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Very volatile and volatile organic compounds (VVOCs/VOCs) and endotoxins in the indoor air of German schools and apartments (LUPE10)

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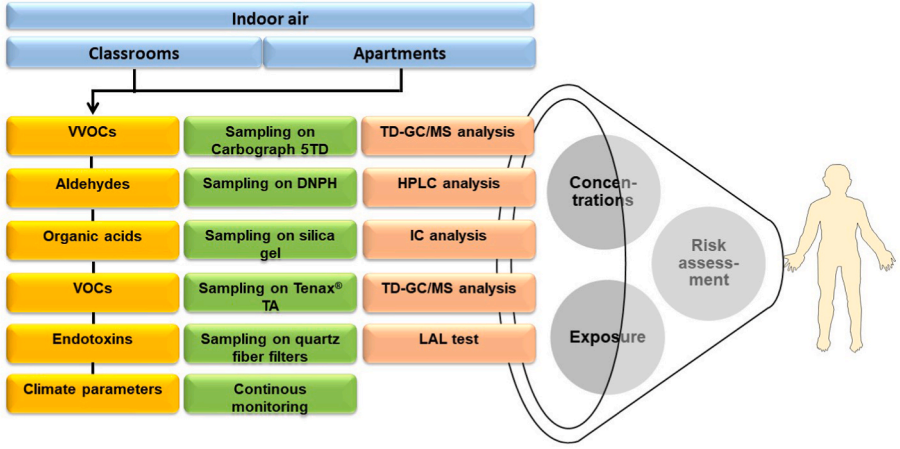
HIGHLIGHTS

- 105 VVOC/VOC were analyzed in indoor air of 27 schools and 27 residences.
- Airborne endotoxins were quantified in indoor particulate matter in the same buildings.
- Concentrations of endotoxins in homes is significantly lower than in schools.
- VVOCs have a large proportion of the content of volatile substances in indoor air.
- Valid indoor air values are often lacking to assess the risks of VOCs and VVOCs.

GRAPHICAL ABSTRACT



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ABSTRACT

People, including sensitive population groups such as children, spend over 90 % of their time indoors and are exposed to volatile and very volatile organic compounds (VOCs/VVOCs) and endotoxins. We measured 34 VVOCs, 69 VOCs, two organic acids, and endotoxins in the indoor air of 34 apartments and 27 classrooms using four different sampling techniques and analytical methods. Our study aimed to provide a comprehensive

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VVOC
Aldehydes
TVOC
Endotoxin

overview of a broad spectrum of substances rarely measured in indoor air. The following substance classes showed the highest sum medians in classrooms and apartments: alcohols 249 μg/m^3 and 518 μg/m^3, aldehydes/acetone 81.6 μg/m^3 and 121 μg/m^3 and organic acids 61 μg/m^3 and 82 μg/m^3. The individual substances with the highest medians were ethanol > acetic acid > acetone > decamethylcyclopentasiloxane > formaldehyde > acetaldehyde. The median of the total volatile organic compounds as the sum of the VOCs of C_6-C_{16} was 253 μg/m^3 (range: 638–3369 μg/m^3) in the apartments and 277 μg/m^3 (61–900 μg/m^3) in the classrooms. The median (95th percentile) levels of endotoxins in the classrooms and apartments were 5.8 EU/m^3 (15.3 EU/m^3) and 0.26 EU/m^3 (0.91 EU/m^3), respectively. Concentrations in apartments are significantly lower than in schools. According to current knowledge, levels pose no health risk.

In addition to the classic VOCs, VVOCs should also be measured to a greater extent, as considerable exposure to substances from this group is expected indoors. These results underline the urgent need for further research to improve indoor air quality and protect public health.

1. Introduction

People spend most of their lives indoors. For example, the US Exposure Factor Handbook assumes that 6-11-year-old children and adults spend 21 and 19 h indoors and 15 and 16 h in the home (US EPA, 2011). In these indoor spaces, users are exposed to many organic substances, which can occur in concentrations with significant health effects. In addition to residential interiors, children also spend a large proportion of their daily time in school interiors, for which high indoor air quality requirements must be met. However, our knowledge of the exposure situation of room users is still limited, as measurement data is often only available for some of the substances present, and their composition also changes over time. This applies in particular to school classrooms, although a high level of protection should be ensured due to the specific sensitivity of children.

As the volatility of organic substances increases with their boiling point, a WHO working group has proposed a general classification of volatile and less volatile substances according to this criterion. According to this definition, VOCs (volatile organic compounds) are gaseous substances with a boiling point between approx. 50–100 °C and approx. 240–260 °C. If the boiling point is below 50–100 °C, these are so-called VVOCs (very volatile organic compounds). In analytical practice, ISO 16000-6 defines VOCs as those organic compounds that are collected on the solid sorbent Tenax® TA and elute from a non-polar or slightly polar gas chromatographic separation column between n-hexane and n-hexadecane (C_6-C_{16}) (ISO 16000-6, 2021; DIN, 2020). In contrast, a uniform definition of "VVOC" is missing so far. Salthammer (2022) has discussed the differences between various approaches to classifying VVOCs. Moreover, due to their low boiling points, other analytical methods are required for their sampling and determination, developed recently in detail by several working groups (Even et al. 2021, 2023; Schieweck et al., 2018).

VOCs are important substances in indoor air. In addition to the input from outdoor air, the sources of VOCs in indoor spaces can be manifold. In their summary of the results of 65 VOCs in 42 European studies from 2000 to 2020, Halios et al. (2022) concluded that building and construction materials were the source of 80 % of the substances, consumer goods of 63 %, combustion processes of 30 % and space heating of 14 %. However, human activities such as tobacco smoking or humans themselves can also be a source of VOCs and VVOCs.

The effects of VOCs/VVOCs are complex due to the large number of individual substances and range from slight disturbances of well-being to toxic effects, depending on the level of exposure. A connection has been made very often between the level of VOC concentration indoors and unspecific symptoms such as tiredness, headaches, reduced performance, and irritation of the mucous membranes of the eyes and upper respiratory tract. To describe the health effects of indoor environments, the World Health Organization has defined the term "sick building syndrome" (SBS), which refers to non-specific health impairments associated with indoor environments (Tran et al., 2020). However, not only chemical factors such as VOCs/VVOCs are associated with the increased incidence of SBS, but also physical, biological, and building-related factors such as humidity, as well as psychosocial and personal factors, are possible influencing factors (Aziz et al., 2023). Regarding the severity of the health effects, carcinogenic substances occurring indoors are of particular health concern. These include, for example, VOCs such as benzene and 1-2-dichloroethane, as well as VVOCs such as formaldehyde, acetaldehyde, acrolein, vinyl chloride, 1, 3-butadiene, 1,2-dichloropropane and trichloroethylene. Various reviews have summarized the scientific knowledge on the link between indoor air quality and health (Chithra and Shiva Nagendra, 2018, Shrubsole et al., 2019; Tran et al., 2020; NICE, 2020; Palacios et al., 2021; Halios et al., 2022; Kumar et al., 2023; Tran et al., 2023).

Until now, measurement data for VVOCs in indoor air have only been available to a minimal extent. The typical VOC analysis cannot achieve reliable results according to ISO 16000-6, and a unique analytical method is rarely available. To trap VVOCs ≤ C_6 of different volatility and polarity, at least three different analytical techniques are required, according to Schieweck et al. (2018) and Schieweck (2021). For sampling low-molecular aldehydes, such as formaldehyde and acetaldehyde, a reliable analytical procedure has been established for years (ISO 16000-3). Thus, extensive measurement results are available for these VVOCs.

Endotoxins are components of the outer cell wall of gram-negative bacteria and consist of lipopolysaccharides (LPS). In a recent review, Salthammer (2022) summarized the exposure to endotoxins in indoor spaces. The main factors influencing indoor air concentrations were the age of the house, the type and frequency of cleaning, the location in rural or urban areas, the presence of textile or smooth floor coverings, and the presence of pets in the rooms. It is assumed that the interaction of LPS with receptors in the respiratory tract, particularly in the alveolar region, leads to inflammatory effects triggered and maintained by an increased release of pro-inflammatory cytokines, reactive oxygen species, and lysosomal enzymes (DECOS, 2010). The systemic effects could also be due to pulmonary-produced cytokines that can enter the bloodstream. Based on experimental and epidemiological studies, especially in polluted agricultural workplaces, symptoms such as dry cough, shortness of breath, reduced lung function, and fever and fatigue have been observed in acute exposure (DECOS, 2010; Liebers et al., 2020). Prolonged exposure can also cause bronchial constriction, joint pain, and headaches. In occupational settings, the Dutch Expert Committee on Occupational Safety recommended a limit value of 90 EU/m^3 based on a study of the effects of a 6-h exposure of volunteers selected for their sensitivity to endotoxins (DECOS, 2010). This value, averaged over 8 h, ensures adequate protection against acute and chronic effects. No values have yet been set for general indoor living spaces.

Our study aimed to measure a broad spectrum of VVOCs (≤C6; including low-molecular aldehydes and acetone), VOCs (C_6-C_{16}), and low-molecular organic acids (formic acid and acetic acid) in the indoor air of typical apartments and classrooms of elementary schools. Four analytical methods were applied to cover this range of organic volatiles, as demonstrated by Schieweck (2021), for measuring wooden material emissions and indoor air in new prefabricated wooden houses. In addition, the endotoxin concentrations in airborne dust (PM_{10}) were

measured. Hence, it is the first time such a broad spectrum of airborne pollutants and endotoxins in airborne dust were analyzed in apartments and classrooms. This study is a sub-project of various studies performed by health authorities of the German federal states (Länderuntersuchungsprogramme, LUPE), the overall aim of which is to determine the exposure of the population and sensitive subsets and to develop strategies to minimize exposure (see, e.g., Fromme et al., 2023).

