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Analytical chemistry of carbonyl compounds in indoor air

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Carbonyl compounds are ubiquitous in outdoor and indoor air. Due to the high electronegativity of the oxygen atom, they are polar in nature and the C=O group opens possibilities for many types of chemical reactions. Their physical and chemical properties are additionally influenced by substituents and conjugated double bonds. The concentration ranges are also highly variable. Formaldehyde can reach 100 ppb or more in indoor air, but reaction products such as 4-oxopentanal (4-OPA) are in the lower ppb range or even below 1 ppb. Another point concerns the dynamics of carbonyls. When examining the emission of formaldehyde in test chambers, an equilibrium concentration is usually established, so that changes over time can be neglected during the measurement. On the other hand, many substances and scenarios are subject to strong fluctuations in concentration over short time periods. The analysis is also made more difficult by the fact that different methods are often required for saturated carbonyls, unsaturated carbonyls and dicarbonyls. This work focuses on aprotic carbonyl compounds such as aldehydes, ketones, lactams and pyrones with relevance for the indoor environment that do not contain any other reactive groups. The range of interesting compounds has grown significantly in recent years, notably through the derivation of health-based guide values, as well as through investigations into new products, human activities and human emissions from the skin and respiratory gas. Classical and modern analysis methods are discussed, which can be considered for the respective research question. Many small molecules require derivatization as a first step, followed by separation via gas chromatography or HPLC. Substance-specific detection without chromatographic separation is routinely used for formaldehyde. With some limitations, the identification of carbonyls in multicomponent mixtures is possible using online mass spectrometry. In particular, proton-transfer-reaction mass spectrometry (PTR-MS) has established as a method with high sensitivity and high time resolution.

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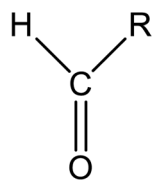
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1 Introduction

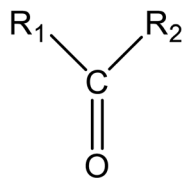
To date, thousands of organic compounds have been analytically detected in indoor air. A systematic compilation is just as impossible as it is useless, since the spectrum of substances changes over time for a variety of reasons such as substance substitution, legislation and lifestyle. In addition, many substances are not directly introduced into the room air, but are formed by biotic and abiotic chemical processes.

In order to still get an overview, classical environmental chemistry distinguishes between the concepts media-related, sector-related, substance-related¹ and effect-related.² A media-related concept is used when specific matrices such as air or dust are to be examined. This is the case with surveys. Sectors relate to defined product groups (e.g. building materials, furniture) and processes (e.g. cooking, combustion, ozone reactions), while effect-related concepts focus on exposure and health aspects. Substance-related concepts can relate to individual chemicals such as formaldehyde and radon, but also to substance groups such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons and phthalates.





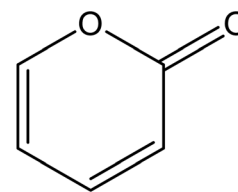
Aldehyde



Ketone



Lactam



2-Pyrone

Fig. 1 Chemical structures of carbonyl compounds.

This review is substance-related and deals with carbonyl compounds that are of importance for the indoor environment. Only aprotic substances that do not have a functional group from which hydrogen atoms can be split off as protons are discussed. Esters are also not taken into account, but only aldehydes, ketones, lactams and pyrones with the chemical structures shown in Fig. 1.

The question of whether such work is necessary arises from history and the current situation. In the early years, formaldehyde was almost exclusively discussed.³ A summary of historical methods for determining formaldehyde in different phases can be found in Walker.⁴ With the beginning of systematic room air measurements, attention was drawn to solvents such as 2-butanone (MEK) and other volatile organic compounds (VOCs).^{5–7} The saturated and unsaturated aldehydes came into focus with investigations into oxidation reactions of unsaturated hydrocarbons and fatty acids through thermal influences, atmospheric oxygen and ozone.⁸ Over time, more relevant carbonyl compounds were identified, in particular through studies on wood and wood-based materials,^{9,10} textile floor coverings,^{11,12} fragrances,¹³ 3D printers,^{14,15} cooking and frying,¹⁶ but also through reactions on the human skin surface.¹⁷

From an analytical point of view, the problem is that carbonyl compounds are chemically very different. Formaldehyde, the simplest aldehyde, is a typical VVOC (very volatile organic compound) with a boiling point of $-20\text{ }^{\circ}\text{C}$; benzophenone is an SVOC (semi-volatile organic compound) with a boiling point of $+305\text{ }^{\circ}\text{C}$. The concentrations can also cover several orders of magnitude. Some substances like 4-oxopentanal (4-OPA) and 6-methyl-5-hepten-2-one (6-MHO) are common products in the reaction of unsaturated hydrocarbons with ozone. Usually, they do not occur in high concentrations, but they are subject to fast dynamics. On the other hand, formaldehyde can cover a wide concentration range from sub-ppb to sub-ppm (note that ppb and ppm refer to volume mixing ratios) and the concentration changes over time take place within seconds as well as within days.

The spectroscopic properties of the $\text{C}=\text{O}$ group limit the possibilities for direct analysis of carbonyl compounds using

UV/VIS and infrared (IR). Therefore, mass spectrometric and chromatographic methods are common. In the past, polarography and ion chromatography have also been considered for the analysis of airborne aldehydes.¹⁸ It is advantageous that targeted derivatization reactions are possible *via* the $\text{C}=\text{O}$ group. Nevertheless, analytical methods are often used today that are hardly suitable for the respective target compounds, and at the same time the results of analytical measurements are sometimes misunderstood or misinterpreted. This article offers an up-to-date overview of the analytical determination of organic carbonyl compounds in indoor air and discusses which methods can be applied for the respective task and which cannot.

2 Carbonyls relevant for the indoor environment

The available literature was evaluated in order to obtain an overview of the organic carbonyl compounds mainly found indoors. In particular, original papers, reviews and the results of environmental surveys were considered. Table 1 represents the result of this search with a total of 54 compounds. The selection is purely analytical and must not be interpreted in terms of health. This means that the substances listed in Table 1 are often detected in the indoor environment, but this is not automatically associated with a health risk. Of course, there are many other carbonyl compounds that can or have been identified in the indoor environment, usually in traces. This is especially true for the oxidation products of terpenes.¹⁹

In detail, the selection is based on the following references: formaldehyde;^{20,21} acetaldehyde;^{22,23} other saturated aldehydes (C3–C11);²⁴ acrolein;²⁵ methacrolein;¹⁶ other unsaturated aldehydes (C4–C11);⁸ pinonaldehyde;²⁶ furfural;^{9,27} glyoxal, methylglyoxal;²⁸ diacetyl;²⁹ acetone, MEK, MIBK, 2-pentanone, 3-octanone;³⁰ MVK;³¹ benzaldehyde, cyclohexanone, acetophenone, benzophenone;³² 2,5-dimethyl benzaldehyde;³³ geranial, neral, linal, *trans*-cinnamaldehyde, amyl cinnamal;¹³ geranylacetone, 4-OPA, 6-MHO;¹⁷ caprolactam;¹⁵ 1-methyl-2-pyrrolidone, 1 ethyl-2-pyrrolidone.³⁴



Table 1 CAS numbers, molecular properties and preferred analytical method of the selected carbonyl compounds (T = Tenax TA, BC = black carbon). Only experimentally determined boiling points at standard atmospheric pressure are given. The respective literature sources are not listed

