments. They were also requested not to consume coffee an hour before the experiment and were only allowed to consume water during the experiment. Strong deodorisers or perfumes were prohibited on the day of the experiment. The occupants were instructed to shower in the evening of the day before the experiment using odourless shower gel provided by the experimental team.

2.4. Experimental conditions and procedures

The experiments were performed in two phases. The rooms were maintained at 23 °C and 30%RH during both phases.

In Phase 1, three types of portable air cleaners labelled PAC1a, PAC2s, and PAC3a were examined, where 'a' stands for air cleaners with additive principle of operation and 's' for subtractive. Table 2 provides detailed information on these air cleaners. Twelve conditions were

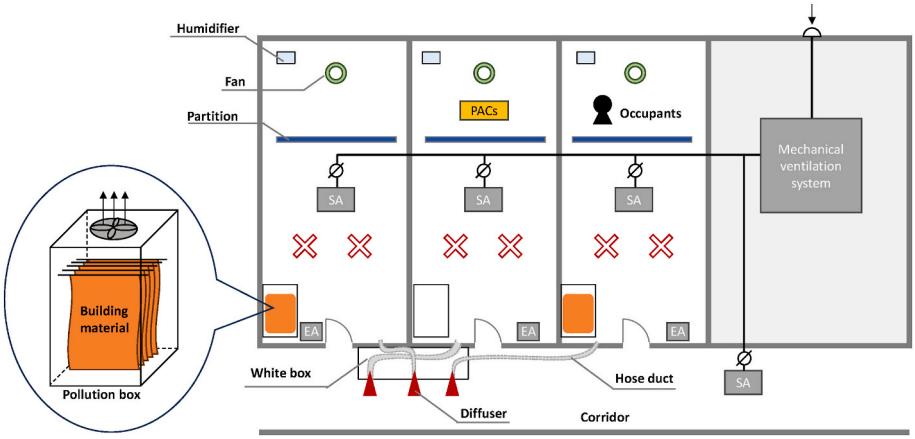


Fig. 1. Outline of experimental rooms.

Fig. 2. Images of experimental rooms. Left: the view inside. Right: the view outside.

Table 1
Demographic data of recruited participants.

Characteristic description	Phase 1		Phase 2	
	Occupants	Panellists	Occupants	Panellists
Total	3	30	6	31
Gender: males, females	3, 0	22, 8	3, 3	23, 8
Age (means ± SD) years old	25.0 ± 2.2	24.6 ± 2.4	27.2 ± 4.7	24.6 ± 2.5
Smokers	1	2	0	4
Any allergies, including hay fever	0	3	0	3
Any asthma	0	1	0	1
Any chronic disease	0	1	0	1
Increased upper airway sensitivity	0	1	1	1
A hearing impairment	0	0	0	0
Wearing glasses or contact lenses	1	17	3	18
Sensitive to air quality	0	4	2	4
CSS score (means ± SD)[a]	–	64.1 ± 10.8	–	62.8 ± 16.0

[a] The mean and standard deviation of CSS score for a sample of 595 individuals were 62.3 and 15.2, respectively [42].

Table 2
Characteristics of each air cleaner. PAC = portable air cleaner.

	PAC1a (additive)	PAC2s (subtractive)	PAC3a (additive)	PAC4s (subtractive)
Principle for removing gaseous contaminant	Ion generator	Activated carbon	UV/ozone reaction	Activated carbon
Presence of particle matter filter	No	Yes (HEPA filter)	No	Yes (HEPA filter)
Nominal airflow through an air cleaner [m^3/h]	(Not available)	290	(Not available)	276

created and examined in experimental rooms (Table 3). Building materials (5 m^2 of old carpets [43] and 5 m^2 of linoleum [44]) placed in pollution boxes, and humans, three people sitting behind the partition, were used as pollution sources. The building materials were placed in pollution boxes one week before the experiment, while people entered the rooms 2 h before the sensory evaluations began. People were seated quietly during measurements (reading, listening to music, watching lectures, etc.) but walked around the room for the first half an hour after entering the experimental rooms to build up their emissions so that the steady-state level of bioeffluents could be obtained before the sensory assessments commenced. The rooms were ventilated with 7.5 L/s, with three people in a room; this rate corresponded to the rate prescribed by the ASHRAE Standard 62.1 to deal with human emissions [15]. One unit of each air cleaner type had been placed in the rooms and turned on 3 h before sensory evaluations commenced; it was turned off 30 min after the sensory measurements were completed. The panellists performed sensory evaluations upon entering the rooms and on the air extracted from the rooms via diffusers. The evaluations were made in rooms without pollution sources, with humans or building materials, while the air cleaners operated or idled. The panellists were divided into three groups and performed sensory evaluations from 12:00 to 13:00 (Group 1), from 13:15 to 14:15 (Group 2), and from 14:30 to 15:30 (Group 3). Phase 1 was conducted for five days in February 2022; the first day was used to practice sensory evaluations and get familiar with measuring procedures and protocols.

In Phase 2, three portable air cleaners labelled PAC1a, PAC2s, and PAC4s (Table 2) were examined; the first two were the same as those examined in Phase 1. In total, thirty various conditions were established and examined in experimental rooms (Table 4). The pollution sources were examined separately, like in Phase 1, but also together (Table 4), so new persons were recruited as the source of human emissions. The rooms where the measurements were made were ventilated with outdoor air at the rates of 7.5 L/s, 12 L/s, 21 L/s and 30 L/s; with three people in the rooms, these ventilation rates corresponded to the rates prescribed by the standard EN16798 [14] (the last three) and ASHRAE Standard 62.1 [15] (the first one). Three units of each air cleaner type were placed in the rooms. Other procedures and processes were the same as in Phase 1. The ventilation rate was set about 20 h before sensory evaluations on the following day, i.e. 30 min after completing the sensory evaluations. Besides the sensory measurements, chemical measurements were performed with and without air cleaners running at the lowest ventilation rate (Table 4), described in section 2.6.2. Phase 2 was conducted for ten days in March 2022.

Table 3
Experimental condition (Phase 1): PAC = portable air cleaner.

Pollution sources	Ventilation rate per person with three people [L/s p]	Total ventilation rate [L/s]	No PAC	PAC1a (1 unit)	PAC2s (1 unit)	PAC3a (1 unit)
Empty (No pollutant)	2.5	7.5	✓	✓	✓	✓
Building materials (5 m^2 carpet and 5 m^2 linoleum)	2.5	7.5	✓	✓	✓	✓
Human emissions - bioeffluents (three people)	2.5	7.5	✓	✓	✓	✓

Table 4
Experimental condition (Phase 2). Asterisks indicate the condition in which the chemical measurements were performed; PAC = portable air cleaner.

Pollution	Ventilation rate [L/s p]	Ventilation rate [L/s]	No PAC	PAC1a (3 units)	PAC2s (3 units)	PAC4s (3 units)
Building materials (5 m^2 carpet and 5 m^2 linoleum)	2.5	7.5	✓*	✓*	✓*	–
	4	12	✓	✓	✓	–
	7	21	✓	✓	✓	–
	10	30	✓	–	–	–
Human emissions - bioeffluents (three people)	2.5	7.5	✓*	✓*	✓*	–
	4	12	✓	✓	✓	–
	7	21	✓	✓	✓	–
	10	30	✓	–	–	–
Building materials (5 m^2 carpet and 5 m^2 linoleum) and human emissions - bioeffluents (three people)	2.5	7.5	✓*	–	✓*	✓*
	4	12	✓	–	✓	✓
	7	21	✓	–	✓	✓
	10	30	✓	–	–	–

2.5. Measurements

Table 5 summarises the measurements performed during the experiments. In Phases 1 and 2, sensory assessments were performed, whereas in Phase 2, chemical measurements were also performed. The temperature, relative humidity, carbon dioxide concentration, particulate matter, and ozone were also measured. Some of these measurements are reported in the Appendix. The air temperature and relative humidity were measured near the centre of each room and the hose duct inlet of the diffuser.

2.5.1. Measurements and analysis of sensory data

The panellists assessed the acceptability of the air quality and odour intensity using the scales presented in Fig. 3. These scales were used in previous experiments where sensory evaluations were made [28–34] and are also included in a standard [20]. The following sentence preceded the scale for acceptability to create the proper context of assessment: 'Imagine that during your daily life in non-industrial buildings, you were exposed to this air. How do you assess the acceptability of the air quality?'. During each evaluation, the panellists assessed either acceptability or odour intensity; in each location, the evaluations were thus made twice (one acceptability and one odour intensity), so each panellist made 12 evaluations during one measuring session a day. The order of evaluations was balanced across the panellists.