2. Material and methods

2.1. Study area, sampling locations, and sampling

The study was conducted in four German federal states: Bavaria, Berlin, North Rhine-Westphalia, and Schleswig-Holstein (Figure S 1). The school principals were contacted by the study group by e-mails provided by the school authorities and asked to participate in the study. Staff from the participating authorities asked people whether they would be willing to take part in the survey. The people who responded first were included in the study. Once the tenants or facility managers had agreed to participate in the study, they were informed in detail about the procedure and objectives of the study in a letter and, if necessary, in an interview. Samples were taken from 27 school classes between February 2019 and May 2019 and February 2020 and March 2020 and from 35 central areas of apartments between February 2019 and May 2019 and February 2020 and March 2020.

All schools were elementary schools except one secondary school. The room sizes in the classrooms ranged from 31 to 104 m^2 (mean value: 61 m^2). A total of 17 classrooms had linoleum flooring, 9 had wooden flooring, and only one had plastic flooring. On average, 5 and 35 pupils were present in the classrooms during the teaching day on which the samples were taken. The apartments were between 46 and 180 m^2 in size (average: 84 m^2). All apartments had smooth flooring, with 25 wooden flooring, six laminate flooring, three tiled or stone flooring, and one linoleum. Four apartments had carpet on the smooth flooring.

All classrooms and apartments were naturally ventilated. No tobacco smoking, open fire sources, or work was known to be a source of VVOCs or VOCs in any of the indoor spaces sampled.

The classrooms were ventilated before the start of the lesson. An active sampling of VVOCs, aldehydes, and VOCs began 15 min after the start of the first lesson and continued throughout the lesson, ending after 30 min. Only the organic acids were collected over 75 min during two lessons, starting 15 min after the first lesson. The rooms were ventilated for 5 min between the first and second lessons by opening the windows. The sampling of organic acids was carried out without interruption.

Sampling was carried out in the living rooms of apartments while the occupants were present. All windows and doors were closed for 8 h before and during sampling without ventilation. Sampling was carried out in parallel in a central room area at a height of approximately 1.2 m. In the classrooms, the sampling devices were located approximately in the middle of the back wall, opposite the blackboard, about 50 cm from the wall and about 90 cm above the floor.

2.2. Analysis of climate parameters

All measurements were carried out using the Testo 435/445 combined measuring instrument (Testo, Lenzkirch). Carbon dioxide (CO_2), an indicator of indoor air quality, temperature, and relative humidity, was measured continuously every minute.

The air exchange rates were determined approximately based on the change in CO_2 concentration in the classrooms and living rooms. For this purpose, the decrease in CO_2 concentration was measured as a function of time. The air exchange rates were determined when the windows were closed. In 16 of the 27 classrooms and 30 of the 35 apartments, the air exchange rate was determined in this way. It ranged between 0 and 0.3/h (mean value: 0.11/h) in the classrooms and between 0.1/h and 1.7/h (mean value: 0.24/h) in the apartments.

2.3. Analysis of VVOCs

The analytical details were previously described by Schieweck et al. (2018). For active sampling of VVOCs (C_3-C_6), stainless steel desorption tubes (Markes International Ltd., 89 mm length, 6.4 mm outer diameter) filled with Carbograph™ 5TD (20/40 mesh, Markes International Ltd., Llantrisant, United Kingdom) were used. GilAir plus pumps (DEHA Haan & Wittmer Ltd., Heimsheim, Germany) with a 125 ml/min sampling flow rate were used. The total sampling volume was 2 L. Concentrations of C_2-C_6 VVOCs were quantified using gas chromatography (Agilent 7890A, Agilent Technologies, Santa Clara, USA) with a mass spectrometer (Agilent 5975C, Agilent Technologies, Santa Clara, USA) and an automated thermal desorption injector (TD-100, Markes International Ltd., Llantrisant, UK). The analytical method was validated initially for VVOCs between C_3 and C_6. Limitations occurred with polar

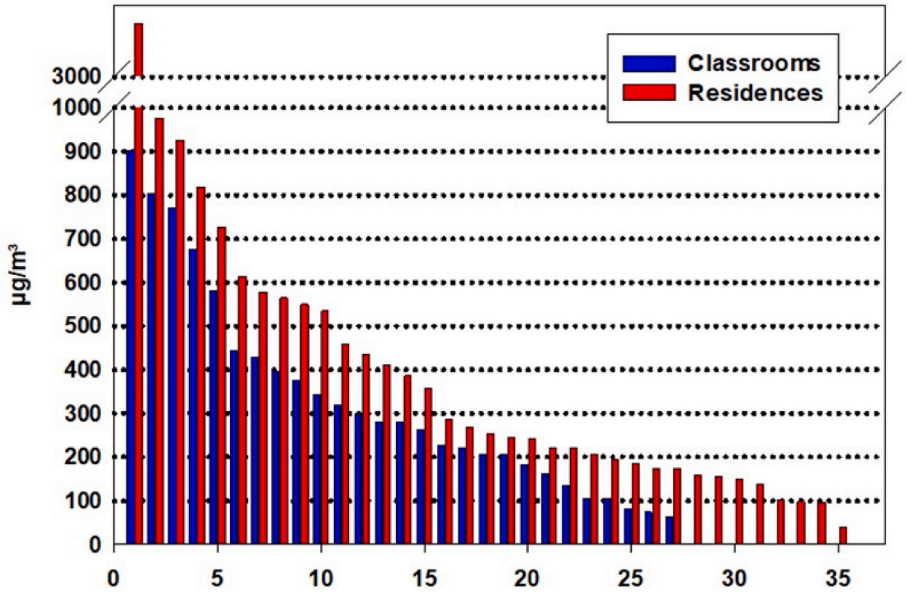

Fig. 1. Total volatile organic compounds (TVOCs) in the indoor air in µg/m.^{3}.

substances and with some aldehydes ≤ C_3 (Schieweck et al., 2018). However, data of some C_1 and C_2 compounds collected in indoor air are also reported in the results section of the present study, as bell-shaped peaks (Gaussian curves) and satisfactory separation were obtained. The limits of detection (LOD) and the limits of quantification (LOQ) were calculated from the linear calibration curves of the C_1 and C_2 substances. Depending on the respective substance, the LOQ was between 1.0 μg/m^3 and 4.0 μg/m^3 (see Table 1). Active air sampling was performed in duplicate.

2.4. Organic acids (formic acid, acetic acid)

Active air sampling for formic and acetic acid was carried out using silica gel-filled cartridges according to VDI 4301-7 (VDI, 2018). The sample volume was 75 l, and the sampling flow was 1 l/min. BiVOC2V2 2-channel pumps (Umweltanalytik Holbach Ltd., Wadern, Germany) were used for sampling. After sampling, the cartridges were eluted with sodium carbonate and extracted in an ultrasonic bath. The concentrations were quantified by ion chromatography (Metrohm 881 Compact IC Pro, Vienne, Austria). The compounds were separated on a conductivity detector coupled to a Metrosep A Supp 7 anion separation column (Metrohm 881 Compact IC Pro, Vienne, Austria). The limit of quantification for both formic acid and acetic acid was 5.0 μg/m^3. Fraunhofer WKI, Germany, carried out the provision and analysis of the sampling tubes. Active air sampling was performed in duplicate.

2.5. Analysis of carbonyl compounds

The concentrations of acetone and C_1-C_4 aldehydes were determined according to ISO 16000-3 (ISO 16000-3, 2022). The measurements were performed using 2,4-dinitrophenylhydrazine (DNPH) low-pressure cartridges (Supelco STD, Steinheim, Germany) with GilAir plus pumps (DEHA Haan & Wittmer Ltd., Heimsheim, Germany). The sample volume was 45 l, and the flow rate was 1.5 l/min. The DNPH cartridges were eluted with acetonitrile (purity for HPLC-MS, Thermo Fisher Scientific, Germany). The concentrations of acetone and the aldehydes were quantified by high-performance liquid chromatography (HPLC) with UV and diode array detector (UltiMate 3000, Thermo Fisher Scientific, Germany). The analytical standards were purchased from Merck (Supelco STD, Steinheim, Germany). The limit of quantification (LOQ) for all compounds was 1.0 μg/m^3. The Bavarian Health and Food Safety Authority carried out the provision and analysis of the sampling tubes.

2.6. Analysis of VOCs

VOCs were collected on stainless steel adsorption tubes filled with Tenax TA (60/80 mesh) by active sampling with BIVOC 2 pumps (Umweltanalytik Holbach Ltd., Wadern, Germany), or GilAir plus pumps (DEHA Haan & Wittmer Ltd., Heimsheim, Germany). Two samples with different volumes (3 standard liters at an airflow rate of 0.10 l/min and 0.6 standard liters at 0.02 l/min) were taken simultaneously per sampling. The sampling systems were set up at a room height of 1–1.5 m and a distance of at least 1 m from the walls. The samples in the apartments were taken after at least 8 h without ventilation, while the samples in the school classrooms were taken under conditions of use during lessons. Before sampling, all adsorption tubes were conditioned under helium flow (60 ml/min, 99.999 % purity, Air Liquide Germany) at 275 °C for 30 min.