| Compound | CAS | MW (g mol ⁻¹) | BP (°C) | Preferred method |
|---------------------------------|------------|---------------------------|---------|---|
| Formaldehyde | 50-00-0 | 30.03 | -20 | DNPH, ³⁵ Hantzsch ³⁶ |
| Acetaldehyde | 75-07-0 | 44.05 | 21 | DNPH ³⁵ |
| Propanal | 123-38-6 | 58.08 | 48 | DNPH ³⁵ |
| Butanal | 123-72-8 | 72.11 | 75 | DNPH ³⁵ |
| 2-Methyl propanal | 78-84-2 | 72.11 | 64 | TD(T)-GC/MS ³⁷ |
| Pentanal | 110-62-3 | 86.13 | 103 | DNPH, ³⁵ TD(T)-GC/MS ³⁷ |
| 3-Methyl butanal | 590-86-3 | 86.13 | 93 | DNPH ³⁵ |
| Hexanal | 66-25-1 | 100.16 | 130 | DNPH, ³⁵ TD(T)-GC/MS ³⁷ |
| Heptanal | 111-71-7 | 114.19 | 153 | TD(T)-GC/MS ³⁷ |
| Octanal | 124-13-0 | 128.21 | 171 | TD(T)-GC/MS ³⁷ |
| Nonanal | 124-19-6 | 142.24 | 195 | TD(T)-GC/MS ³⁷ |
| Decanal | 112-31-2 | 156.26 | 212 | TD(T)-GC/MS ³⁷ |
| Undecanal | 112-44-7 | 170.29 | 225 | TD(T)-GC/MS ³⁷ |
| Acrolein | 107-02-8 | 56.06 | 52 | TD(BC)-GC/MS ²⁵ |
| Methacrolein | 78-85-3 | 70.09 | 73 | TD(BC)-GC/MS ³⁸ |
| cis-2-Butenal | 15798-64-8 | 70.09 | 104 | TD(T)-GC/MS ³⁷ |
| trans-2-Butenal | 123-73-9 | 70.09 | 102 | TD(T)-GC/MS ³⁷ |
| 3-Methyl-2-butenal | 107-86-8 | 84.12 | 134 | TD(T)-GC/MS ³⁷ |
| trans-2-Pentenal | 1576-87-0 | 84.12 | 124 | TD(T)-GC/MS ³⁷ |
| 3-Methyl-2-pentenal | 3592-19-6 | 98.14 | | TD(T)-GC/MS ³⁷ |
| trans-2-Hexenal | 6728-26-3 | 98.14 | 147 | TD(T)-GC/MS ³⁷ |
| trans-2-Heptenal | 18829-55-5 | 112.17 | 166 | TD(T)-GC/MS ³⁷ |
| trans-2-Octenal | 2548-87-0 | 126.20 | | TD(T)-GC/MS ³⁷ |
| trans-2-Nonenal | 18829-56-6 | 140.22 | 189 | TD(T)-GC/MS ³⁷ |
| trans-2-Decenal | 3913-81-3 | 154.25 | 229 | TD(T)-GC/MS ³⁷ |
| trans-2-Undecenal | 53448-07-0 | 168.28 | 245 | TD(T)-GC/MS ³⁷ |
| Furfural | 98-01-1 | 96.08 | 162 | TD(T)-GC/MS ³⁷ |
| Benzaldehyde | 100-52-7 | 106.12 | 179 | DNPH, ³⁵ TD(T)-GC/MS ³⁷ |
| 2,5-Dimethyl benzaldehyde | 5779-94-2 | 134.17 | 245 | DNPH, ³⁵ TD(T)-GC/MS ³⁷ |
| Glyoxal | 107-22-2 | 58.04 | 50 | PFBHA ³⁹⁻⁴¹ |
| Methylglyoxal | 78-98-8 | 72.06 | 72 | PFBHA ³⁹⁻⁴¹ |
| Diacetyl | 431-03-8 | 86.02 | 88 | TD(T)-GC/MS ³⁷ |
| 4-Oxopentanal (4-OPA) | 626-96-0 | 100.12 | | PFBHA, ⁴¹ PTR-MS ¹⁷ |
| Pinonaldehyde | 2704-78-1 | 168.23 | | TD(T)-GC/MS ³⁷ |
| trans-Cinnamaldehyde | 14371-10-9 | 132.16 | 253 | TD(T)-GC/MS ³⁷ |
| Geranial | 141-27-5 | 152.24 | 229 | TD(T)-GC/MS ³⁷ |
| Neral | 106-26-3 | 152.24 | 228 | TD(T)-GC/MS ³⁷ |
| Amyl cinnamal | 122-40-7 | 202.29 | 284 | TD(T)-GC/MS ³⁷ |
| Lilial | 80-54-6 | 204.31 | 275 | TD(T)-GC/MS ³⁷ |
| Acetone | 67-64-1 | 58.08 | 56 | DNPH ³⁵ |
| 2-Butanone (MEK) | 78-93-3 | 72.11 | 80 | TD(T)-GC/MS ³⁷ |
| 3-Buten-2-one (MVK) | 78-94-4 | 70.09 | 81 | TD(BC)-GC/MS ³⁸ |
| 2-Pentanone | 107-87-9 | 86.13 | 102 | TD(T)-GC/MS ³⁷ |
| 4-Methyl-2-pentanone (MIBK) | 108-10-1 | 100.16 | 116 | TD(T)-GC/MS ³⁷ |
| 3-Octanone | 106-68-3 | 128.21 | 168 | TD(T)-GC/MS ³⁷ |
| 6-Methyl-5-hepten-2-one (6-MHO) | 110-93-0 | 126.20 | 173 | PTR-MS ¹⁷ |
| Geranylacetone | 3796-70-1 | 194.31 | 256 | TD(T)-GC/MS ³⁷ |
| Cyclohexanone | 108-94-1 | 98.15 | 156 | TD(T)-GC/MS ³⁷ |
| Acetophenone | 98-86-2 | 120.15 | 202 | TD(T)-GC/MS ³⁷ |
| Benzophenone | 119-61-9 | 182.22 | 305 | TD(T)-GC/MS ³⁷ |
| 1-Methyl-2-pyrrolidone | 872-50-4 | 99.13 | 203 | TD(T)-GC/MS ³⁷ |
| 1-Ethyl-2-pyrrolidone | 2687-91-4 | 113.16 | 213 | TD(T)-GC/MS ³⁷ |
| Caprolactam | 105-60-2 | 113.16 | 270 | TD(T)-GC/MS ³⁷ |
| Coumarin | 91-64-5 | 146.14 | 302 | TD(T)-GC/MS ³⁷ |

3 The carbonyl (C=O) group

3.1 Electronic structure and spectroscopy

In carbonyl groups, the carbon atom is approximately sp² hybridized and forms a σ -bond to the oxygen atom. The remaining p orbital of carbon overlaps with a p orbital of the oxygen atom to form a π -bond. In addition, two non-bonding (n) orbitals remain at the oxygen atom (see Fig. 2).⁴²

The absorption of electromagnetic radiation in the visible (VIS) and ultraviolet (UV) range causes electronic excitation. Organic molecules with an isolated C=O group have an absorption band in the UV range between 250 nm and 350 nm. This corresponds to an $n \rightarrow \pi^*$ transition, *i.e.* the promotion of an electron from a nonbonding orbital on oxygen to the antibonding π^* molecular orbital. In this process, charge is shifted from the electronegative oxygen atom to the delocalized π^* orbital, which is associated with a change in the





Fig. 2 Electronic structure of the carbonyl group and qualitative view of the energy level scheme.

dipole moment. In the case of formaldehyde, the dipole moment of the first excited singlet and triplet state is smaller than that in the ground state.⁴³ Transitions with $n \rightarrow \pi^*$ character are forbidden for reasons of symmetry, so the transition intensities are usually small.⁴⁴ For formaldehyde, the maximum of the UV absorption is at 294 nm, the peak cross section is $8.4 \times 10^{-20} \text{ cm}^2$ per molecule at 296 K.⁴⁵ For the higher aldehydes and ketones with an isolated C=O group, the cross sections of the $n \rightarrow \pi^*$ transition are in a similar range, but the maxima are shifted towards shorter wavelengths, which is due to the electron-donating alkyl groups.⁴⁶ The absorption spectra of various aldehydes are discussed by Calvert and Pitts.⁴⁷ Due to the simplicity of structure, the rotational and vibrational bands of formaldehyde can be resolved, allowing this molecule to be selectively excited.

Infrared spectroscopy offers an excellent opportunity for the analysis of carbonyl compounds, which is used in atmospheric chemistry for monitoring formaldehyde.⁴⁸ The excitation of the C=O stretching vibration is associated with a large change in the dipole moment.⁴⁹ As a result, the IR band of the isolated C=O group, which is in the wave number range from 1700 cm^{-1} to 1800 cm^{-1} , has a particularly high intensity. Fig. 3 shows the theoretical IR spectrum of formaldehyde in the gas phase with the six possible normal modes according to the selection rules. The C=O band is at 1746 cm^{-1} .⁵⁰ In general, electron-donating neighboring groups result in a shift to lower wave numbers and electron-withdrawing neighboring groups result in a shift to higher wave numbers. However, the IR spectroscopic differences are usually too small to be able to distinguish between carbonyl compounds in the room air.