The panellists were instructed not to discuss their assessments or make facial expressions that could indicate their opinions. They took a 2–3 min break between assessments to avoid sensory fatigue; this break was used in previous measurements [45]. They sat in a corridor adjacent to the experimental room during this period. The corridor was well-ventilated, and the temperature and relative humidity were measured, which were similar to the room conditions. The experimenter informed the panellists when and where they should perform their next assessments.

Fig. 3. Scales used by participants in the experiment to assess the air quality. Left: Acceptability. Right: Odour intensity.

Table 5
The list of measurements performed during experiments.

	Measurement items	Phase	Measurement device	Measurement interval
Sensory evaluation	Acceptability (whole body/face)	Phase 1/ Phase 2	–	–
	Odour intensity (whole body/face)	Phase 1/ Phase 2	–	–
Chemical measurements	VOCs (C5–C22)	Phase 2	Tenax TA (3L/6L)	–
	Aldehydes	Phase 2	DNPH (4L)	–
physical measurements	Air temperature	Phase 1	Thermal environment controller in the room [36] (Accuracy: ±0.5°C)	After experiments each day
		Phase 2	HOBO U12-012 Data Logger: Onset Computer Corporation (Accuracy: ±0.35°C)	1 min
	Relative humidity	Phase1	Thermal environment controller in the room [36] (Accuracy: ±5 %)	After experiments each day
		Phase 2	HOBO U12-012 Data Logger: Onset Computer Corporation (Accuracy: ±2.5 %)	1 min
	CO_2 concentration	Phase 1/ Phase 2	Multipoint Sampler and Doser Type 1303: INNOVA AIR TECH INSTRUMENTS A/S (Accuracy: ±5 ppm)	3 min
	Ozone concentration	Phase 2	Model 205 Ozone Monitor™: 2B Technologies (Accuracy: ±2 %)	Before/after experiments of each day
	Particle concentration (0.3–5 μm)	Phase 2	Optical Particle Sizer (OPS) 3330: TSI Incorporated (Accuracy: ± 5–10 % depending on the particle size range)	Before/after experiments of each day
	Ultrafine Particle concentration (~0.1 μm)	Phase 2	P-Trak Ultrafine Particle Counter 8525: TSI Incorporated (Accuracy: ±3 %)	Before/after experiments of each day

The sensory assessments were conducted upon entering the rooms (termed whole-body exposures) and on the air extracted from the rooms via diffusers to the corridor adjacent to the experimental rooms (termed facial exposure) (Figs. 1 and 2); the panellists were not told that the air was extracted from the rooms.

During whole-body exposures, the panellists were instructed to make evaluations by adhering to the following protocol: Two panellists entered the rooms by pushing the door (which closed automatically after they had entered the room), approached the crosses on the floor (about 1.5 *m* away from the door), inhaled the room air and made immediately rating on the scale printed on the paper. Then, they immediately left the room to reduce the time they spent inside. Instructions were made not to breathe the air when approaching the cross and to make an assessment after only one inhalation.

During facial exposures, the panellists were instructed to make evaluations by adhering to the following protocol: The panellists approached the diffuser singly, put the face in the centre of the diffuser, took one inhalation of the air from the diffuser and made the assessment.

Once they finished either the facial or whole-body assessment, they returned the voting sheet to the box with the front side of the sheet down.

The ratings made on the paper scales were digitised. The scales were coded as follows: clearly acceptable = 1, just acceptable/just unacceptable = 0.001/-0,001, clearly unacceptable = −1, no odour = 0, overpowering odour = 5. The averages were calculated based on the sensory evaluations made by the panellists.

The Wilcoxon signed-rank test was used to examine whether there were significant differences in the ratings between different conditions with and without air cleaner; the significance level was set at $p = .05$ (2-Tail). The effect size was also calculated, where the lower limits for small, medium, and large effects were set at 0.10, 0.30 and 0.50 [46].

2.5.2. *Chemical measurements*

Chemical measurements were performed in Phase 2 at the lowest ventilation rate of 7.5 L/s (Table 4). Stainless steel tubes with Tenax TA and DNPH cartridges were used to collect the air for analyses. Sampling was done parallel to sensory measurements; 3L and 6L air was sampled on the tubes containing Tenax TA and 4L air on the DNPH cartridges. The sampling flow rate was set at 0.1 L/min and achieved by the calibrated pumps. Besides the measurements in rooms, blank samples were collected. After collection, the Tenax TA tubes were tightly corked, wrapped in aluminium foil, and stored at room temperature. Sampled DNPH tubes were tightly corked and stored in a freezer.

The tubes were sent for analysis to commercial laboratories. The Tenax TA tubes were analysed using gas chromatography-mass spectrometry (GC-MS), and the DNPH tubes were analysed using high-pressure liquid chromatography (HPLC). 3 L samples on Tenax TA were analysed for very volatile organic compounds (VVOCs), while 3L and 6L samples on Tenax TA for volatile organic compounds (VOCS); 6 L samples on TENAX were used to analyse semi-volatile organic compounds (SVOCs). Samples on DNPH cartridges were analysed for aldehydes.

The measurements of VOCs using Tenax TA tubes were performed according to DIN ISO 16000–6:2022–03 [47], with a limit of detection (LOD) of 1 μg/m^3. Concerning the DNPH tube, the LOD was 0.03 μg/tube (approximately 0.75 μg/m^3) for formaldehyde, acetaldehyde, and butanal and 0.05 μg/tube (approximately 1.25 μg/m^3) for propanal and 0.2 μg/tube (approximately 5 μg/m^3) for acrolein with expanded uncertainty was 15 %.

3. Results

Fig. 4 shows the thermal environments in Phase 1. In each room in Phase 1, the temperature, humidity, and enthalpy were approximately 22 °C, 22–31 %, and 30–35 kJ/kg, respectively. In Phase 1, relative humidity in the room with humans was slightly higher than in other rooms. Fig. 5 shows the thermal environments in Phase 2. The values are the mean and standard deviation of the results for the entire experimental period for each room. In Phase 2, the temperature, humidity, and enthalpy were approximately 23 °C, 35–40 %, and 38–40 kJ/kg, respectively.

Fig. 6 shows the results of the whole-body sensory evaluations performed in Phase 1; the facial evaluations are presented in the Appendix.

There were no significant differences in the ratings of acceptability when there was no additional pollution or with building materials when PAC1a was in operation. When humans were present, the acceptability of air quality significantly decreased. There were no effects on perceived odour intensity. Although it turned out that PAC1a did not have a positive effect on air quality, it was included in Phase 2 to examine whether the results could be repeated.

In the case of PAC3a, there were no significant effects on the rating of acceptability of air quality when it was in operation independently of the presence or absence of any type of pollution source. However, odour intensity increased significantly when sources were absent, and humans were present during its operation. PAC3a was consequently not included in Phase 2.

In the case of PAC2s, its operation significantly improved the acceptability of air quality and reduced odour intensity when the pollution source was building materials; no significant differences in sensory ratings were seen in the other cases.

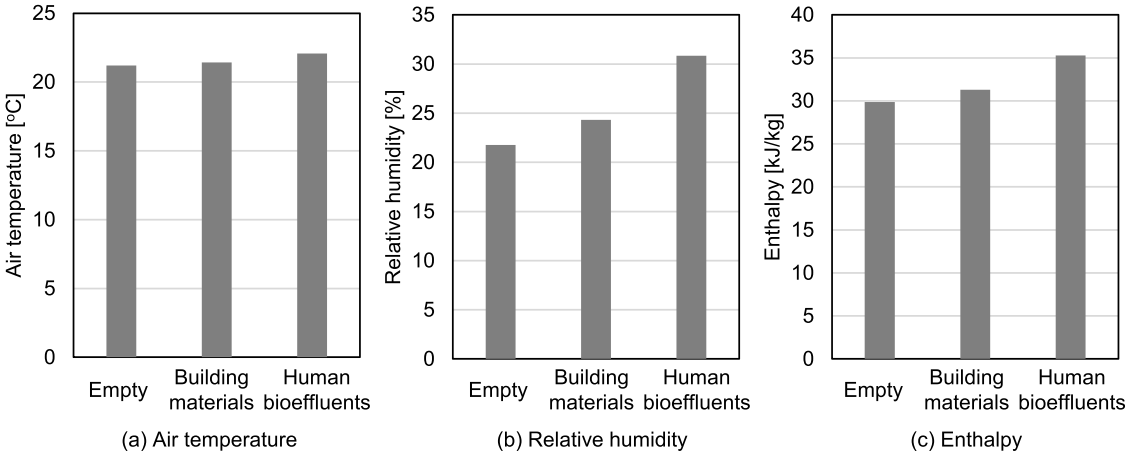


Fig. 4. Results of the thermal environments in Phase 1. (Mean).