Thermodesorption gas chromatography-mass spectrometry (TD-GC-MS) analyses of the samples were performed using a PerkinElmer instrument consisting of an ATD350 thermal desorber with a Tenax® TA (60/80 mesh) cold trap and a heated transfer line (260 °C), a Clarus 680 gas chromatograph and a Clarus SQ8 S quadrupole mass spectrometer. Helium (99.999 % purity, Air Liquide Germany) was used as a desorption and carrier gas. The samples were desorbed via a two-stage desorption. The primary desorption from the sample tube onto the cold trap (−8 °C) was carried out at 275 °C for 15.1 min with an inlet split ratio of 30:1 ml/min. For secondary desorption and transfer to the GC, the cold trap was rapidly heated to a temperature of 270 °C, which was maintained for 15 min. The outlet split ratio was set to 5:1 ml/min.

Chromatographic separation was performed on a PerkinElmer Elite VMS column (length: 30 m; inner diameter: 0.25 mm; film thickness: 1.40 μm) with a column flow rate of 1 ml/min. The temperature program started at 36 °C (held for 3 min), was increased at a rate of 6 °C/min to 120 °C, then at a rate of 8 °C/min to 230 °C (held for 6 min), and finally at a rate of 20 °C/min to 240 °C (held for 3.52 min). The temperature of the transfer line was set to 260 °C. MS analysis was performed in TIC (total ion chromatogram) mode using electron ionization (70 eV) at a source temperature of 240 °C. The target compounds were identified by two characteristic ions, with one of the ions serving for quantification.

Calibration was performed over eight concentration levels, each with three data points ranging from 1 to 30 ng/μl. A control sample with a medium concentration was analyzed for all ten samples or at least for each run. Calibration and control samples were prepared by spiking adsorbent tubes with analyte solutions in methanol while the tubes were flushed with a nitrogen flow of 30 ml/min. The nitrogen flow was maintained for 5 min after spiking. The analyte solutions were prepared with naphthalene from Honeywell Fluka (>99 % purity). The limit of detection (LOD) and limit of quantification (LOQ) were determined using the signal-to-noise ratio at a ratio of 3:1 and 9:1, respectively (see Table 1). The Schleswig-Holstein State Social Services Agency carried out the provision and analysis of the sampling tubes.

2.7. Sampling of PM_{10} and analysis of endotoxins

PM_{10} dust was collected in the classrooms during teaching time on two consecutive days for approx. 5.5 h per day, using a medium volume sampler (Derenda, Stahnsdorf, Germany) equipped with a flow-controlled pump with a constant flow rate of 2.3 m^3/h. The measuring devices were located in the center of the room's back wall, opposite the panel, about 50 cm from the wall. The sampling heads were located at a height of about 90 cm above the floor. The sample inlet was a PM_{10} collector with a collection efficiency of 50 % for particles with an aerodynamic diameter of 10 μm. PM_{10} was collected on 47 mm binder-free quartz fiber filters from Macherey-Nagel (MN 85/90 BF). The filter was heated at 500 °C for 8 h before use and then packed in petri dishes for transportation. Only decontaminated tweezers were used to handle the filters. The filter cartridges were cleaned in an ultrasonic bath with methanol, baked at 80 °C for 8 h, and then sterile-packed. After sampling, the filters were stored in the laboratory at −20 °C until measurement. The filters were placed near the sampling location as blank samples. The same collection systems were also used in the apartments. Here, dust was collected in the air in the central living area of the apartments over 48 h on two consecutive days. The endotoxin concentration was determined using Limulus amoebocyte lysate (LAL), for which the filters were extracted with LAL water containing 0.05 % Tween 20 on the shaker and measured using a kinetic color test (Kinetic-QCLTM) from Lonza. This method is based on the spectrophotometric measurement of the color at different time intervals after adding the chromogenic substrate to the test sample. The time required for the color change is inversely proportional to the amount of endotoxin present. The concentration of unknown samples can be calculated by interpolating them into a standard curve. Quantification was performed using a 5-point calibration ranging from 0.005 to 50 EU/ml.

2.8. Statistical methods

All data were analyzed using the statistical software package SPSS 21 (IBM Inc.). Unless otherwise stated, values below the LOQ were set to half the LOQ. Correlations were performed using the Spearman rank correlation coefficient. The equality of the groups' central tendencies

Table 1
VVOCs and VOCs in the indoor air of 35 apartments and 27 classrooms of schools in µg/m.[3].

Name	CAS No.	LOQ	N > LOQ	Mean	Median	95th percentile	Max	N > LOQ	Mean	Median	95th percentile	Max
			Apartments					**Classrooms**				
Alkanes												
n-Pentane [a]	**109–66–0**	**1.0**	**28**	**10.2**	**4.0**	**40**	**115**	**9**	**1.5**		**5.5**	**6.0**
iso-Pentane [a]	**78–78–4**	**3.0**	**33**	**38.2**	**14.5**	**190**	**376**	**12**	**3.5**	**2.0**	**8.9**	**10.0**
2-Methylpentane [a]	**107–83–5**	**1.0**	**13**	**3.8**	**0.5**	**16.0**	**49.5**	**6**	**0.9**		**3.0**	**3.0**
3-Methylpentan[a]	96-14-0	2.0	7	3.2		12.4	40.5	1				2.0
n-Hexane	110-54-3	0.1	32	2.3	0.4	10.2	28.0	26	0.6	0.4	1.3	3.7
n-Heptane	142-82-5	0.2	34	7.3	1.0	38.0	92.0	23	1.5	0.6	3.5	16.1
n-Octane	111-65-9	0.1	33	6.6	0.7	11.9	175	26	0.4	0.4	0.8	1.0
n-Nonane	111-84-2	0.1	33	5.4	0.6	11.1	133	19	0.3	0.3	0.7	1.5
n-Decane	124-18-5	0.1	35	3.7	0.9	12.4	61.0	25	0.8	0.5	1.3	6.3
n-Undecane	1120-21-4	0.2	32	3.7	1.2	12.2	38.0	24	1.7	0.8	6.4	15.5
n-Dodecane	112-40-3	0.5	32	3.3	1.8	12.2	19.5	25	2.2	1.4	7.3	10.7
n-Tridecane	629-50-5	0.5	27	1.6	0.9	4.7	15.6	11	0.7		2.2	3.3
n-Tetradecane	629-59-4	0.2	34	1.2	1.0	2.5	4.4	26	0.8	0.8	1.7	1.8
n-Pentadecane	629-62-9	0.3	27	0.7	0.6	1.8	4.6	23	0.6	0.7	1.0	1.4
n-Hexadecane	544-76-3	0.3	31	0.8	0.7	1.8	3.5	27	0.8	0.7	1.2	1.6
Cyclohexane	110-82-7	0.1	16	0.8		1.0	22.0	7	0.1		0.6	0.7
Methylcyclopentane	96-37-7	0.1	16	1.2		5.6	24.0	10	0.2		0.4	1.9
Methylcyclohexane	108-87-2	0.1	28	7.3	0.4	5.7	225	16	0.5	0.2	2.3	4.1
Alcohols												
Ethanol [a]	**64–17–5**	**5.0**	**35**	**598**	**431**	**1257**	**2652**	**23**	**264**	**170**	**690**	**1433**
n-Propanol [a]	**71–23–8**	**6.0**	**33**	**5.1**	**1.8**	**21**	**38.0**	**26**	**34.5**	**2.2**	**50.0**	**726**
Isopropanol[a]	67-63-0	7.0	35	19.2	7.9	53.4	236	27	87.7	9.4	570	865
1-Butanol	71-36-3	0.7	33	9.8	7.0	25.5	72.0	21	6.6	5.0	13.9	27.0
2-Ethyl-1-hexanol	104-76-7	1.7	30	5.9	5.0	11.1	25.0	22	8.4	6.0	17.5	64.0
Benzyl alcohol	100-61-6	4.4	0				2.5	6	10.8	2.5	26	161
Aromatics												
Benzene	**71–43–2**	**0.1**	**35**	**1.18**	**0.6**	**3.2**	**9.6**	**27**	**0.63**	**0.5**	**1.2**	**1.9**
Toluene	**108–88–3**	**0.1**	**35**	**16.3**	**2.9**	**77.5**	**194**	**27**	**2.4**	**1.6**	**7.8**	**10.1**
m/p-Xylene	**108–38–3**	**0.1**	**35**	**13.7**	**1.3**	**60.0**	**237**	**27**	**1.7**	**1.3**	**4.7**	**5.1**
o-Xylene	95-47-6	0.1	35	5.0	0.8	17.1	88.0	27	0.7	0.7	1.9	2.2
Ethylbenzene	100-41-4	0.1	35	3.5	0.7	14.5	55.0	26	0.6	0.5	1.9	2.0
Styrene	100-42-5	0.1	34	1.4	0.7	6.7	8.8	25	0.5	0.4	1.3	1.6
1,2,4-Trimethylbenzene	95-63-3	0.2	35	6.3	1.1	29.3	92.0	25	1.0	0.7	2.3	4.6
1,3,5-Trimethylbenzene	108-67-8	0.2	25	1.9	0.3	7.2	34.0	17	0.29	0.2	1.0	1.1
2-Ethyltoluene	611-14-3	0.1	25	1.7	0.5	6.0	24.0	18	0.41	0.2	1.3	4.0
3-Ethyltoluene	620-14-4	0.1	35	5.1	0.8	19.8	88.0	27	0.66	0.4	1.8	2.4
n-Propylbenzene	103-65-1	0.1	27	1.1	0.2	3.2	19.0	15	0.15	0.1	0.5	0.7
Naphthalene	91-20-3	0.1	35	0.2	0.2	0.5	1.2	27	0.6	0.3	2.8	4.5
1-Methylnaphthalene	90-12-0	0.1	16	0.1		0.1	0.4	16	0.12	0.1	0.4	0.5
2-Methylnaphthalene	91-57-6	0.2	10	0.1		0.3	0.5	11	0.24	0.1	1.0	1.2
Biphenyl	92-52-4	0.1	2	0.05			0.1	5	0.07			0.2
Terpenes												
Isoprene [a]	**78–79–5**	**1.0**	**35**	**16.3**	**13.5**	**35.1**	**52.5**	**22**	**10.1**	**8.0**	**25.0**	**26.0**
α-Pinene	**80–56–8**	**0.1**	**34**	**16.9**	**5.9**	**67.6**	**145**	**27**	**4.4**	**1.9**	**16.0**	**36.0**
β-Pinene	127-91-3	0.1	33	4.4	2	13.8	33.7	24	1.1	0.5	2.7	8.9
Δ3-Carene	498-15-7	0.1	34	7.4	3.2	26.8	29.4	27	3.7	0.9	15.5	49.0
Limonene	138-86-3	0.1	35	28	17.6	70	135	27	48	7.0	115	700
Cineole	470-82-6	0.4	34	3.8	2	16.1	21.7	22	7.4	1.0	3.3	171
Longifolene	475-20-7	0.2	12	0.2			1.1	9	0.2			0.6
Aldehydes/ketones												
Aceton [a]	**67–64–1**	**1.0**	**35**	**60.8**	**27.8**	**214**	**274**	**27**	**38.9**	**45.1**	**78.6**	**100**
Formaldehyde [a]	**50–00–0**	**1.0**	**34**	**19.1**	**17.0**	**43.9**	**76.3**	**26**	**15.5**	**15.7**	**34.7**	**41.8**
Acetaldehyde [a]	**75–07–0**	**1.0**	**33**	**19.5**	**10.5**	**72.2**	**97.4**	**22**	**8.7**	**7.8**	**21.6**	**25.2**
Acrolein[a]	107-02-8	1.0	25	3.6	4.0	7.5	9.0	22	3.4	3.0	7.0	8.0
Methacrolein[a]	78-85-3	1.0	18	1.2	0.8	3.2	4.5	3	1.0			1.0
Propanal[a]	123-38-6	1.0	13	2.0		6.7	11.8	7	1.0		3.0	3.7
Butanal	123-72-8	1.3	16	1.5		3.0	12.0	11	1.4	0.5	2.7	8.0
Pentanal	110-62-3	1.0	33	6.3	4.0	15.0	22.0	26	3.1	2.0	7.4	9.0
Hexanal	66-25-1	0.8	34	12.7	10.0	32.0	37.0	27	5.9	5.0	12.8	15.0
Heptanal	11-71-7	2.2	15	2.1	1.0	4.0	7.0	7	1.5			4.0
Octanal	124-13-0	0.9	34	3.5	3.0	7.0	9.0	26	3.0	3.0	5.0	7.0
Nonanal	124-19-6	2.7	33	12.1	12.0	22.0	30.0	26	13.8	15.0	23.0	29.0
Decanal	112-31-2	10	3	14.3	14	17.6	18.0	0				
Benzaldehyde	100-52-7	0.1	34	3.2	2.8	6.6	7.1	27	6.67	3.2	14.79	64.6
Ethers/esters												
Methyl acetate [a]	**79–20–9**	**1.0**	**22**	**2.9**	**2.0**	**9.8**	**12.5**	**13**	**1.6**	**1.0**	**3.0**	**10.0**
Ethyl acetate [a]	**141–78–6**	**2.0**	**32**	**22.1**	**9.0**	**75.5**	**191**	**14**	**3.1**	**2.5**	**10.4**	**13.0**
Butyl acetate	123-86-4	0.4	31	3.7	2.2	14.0	21.0	19	7.1	0.7	2.9	157
Ethylen glycol monomethyl ether	109-86-4	0.5	2	0.3			1.0	2	0.3			0.5
Ethylen glycol monoethyl ether	110-80-5	1.1	1				1.0	0				