3.2 Chemistry

The C=O double bond is highly polar due to the different electronegativity of C and O and the easy polarizability of the π bond. Thus, because of its strong partial positive charge, the carbonyl carbon is a prominent electrophilic center in the



Fig. 3 Simulated IR spectrum of formaldehyde in the gas phase. The wavenumbers of the six normal modes were taken from the publication by Nakanaga *et al.*⁵⁰ The terms in brackets refer to different types of molecular vibrations (*sym stretch*: symmetrical stretching; *asym stretch*: antisymmetrical stretching; *stretch*: linear stretching; *scissor*: scissoring or bending; *rock*: rocking; *wag*: wagging).

aldehydes and ketones and is easily attacked by nucleophiles. Conversely, the oxygen is a nucleophilic center that is attacked by acid cations, for example H^+ . In the presence of an α -hydrogen atom, they undergo keto-enol tautomerism. So the chemistry of carbonyl compounds is diverse.⁴²

Fig. 4 shows five reactions that are important from an analytical point of view. Hemiacetals or hemiketals are formed with alcohols, which then react further with the elimination of water to form acetals and ketals. The reaction can be catalysed by acids and bases. However, even in the absence, a noticeable reaction is observed if the alcohol is used as the solvent. This is important when preparing analytical standards in methanol. The Hantzsch reaction originally served to synthesize 1,4-dihy-





Fig. 4 Chemical reactions of carbonyl compounds relevant to the analytical chemistry of these compounds.

dropyridines and pyridines.⁴² However, it has been shown that the dihydrolutidines synthesized with aldehydes and ketones are chromophores with broad absorption bands in the visible range and some of them also fluoresce. This makes these compounds interesting for analytical applications. The reaction of aldehydes and ketones with hydrazines to form hydrazones and the reaction of aldehydes with certain hydrazones also find wide attention in analytical chemistry. The resulting compounds have broad absorption bands in the UV and/or VIS. Oximes are formed when aldehydes and ketones react with hydroxylamine or its derivatives. It should be noted that only the formal reaction equations are shown in Fig. 4. The exact mechanisms can be found in organic chemistry textbooks.^{42,51} Other derivatization reactions for the analysis of aldehydes and ketones have been published,^{18,52} but these have largely lost their importance and will not be discussed here.

4 Colorimetry

4.1 UV/VIS spectrometry and fluorescence

The simple colorimetric methods have the general disadvantage that no substance separation takes place. In the case of substance mixtures, one must therefore ensure that the wavelength selected for detection, whether in absorption or emission, is specific to the target compound, which is essen-

tially formaldehyde. The application of the Hantzsch reaction to formaldehyde analysis with 2,4-pentanedione (acetyl acetone) and ammonium acetate using UV spectrometry of the formed 3,5-diacetyl-1,4-dihydropyridine (DDL) (see Fig. 5) was first published by Nash.⁵³ Belman⁵⁴ suggested using the fluorescence of DDL for formaldehyde analysis because of higher selectivity and sensitivity. The full photophysical properties of DDL (absorption coefficient, fluorescence quantum yield, thermal and photochemical degradation) were later described in detail.⁵⁵ DDL shows a broad absorption band at 412 nm and a fluorescence band at 510 nm. The derivatives of other carbonyl compounds with 2,4-pentanedione and ammonium acetate do not fluoresce, so the detection is specific for formaldehyde.⁵⁶ However, the fluorescence quantum yield is strongly temperature dependent,⁵⁷ so that attention must be paid to temperature constancy during the analysis. Salthammer⁵⁵ showed that the fluorescence quantum yield of DDL decreases by 11% when the temperature is increased from 20 °C to 30 °C.

Sampling is carried out by passing formaldehyde laden air through an absorber bottle where formaldehyde is quantitatively trapped in distilled water. The typical collected air volume is 60–80 l with an air flow rate of 2 l min⁻¹. Then the reagents are added and at 40 °C the reaction is complete in a few minutes. This so-called acetyl acetone method is available as a European standard.⁵⁸ The analytical details and comparisons with other methods are published in several papers,^{20,52,59–61}



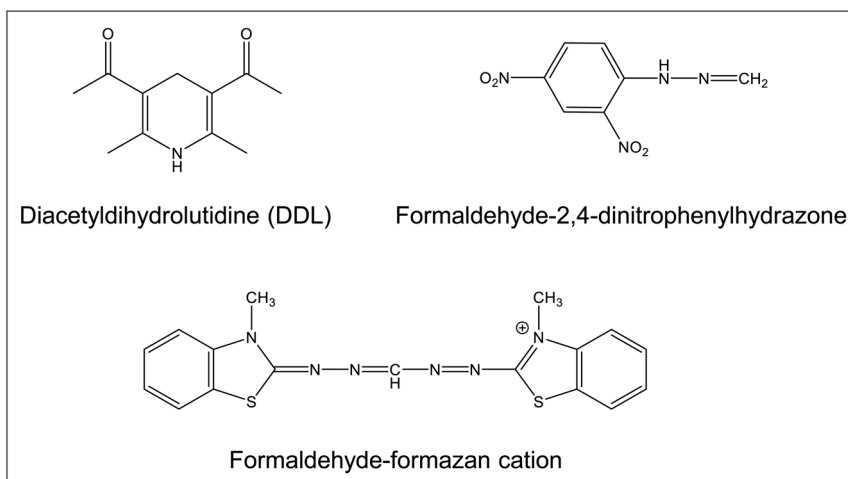


Fig. 5 Chromophores resulting from the reaction of formaldehyde with acetyl acetone (2,4-pentanedione), DNPH and MBTH.

the full procedure can be found in EN 717-1.⁵⁸ In Europe, EN 717-1 is recommended for determining the release of formaldehyde from wood-based materials in test chambers.

At this point, two publications must be addressed separately. Roffael's book⁶² deals with the role of formaldehyde in relation to wood and wood-based materials. Not only the historical and current methods for determining formaldehyde are discussed, but also the numerous international standards. Dugheri *et al.*⁶³ provide an excellent overview of sampling and analysis methods for formaldehyde. Active and passive sampling devices are listed in detail, as well as the various analysis techniques.

The fast course of the Hantzsch reaction and the simple fluorimetric detection also make the acetyl acetone method interesting for automated online analysis with high time resolution. Corresponding devices are commercially available and their suitability for the sensitive formaldehyde analysis indoors and outdoors has been proven.^{20,64–66} When used in the field, however, the disadvantage is that the relatively large bottles with reagents also have to be carried along. With the conventional acetylacetone method, quantification limits (LOQ) of around 1 ppb ($1.2 \mu\text{g m}^{-3}$) can be reached. The online method is even more sensitive at 0.3–0.5 ppb.

A completely different picture emerges with the MBTH method. Here, aldehydes react with 3-methyl-2-benzothiazolone hydrazone (MBTH) to form a colored formazan cation (see Fig. 5).^{67,68} Sampling is carried out directly in an aqueous solution of MBTH. Ammonia iron(III) sulfate and acetic acid are then added to complete the reaction. Similar to acetyl acetone, MBTH is suitable for automated analysis. Goebel *et al.*,⁶⁹ as well as Toda *et al.*⁷⁰ present devices for the near real time measurement of gaseous formaldehyde. However, the detection technique is UV/VIS spectrometry at 628–629 nm, which makes the method non-specific. With the MBTH method, a sum value is always determined for different aldehydes, only the calibration is done with formaldehyde. This

aspect is often ignored or misinterpreted. Therefore it can be assumed that formaldehyde concentrations measured with the MBTH method tend to be too high. This can cause problems when comparing formaldehyde data measured with different methods.⁷¹ Chan *et al.*⁷² argue that concentrations of aliphatic aldehydes are generally lower than formaldehyde, but this is not necessarily the case. Fig. 6 shows the results of a study by Giesen *et al.*⁷³ It is a comparison of aldehyde measurements with 13 different materials (samples) in the air of environmental test chambers. The MBTH method suggests a formaldehyde concentration, which in fact results from the sum of several aldehyde components. Similar problems also arise for other colorimetric methods, which are not discussed here.^{20,52}

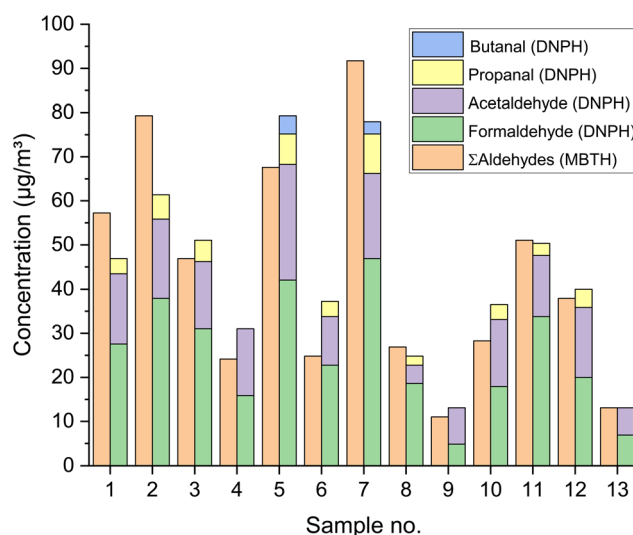


Fig. 6 Results of aldehyde measurements with DNPH and MBTH in test chambers on 13 different materials. Experimental details and data are published by Giesen *et al.*⁷³



4.2 Enzymatic detection of formaldehyde

For an initial estimation of the formaldehyde concentration in the indoor environment, quick tests are sometimes used, which are available in pharmacies and drugstores and can also be handled by non-experts. The principle is often based on an enzymatic reaction with a color change, the assessment is made optically against reference colors that are assigned to the corresponding concentration ranges. Such quick tests are quite suitable for an initial screening. However, one must always be aware that this is a very rough method that neither allows an exact concentration determination nor a health-related assessment.