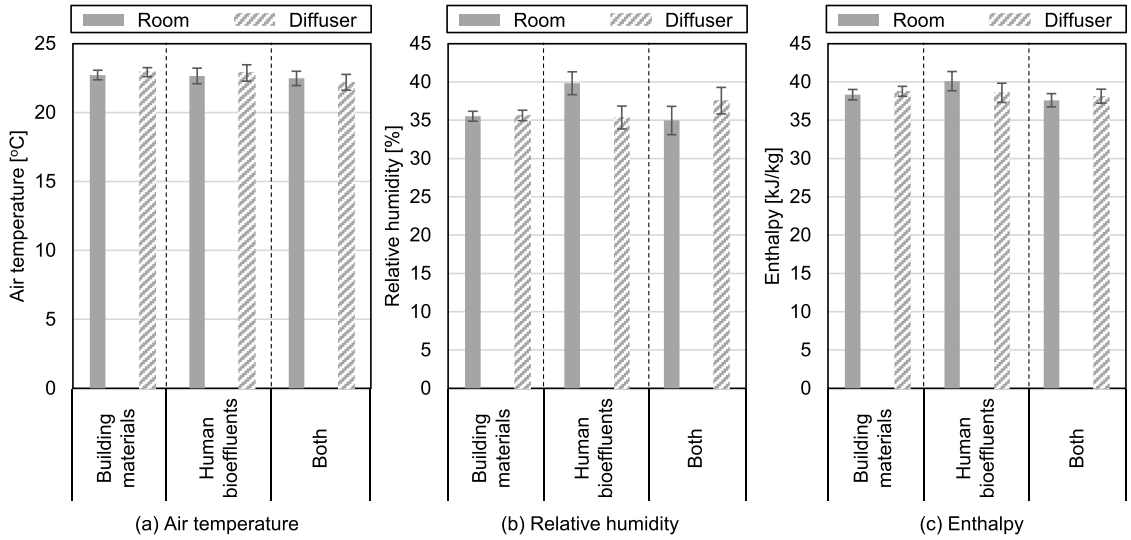


Fig. 5. Results of the thermal environments in Phase 2. (Mean ± SD throughout the entire experimental period).

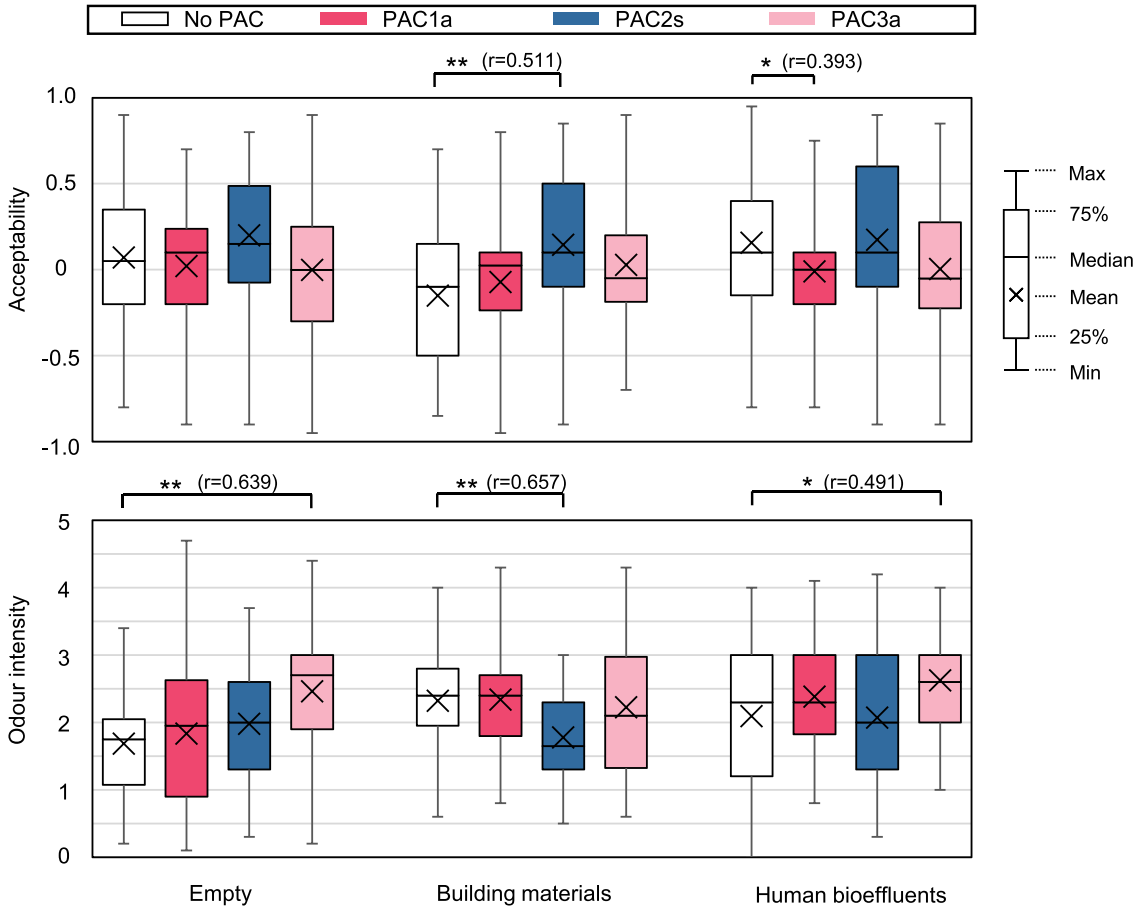


Fig. 6. Results of the whole-body sensory evaluations in Phase 1. Asterisks indicate the level of significance: *.01< p < 0.05, **p < 0.01.

Fig. 7 shows the results of the whole-body sensory evaluations in Phase 2; the facial evaluations are presented in the Appendix. Increasing the ventilation rate in the experimental rooms improved perceived air quality, as would be expected, while air cleaners improved perceived air quality only in some conditions (Fig. 8).

Operation of PAC1a did not improve air quality, and it significantly decreased the acceptability of air quality, as had been already shown in Phase 1. Operation of PAC2s significantly improved the acceptability of air quality when sources were building materials but not when the sources were humans. This result again confirmed the findings observed in Phase 1. When the sources were humans and building materials, the acceptability of air quality was not systematically improved when this