(*continued on next page*)

Table 1 (*continued*)

Name	CAS No.	LOQ	N > LOQ	Mean	Median	95th percentile	Max	N > LOQ	Mean	Median	95th percentile	Max
			Apartments					**Classrooms**				
Ethylen glycol monobutyl ether	111-76-2	1.2	16	4.4	0.5	6	100	22	19.0	9.0	69.1	119
Ethylen glycol monophenyl ether	122-99-6	2.0	7	1.4	1	3.3	4	26	13.6	7.0	50.0	55.0
Diethylen glycol monobutyl ether	112-34-5	5.0	0					7	11.6		60.0	94.0
Butyldiglycol acetat	124-17-4	1.1	0					0				
Propylene glycol monobuty ether	5131-66-8	1.3	13	3.6		19.0	30.0	23	11.3	3	53.0	74.0
TXIB	6846-50-0	0.2	21	0.6	0.4	2.23	3.2	25	1.2	0.8	2.9	5.7
Halogenated compounds												
Tetrachloroethylene	**127–18–4**	**0.1**	**19**	**0.1**	**0.1**	**0.36**	**0.7**	**9**	**0.2**			**3.5**
1,2-Dichloroethane	**107–06–2**	**0.2**	**19**	**1.6**	**0.2**	**2.79**	**37.1**	**4**	**0.3**			**4.0**
Organic acids												
Formic acid[a]	64-18-6	5.0	34	13.6	15.0	20.2	21.5	18	12.7	15.0	23.0	27.5
Acetic acid[a]	64-19-7	5.0	34	77.3	71.5	145	210	18	66.5	64.0	135	168
Others												
Octamethylcyclotetrasiloxane (D4)	556-67-2	0.1	32	1.5	1.0	3.65	9.7	27	1.17	0.8	2.7	2.8
Decamethylcyclopentasiloxane (D5)	541-02-6	0.1	35	73.8	25.9	287	793	27	55.2	17.1	176	238
Benzothiazole	95-16-9	0.5	7	0.4		0.8	1.1	14	0.8	0.5	1.6	8.7
TVOC (C_6-C_{16})			35	436	253	939	3369	27	329	277	793	900

TVOC: total volatile organic compounds;
[a] VVOC as defined by ISO 16000-6 (in bold).

was tested using the Wilcoxon test.

3. Results and discussion

3.1. Climate parameters and particulate matter

The results of the climate parameters, including carbon dioxide (CO_2), are shown in Table S 1. The indoor air temperatures in the classrooms were between 15 °C and 26 °C (median: 21 °C) and in the apartments between 16 °C and 24 °C (median: 22 °C). The daily median of relative humidity ranged between 25 % and 58 % (median: 43 %) and between 29 % and 57 % (median: 40 %). No statistically significant differences existed between schools and homes for the above climate parameters. The CO_2 concentrations in the indoor air ranged from 433 to 1870 ppm (median: 1136 ppm; 95th percentile: 1814 ppm) in the classrooms and from 403 to 1453 ppm (median: 799 ppm; 95th percentile: 1360 ppm) in the apartments. As expected, the CO_2 concentrations in school classrooms were statistically significantly higher ($p < 0.001$) than in the apartments. In addition to the large number of people per room volume, the generally poorer classroom ventilation is a possible explanation. A statistically significant correlation was found between the average number of pupils in the classrooms and the average CO_2 concentrations.

In Germany, the German Working Group on Indoor Guideline Values has derived hygiene-based guideline values for carbon dioxide in indoor air from the evaluation of current intervention studies (Ad-hoc-AG, 2008). According to this, concentrations below 1000 ppm of CO_2 in indoor air are considered harmless, concentrations between 1000 and 2000 ppm are considered conspicuous, and concentrations above 2000 ppm are considered unacceptable. If the median CO_2 values are considered, the levels were above 1000 ppm only in 15 % of the apartments but in 62 % of the classrooms. Median CO_2 concentrations of over 2000 ppm were not measured in the two indoor spaces examined.

The results of the PM_{10} measurements are summarized in Table S 1. The concentrations measured in classrooms were between 9.1 and 210 µg/m^3 (median: 82 µg/m^3) and between 3.6 and 52 µg/m^3 (median: 10.2 µg/m^3) in apartments. The measured PM_{10} values were statistically significantly higher ($p < 0.001$) in the classrooms than in the apartments.

3.2. VVOC and VOC concentrations

Overall, 35 VVOCs and 69 VOCs could be detected using different independent analytical methods. The individual results of all VOCs and the more frequently detected VVOCs are summarized in Table 1. The statistical parameters of all VVOCs quantified are also listed in Table S 2. In the apartments, the substances with the highest medians (>10 µg/m^3) were, in descending order, ethanol > acetic acid > acetone > decamethylcyclopentasiloxane (D5) > acetaldehyde > limonene > formaldehyde > formic acid > iso-pentane > decanal > isoprene > nonanal. In the classrooms, the order was ethanol > acetic acid > acetone > D5 > formaldehyde, formic acid > nonanal.