Feldbrügge *et al.*⁷⁴ describe the formaldehyde dehydrogenase catalyzed reaction of formaldehyde with NAD^+ to formic acid and NADH. A diaphorase enzyme then transfers NADH and a colorless tetrazolium salt into NAD^+ and a colored formazan derivative. A further development of this method was published by Monkawa *et al.*,⁷⁵ who used the water soluble tetrazolium salt WST-8. In principle, it is also possible to determine the formaldehyde concentration by means of absorption measurements, although optical comparison has prevailed in the quick tests for reasons of simplicity.

5 Chromatography

5.1 HPLC-UV

The most important method for the analytical determination of low-molecular-weight carbonyl compounds in ambient air worldwide is DNPH. The exact procedures for sampling, separation of signals by HPLC and analysis are specified in ISO 16000-3³⁵ and can be read there. It is common practice that derivatization with 2,4-dinitrophenylhydrazine (see Fig. 4) is performed directly during sampling on DNPH impregnated silica cartridges. This can lead to the release of acetonitrile into the room air, so that VOC sampling using Tenax TA must not be carried out at the same time. The hydrazone formed with formaldehyde is shown in Fig. 5. The analysis is carried out by means of HPLC-UV (360 nm) after the formed hydrazones have been eluted from the cartridge with acetonitrile. The different hydrazones absorb light between 340 nm and 427 nm.⁵² Typical sampling times are 5–60 min at an air flow rate of 0.5–1.5 l min⁻¹. To achieve a limit of quantification (LOQ) of 1–2 µg m⁻³, an air collection volume of at least 60 l is required. The European standard EN 16516⁷⁶ “Construction products: Assessment of release of dangerous substances – determination of emissions into indoor air” stipulates the use of ISO 16000-3 for formaldehyde, acetaldehyde, propanal and butanal. Based on the DNPH reaction, Aiello and McLaren⁷⁷ have developed an automated sampling analysis system that enables the sensitive determination of formaldehyde, acetaldehyde, propanal, acetone and benzaldehyde over 2 h cycles. The DNPH method is sensitive to nitrogen oxides⁷⁸ and ozone,⁷⁹ so these compounds must be removed before the sampled air reaches the cartridge. Williams *et al.*⁸⁰ showed that carbon monoxide reacts with DNPH and interferes with

the determination of acetone. DNPH-coated precolumns can also be used to remove interfering aldehydes and ketones from sampled air. This principle is applied in the gas chromatographic reactive sorption concentration (RSC) method.⁸¹

However, the DNPH method specified according to the 2022 version of ISO 16000-3³⁵ is far from being suitable for all carbonyl compounds. The standard applies to the saturated linear C1–C6 aldehydes, 3-methylbutanal, acetone, benzaldehyde, the methyl benzaldehydes and 2,5-dimethyl benzaldehyde. Acrolein and 2-butenal (crotonaldehyde) cannot be determined according to ISO 16000-3.³⁵ Ho *et al.*⁸² examined the hydrazone derivatives of the unsaturated carbonyls acrolein, methacrolein, 2-butenal and 3-buten-2-one (MVK) and found that the DNPH is not suitable for these compounds. This is due in particular to the formation of dimers and trimers. However, Ho *et al.*⁸³ also applied the DNPH method to the analysis of dicarbonyls and C7–C10 aldehydes. Salthammer and Mentese⁶¹ compared analytical methods for the determination of carbonyl compounds and found a very good agreement between the acetyl acetone and the DNPH method for formaldehyde. In contrast, when sampling on impregnated cartridges, the DNPH method gave lower results for pentanal and hexanal in comparison with thermal desorption gas chromatography/mass spectrometry (TD-GC/MS) using Tenax TA as the adsorbent. The reason for this lies in the increasing hydrophobicity of the aldehyde with the chain length. The formation of water from the condensation reaction increasingly wets the silica surfaces of the cartridge as the reaction progresses. DNPH is also only slightly soluble in water.

The DNPH method is very well suited for passive sampling, whereby furfural and the higher aldehydes up to C11 (undecanal) can also be analytically recorded. Birmili *et al.*²⁴ determined the collection rates of a badge type passive sampler in a test chamber *versus* active methods according to ISO 16000-3 and TD-GC/MS for a total of 14 aldehydes. Villanueva *et al.*⁸⁴ applied a cylinder type passive sampler with integrated ozone scrubber for the analysis of formaldehyde and acetaldehyde in air. These and other types of passive samplers are discussed by Dugheri *et al.*⁶³ Note that sampling rates only apply to a specific type of passive sampler and must therefore be determined individually.

Many variants of the DNPH method are known in the literature. Chi *et al.*⁸⁵ present a method for 32 carbonyl compounds by HPLC and electrospray ionization (ESI) tandem mass spectrometry (MS/MS) after derivatization with DNPH. A gradient capillary electrochromatography method was developed by Feng and Zhu⁸⁶ to measure 12 carbonyls in indoor air. Zhang *et al.*⁸⁷ optimized a DNPH-HPLC-MS method for the simultaneous determination of 30 atmospheric carbonyls. These and other methods have their place in special tasks, for example in the analysis of exhaust gas, but are rarely used to examine indoor air quality.

5.2 TD-GC/MS

Similar to the HPLC method discussed in the previous section, sampling on adsorbents with subsequent thermal desorption



(TD) and GC/MS analysis is also standardized with ISO 16000-6.³⁷ VOCs are defined as compounds that elute between *n*-hexane and *n*-hexadecane on a 5% phenyl 95% methyl polysiloxane phase capillary column. Tenax TA is the preferred adsorbent for this retention range. Organic compounds eluting before *n*-hexane are defined as VVOCs and organic compounds eluting after *n*-hexadecane are defined as SVOCs. For compounds with higher vapor pressures than that of *n*-hexane (approx. 16 kPa at 20 °C), other sorbents such as graphitized carbon, carbon molecular sieve and multiple sorbents are preferred. An air collection tube is normally filled with 200 mg Tenax TA, typical collection rates are 4–6 l at an air flow rate of 100–150 ml min⁻¹. The desorption of the collected molecules takes place at 300 °C in an inert gas stream. A quadrupole mass filter is standard for detection and quantification after gas chromatographic separation.⁸⁸ Identification is based on a retention index *versus* internal and external standards and using the electron ionization mass spectrum (70 eV). If a six-membered transition state is possible after excitation, carbonyl compounds undergo rearrangement and fragmentation reactions. However, identification with the help of spectral libraries usually succeeds without problems.⁸⁹ ISO 16000-6³⁷ generally requires a limit of quantification (LOQ) of at least 1 µg m⁻³ or less. This can be achieved with the usual sampling volumes of 4–6 l. An important issue concerns the accuracy and repeatability of ISO 16000-6 measurements. Wilke *et al.*⁹⁰ evaluated the results of six round robin tests carried out in test chambers with a typical VOC spectrum and found a relative standard deviation of 28%. It must also be stated at this point that there are alternative definitions for VVOCs, VOCs and SVOCs, for example from the World Health Organization (WHO) and the U.S. EPA.^{31,91}

The thermal desorption process is also ideal for the passive detection of indoor air pollutants. In the axial collection type, single sorbent filled stainless steel tubes are fitted with a cap containing a fine mesh gauze that defines the sample surface. The other end of the tube is capped and kept sealed. Radial collectors are cylindrical and comprise a sorbent sampling cartridge housed in a porous polymer that allows sampling along and around the whole surface.⁹² When sampling in the field, it must be remembered that Tenax TA (2,6-diphenyl oxide polymer) decomposes in the presence of ozone, nitrogen oxides and other reactive gases to form carbonyl compounds.^{93,94}

From Table 1 it can be seen that the carbonyl compounds relevant for indoor environments cover a wide boiling point range between approximately –20 °C and +305 °C, but only a small proportion can be analyzed using the DNPH method. In Fig. 7 the retention indices of some carbonyl compounds are plotted in comparison to *n*-hexane and *n*-hexadecane. The horizontal red lines mark the boundary between VVOC/VOC and VOC/SVOC. The indices were calculated based on an alkane series for non-isothermal conditions.⁸⁸ Strictly speaking, MEK is a VVOC and benzophenone is an SVOC, but these substances can be determined analytically after sampling on Tenax TA using TD-GC/MS according to ISO 16000-6.³⁷ Even