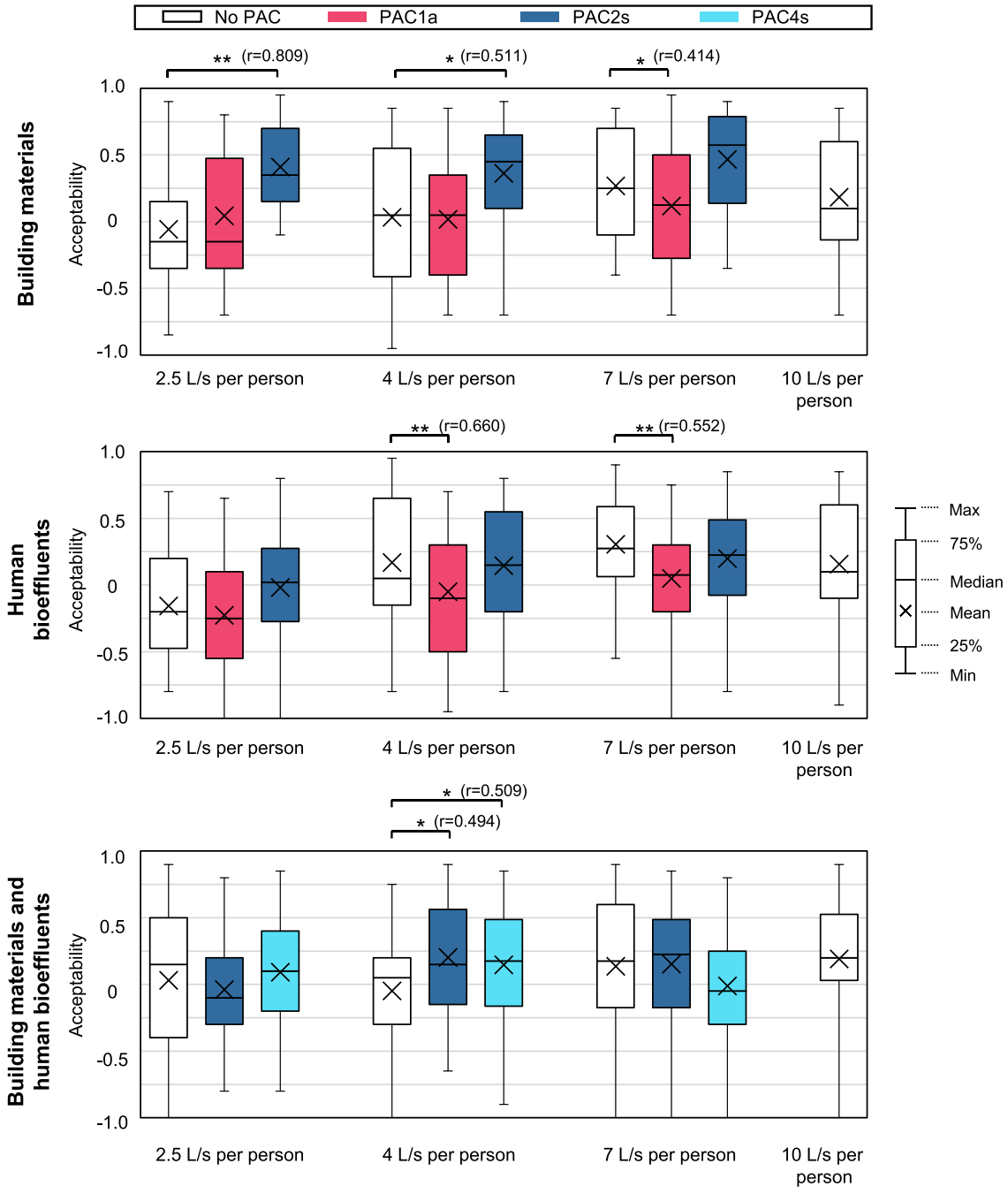


Fig. 7. Results of the whole-body sensory evaluations of acceptability of air quality in Phase 2. Asterisks indicate the level of significance: *.01< p < 0.05, **p < 0.01.

air cleaner was in operation. Similar results were observed with the air cleaner PAC4s having a similar principle to PAC2s (activated carbon).

Fig. 9 compares whole-body and facial sensory evaluations. The acceptability of air quality was generally assessed to be higher, and the odour intensity was lower when the air was presented via diffusers. This effect tended to increase with lower acceptability and higher odour intensity. This result does not match previous reports [48,49].

Fig. 10 compares the acceptability of the air quality and odour intensity. There was a strong correlation between both assessments, as shown in previous studies [50].

Figs. 11–14 summarise the results of chemical measurements. A slight decrease of formaldehyde and acetaldehyde concentrations was observed when PAC4s was in operation but not when other air cleaners were in operation (Fig. 11). The results of chemical measurements generally did not match the sensory evaluations, especially for PAC2s. The sum of VOCs (by adding the concentrations of detected pollutants between C6 and C16) [51] is shown in Fig. 12. Considerable reductions in concentration were seen when PAC2s and PAC4s were in operation, and these results are similar to sensory assessments. Figs. 13 and 14 show further that the concentrations of many pollutants decreased for subtractive air cleaners. However, they also show that the effects on perceived air quality cannot be attributed to one or a few compounds and are most likely mainly caused by the combined effect of many pollutants. Nine chemicals were detected during PAC2s operation in the building materials condition, whereas 14 were detected when building materials and human bioeffluents were present together; for PAC4s, 19

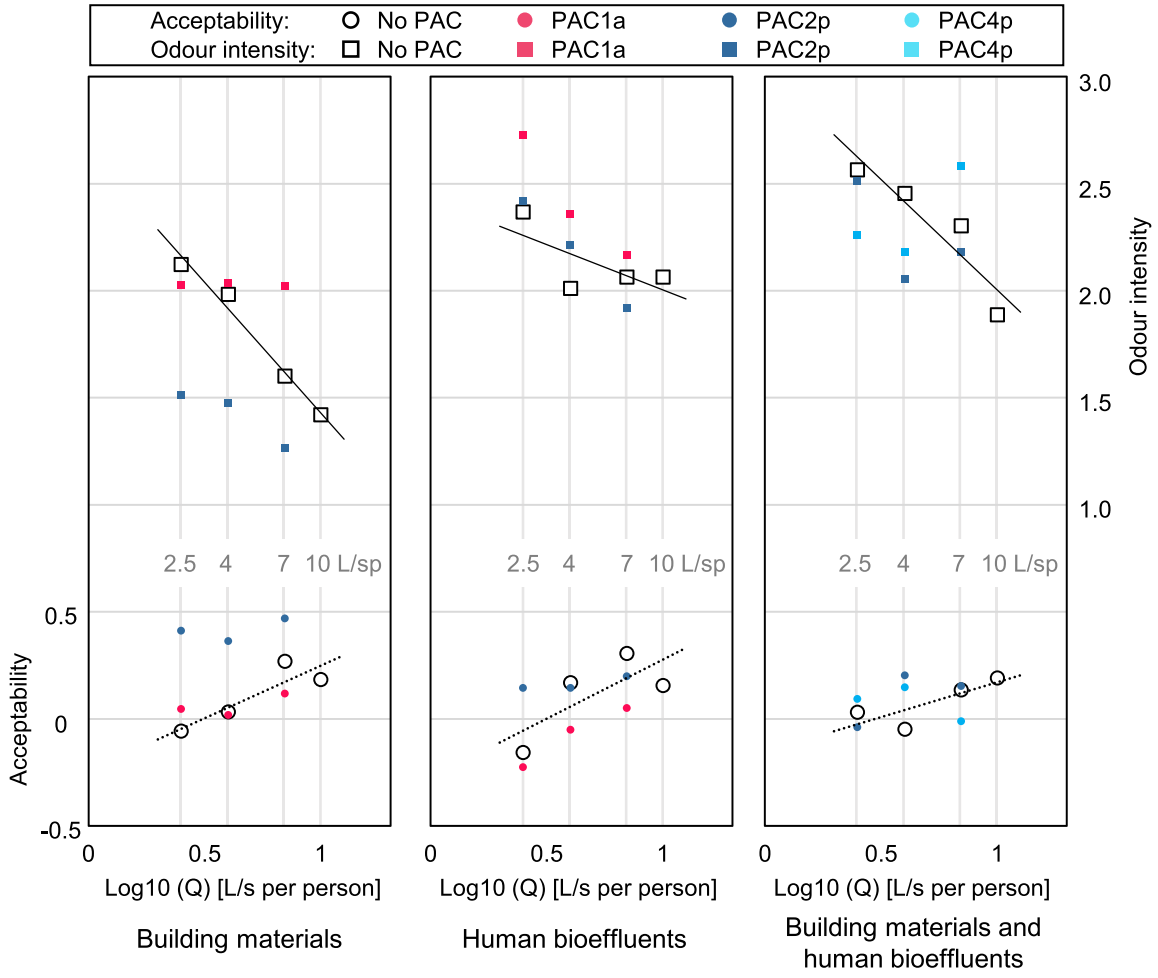


Fig. 8. The effect of ventilation on the whole-body ratings of acceptability of air quality and odour intensity in rooms with different pollution sources. Plots show means.