For the analyzed substance classes, the following sum medians were found in the classrooms (apartments): Terpenes: 22.5 µg/m^3 (46.1 µg/m^3), aldehydes/acetone: 81.6 µg/m^3 (121 µg/m^3), alkanes 15.2 µg/m^3 (33.5 µg/m^3), aromatics: 8.3 µg/m^3 (10.7 µg/m^3), organic acids 61 µg/m^3 (82 µg/m^3), alcohols 249 µg/m^3 (518 µg/m^3), siloxanes 17.4 µg/m^3 (27.6 µg/m^3), and ethers/esters 51.0 µg/m^3 (22.6 µg/m^3). Overall, the medians in the schools were lower, except for ethers. The differences between the two study sites were statistically significant for the aldehydes, alkanes, aromatics, and alcohol groups. The proportion of substances defined as VVOCs in our study on the total content of the respective group (sum of VOCs and VVOCs) in classrooms (apartments) was 91 % (76 %) for the aldehydes and acetone, 6 % (53 %) for the ethers/esters, 23 % (63 %) for the alkanes, 36 % (30 %) for the terpenes, and 25 % (18 %) for the organic acids. Among the alcohols, ethanol largely dominates the total content of this group. In addition to ventilation and using, e.g., cleaning agents, the level of VOCs in indoor air is also influenced by the emissions from building materials and furnishings. For example, Wang et al. (2022) critically reviewed the multiple factors on VOC emission behaviors indoors and concluded that temperature and relative humidity has a large impact. In our study, only aromatic compounds, but not the other substance classes, showed a statistically significant correlation with the schools' mean temperature ($r = 0.41$; $p = 0.04$) and median CO_2 concentrations ($r = 0.56$; $p = 0.002$). No correlations were found for the median relative humidity. In the living rooms, only the ethers were significantly correlated with the mean indoor air temperature ($r = 0.398$; $p = 0.02$), while for the median relative humidity, a significant positive correlation with the terpenes,

aldehydes, alcohols, and organic acids ($r = 0.42–0.59$; $p < 0.05$) could be observed. The median CO_2 values correlated in these indoor spaces only for the group of terpenes and aldehydes. Likely, statistically significant correlations can only be found to a limited extent due to the many factors influencing indoor air concentration levels, the narrow range of temperature and relative humidity, and the limited number of properties examined.

The scientific literature contains many study results on the classic VOCs in the C_6-C_{16} spectrum or individual groups such as aromatics. The spectrum of the substances investigated is often very different and sometimes limited in number. In our study, for the first time, many VVOCs were determined in indoor air in addition to the classic VOCs to generate meaningful data for two critical indoor spaces regarding exposure. Table 2 compares the VOCs/VVOCs found at higher concentrations in our study with other studies. While Li et al. (2019) and Daniel et al. (2019) report the results of extensive representative studies, the results given by the other three publications are a compilation of several studies. A nationwide study as part of the Canadian Health Measures Survey (CHMS), in which 88 VOCs were examined in 3524 residential homes, provided very comprehensive current results (Li et al., 2019). The substances with the highest concentrations in this study compared to our residential measurements were limonene (24.9 vs. 17.6 μg/m^3), decamethylcyclopentasiloxane (D5) (9.6 vs. 25.9 μg/m^3), toluene (7.3 vs. 2.9 μg/m^3), hexanal (8.7 vs. 10.0 μg/m^3), nonanal (7.4 vs. 12.0 μg/m^3), and α-pinene (5.8 vs. 5.9 μg/m^3), which alone were responsible for more than half of the total of all VOCs. The clear difference between the two studies is striking in the case of D5. This siloxane is used in various applications in cosmetics, personal care products, cleaning agents, coatings for packaging and paints, lubricants, and medical devices. Different application quantities and application areas appear to be responsible for the differences. Nevertheless, emission behavior is very complex. For example, in an experiment in a classroom, Yang et al. (2018) characterized the emission behaviors of D5 from the skin lipids of room users. Key parameters affecting emissions, like the physicochemical characteristics of D5 and environmental conditions, were determined. They found that, in particular, the thermal conditions on the skin, the penetration into clothing, and subsequent emission can be important. Additionally, the reuse of personal care products also significantly influences D5 emissions. In the second study, volatile substances were analyzed in 639 homes between 2014 and 2017 as part of the representative German Environmental Survey for Children and Adolescents (GerES V) (Fernandez Lahore et al., 2025). The median values found in this study are comparable, whereby differences can best be explained by temporal changes in the utilization patterns of individual substances. This applies, for example, to formaldehyde, whose concentrations in indoor air have been declining in recent years. Moreover, here is a brief description of the other studies. Halios et al. (2022) compiled the results of 65 volatile substances measured in European homes from 2000 to 2020 and calculated weighted average geometric means for the individual substances. In a review paper, Logue et al. (2011) compiled the results of 267 organic substances in residential interiors from 77 studies from 1995 to 2010, mainly from North America and Europe. These data were then used to calculate representative mid- and upper-range concentrations relevant to chronic exposures. In a further study, Cometto-Muñiz and Abraham (2015) summarized the results of 47 studies from homes and schools worldwide and calculated, for example, the median concentrations. As expected, the studies show differences in the respective concentrations. Overall, the differences in the medians for some groups, such as terpenes, are relatively small, while for others, such as aromatics, there are clear indications of a decrease in indoor pollution.

Table 2
More extensive studies that measured or estimated indoor air exposure to VOCs and VVOCs compared to substances found with high medians in our study in μg/m.^{3}.

	This study	Halios et al., (2022) *	Logue et al. (2011)	Cometto-Muñiz and Abraham (2015)	Fernandez Lahore et al. (2025)	Li et al. (2019)
Alcohols						
Ethanol	431	92.0	160	92.0	–	–
iso-Propanol	7.9	–	–	–	–	2.1
1-Butanol	7.0	6.2	55.0	51.4	–	1.5
2-Ethyl-1-hexanol	5.0	3.7			4.6	1.6
Aldehydes/Aceton						
Formaldehyde	17.0	18.0	23.0	53.4	24.9	–
Aceton	27.8	11.4	21.0	32.8	–	4.9
Acetaldehyde	10.5	10.1	13.0	20.0	5.5	–
Decanal	14.0	–	0.9	1.8	1.3	1.5
Nonanal	12.0	–	–	18.0	6.1	7.4
Hexanal	10.0	13.3	8.4	7.5	10.9	8.7
Aromatics						
Toluene	2.9	15.9	18.0	14.8	4.7	7.3
Xylenes	2.1	6.4	5.6	8.3	2.6	3.5 [a]
Ethers/esters						
Ethylacetate	9.0	4.3	1.0	16.7	16.6	–
Butylacetate	2.2	–	–	7.5	4.9	–
Alkanes						
n-Pentane	4.0	1.7	–	3.6	–	2.5
iso-Pentane	14.5	–	–	5.5	–	–
Decane	0.9	–	3.8	16.0	1.1	1.0
Heptane	1.0	–	2.5	11.0	<1.0	1.1
Terpenes						
Limonene	17.6	–	18.0	19.2	12.0	24.9
Isoprene	13.5	–	2.0	7.1	–	–
3-Carene	3.2	–	3.7	15.8	2.3	–
α-Pinene	5.9	–	12.0	11.0	6.4	5.8
Organic acids						
Acetic acid	71.5	–	9.4	21.9	–	
Formic acid	15.0	–	–	–	–	
Siloxanes						
D4	1.0	–	–	–	<1.0	2.5
D5	25.9	–	–	–	14.0	9.6

[a] only m-,p-xylenes; * results as weighted average geometric mean.

3.3. Comparison with toxicologically derived values

A health evaluation of individual VOCs/VVOCs is only possible to a limited extent, as toxicologically based values are only available for a few substances. Table S 3 shows the 95th percentiles of the indoor air concentrations determined in our study with the reference concentration (RfC) of the US Environmental Protection Agency (US EPA) and the guide value I (GV I) of the German Committee on Indoor Guide Values (AIR), both of which describe a concentration below which no health effects need be expected even in the case of lifelong exposure. In addition, the guide value II (GV II) is specified as a hazard value. In the indoor rooms examined in this study, the GV II is not exceeded in any room. In the 35 apartments, the GV I/RfC was exceeded in one room for the sum of C_9-C_{14} alkanes, for propanal, for decamethylcyclopentasiloxane (D5), and in two rooms for the sum of xylenes and naphthalene (RfC only). In the 27 classrooms, benzaldehyde was exceeded in one room and ethylene glycol monophenyl ether in four, probably due to the use of perfumes. However, some substances were present in concentrations in the room air which were not far from GV I. This applies in particular to aldehydes such as formaldehyde and acetaldehyde but also to D5, whose 95th percentiles in apartments utilized 44 % of the GV 1 for formaldehyde, 72 % for acetaldehyde, and 72 % for D5.

Carcinogenic substances pose a particular assessment problem. While the US EPA only specifies the concentrations associated with a theoretical cancer risk assuming lifelong exposure of between 1 case per 1000000 (1×10^{-6}) exposed persons and 1 case per 10000 (1×10^{-4}) exposed persons, the German AIR derives so-called risk-related cancer guide levels and preliminary cancer guide levels (for an explanation, see Table S 5 and Fromme et al., 2019). For 1,3-butadiene, vinyl chloride, and trichloroethylene, the analytical methods in our study are not sensitive enough to cover the entire risk range between 1×10^{-6} and 1×10^{-4}. However, the RfC for non-carcinogenic effects is always undercut for vinyl chloride and trichloroethylene. For 1,2-dichloroethane, a theoretical carcinogenic risk of 2.6×10^{-6} (64×10^{-6}) and 5.2×10^{-6} (73×10^{-6}) results in classrooms and apartments at the median (95th percentile) using the US EPA unit risk and for benzene using the unit risk of the German occupational health and safety authorities of 5×10^{-6} (12×10^{-6}) and 6×10^{-6} (32×10^{-6}) respectively. There is no generally accepted definition of a tolerable or acceptable risk to carcinogenic substances for the general population with no specific occupational exposure. Nevertheless, organizations such as the World Health Organization (WHO), the US EPA, and the US Agency for Toxic Substances and Disease Registry (ATSDR) suggest that risk ranges between 10^{-4} and 10^{-6} for staged regulatory action. Without legal regulation, the European Chemicals Agency (ECHA) recommends an indicative risk of 1×10^{-6} in its guidance on risk assessment for the general population (ECHA, 2012). Against this background, further efforts are necessary to reduce the population's exposure to achieve the ECHA target value of a risk of 1×10^{-6}.