Fig. 7 Gas chromatographic retention indices of several carbonyl compounds *versus* boiling point in comparison to *n*-hexane and *n*-hexadecane. The indices were determined against a series of alkanes using a laboratory-specific method for non-isothermal conditions.⁸⁸

2-methylpropanal (not displayed in Fig. 7), which is a VVOC with a retention index of around 500, can be analyzed using TD-GC/MS. Pentanal, although a C5 compound, already belongs to the group of VOCs. A comparison with the DNPH method has shown that aldehydes from C5 can be determined more precisely using TD-GC-MS with sampling on Tenax TA.⁶¹ Benzaldehyde and its methyl derivatives are qualified for analysis according to ISO 16000-3, but can be determined more easily and precisely according to ISO 16000-6. Acetone is clearly a VVOC and can be reliably determined using the DNPH method. The general problem with VVOCs is that not all substances are covered by one sampling technique.³¹ Schieweck *et al.*³⁸ have developed a thermal desorption method for C3–C6 compounds with sampling on graphitized carbon, which also works for various carbonyl compounds (see Table 1). A medium-polarity capillary column proved to be suitable for the gas chromatographic separation. Richter *et al.*⁹⁵ recommend combinations of graphitized carbon black, carbon molecular sieve and Tenax GR for the sampling of C1–C6 VVOCs with gas chromatographic separation on a polar capillary column. Even *et al.*⁹⁶ have compared several gas chromatographic methods for VVOC analysis and conclude that water removal is the greatest practical challenge.

Particular analytical problems are caused by the unsaturated compounds and dicarbonyls.^{82,97} Various methods have been published for acrolein, the simplest unsaturated aldehyde, which are summarized by Schieweck *et al.*²⁵ The authors conclude that TD-GC/MS after sampling on graphitized carbon black is the most practical method for acrolein, because it is robust, easy-to-handle and very suitable for routine analyses and surveys. With an air collection volume of 4 l a LOQ of 0.3 µg m⁻³ can be achieved. Sampling on graphitized black carbon with subsequent TD-GC/MS analysis also allows the determination of methylacrolein and MVK.³⁸ The higher unsaturated



turated aldehydes starting from butenal can be determined using TD-GC/MS and with Tenax TA as a sorbent. Fig. 8 shows a multistandard. The substances were dissolved in methanol, spiked onto Tenax TA and the solvent was evaporated in an inert gas flow. The compounds shown in red color and in italics are used only to identify their retention time on the capillary gas chromatographic column. The analytical details are provided in the figure caption.

An alternative sampling technique is to collect air in stainless steel canisters. The contained VOCs are then pre-concentrated and injected into a GC/MS for separation, identification and quantification. Method TO-15A⁹⁸ of the U.S. EPA for ambient air provides a list of organic compounds that can be determined in this way, including acrolein, acetone, MEK, MIBK and 2-hexanone. With appropriate validation, other carbonyl compounds can also be determined according to TO-15A.

The preparation of liquid standards for identification and quantification in GC/MS measurements can lead to a well-known artifact in carbonyl analysis. Methanol is often used as a solvent because it can be easily removed after spiking onto the respective sorbent. However, as shown in Fig. 4, carbonyl compounds react with alcohols first to form hemiacetals and then further to form acetals. Uhde and Salthammer⁹⁹ observed the formation of 1,1-dimethoxy-cyclohexane from cyclohexanone in methanolic standard solutions. However, the reaction proceeds slowly under these conditions and can be prevented by storing the standard solution at -80°C .

5.3 Other chromatographic methods

Most of the methods discussed in the following were developed for applications in outdoor air. Anderson *et al.*⁴¹

studied dicarbonyl compounds (glyoxal, methylglyoxal, glutaraldehyde, diacetyl, and 4-OPA) in a simulated indoor air environment. The target compounds were collected in methanol and then derivatized to oximes (see Fig. 4) with *O*-(2,3,4,5,6-pentafluorobenzyl) hydroxylamine (PFBHA) according to a method published by Yu *et al.*³⁹ The mass spectrometric detection after gas chromatographic separation was carried out using an ion trap.¹⁰⁰ PFBHA was used by Seaman *et al.*⁴⁰ to determine the unsaturated aldehydes acrolein, methacrolein, MVK, 2-butenal and the dicarbonyls glyoxal and methylglyoxal. In this case, however, before the derivatization step, a formation of carbonyl-bisulfite adducts takes place. Wells and Ham used oxime formation with *O*-*tert*-butylhydroxylamine hydrochloride (TBOX) for the GC/MS detection of dicarbonyls resulting from the reaction of limonene with ozone.¹⁰¹

As an alternative to DNPH, dansylhydrazine (DNSH) can be used as a derivatization reagent with separation and detection *via* HPLC-UV for the analysis of carbonyl compounds. However, in the case of the unsaturated aldehydes, the identification of the derivatives is complex. For example, acrolein forms two mono-derivative isomers and one dimeric derivative with DNSH.¹⁰²

Ho and Yu^{82,103} developed a technique based on derivatization with pentafluorophenyl hydrazine (PFPH) and TD-GC/MS. The carbonyl compounds are collected on Tenax TA coated with PFPH. The authors describe their method as suitable for a wide range of aliphatic aldehydes (up to C8), acrolein, furfural and dicarbonyls. Li *et al.*¹⁰⁴ used collection onto solid sorbent coated with PFPH, followed by solvent extraction and GC/MS for the analysis of 20 airborne carbonyl compounds in



Fig. 8 Chromatogram of a multistandard of unsaturated aliphatic aldehydes for analysis according to ISO 16000-6.³⁷ Acrolein and methacrolein (in red) only serve to identify them on the capillary column via the retention time. Analytical parameters: GC: Agilent 7890; MS: 5977A; TD: Markes Unity TD100; Trap: $-30^{\circ}\text{C}/300^{\circ}\text{C}$; column: 5 MS Ultra inert 60 m \times 250 μm \times 0.25 μm ; carrier gas: He; oven: $32^{\circ}\text{C} \rightarrow 300^{\circ}\text{C}$; Mode: scan.



the C1–C10 range. Pang *et al.*¹⁰⁵ collected carbonyls on PFPH-coated Tenax TA, followed by solvent desorption and GC/MS analysis. The authors state that their method is reliable for 21 investigated carbonyl compounds in the C1–C9 range. When sampling takes place in a liquid medium, the relative derivatization performance between carbonyl compound and PFPH depends on the solvent.¹⁰⁶ Bourdin and Desauziers¹⁰⁷ used solid-phase microextraction (SPME) for the on-fiber derivatization of carbonyl compounds. The combination of a polydimethylsiloxane-divinylbenzene fiber with PFBHA proved to be suitable. For the investigated compounds formaldehyde, acetaldehyde and hexanal, acceptable to good limits of quantification were achieved using GC/MS analysis in the single ion mode (SIM) and in the extracted ion chromatogram (EIC). In general, SPME and other micromethods are well suited for screening purposes due to their easy handling.¹⁰⁸ However, this is often offset by disadvantages in terms of sensitivity and calibration effort compared to conventional sampling techniques.

6 Molecular spectroscopy

Finlayson-Pitts and Pitts⁴⁸ summarize the state-of-the-art analysis of carbonyl compounds in ambient air up to the year 2000. Many online methods have been developed for sensitive formaldehyde analysis in the ppt range. These include tunable diode laser spectroscopy (TDLS), cavity ring-down spectroscopy (CRDS), Fourier transform infrared (FTIR) and differential absorption optical spectroscopy (DOAS). Various comparison measurements with classical methods have been published: DOAS and CRDS with Hantzsch;¹⁰⁹ DOAS and PTR-MS (see next section) with Hantzsch and DNPH.¹¹⁰ DOAS and FTIR with Hantzsch and DNPH.⁶⁴ A work by Hanoune *et al.*¹¹¹ comparing infrared diode laser spectroscopy with DNPH was performed indoors.