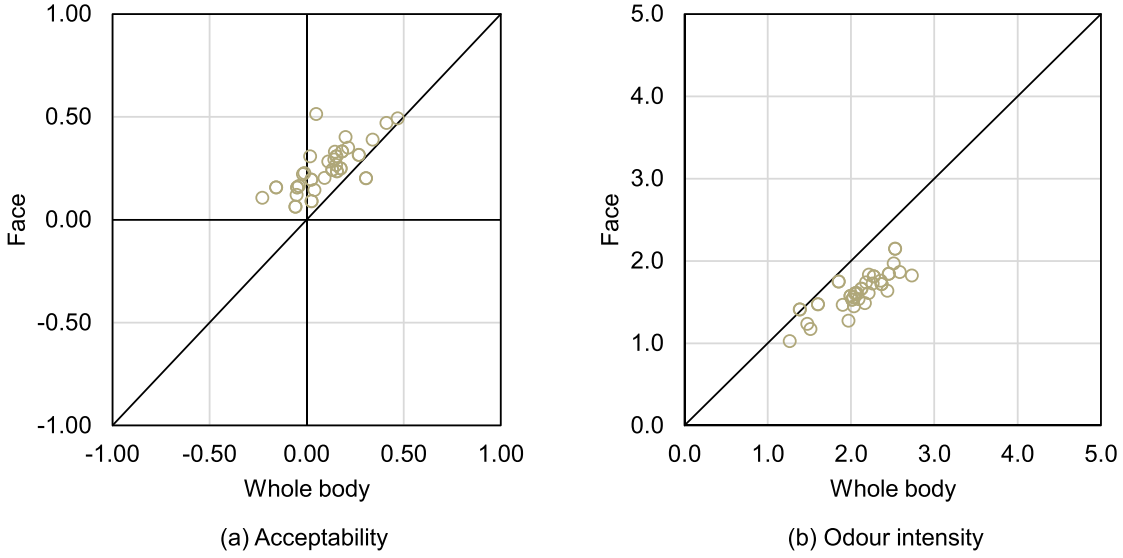


Fig. 9. Comparison of the whole-body and facial sensory evaluations.

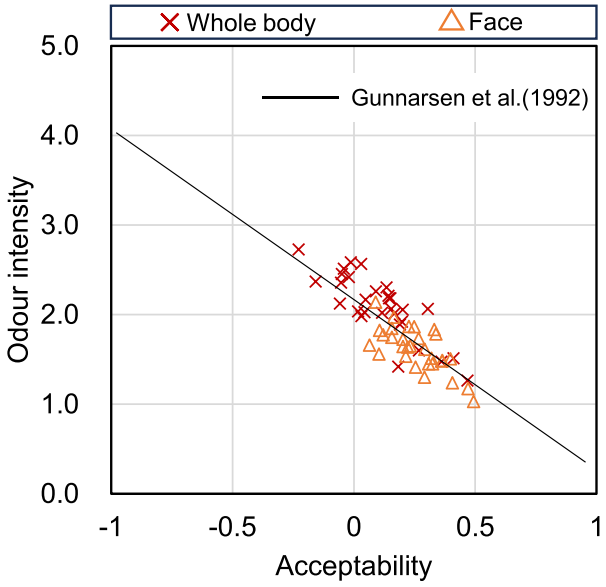


Fig. 10. Comparison of the sensory evaluations of acceptability and odour intensity.

chemicals were detected. Chemicals that were not detected when PAC2s was operated in the condition with building materials but were detected when PAC2s or PAC4s were operated in the condition with building materials and human bioeffluents together included n-pentane, 2-butanone (MEK), ethyl acetate, benzene, pentanal, 1,2- propanediol, toluene, hexanoic acid, 6-MHO, octanal and n-decanal. Some of them, such as n-pentane, pentanal, toluene, 6-MHO, octanal and n-decanal, were substances previously identified as emitted from humans [52].

4. Discussion

In this study, we examined the method for assessing the performance of different air cleaners using sensory evaluations of air quality. We also characterised the performance of air cleaners by performing chemical analyses.

The proposed method comprises two phases of testing of air cleaners. The first phase examines whether the air cleaner can improve air quality, whether there is no effect, or whether it reduces air quality (qualitative testing). In contrast, the second phase thoroughly examines the air cleaner performance (quantitative testing). The idea behind the proposal is the efficient use of resources: air cleaners that do not pass Phase 1 should not be tested in Phase 2. In the present study, we documented that the proposal is justified and the air cleaners that do not pass Phase 1 (air cleaner PAC1a) should not be tested in Phase 2. This has been documented through sensory evaluations and chemical measurements.

Phase 2 provided a detailed characterisation of the performance of

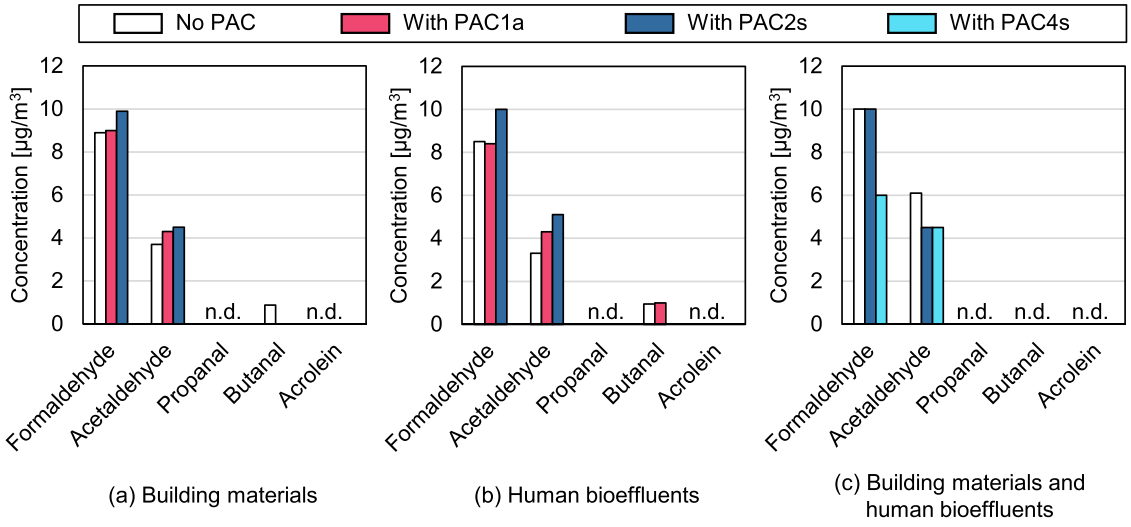


Fig. 11. Concentration of aldehydes. N.d. indicates not detected.

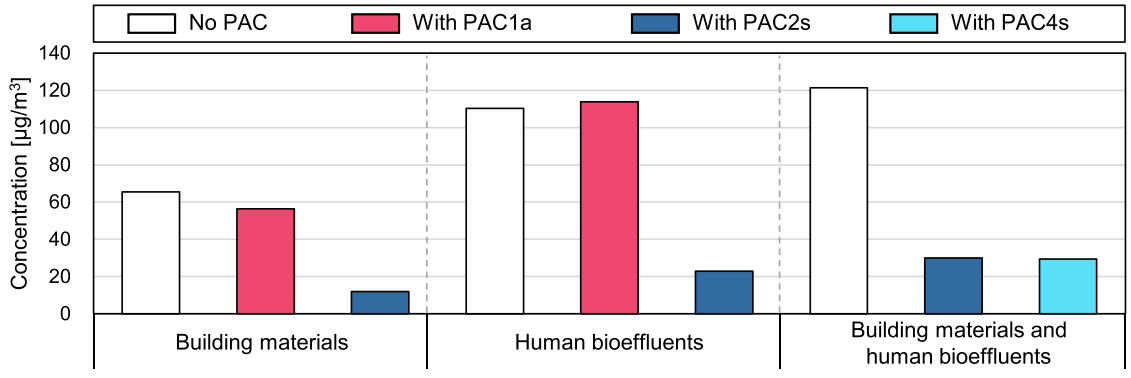


Fig. 12. Sum of VOCs.