3.4. Comparison with TVOC-value

In addition to determining individual VOCs, the sum of the concentrations of the individual volatile organic compounds, the so-called TVOC value (Total Volatile Organic Compounds), can be used (Mølhave et al., 1997, Ad-hoc-AG, 2007). In our study, TVOC is the sum of all substances that elute analytically in the retention range between n-hexane and n-hexadecane (from C_6-C_{16}). In addition to a toxicological analysis of individual substances, this provides an impression of the level of contamination in an indoor space and enables an initial rough hygienic assessment (Ad-hoc-AG, 2007). It is important to note that the TVOC concept does not consider the possibility of interactions between the individual VOCs and is not a toxicological-based assessment (Mølhave, 2003). Instead, it is an indicator or screening tool for assessing indoor air quality (Salthammer, 2022).

For TVOC in this study, a median (95th percentile) of 253 μg/m^3 (939 μg/m^3) and a range of 638–3369 μg/m^3 was determined in the apartments. The classrooms' median was 277 μg/m^3, and the 95th percentile was 793 μg/m^3 (range: 61–900 μg/m^3). There are no statistically significant differences in TVOC concentrations between apartments and classrooms. The individual results for apartments and classrooms are also shown graphically in Fig. 1. In the living rooms, the TVOC values correlated significantly with the groups of alkanes ($r = 0.861$; $p < 0.001$) and aromatics ($r = 0.881$; $p < 0.001$) and in the classrooms with the terpenes, aldehydes, alcohols, and siloxanes ($r = 0.447$–0.651; $p < 0.05$).

Compared to our study, a representative German study conducted in 2014–2017 showed a comparable pollution situation in 639 apartments with a median of 270 μg/m^3 and a 95th percentile of 950 μg/m^3 (Fernandez Lahore et al., 2025). Comparable medians were also reported in a Swiss study in 169 energy-efficient homes (Yang et al., 2020) with 212 μg/m^3 and in 20 conventional homes in Sweden (Langer et al., 2015) with 272 μg/m^3. In China, a very low median of 5 μg/m^3 (mean: 218 μg/m^3; range: 5–1850 μg/m^3) was observed in the control group of an epidemiological study in 75 apartments (Sun et al., 2022), and a significantly higher TVOC median of 1270 μg/m^3 (range: 290–3060 μg/m^3) was reported in 31 living rooms of apartments in another Chinese study (Chen et al., 2017). A concentration range of 104–1151 μg/m^3 was also seen in the study of 251 apartments in 8 Chinese cities (Pei et al., 2020). Significantly fewer results have been published for schools. For example, Madureira et al. (2015) found lower values in 73 classrooms of 20 Portuguese schools with a median of 140 μg/m^3 (range: 9–820 μg/m^3) than in our study, while they were in a comparable range in 9 Spanish classrooms with mean values between 214 and 452 μg/m^3 (Becerra et al., 2020). A slightly lower TVOC median of 179 μg/m^3 was also found in 63 German daycare centers (Fromme et al., 2016). A comparison must always be made cautiously due to the different number of individual substances measured.

Tsang et al. (2024) currently provide a worldwide overview of TVOC quality standards set for indoor spaces, which range between 200 and 1000 μg/m^3. For example, 200 and 600 μg/m^3 indoor air quality objectives in Hong Kong were recommended as an 8-h average value, indicating excellent indoor air quality, respectively (GHK, 2019). In China, a national standard of <600 μg/m^3 averaged over 8 h was set in 2022. In Germany, the Committee on Indoor Guide Values has set a hygienically safe value of <300 μg/m^3 and a still safe range of 300–1000 μg/m^3, at which initial measures are required (Ad-hoc-AG, 2007). In our study, a median of 41 % of classrooms and 43 % of apartments exceed 300 μg/m^3, while 1000 μg/m^3 is only exceeded in one apartment.

3.5. Endotoxin concentrations

The endotoxins could be determined in all airborne dust samples. While a median (95th percentile) of 5.8 EU/m^3 (15.3 EU/m^3) was found in the classrooms, the characteristic values in the apartments were significantly lower at 0.26 EU/m^3 (0.91 EU/m^3). The individual results for apartments and classrooms are shown graphically in Fig. 2. The difference between apartments and classrooms was statistically significant ($p < 0.001$). In addition, a significant negative correlation of the endotoxin concentrations with the average indoor temperature ($r = -0.441$; $p = 0.027$) was observed in the classrooms but not with the number of pupils in the room, the individual VOC groups, or the TVOC value. There were no significant correlations in apartments, not even with pets indoors. The mean values in the seven apartments with pets and the 21 apartments without pets were 0.29 EU/m^3 each. In this study, there was no carpeting in any room; only four had partial carpets on a smooth floor covering. No differences existed between the air levels in rooms with such carpets and those with soft floor coverings (mean values 0.34 vs. 0.32 EU/m^3).

The maximum endotoxin levels measured in classrooms (16.5 EU/

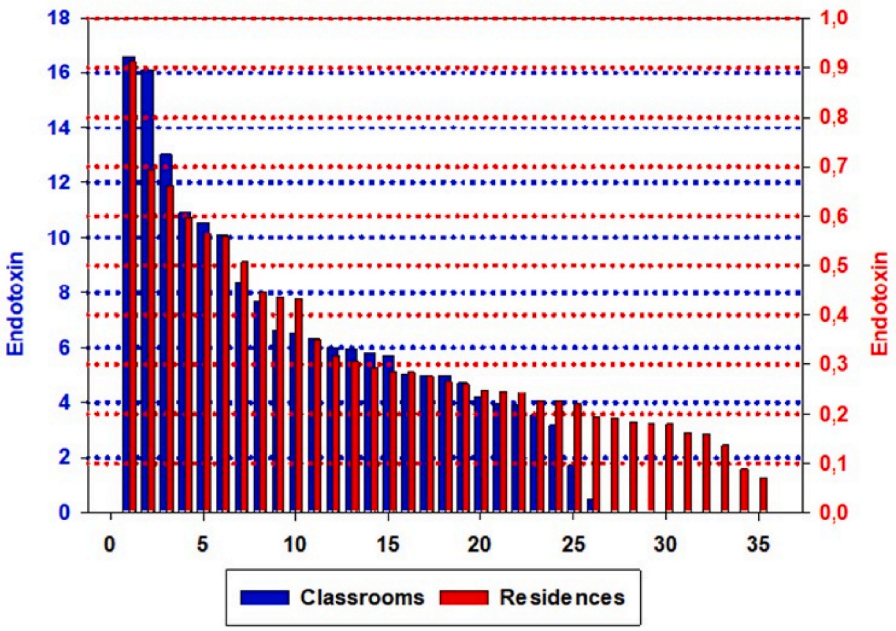

Fig. 2. Endotoxin level in the indoor air in EU/m.^{3}.

m^3) and especially in apartments (0.91 EU/m^3) are well below the limit value of 90 EU/m^3 proposed by the Dutch Expert Committee on Occupational Safety for Workplaces (DECOS, 2010). There are no such values for the general population outside of workplaces.

Table 3 compares the results of studies in classrooms and homes published in the scientific literature. In schools, our current results are lower than in a previous German study, in which a median (95th percentile) of 15.3 EU/m^3 (58.2 EU/m^3) was found in the air of 14 classrooms in 7 schools using the same methodology (Fromme et al., 2013). Although other sampling techniques were used for collecting $PM_{4\text{-}20}$ or IOM Inhalable Dust Samplers, studies in Singapore and Denmark have comparable results with our research (Holst et al., 2015; Sankaran et al., 2023). For example, the highest mean endotoxin concentrations in the $PM_{4\text{-}20}$ fraction (5.6 EU/m^3) and the lowest (0.9 EU/m^3) in the $PM_{0.06\text{-}1}$ fraction were found in the samples collected from daycare centers in Singapore using a cascade impactor (Sankaran et al., 2023).

Table 3
Endotoxin levels in the air of apartments and classrooms in EU/m.^{3}.