Another technique that has now become established for measuring formaldehyde in environmental test chambers and indoor air is photoacoustic spectroscopy (PAS). This involves irradiation of a sample with intermittent infrared light and detecting the periodic temperature changes in the sample as pressure fluctuations.¹¹² The type of excitation is decisive for the selectivity and sensitivity. Conventional PAS devices work with a broadband IR source, the desired wavelength is selected with a narrow-band filter. In the case of carbonyl compounds, the less specific C–H vibrations between 2500 cm^{−1} and 3000 cm^{−1} (see Fig. 3) are usually observed. The poor resolution makes conventional PA spectroscopy unsuitable for the indoor air analysis of carbonyls. More advanced devices use laser excitation, whereby the analysis is usually limited to the well-resolved vibrational bands of formaldehyde. Hirschmann *et al.*¹¹³ measured the spectrum of formaldehyde from 1772 cm^{−1} to 1777 cm^{−1} by tuning a quantum cascade laser with a spectral resolution of 0.018 cm^{−1}. The band at 1773.959 cm^{−1} was finally selected

for analysis. The cross section of the formaldehyde C=O IR absorption band in this range is in the order of 10^{−18} cm² per molecule,¹¹⁴ depending on the spectral integration width. This enables the specific monitoring of formaldehyde with detection limits in the sub-ppb range. Photoacoustics with quantum cascade lasers as a light source has now been further developed for routine analysis and, like the online Hantzsch method, enables specific, sensitive and precise formaldehyde analysis in indoor test chamber environments with high time resolution.

This is shown in Fig. 9 using the example of a chamber experiment with a burning candle according to EN 16738.¹¹⁵ The blue curve represents the time course of the formaldehyde chamber concentration, which was measured with a photoacoustic device (Gasera Ltd) and laser excitation of the C=O vibrational band at a time resolution of 10 s. The DNPH measurements (red dots) carried out for comparison correctly reflect the respective mean value over the sampling period of 60 minutes (red bars), but cannot depict the dynamics of the concentration profile.

When using suitable IR laser light sources and multi-pass optical cells, classic IR spectroscopy can also be used under certain conditions for the specific determination of formaldehyde. The gas analysis to determine the formaldehyde release from wood-based materials is standardized according to ISO 12460-3,¹¹⁷ with the formaldehyde determination being carried out using the acetylacetone method. It is currently under discussion whether IR laser spectroscopy should also be permitted, provided the method shows equivalent test results to acetylacetone analysis.

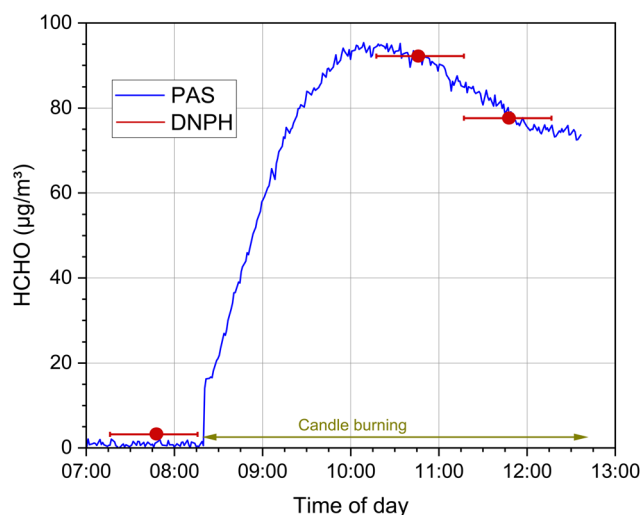


Fig. 9 Time course of the formaldehyde concentration when burning a candle in a 1 m³ test chamber according to EN 16738¹¹⁵ ($T = 23\text{ }^{\circ}\text{C}$, relative humidity = 50%, air exchange rate = 2 h^{−1}, see also Salthammer *et al.*¹¹⁶ for the detailed experimental conditions). The blue curve represents the online measurement with a photoacoustic device (Gasera One), the red dots are the concentrations determined from a 60 min sampling using the DNPH method, the red lines indicate the duration of the sampling.



7 Online mass spectrometry

In recent years, proton-transfer-reaction mass spectrometry (PTR-MS)^{118,119} has experienced increased application to indoor air issues. The reason for this is a wide range of studies on trace substances,¹²⁰ chemical reactions¹²¹ and the personal chemical cloud of humans.^{122,123} A PTR-MS device consists of an ion source, a reaction and drift tube for transferring the proton to the target molecule (R) and a mass selective detector. In most cases, H_3O^+ ions are used, so the reaction proceeds according to eqn (1). A related technique is Selected Ion Flow Tube Mass Spectrometry (SIFT-MS), which is particularly applied for breath gas analysis.¹²⁴ SIFT-MS employs eight reagent ions (H_3O^+ , NO^+ , O_2^+ , OH^- , O^- , O_2^- , NO_2^- and NO_3^-), which greatly facilitates the identification of isomeric organic compounds.



The $[\text{M} + 1]^+$ ions generated in the PTR-MS drift tube can be analyzed using either a low-resolution quadrupole filter (QMS) or a high-resolution time-of-flight (ToF) detector. Quadrupoles have only limited applications and are not usually used to identify components in mixtures of substances.¹²⁵ However, reaction (1) only occurs if the proton affinity of the target molecule is higher than that of water (691 kJ mol^{-1}).¹²⁶ This means that PTR-MS is hardly suitable for the analysis of formaldehyde, which has a proton affinity of 712 kJ mol^{-1} .¹²⁶ In this case increasing humidity strongly supports the back reaction.^{127,128} Another analytical problem is the fragmentation of molecules with longer chain lengths, which has been investigated for aldehydes and ketones by Španěl *et al.*¹²⁹ There is no fragmentation observable up to propanal (C3). Starting with butanal (C4), the $[\text{M} + 1]^+$ ions increasingly split off water, which is shown in eqn (2) for the hexanal example. The ratio of m/z 101.096 to m/z 83.086 is approximately 1:1.^{129,130} On the other hand, the fragmentation of aldehydes is advantageous insofar that it can be used to distinguish from ketones of the same molecular mass, which, according to the results of Španěl *et al.*,¹²⁹ do not fragment. A comprehensive library with fragmentation reactions of organic compounds after protonation was published by Pagonis *et al.*¹³¹



The concentration of the target molecule $[\text{R}]$ can be obtained from eqn (3) if the drift time t_r in the reaction tube and the proton-transfer rate constant k_{PT} are known. $[\text{RH}^+]$ and $[\text{H}_3\text{O}^+]$ are the concentrations of the product and the primary ion, respectively. This shows the difference between PTR-MS and other analytical procedures, because there is no calibration in the classic sense using conventional statistical methods.¹³² The drift time t_r has to be calculated from the respective instrument settings.¹³³

$$[\text{R}] = \frac{1}{k_{\text{PT}} \cdot t_r} \frac{[\text{RH}^+]}{[\text{H}_3\text{O}^+]} \quad (3)$$

The reaction rate constant k_{PT} can only be determined experimentally to a very limited extent, since the corresponding test gas is required for this. It is much easier to calculate k_{PT} from the ion-dipole collision theory. With the so-called “capture theory”, Su¹³⁴ has developed parameterizations based on trajectory analyses. Eqn (4) shows the principle. According to Langevin, the reaction constant consists of a non-polar part k_L , which only takes into account the polarizability α , and a polar part k_{μ_D} . In practice, k_{PT} is obtained by multiplying k_L with the capture parameter K_{cap} , which depends on the dipole moment μ_D of the molecule and the temperature T in the reaction chamber. The parametrization procedure for calculating K_{cap} was originally published by Su¹³⁴ and has been summarized by Cappellin *et al.*¹³³ and Salthammer *et al.*¹³⁵ for PTR-MS applications.

$$k_{\text{PT}} = k_L + k_{\mu_D} = k_L(\alpha) \times K_{\text{cap}}(\mu_D, T) \quad (4)$$

The calculation according to the capture theory also raises some problems. Firstly, the polarizabilities and dipole moments for many organic compounds in the gas phase are not known or only known imprecisely. Secondly, k_{PT} also depends on the reaction conditions in the drift tube, in particular on the ratio of the electric field strength (E) to the molecular density (N). Fig. 10 shows the k_{PT} values for three polar molecules as a function of E/N . Note that the k_{PT} of non polar compounds is not affected by the E/N value. E/N ratios of 100–120 Td are typical for PTR-MS measurements. Lower values result in more water clusters, higher values result in more complicated fragmentation patterns.