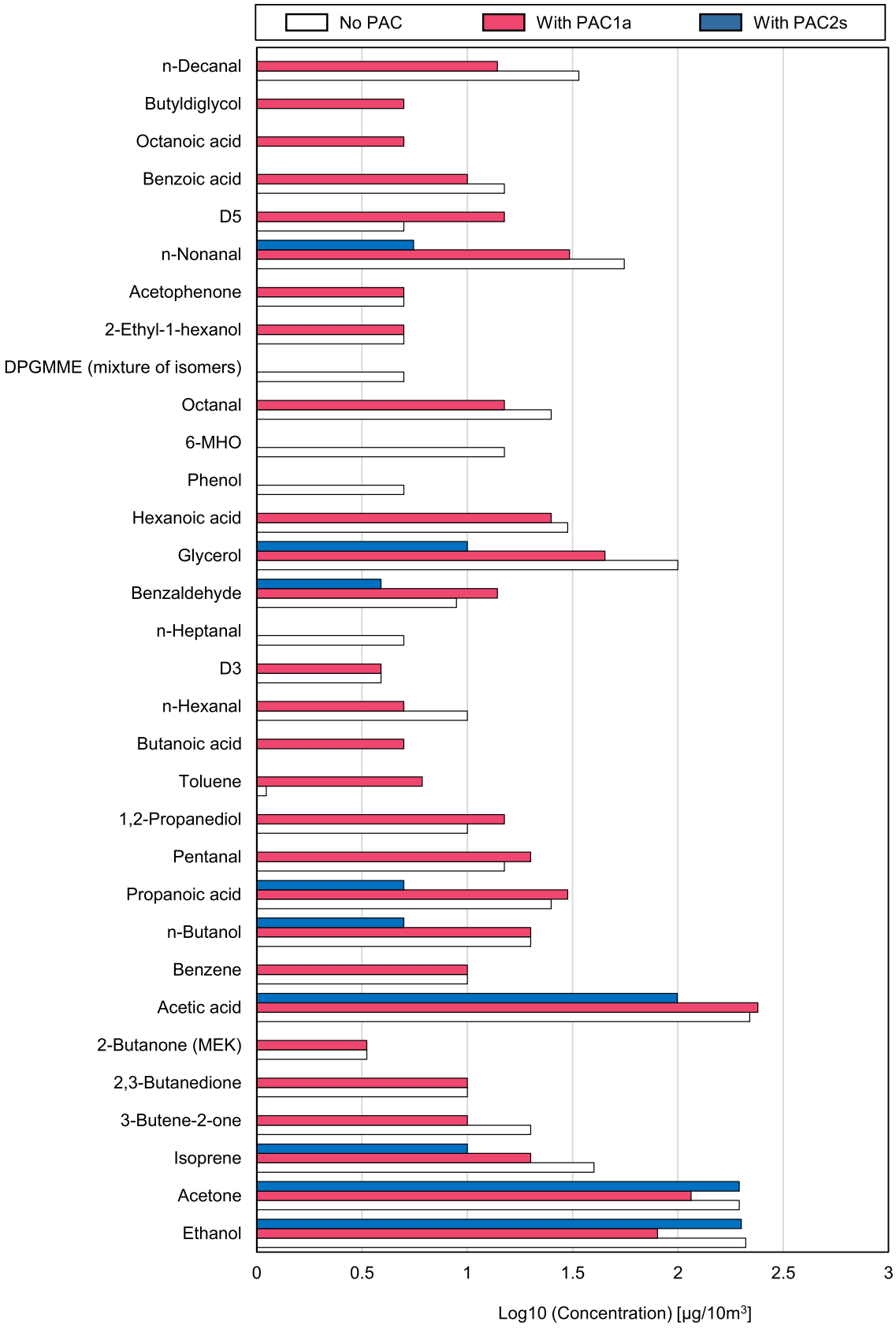


Fig. 13. Concentration of all detected VOCs. The pollution sources were building materials.

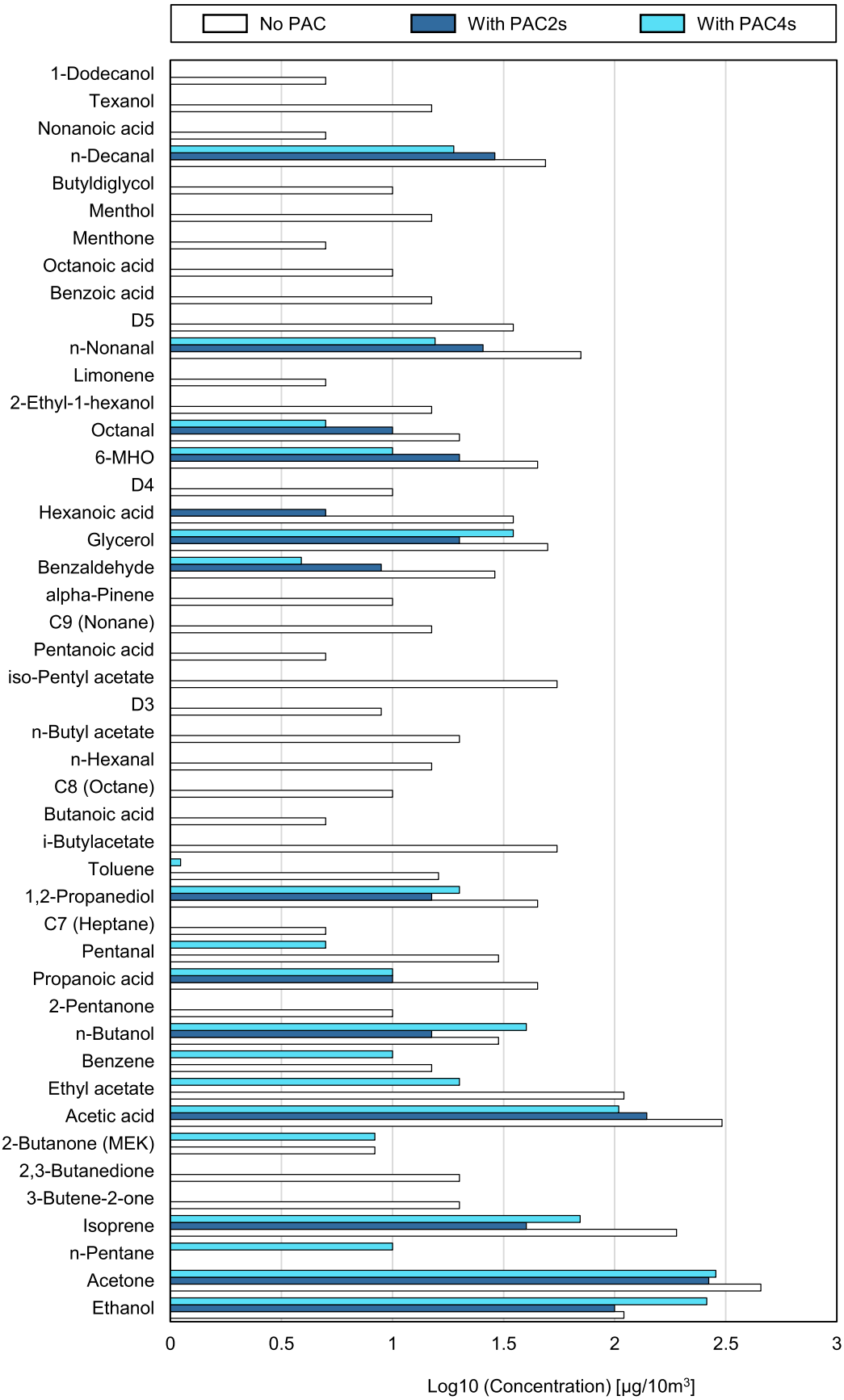


Fig. 14. Concentration of all detected VOCs. The pollution sources were building materials and humans.

air cleaners and compared their effect on perceived air quality against the effect obtained by increased ventilation. Generally, the results showed that air cleaners examined in the present study improved the perceived air quality when the air was polluted by emissions from building materials and not by humans and at ventilation rate levels below 21 L/s (or 7 L/s per person with three people in a room). These results should not be generalised but confirm the necessity of testing air cleaners in Phase 2 under different conditions to assess their potential performance in actual applications better.

In Phase 2, the effects of air cleaners were also examined using chemical measurements. If the total concentration of volatile organic compounds was considered a metric of air cleaner performance, the results showed a positive effect of air cleaners independently of pollution source at the ventilation rate at which chemical analyses were performed. However, these results were somewhat inconsistent with the sensory evaluations, where similar effects were not seen across different sources of pollution. Previous studies have also shown the inconsistency between chemical measurements and sensory evaluations [30,35]. Chemical measurements also could not document which pollutants could be responsible for the observed sensory effects. Consequently, chemical measurements alone should not be used to characterise the performance of air cleaners and their effects on air quality. Therefore, until other equivalent measurements replace sensory evaluations, they should constitute the element of the testing protocol.