Reference	N	Median (min-max)	Country, year
Classrooms			
This study	27	5.8 (0.43–16.6)	Germany, 2019-20
Sankaran et al. (2023)	22 [f]	5.6[b] (0–16.9)[d]	Singapore, 2015/16
Fromme et al. (2013)	14	15.3 (0.5–84)	Germany, 2012
Holst et al. (2015)	20	7.33 (2.83–225)[c]	Denmark, 1999/2000
Apartments			
This study	35	0.26 (0.07–0.91)	Germany, 2019-20
Huang et al., 2023	120	0.87 (0–~40)	Taiwan, 2017-20
Bose et al., 2016	84	0.06 (0.01–0.36)[e]	USA
Ramagopal et al., 2014	75	1.0 (0.09–16)	USA
Yoda et al. (2017)	55	0.13[a] (0.01–0.57)	Japan, 2014
Yen et al., 2020	120	0.67 (0.02–8.13)	Taiwan, 2010-12
Frankel et al., 2012	5	1.48[b] (0.32–38)	Denmark, 2010/11
Bari et al., 2014	74	0.41 (0.005–53) summer 0.12 (0.002–12) winter	Canada, 2010
Hyvärinen et al., 2006	5	0.43[a] (0.05–3.99)	Finland, 2008
Pavilonis et al. (2013)	115	0.21[a] (0.01–4.52)	USA, 2007-11
Mazique et al. (2011)	85	0.05 (0.001–1.68)	USA, 2007/08
Menetrez et al., 2009	10	0.05[b] (0.024–0.08)	USA, 2007
Wheeler et al., 2011	100 76	0.47[a] (0.06–4.1) summer 0.14[a] (0.02–1.45) winter	Canada, 2007
Chen et al., 2017	40	1.4[a] (0.2–6.0)[g]	USA, 2005
Horick et al. (2006)	82	0.81[b] (0.23–5.87)	USA
Delfino et al., 2015	45	0.61 (0.002–25.3)	USA, 2004
Dassonville et al., 2008	162	0.59 (<0.05–17700)	France, 2003

[a] geometric mean.
[b] mean.
[c] 10th and 99th percentile.
[d] $PM_{8\text{-}20}$.
[e] : interquartile range.
[f] daycare centers.
[g] PM_{10}.

Most published studies on residential interiors reported a median exposure level similar to ours, although the range of individual results can be extensive. In addition to home characteristics such as flooring and cleaning activities, the presence and number of pets can explain this (Horick et al., 2006; Mazique et al., 2011; Pavilonis et al., 2013; Yoda et al., 2017).

Overall, when comparing the results, it must be taken into account that sampling was carried out very differently in the studies, and influences on the results are to be expected. For example, the following methods were used: PM_{10} collection on glass fiber filters with a medium volume sampler and an airflow rate of 2.5 m^3/per hours over 6 h; cascade impactor with eight size classes over 4–5 days for a total of 35 h; polytetrafluoroethylene (PTFE) membrane filters using a sampling pump operating at 20 l/min with a sampling time of 24 h.

4. Conclusion

This study analyzed a broad spectrum of organic substances in indoor air. Overall, 35 VVOCs (including low-molecular aldehydes and acetone), 69 VOCs, formic acid and acetic acid, as well as airborne endotoxins, were quantified in the indoor air of 34 central living rooms of apartments and 27 elementary school classrooms. The aim was to collect initial data on indoor air pollution and, in addition to the more frequently measured VOCs, to include VVOCs and endotoxins that had previously only been rarely measured. It turned out that the proportion of substances defined as VVOCs in our study on the total levels of the individual groups was high in some cases.

According to current knowledge, exposure to airborne endotoxins is

low, especially in apartments, and does not pose a significant health risk. A health assessment of the results of the individual VOCs and VVOCs is complex, as only limited toxicologically derived values for indoor air are available to date. An urgent need is to derive more scientifically based values for indoor air. This is also important because the composition of indoor air has changed in recent years, and the before important halogenated compounds and aromatics, for which sufficient values are available, are becoming significantly less critical. Overall, the existing guide values are only exceeded in individual cases. Further risk reduction is required for some substances, such as benzene and 1,2-dichloroethane, for which the carcinogenic effects are in the foreground. Our study shows that in addition to the typical VOCs, VVOCs should also be increasingly included in the range of substances analyzed, as there can be significant exposure to substances in this group indoors.

CRediT authorship contribution statement

Hermann Fromme: Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization. **Marina Sysoltseva:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Alexandra Schieweck:** Methodology, Formal analysis, Data curation, Conceptualization. **Claudia Röhl:** Methodology, Investigation, Formal analysis, Data curation. **Felicia Gerull:** Validation, Project administration, Formal analysis, Data curation. **Rafael Burghardt:** Methodology, Investigation, Formal analysis, Data curation. **Andreas Gessner:** Methodology, Investigation, Formal analysis, Data curation. **Heike Papavlassopoulos:** Software, Methodology, Formal analysis, Data curation. **Wolfgang Völkel:** Writing – original draft, Validation, Supervision. **Wolfgang Schober:** Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests which may be considered as potential competing interests:Hermann Fromme reports financial support was provided by Bavarian Ministry of Health and Care. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2025.121178.

Data availability

The data that has been used is confidential.

References

Ad-hoc-AG (German Working Group on Indoor Guideline Values), 2007. Evaluation of indoor air contaminants by means of reference and guideline values. Bundesgesundheitsblatt 50, 990–1005 [in German].

Ad-hoc-AG, 2008. Health evaluation of carbon dioxide in indoor air. Bundesgesundheitsblatt 51, 1358–1369 [in German].

Aziz, N., Adman, M.A., Suhaimi, N.S., Misbari, S., Alias, A.R., Aziz, A.A., Lee, L.F., Hossain Khan, M.M., 2023. Indoor air quality (iaq) and related risk factors for sick building syndrome (SBS) at the office and home: a systematic review. IOP Conf. Ser. Earth Environ. Sci. 1140, 012007.

Bari, A, MacNeill, M, Kindzierski, WB, Wallace, L, Héroux, M-E, Wheeler, AJ, 2014. Predictors of coarse particulate matter and associated endotoxin concentrations in residential environments. Atmos. Environ. 92, 221–230.

Becerra, J.A., Lizana, J., Gil, M., Barrios-Padura, A., Blondeau, P., Chacartegui, R., 2020. Identification of potential indoor air pollutants in schools. J. Clean. Prod. 242, 118420.

Bose, S, Rivera-Mariani, F, Chen, R, Williams, D, Belli, A, Aloe, C, McCormack, MC, Breysse, PN, Hansel, NN, 2016. Domestic exposure to endotoxin and respiratory morbidity in former smokers with COPD. Indoor Air 26 (5), 734–742.

Chen, X., Li, F., Liu, C., Yang, J., Zhang, J., Peng, C., 2017. Monitoring, human health risk assessment, and optimized management of typical pollutants in indoor air from random families of university staff in Wuhan City, China. Sustainability 9, 1115.

Chithra, V.S., Shiva Nagendra, S.M., 2018. A review of scientific evidence on indoor air of school building: pollutants, sources, health effects and management. Asian J Atmos Environ 12, 87–108.

Cometto-Muñiz, J.E., Abraham, M.H., 2015. Compilation and analysis of types and concentrations of airborne chemicals measured in various indoor and outdoor human environments. Chemosphere 127, 70–86.

Dassonville, C, Demattei, C, Vacquier, B, Bex-Capelle, V, Seta, N, Momas, I, 2008. Indoor airborne endotoxin assessment in homes of Paris newborn babies. Indoor Air 18 (6), 480–487.

DECOS, 2010. Endotoxins. Health-Based Recommended Occupational Exposure Limit. Online, The Hague, The Netherlands. https://www.healthcouncil.nl/documents/advisory-reports/2010/07/15/endotoxins-health-based-recommended-occupational-exposure-limit.

Delfino, RJ, Staimer, N, Tjoa, T, Gillen, DL, 2015. Relations of exhaled nitric oxide and FEV1 to personal endotoxin exposure in schoolchildren with asthma. Occup. Environ. Med. 72 (12), 830–836.

DIN, EN, 2020. DIN EN 16516:2020-1. Construction Products: Assessment of Release of Dangerous Substances - Determination of Emissions into Indoor Air. German version.

ECHA (European Chemicals Agency), 2012. Guidance on information requirements and chemical safety assessment. Chapter R.8: characterisation of dose [concentration]-response for human health. https://www.echa.europa.eu/documents/10162/13632/information_requirements_r8_en.pdf.

Even, M., Juritsch, E., Richter, M., 2021. Measurement of very volatile organic compounds (VVOCs) in indoor air by sorbent-based active sampling: identifying the gaps towards standardisation. TrAC, Trends Anal. Chem. 140, 116265.

Even, M., Juritsch, E., Richter, M., 2023. Selection of gas standards, gas chromatography column and adsorbents for the measurement of very volatile organic compounds (C1-C6) in indoor air. Anal. Chim. Acta 1238, 340561.

Fernandez Lahore, A., Bethke, R., Daniels, A., Neumann, K., Birmili, W., 2025. German environmental study on the health of children and Adolescents 2014–2017 (GerES V). Part 2: indoor air quality. Report 01/2025. https://www.umweltbundesamt.de/publikationen/deutsche-umweltstudie-zur-gesundheit-von-kindern-1.

Frankel, M, Bekö, G, Timm, M, Gustavsen, S, Hansen, EW, Madsen, AM, 2012. Seasonal variations of indoor microbial exposures and their relation to temperature, relative humidity, and air exchange rate. Appl. Enviro.n Microbiol. 78 (23), 8289–8297.

Fromme, H., Bischof, W., Dietrich, S., Lahrz, T., Schierl, R., Schwegler, U., 2013. Airborne allergens, endotoxins, and particulate matter in elementary schools, results from Germany (LUPE 2). J. Occup. Environ. Hyg. 10, 573–582.

Fromme, H., Lahrz, T., Burkhardt, R., Fembacher, L., Kraft, M., Sievering, S., Kadler, D., Dietrich, S., 2016. Air quality in daycare centers - exposure to carbon dioxide (CO2), volatile organic compounds (VOCs), and fine dusts – LUPE 3. Gefahrst. Reinhalt. Luft 76, 55–61 [in German].

Fromme, H., Debiak, M., Sagunski, H., Röhl, C., Kraft, M., Kolossa-Gehring, M., 2019. The German approach to regulate indoor air contaminants. Int. J. Hyg Environ. Health 222, 347–354.