Table 2 lists carbonyl compounds for which k_{PT} values calculated according to the capture theory ($E/N = 120$ Townsend) are available. The dipole moments and polarizabilities for the



Fig. 10 Dependence of the proton-transfer reaction constant k_{PT} on the E/N ratio (electric field to molecular density) set in the PTR-MS device at 353 K for benzaldehyde, octanal and 3-octanone. The values in brackets indicate the respective dipole moment in Debye. The data were taken from Salthammer *et al.*¹³⁵



Table 2 CAS numbers, proton affinities (PA),¹²⁶ dipole moments (μ_D), polarizabilities (α) and proton-transfer rate coefficients k_{PT} at 353 K¹³⁵ or 363 K¹³³ (120 Td) of carbonyl compounds

| Compound | CAS | PA (kJ mol ⁻¹) | μ_D (Debye) | α (10 ⁻²⁴ cm ³) | k_{PT} (10 ⁻⁹ cm ³ s ⁻¹) |
|--|-----------|----------------------------|-----------------|---|--|
| Acetaldehyde ¹³⁵ | 75-07-0 | 768.5 | 2.94 | 4.45 | 3.13 |
| Propanal ¹³⁵ | 123-38-6 | 786.0 | 2.85 | 6.14 | 3.12 |
| Butanal ¹³⁵ | 123-72-8 | 792.7 | 2.83 | 7.90 | 3.16 |
| 2-Methyl propanal ¹³⁵ | 78-84-2 | 797.3 | 2.91 | 7.88 | 3.21 |
| Pentanal ¹³⁵ | 110-62-3 | 796.6 | 2.85 | 9.68 | 3.22 |
| Hexanal ¹³⁵ | 66-25-1 | | 2.83 | 11.45 | 3.24 |
| Heptanal ¹³⁵ | 111-71-7 | | 2.86 | 13.25 | 3.29 |
| Octanal ¹³⁵ | 124-13-0 | | 2.85 | 15.04 | 3.30 |
| Nonanal ¹³⁵ | 124-19-6 | | 2.85 | 16.84 | 3.32 |
| Decanal ¹³⁵ | 112-31-2 | | 2.85 | 18.66 | 3.35 |
| Acrolein (<i>trans</i>) ¹³⁵ | 107-02-8 | 797.0 | 3.43 | 6.34 | 3.54 |
| Acrolein (<i>cis</i>) ¹³⁵ | 107-02-8 | 797.0 | 2.81 | 6.14 | 3.11 |
| Methacrolein ¹³³ | 78-85-3 | 808.7 | 2.80 | 8.41 | 3.20 |
| <i>trans</i> -2-Butenal ¹³⁵ | 123-73-9 | | 4.20 | 8.40 | 4.11 |
| <i>trans</i> -2-Hexenal ¹³⁵ | 6728-26-3 | | 4.37 | 12.02 | 4.33 |
| Furfural (<i>trans</i>) ¹³⁵ | 98-01-1 | | 3.60 | 9.82 | 3.70 |
| Furfural (<i>cis</i>) ¹³⁵ | 98-01-1 | | 4.31 | 9.88 | 4.15 |
| Benzaldehyde ¹³⁵ | 100-52-7 | 834.0 | 3.42 | 12.53 | 3.71 |
| Glyoxal (<i>cis</i>) ¹³⁵ | 107-22-2 | | 3.68 | 4.64 | 3.51 |
| 4-OPA ¹³⁵ | 626-96-0 | | 2.95 | 9.73 | 3.24 |
| Pinonaldehyde ¹³³ | 2704-78-1 | | 2.26 | 18.56 | 2.96 |
| Acetone ¹³⁵ | 67-64-1 | 812.0 | 3.11 | 6.15 | 3.29 |
| MEK ¹³⁵ | 78-93-3 | 827.3 | 2.97 | 7.86 | 3.25 |
| 2-Pentanone ¹³³ | 107-87-9 | 832.7 | 2.84 | 10.07 | 3.24 |
| MIBK ¹³⁵ | 108-10-1 | | 2.87 | 11.36 | 3.27 |
| 3-Octanone ¹³⁵ | 106-68-3 | | 2.71 | 14.90 | 3.18 |
| 6-MHO ¹³⁵ | 110-93-0 | | 2.88 | 15.12 | 3.34 |
| Geranylacetone ¹³⁵ | 3796-70-1 | | 2.78 | 23.77 | 3.44 |
| Cyclohexanone ¹³⁵ | 108-94-1 | 841.0 | 3.45 | 10.57 | 3.65 |
| Acetophenone ¹³⁵ | 98-86-2 | 861.1 | 3.16 | 14.20 | 3.55 |
| Benzophenone ¹³⁵ | 119-61-9 | 882.3 | 3.11 | 22.62 | 3.63 |
| 1-Methyl-2-pyrrolidone ¹³⁵ | 872-50-4 | 923.5 | 4.12 | 10.28 | 4.05 |

gas phase were calculated using quantum chemical methods. The values of Salthammer *et al.*¹³⁵ refer to 353 K, those of Cappellin *et al.*¹³³ to 363 K.

The PTR-MS method is now firmly established in the determination of airborne carbonyl compounds and is always in demand when small concentrations with high dynamics have to be monitored. However, one must not overlook the disadvantages related to calibration, which will be discussed in a later section.

8 Ion mobility spectrometry

Another analysis method that works with a drift tube is ion mobility spectrometry (IMS). The technique is widely used for routine detection of explosives and drugs. With regard to carbonyls, IMS is suitable for monitoring the production process of beer with the off-flavor target compounds diacetyl and 2,3-pentanedione.¹³⁶ The molecule is ionized in the tube and moves in an electric field depending on its mass and other molecular properties with a specific drift velocity to the detector, which is often an electrometer. The drift time of the ions is usually in the millisecond range and also depends on the length of the drift tube. Sensitivity and selectivity of the IMS can be significantly increased by combination with gas chromatography and mass spectrometry.^{137–139}

So far there have only been a few applications of the IMS in the chemical analysis of indoor air. The reason for this is that other methods such as TD-GC/MS have clear advantages in non-target analysis. IMS can always be considered when dealing with a small and defined spectrum of organic molecules. Tiebe *et al.*¹⁴⁰ used IMS to detect 14 microbial volatile organic compounds (MVOCs), including various ketones, that can serve to screen for mold infestation in rooms. However, the detection limits for these carbonyls were disproportionately high at 8–14 $\mu\text{g m}^{-3}$. A combination of gas chromatography and IMS was used by Ruzsanyi *et al.*¹⁴¹ to detect saturated and unsaturated carbonyl compounds released from the skin surface. By using a short multi-capillary column, a time resolution of about 5 min could be achieved.

There are a few other publications that deal with the application of IMS for analytical questions of indoor air.¹⁴² In conclusion it can be stated that the method certainly has some interesting features, but no significant advantages over those already discussed.

9 Discussion

Szulejko and Kim¹⁴³ provide a summary of derivatization techniques for the determination of carbonyls in air, which also addresses sampling techniques such as solid phase micro



extraction (SPME), which is not addressed in detail in this work. The authors conclude that despite many problems, carbonyl analysis techniques still rely heavily on the combined application of DNPH derivatization, HPLC separation and UV or MS detection. Table 1 lists analytical methods recommended for each compound. However, this does not mean that the determination must always be carried out using this method. The release of formaldehyde from wood-based materials is a slow process¹⁴⁴ that can be easily tracked using EN 717-1.³⁶ In contrast, 4-OPA and 6-MHO are formed and released within seconds when the skin surface is exposed to ozone, which necessitates high-resolution online detection.¹⁷ Table 3 summarizes the methods discussed in this work. The table is not complete, but derivatization methods that are rarely used today, such as chromotropic acid and pararosaniline, are not considered and can be looked up in Vairavamurthy *et al.*⁵² and Szulejko and Kim.¹⁴³ Moreover, some of the methods listed in Table 3 aim at detecting outdoor air species, which often requires very low detection limits. In the indoor environment, however, compliance with guide values is often important,¹⁴⁵ which requires good precision and reproducibility, but usually does not pose an analytical challenge with regard to the detection limit. An exception is acrolein.²⁵

One has to realize that several methods are usually required to detect a wide range of carbonyl compounds in the room air. By default, this is the DNPH method according to ISO 16000-3³⁵ in combination with the TD-GC/MS method according to ISO 16000-6.³⁷ Some substances can be determined using both methods. As a rule of thumb, the TD-GC/MS method delivers better results from a chain length of C5.⁶¹ Other methods can be used alternatively or additionally. Today it is undisputed that unsaturated carbonyls cannot be determined quantitatively

with the DNPH method. With regard to the dicarbonyls, the statements are contradictory.

Most absorption and IR spectroscopic online methods are only suitable for formaldehyde. In absorption spectroscopy, this is due to the comparatively well-resolved and red-shifted spectral structure. However, the weak $n \rightarrow \pi^*$ transition requires long light paths, so techniques such as DOAS cannot necessarily be recommended for indoor use. A different picture emerges for photoacoustics. Quantum cascade lasers enable the targeted excitation of the C=O stretching vibration band of formaldehyde and the necessary detection limits can also be achieved.¹¹³ The technical designs of the available devices correspond to practical requirements.