We observed differences between the whole-body and facial sensory evaluations. These differences were also observed in previous studies [48,49]. However, the direction of the effect was opposite to the one observed in this work. We cannot explain the reason for this difference. The reasons should be investigated in future experiments. Unless it is elucidated, no firm recommendations can be made on whether the sensory evaluations of air quality when testing the performance of air cleaners should be made on the air extracted from the experimental rooms (facial exposures) or upon entering the rooms (whole-body exposures).

Although acceptability and odour intensity ratings were strongly correlated (Fig. 9), the overall results of sensory evaluations for individual conditions were not always consistent (Figs. 7 and 9). For that reason, at this moment, it can be recommended to use both sensory evaluations of odour intensity and acceptability of air quality when testing the performance of air cleaners using sensory methods. They both provide a more complex characterisation of sensory effects, and additionally odour intensity ratings are not affected by the air's thermodynamic conditions [48].

The relationship between ventilation rates and sensory ratings of acceptability of air quality and odour intensity was non-linear (Figs. 7 and 8). These relationships were different for different pollution sources. Similar results were observed previously by Knudsen et al. [49]. Consequently, when determining the efficiency of air cleaners and comparing them against the effects obtained by ventilation, it is necessary to perform the tests at different ventilation rates. Examining the air cleaner efficiency only at one ventilation rate is insufficient, and these results should not be extrapolated to other ventilation rates. Considering this effect, the method for estimating the efficiency of air cleaners in improving air quality using sensory evaluations of air quality should be developed.

The ISO 16000-44 standard was approved in 2023. It describes a test method for measuring perceived indoor air quality for testing the performance of gas phase air cleaners [20]. The method in the standard is similar to the one examined in the present experiments. The perceived air quality is determined using the acceptability of the air quality and odour intensity. The air assessed by a panel is presented via a sniffing device (facial exposure). If measurement accuracy can be guaranteed, the panel can also enter a chamber directly to assess the air (whole-body exposure). The air change rate of the test chamber is set at 0.50/h (±0.03/h) and 2.0/h (±0.12/h) in ISO, which is the same as in the present study at 7.5 L/s and 30 L/s. The experimental methods used in this study are generally comparable with those proposed by the standard. Therefore, the methodology described and examined in the present paper supports and validates, to some extent, the approach proposed by ISO 16000–44.

The purpose of this study was not to compare the performance of different air cleaners against each other but to examine the method that can be used to test their performance. Although we observed that subtractive air cleaners performed better than additive air cleaners, these results should not be generalised. We did not calculate clean air delivery rates either based on sensory evaluations or compared them with the effects of ventilation on perceived air quality in the presence of different pollution sources. This was outside the scope of this study. However, we will report these calculations in future publications.

In future studies, the proposed method should be used in different configurations of air cleaners and performed in the round-robin testing before it can be applied in practice to examine the performance of air cleaners.

5. Conclusion

- A prototype method for testing gas-phase air cleaners using sensory assessment was examined. This study generally followed methodologies proposed by the ISO 16000-44 standard, and the results validate and support them. However, more testing is still necessary before its full application in practice.
- The proposed method includes two phases. The results confirmed that Phase 1 effectively eliminates the air cleaners that do not improve air quality. Phase 2 is necessary since it provides detailed information on the actual performance of air cleaners.
- The present results showed differences between the results of chemical measurements and sensory evaluations, demonstrating that chemical analyses alone do not provide sufficient information regarding air cleaner performance. Sensory evaluations are an important part when the performance of air cleaners is documented.

CRediT authorship contribution statement

Kanta Amada: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Lei Fang:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Simon Vesth:** Methodology, Data curation. **Shin-ichi Tanabe:** Writing – review & editing, Validation, Conceptualization. **Bjarne W. Olesen:** Project administration, Funding acquisition, Conceptualization. **Pawel Wargocki:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Acknowledgments

This study was partially supported by the Bjarne Saxhofs Foundation (Denmark) and by The Energy Technology Development and Demonstration Program, EUDP (Denmark), grant number 64018–0599, which provided support to IEA Annex 78 and by the Mitsubishi Electric Corporation. The authors would like to thank Editage (www.editage.com) for editing the English language.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111630.

References

[1] P. Nejat, F. Jomehzadeh, M.M. Taheri, M. Gohari, M.Z.A. Majid, A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries), Renew. Sustain. Energy Rev. 43 (2015) 843–862, https://doi.org/10.1016/j.rser.2014.11.066.

[2] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on buildings energy information: Trends, end-uses, fuels and drivers, Energy Rep. 8 (2022) 626–627, https://doi.org/10.1016/j.egyr.2021.11.280.

[3] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (2021) 231–252, https://doi.org/10.1038/sj.jea.7500165.

[4] B. Poirier, G. Guyot, M. Woloszyn, H. Geoffroy, M. Ondarts, E. Gonze, Development of an assessment methodology for IAQ ventilation performance in residential buildings: an investigation of relevant performance indicators, J. Build. Eng. 43 (2021) 103140, https://doi.org/10.1016/j.jobe.2021.103140.

[5] Y. Zhang, J. Mo, Yu Li, J. Sundell, P. Wargocki, J. Zhang, J.C. Little, R. Corsi, Q. Deng, M.H.K. Leung, L. Fang, W. Chen, J. Li, Y. Sun, Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review, Atmos. Environ. 45 (2011) 4329–4343, https://doi.org/10.1016/j.atmosenv.2011.05.041.

[6] W.J. Fisk, Health and productivity gains from better indoor environments and their relationship with building energy efficiency, Annu. Rev. Energy Environ. 25 (2000) 537–566, https://doi.org/10.1146/annurev.energy.25.1.537.

[7] A.P. Jones, Indoor air quality and health, Atmos. Environ. 33 (1999) 4535–4564, https://doi.org/10.1016/S1352-2310(99)00272-1.

[8] P. Wargocki, D.P. Wyon, J. Sundell, G. Clausen, P.O. Fanger, The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity, Indoor Air 10 (2000) 222–236, https://doi.org/10.1034/j.1600-0668.2000.010004222.x.

[9] A. Rackes, M.S. Waring, Alternative ventilation strategies in U.S. offices: comprehensive assessment and sensitivity analysis of energy saving potential, Build. Environ. 116 (2017) 30–44, https://doi.org/10.1016/j.buildenv.2017.01.027.

[10] J. Sundell, H. Levin, W.W. Nazaroff, W.S. Cain, W.J. Fisk, D.T. Grimsrud, F. Gyntelberg, Y. Li, A.K. Persily, A.C. Pickering, J.M. Samet, J.D. Spengler, S. T. Taylor, C.J. Weschler, Ventilation rates and health: Multidisciplinary review of the Scientific literature, Indoor Air 21 (2011) 191–204, https://doi.org/10.1111/j.1600-0668.2010.00703.x.

[11] W. Ji, C. Chen, B. Zhao, A comparative study of the effects of ventilation-purification strategies on air quality and energy consumption in Beijing, China, Build. Simulat. 14 (2021) 813–825, https://doi.org/10.1007/s12273-020-0694-2.

[12] B.W. Olesen, C. Sekhar, P. Wargocki, The concept for substituting ventilation by gas phase air cleaning, AIVC VIP 42 (2021).

[13] ISO, Energy Performance of Buildings — Indoor Environmental Quality — Part 1: Indoor Environmental Input Parameters for the Design and Assessment of Energy Performance of Buildings, 17772-1, 2017.

[14] CEN TR 16798-2: Energy Performance of Buildings — Part 2: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics — Module M1-6 — Technical Report — Interpretation of the Requirements in EN 16798-01.

[15] ASHRAE, ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[16] Y. Zhang, J. Mo, Y. Li, J. Sundell, P. Wargocki, J. Zhang, J. Little, R. Corsi, Q. Deng, M. Leung, J. Siegel, L. Fang, W. Chen, J.Y. Sun, Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review, Atmos. Environ. 45 (2011) 4329–4343, https://doi.org/10.1016/j.atmosenv.2011.05.041.

[17] ISO/TR 17772-2:2018. Energy Performance of Buildings — Overall Energy Performance Assessment Procedures — Part 2: Guideline for Using Indoor Environmental Input Parameters for the Design and Assessment of Energy Performance of Buildings.

[18] ASHRAE, ANSI/ASHRAE Addendum Aa to ANSI/ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality.