Fromme, H., Sysoltseva, M., Achten, C., Bühl, T., Röhl, C., Leubner, S., Gerull, F., Gessner, A., Kraft, M., Burghardt, R., Schober, W., Völkel, W., 2023. Polycyclic aromatic hydrocarbons including dibenzopyrenes in indoor air samples from schools and residences in Germany. Atmos. Environ. 309, 119946.

GHK (The Government of Hong Kong), 2019. Guidance notes for the management of indoor air quality in offices and public places. https://www.iaq.gov.hk/wp-content/uploads/2021/04/gn_officeandpublicplace_eng-2019.pdf.

Halios, C.H., Landeg-Cox, C., Lowther, S.D., Middleton, A., Marczylo, T., Dimitroulopoulou, S., 2022. Chemicals in European residences - Part I: a review of emissions, concentrations and health effects of volatile organic compounds (VOCs). Sci. Total Environ. 839, 156201.

Holst, G., Høst, A., Doekes, G., Meyer, H.W., Madsen, A.M., Sigsgaard, T., 2015. Determinants of house dust, endotoxin, and β-(1→3)-D-glucan in homes of Danish children. Indoor Air 25, 245–259.

Horick, N., Weller, E., Milton, D.K., Gold, D.R., Li, R., Spiegelman, D., 2006. Home endotoxin exposure and wheeze in infants: correction for bias due to exposure measurement error. Environ. Health Perspect. 114, 135–140.

ISO 16000-6, 2021. 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. Beuth Verlag, Berlin, Germany.

Huang, HC, Zou, ML, Chen, YH, Jiang, CB, Wu, CD, Lung, SC, Chien, LC, Lo, YC, Chao, HJ, 2023. Effects of indoor air quality and home environmental characteristics on allergic diseases among preschool children in the Greater Taipei Area. Sci. Total Environ. 897, 165392.

Hyvärinen, A, Roponen, M, Tiittanen, P, Laitinen, S, Nevalainen, A, Pekkanen, J, 2006. Dust sampling methods for endotoxin - an essential, but underestimated issue. Indoor Air 16 (1), 20–27.

ISO 16000-3, 2022. Indooe Air – Part 3; Determination of Formaldehyde and Other Carbonyl Compounds in Indoor Air and Test Chamber Air – Active Sampling Method.

Kumar, P., Singh, A.B., Arora, T., Singh, S., Singh, R., 2023. Critical review on emerging health effects associated with the indoor air quality and its sustainable management. Sci. Total Environ. 872, 162163.

Langer, S., Bekö, G., Bloom, E., Widheden, A., Ekberg, L., 2015. Indoor air quality in passive and conventional new houses in Sweden. Build. Environ. 93, 92–100. https://doi.org/10.1016/j.buildenv.2015.02.004.

Li, Y., Cakmak, S., Zhu, J., 2019. Profiles and monthly variations of selected volatile organic compounds in indoor air in Canadian homes: results of Canadian national indoor air survey 2012–2013. Environ. Int. 126, 134–144.
Liebers, V., Brüning, T., Raulf, M., 2020. Occupational endotoxin exposure and health effects. Arch. Toxicol. 94, 3629–3644.
Logue, J.M., McKone, T.E., Sherman, M.H., Singer, B.C., 2011. Hazard assessment of chemical air contaminants measured in residences. Indoor Air 21, 92–109.
Madureira, J., Paciencia, J., Rufo, J., Ramos, E., Barros, H., Teixeira, J.P., de Oliveira Fernandes, E., 2015. Indoor air quality in schools and its relationship with children's respiratory symptoms. Atmos. Environ. 118, 145–156.
Mazique, D., Diette, G.B., Breysse, P.N., Matsui, E.C., McCormack, M.C., Curtin-Brosnan, J., Williams, D.L., Peng, R.D., Hansel, N.N., 2011. Predictors of airborne endotoxin concentrations in inner city homes. Environ. Res. 111, 614–617.
Menetrez, MY, Foarde, KK, Esch, RK, Schwartz, DT, Dean, TR, Hays, MD, Cho, SH, Betancourt, DA, Moore, SA, 2009. An evaluation of indoor and outdoor biological particulate matter. Atmos. Environ. 43, 5476–5483.
Mølhave, L., 2003. Organic compounds as indicators of air pollution. Indoor Air 13 (Suppl. 6), 12–19.
Mølhave, L., Clausen, G., Berglund, B., De Ceaurriz, J., Kettrup, A., Lindvall, T., Maron, M., Pickering, A.C., Risse, U., Rothweiler, H., Seifert, B., Younes, M., 1997. Total volatile organic compounds (TVOC) in indoor air quality investigations. Indoor Air 7, 225–240.
NICE (National Institute for Health and Care Excellence), 2020. Indoor air quality at home. https://www.nice.org.uk/guidance/NG149.
Palacios, Kristopher Steele, Tan, Zhengzhen, Zheng, Siqi, 2021. Human Health and Productivity Outcomes of Office Workers Associated with Indoor Air Quality: A Systematic Review, MIT Center for Real Estate Research Paper No. 21/14.
Pavilonis, B.T., Anthony, T.R., O'Shaughnessy, P.T., Humann, M.J., Merchant, J.A., Moore, G., Thorne, P.S., Weisel, C.P., Sanderson, W.T., 2013. Indoor and outdoor particulate matter and endotoxin concentrations in an intensely agricultural county. J. Expo. Sci. Environ. Epidemiol. 23, 299–305.
Pei, J., Yin, Y., Liu, J., Dai, X., 2020. An eight-city study of volatile organic compounds in Chinese residences: compounds, concentrations, and characteristics. Sci. Total Environ. 698, 134137.
Ramagopal, M, Wang, Z, Black, K, Hernandez, M, Stambler, AA, Emoekpere, OH, Mainelis, G, Shalat, SL, 2014. Improved exposure characterization with robotic (PIPER) sampling and association with children's respiratory symptoms, asthma and eczema. J. Expo. Sci. Environ. Epidemiol. 24 (4), 421–427.
Salthammer, T., 2022. Tvoc – revisited. Environ. Int. 167, 107440.
Sankaran, G., Tan, S.T., Yap, R., Chua, M.L., Ng, L.C., George, S., 2023. Characterization of size-differentiated airborne particulate matter collected from indoor environments of childcare facilities. Chemosphere 340, 139670.
Schieweck, A., Gunschera, J., Varol, D., Salthammer, T., 2018. Analytical procedure for the determination of very volatile organic compounds (C(3)-C(6)) in indoor air. Anal. Bioanal. Chem. 410 (13), 3171–3183.
Schieweck, A., 2021. Very volatile organic compounds (VVOC) as emissions from wooden materials and in indoor air of new prefabricated wooden houses. Build Eniron 190, 107537.
Shrubsole, C., Dimitroulopoulou, S., Foxall, K., Gadeberg, B., Dou, A., 2019. IAQ guidelines for selected volatile organic compounds (VOCs) in the UK. Build. Environ. 165, 106382.
Sun, J., Wang, J., Yang, J., Shi, X., Li, S., Cheng, J., Chen, S., Sun, K., Wu, Y., 2022. Association between maternal exposure to indoor air pollution and offspring congenital heart disease: a case-control study in East China. BMC Public Health 22, 767.
Tran, M.T., Wei, W., Dassonville, C., Martinsons, C., Ducruet, P., Mandin, C., Héquet, V., Wargocki, P., 2023. Review of parameters measured to characterize classrooms' indoor environmental quality. Buildings 13, 433.
Tran, V.V., Park, D., Lee, Y.C., 2020. Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. Int. J. Environ. Res. Publ. Health 17, 2927.
Tsang, T.-W., Mui, K.-W., Wong, L.-T., 2024. Indoor air quality (IAQ) management in Hong Kong: the way forward. Atmosphere 15, 546.
US EPA, 2011. Exposure factors Handbook. https://www.epa.gov/expobox/exposure-factors-handbook-2011-edition.
Wang, H., Xiong, J., Wei, W., 2022. Measurement methods and impact factors for the key parameters of VOC/SVOC emissions from materials in indoor and vehicular environments: a review. Environ. Int. 168, 107451.
Yang, T., Xiong, J., Tang, X., Misztal, P.K., 2018. Predicting indoor emissions of cyclic volatile methylsiloxanes from the use of personal care products by university students. Environ. Sci. Technol. 52 (24), 14208–14215.
Wheeler, AJ, Dobbin, NA, Lyrette, N, Wallace, L, Foto, M, Mallick, R, Kearney, J, Van Ryswyk, K, Gilbert, NL, Harrison, I, Rispler, K, Héroux, M-E, 2011. Residential indoor and outdoor coarse particles and associated endotoxin exposures. Atmos. Environ. 45, 7064–7071.
Yang, S., Perret, V., Hager Jörin, C., Niculita-Hirzel, H., Goyette Pernot, J., Licina, D., 2020. Volatile organic compounds in 169 energy-efficient dwellings in Switzerland. Indoor Air 30, 481–491.
Yen, YC, Yang, CY, Wang, TN, Yen, PC, Ho, CK, Mena, KD, Lee, TC, Chen, KS, Lin, YC, Chen, PS, 2020. Household airborne endotoxin associated with asthma and allergy in elementary school-age children: a case-control study in Kaohsiung, Taiwan. Environ. Sci. Pollut. Res. Int. 27 (16), 19502–19509.
Yoda, Y., Tamura, K., Shima, M., 2017. Airborne endotoxin concentrations in indoor and outdoor particulate matter and their predictors in an urban city. Indoor Air 27, 955–964.