[19] A. Afshari, J. Mo, E. Tian, O. Seppänen, Testing portable air cleaning units –Test methods and standards: a Critical Review, REHVA Journal October (2022) 35–46. https://www.rehva.eu/rehva-journal/chapter/testing-portable-air-cleaning-units-test-methods-and-standards-a-critical-review.

[20] ISO, Indoor Air -Part 44: Test Method for Measuring Perceived Indoor Air Quality for Use in Testing the Performance of Gas Phase Air Cleaners, 16000-44, 2023.

[21] AFNOR NF B44-200, Independent Air Purification Devices for Tertiary Sector and Residential Applications – Test Methods – Intrinsic Performances, 2016.

[22] ISO, Test Methods for Assessing the Performance of Gas-phase Air Cleaning Media and Devices for General Ventilation Part 3: Classification System for GPACDs Applied to Treatment of Outdoor Air, 10121-3, 2022.

[23] C.J. Weschler, N. Carslaw, Indoor chemistry, Environ. Sci. Technol. 52 (2018) 2419–2428, https://doi.org/10.1021/acs.est.7b06387.

[24] P.O. Fanger, What is IAQ? Indoor Air 16 (2006) 328–334, https://doi.org/10.1111/j.1600-0668.2006.00437.x.

[25] K. Azuma, H. Jinno, T. Tanaka-Kagawa, S. Sakai, Risk assessment concepts and approaches for indoor air chemicals in Japan, Int. J. Hyg Environ. Health 225 (2020) 113470, https://doi.org/10.1016/j.ijheh.2020.113470.

[26] P. Wargocki, K. Kostyrko, Measurements of perceived indoor air quality, in: Handbook of Indoor Air Quality, Springer Singapore, Singapore, 2022, pp. 609–643, https://doi.org/10.1007/978-981-16-7680-2_81.

[27] ISO 16000-30, Indoor Air - Part 30: Sensory Testing of Indoor Air, 2014.

[28] G. Iwashita, K. Kimura, Method for evaluating efficiency in removing perceived air pollutants by air cleaners, Indoor Air 3 (1993) 315–321, https://doi.org/10.1111/j.1600-0668.1993.00014.x.

[29] Y. Sheng, L. Fang, J. Nie, Experimental analysis of indoor air quality improvement achieved by using a Clean-Air Heat Pump (CAHP) air-cleaner in a ventilation system, Build. Environ. 122 (2017) 343–376, https://doi.org/10.1016/j.buildenv.2017.06.032.

[30] R.J. Shaughnessy, E. Levetin, J. Blocker, K.L. Sublette, Effectiveness of portable indoor air cleaners: sensory testing results, Indoor Air 4 (1994) 179–188, https://doi.org/10.1111/j.1600-0668.1994.t01-1-00006.x.

[31] J. Kolarik, P. Wargocki, Can a photocatalytic air purifier be used to improve the perceived air quality indoors? Indoor Air 20 (2010) 255–262, https://doi.org/10.1111/j.1600-0668.2010.00650.x.

[32] B. Krejcirikova, J. Kolarik, P. Wargocki, The effects of cement-based and cement-ash-based mortar slabs on indoor air quality, Build. Environ. 135 (2018) 213–223, https://doi.org/10.1016/j.buildenv.2018.03.011.

[33] E.K. Darling, C.J. Cros, P. Wargocki, J. Kolarik, G.C. Morrison, R.L. Corsi, Impacts of a clay plaster on indoor air quality assessed using chemical and sensory measurements, Build. Environ. 57 (2012) 370–376, https://doi.org/10.1016/j.buildenv.2012.06.004.

[34] X.J. Zhang, L. Fang, P. Wargocki, D. Szulc, T. Tanaka, K. Kagawa, Effect of streamer plasma air purifier on SBS symptoms and performance of office work, in: 7th International Symposium on Heating, Ventilating and Air Conditioning, 2011, pp. 375–380.

[35] T.A. Moya, M. Ottelé, A. van den Dobbelsteen, P.M. Bluyssen, Effect of an active plant-based system on perceived air pollution, Int. J. Environ. Res. Public Health 18 (2021) 8233, https://doi.org/10.3390/ijerph18158233.

[36] L. Fang, P. Wargocki, A. Targowski, T. Tanaka, K. Kagawa, Performance of a streamer plasma air purifier examined with sensory assessments of air quality, in: 12th International Conference on Indoor Air Quality and Climate, 2011.

[37] J. Mo, Y. Zhang, Q. Xu, Y. Zhu, J.J. Lamson, R. Zhao, Determination and risk assessment of by-products resulting from photocatalytic oxidation of toluene, Appl. Catal. B Environ. 89 (2009) 570–576, https://doi.org/10.1016/j.apcatb.2009.01.015.

[38] A. Afshari, O. Seppänen, W.O. Bjarne, J. Mo, Effect of portable gas-phase air cleaners on indoor air quality, REHVA Journal October (2021) 28–35. https://www.rehva.eu/rehva-journal/chapter/effect-of-portable-gas-phase-air-cleaners-on-indoor-air-quality.

[39] B. Stephens, E.T. Gall, M. Heidarinejad, D.K. Farmer, Interpreting air cleaner performance data, ASHRAE J. 64 (3) (2022) 20–30. https://www.ashrae.org/file%20library/technical%20resources/covid-19/20-31_stephens.pdf.

[40] J. Toftum, G. Langkilde, P.O. Fanger, New indoor environment chambers and field experiment offices for research on human comfort, health and productivity at moderate energy expenditure, Energy Build. 36–9 (2004) 899–903, https://doi.org/10.1016/j.enbuild.2004.02.001, 2004.

[41] H.N. Knudsen, G. Clausen, P.O. Fanger, Sensory characterisation of emissions from materials, Indoor Air 7–2 (1997) 107–115, https://doi.org/10.1111/j.1600-0668.1997.t01-2-00004.x.

[42] S. Nordin, M. Bende, E. Millqvist, Normative data for the chemical sensitivity scale, Environmental Psychology 24 (2004) 399–403, https://doi.org/10.1016/S0272-4944(03)00074-4.

[43] P. Wargocki, D.P. Wyon, Y.K. Baik, G. Clausen, P.O. Fanger, Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads, Indoor Air 9–3 (1999) 165–179, https://doi.org/10.1111/j.1600-0668.1999.t01-1-00003.x.

[44] Z.S. Bakó-Biró, P. Wargocki, D.P. Wyon, P.O. Fanger, Poor indoor air quality slows down metabolic rate of office workers, Proceedings of indoor air 1 (2005) 76–80.

[45] P. Wargocki, P.O. Fanger, P. Krupicz, A. Szczecinski, Sensory pollution loads in six office buildings and a department store, Energy Build. 36–10 (2004) 995–1001, https://doi.org/10.1016/j.enbuild.2004.06.006.

[46] A. Mizumoto, O. Takeuchi, Basics and considerations for reporting effect sizes in research papers, Studies in English Language Teaching 31 (2008) 57–66.

[47] DIN ISO 16000-6, Indoor Air - Part 6: Determination of Organic Compounds (VVOC, VOC, SVOC) in Indoor and Test Chamber Air by Active Sampling on Sorbent Tubes, Thermal Desorption and Gas Chromatography Using MS or MS FID, 2022.

[48] L. Fang, G. Clausen, P.O. Fanger, Impact of temperature and humidity on the perception of indoor air quality, Indoor Air 8 (1998) 80–90, https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x.

[49] H. N. Knudsen, P. Wargocki, P. J. Vondruskova. Effect of ventilation on perceived quality of air polluted by building materials - a summary of reported data. HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings, 1, 57-62.

[50] L. Gunnarsen, P.O. Fanger, Adaptation to indoor air pollution, Environ. Int. 18–1 (1992) 43–54, https://doi.org/10.1016/0160-4120(92)90209-M.
[51] L. Mølhave, G. Clausen, B. Berglund, J. De Ceaurriz, A. Kettrup, T. Lindvall, M. Maroni, A.C. Pickering, U. Risse, H. Rothweiler, B. Seifert, M. Younes, Total volatile organic compounds (TVOC) in indoor air quality investigations, Indoor Air 7–4 (1997) 225–240, https://doi.org/10.1111/j.1600-0668.1997.00002.x.
[52] S. Tsushima, P. Wargocki, S. Tanabe, Sensory evaluation and chemical analysis of exhaled and dermally emitted bioeffluents, Indoor Air 28 (2018) 146–163, https://doi.org/10.1111/ina.12424.