The PTR-MS method requires a detailed evaluation and critical discussion. The method undoubtedly has a number of advantages when it comes to sensitivity and temporal resolution. However, even when using a time-of-flight mass detector (ToF), it is not possible to distinguish the $[M + 1]^+$ ions from molecules of identical monoisotopic masses. This is only possible using typical fragmentation patterns. Moreover, the fragmentation reactions depend on the E/N ratio in the drift tube and increase with increasing E/N .¹¹⁸ This may also be the reason why different ratios of fragmentation ions are reported in the literature.¹³¹ The interpretation of fragmentation patterns becomes more difficult with increasing number of chlorine, bromine and sulfur atoms due to their natural isotopic distribution. In addition, substances such as 1-octen-3-ol and octanal show almost indistinguishable fragmentation patterns.¹⁴⁸

The more important point concerns the calibration of PTR-MS measurements. Standard methods such as ISO 16000-3³⁵ and 16000-6³⁷ have the advantage that their calibration is traceable and they can therefore be accredited. This is not the

Table 3 Analytical methods for the quantitative determination of carbonyl compounds in indoor and outdoor air

| Method | Comments |
|--|---|
| Hantzsch ^{53,54} | Selective for formaldehyde with fluorescence detection, ⁵⁵ standardized by EN 717-1 ³⁶ |
| Hantzsch online ¹¹⁰ | Selective for formaldehyde with fluorescence detection |
| DNPH (HPLC-UV) | Recommended for selected aldehydes and ketones, standardized by ISO 16000-3 ³⁵ and ASTM 5197-21 ¹⁴⁶ |
| DNPH (HPLC-MS) ⁸⁷ | 30 carbonyls |
| DNPH (HPLC-MS/MS) ⁸⁵ | 32 carbonyl compounds |
| DNSH (HPLC-UV) ¹⁰² | 15 saturated and unsaturated aldehydes |
| PFBH (TD-GC/MS) ¹⁰³ | 14 carbonyls and dicarbonyls |
| PFBH (GC/MS) ¹⁰⁵ | 21 carbonyls |
| PFBH (GC-MS) ⁴¹ | Dicarbonyls |
| PFBH (GC/MS) ⁴⁰ | Dicarbonyls and unsaturated aldehydes |
| TBOX (GC/MS) ¹⁰¹ | Dicarbonyls from limonene/ozone reaction |
| TD-GC/MS (Tenax TA) | Carbonyls $\geq C_4$, standardized by ISO 16000-6 ³⁷ |
| TD-GC/MS (carbon black) ^{25,38} | Saturated and unsaturated aldehydes $\leq C_4$ |
| Canister sampling (GC/MS) ⁹⁸ | Acrolein, acetone, MEK, MIBK, 2-hexanone, standardized by U.S. EPA TO-15A |
| MBTH ⁷³ | Not specific, sum value for aldehydes |
| TDLS ¹¹¹ | Selective for formaldehyde |
| DOAS ^{109,110} | Selective for formaldehyde |
| CRDS ¹⁰⁹ | Selective for formaldehyde |
| FTIR ⁶⁴ | Selective for formaldehyde |
| PAS (laser excitation) ¹¹³ | Selective for formaldehyde |
| PTR-MS ^{118,147} | Broad range of carbonyls and dicarbonyls |
| SIFT-MS ¹²⁴ | Broad range of carbonyls and dicarbonyls |
| IMS ^{138,139} | Suitable for preselected carbonyls and dicarbonyls |
| Other methods | Vairavamurthy <i>et al.</i> , ⁵² Szulejko and Kim ¹⁴³ |



case with the PTR-MS. The k_{PT} values at 353 K of the three carbonyls shown in Fig. 10 are calculated and differ by 15–25% in the range from 80 Td to 140 Td. Another critical parameter in eqn (3) is the drift time t_{r} , which is made up of measured variables such as the length of the drift tube and the drift voltage, but also of calculated variables such as the reduced ion mobility. Therefore, the PTR-MS can only be calibrated for a specific device setting. Pham *et al.*¹⁴⁹ investigated the VOC release rates from 3D printed samples by coupling a microchamber/thermal extractor system with a PTR-MS. Where available, the authors use compound specific reaction rate coefficients for calibration. Otherwise a default value of $k_{\text{PT}} = 2.0 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ was applied. Pagonis *et al.*¹⁵⁰ used a 10 component test gas for six point calibration. For other compounds, calibration factors were determined by averaging the factors of all calibrants. Lunderberg *et al.*¹²⁰ also performed the calibration of their PTR-MS with authentic external standards. If these were not available, the default values of the device were used; the authors estimate the error at –40% to +60%. It is clear that the use of such default values disqualifies analytical methods when it comes to health assessments of building product emissions or indoor air quality. The three cited publications^{120,149,150} correctly emphasize that PTR-MS is the method of choice to characterize the dynamic nature of VOCs and is especially suited to measuring highly volatile compounds. However, there is still a long way to go before the method can be used for tasks that require accredited measurements. This applies in particular to the polar carbonyl compounds, whose reaction constants are strongly influenced by the system settings.

10 Conclusion

For various reasons, it is important and necessary to determine the quality and quantity of carbonyl compounds in the room air. Substances such as formaldehyde²⁰ and acetaldehyde²³ are classified as carcinogenic and are subject to strict regulations, guide values have been published for various aldehydes, ketones and lactams,¹⁴⁵ substances such as decanal,¹⁵¹ 4-OPA, 6-MHO, geranylacetone,¹⁷ glyoxal and acrolein¹⁵² are markers for chemical reactions. Individual compounds can be specifically analyzed and with the necessary accuracy. However, the task becomes more difficult when many carbonyl compounds have to be determined in parallel and the appropriate methods have to be selected in a targeted manner. This contribution should help to choose the right analytical method and to keep the effort as low as possible but as large as necessary.

Abbreviations

| | |
|------|----------------------------------|
| BP | Boiling point |
| CRDS | Cavity ring down spectroscopy |
| DDL | 3,5-Diacetyl-1,4-dihydrolutidine |
| DNPH | 2,4-Dinitrophenylhydrazine |

| | |
|----------------------|---|
| DNSH | Dansylhydrazine |
| DOAS | Differential optical absorption spectroscopy |
| EIC | Extracted ion chromatogram |
| EN | European norm |
| E/N | Ratio of electric field strength and molecular density in the PTR-MS drift tube |
| ESI | Electrospray ionization |
| FTIR | Fourier-transform infrared |
| GC/MS | Gas chromatography/mass spectrometry |
| HPLC | High performance liquid chromatography |
| IMS | Ion mobility spectrometry |
| IR | Infrared |
| ISO | International organization for standardization |
| K_{cap} | Capture parameter in ion-dipole collisional theory |
| k_{L} | Proton-transfer rate constant according to Langevin |
| k_{PT} | Proton-transfer rate constant |
| $k_{\mu_{\text{D}}}$ | Dipole related proton-transfer rate constant |
| LOQ | Limit of quantitation |
| MBTH | 3-Methyl-2-benzothiazolinone hydrazone |
| MS/MS | Tandem mass spectrometry |
| MVOC | Microbial volatile organic compound |
| MW | Molecular weight |
| NAD^+ | Oxidized nicotinamide adenine dinucleotide |
| NADH | Reduced nicotinamide adenine dinucleotide |
| PAS | Photo acoustic spectroscopy |
| PFBHA | O-(2,3,4,5,6-Pentafluorobenzyl) hydroxylamine |
| PFPH | Pentafluorophenyl hydrazine |
| ppb | Parts per billion (refers to the volume mixing ratio) |
| ppm | Parts per million (refers to the volume mixing ratio) |
| PTR-MS | Proton-transfer-reaction mass spectrometry |
| SIFT-MS | Selected ion flow tube mass spectrometry |
| SIM | Single ion mode |
| SPME | Solid phase micro extraction |
| SVOC | Semi volatile organic compound |
| TBOX | O-tert-Butylhydroxylamine hydrochloride |
| TD | Thermal desorption |
| TDLS | Tunable diode laser spectroscopy |
| Tenax GR | Graphitized Tenax |
| UV | Ultraviolet |
| VIS | Visible |
| VOC | Volatile organic compound |
| VVOC | Very volatile organic compound |
| WST-8 | Sodium-2-(2-methoxy-4-nitrophenyl)-3-(4-nitrophenyl)-5-(2,4-disulfophenyl)-2H-tetrazolium |

Conflicts of interest

The author has no conflicts of interest to declare.

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References

- 1 S. Manahan, *Environmental Chemistry*, CRC Press, Boca Raton, FL, 2017.
- 2 *Principles of Toxicology: Environmental and Industrial Applications*, ed. S. M. Roberts, R. C. James and P. L. Williams, John Wiley & Sons Inc., Hoboken, NJ, 2022.
- 3 P. J. Walsh, C. S. Dudley and E. D. Copenhaver, *Indoor Air Quality*, CRC Press, Boca Raton, FL, 1984.
- 4 J. F. Walker, *Formaldehyde*, Robert E. Krieger Publishing Company, Huntington, NY, 1975.
- 5 S. K. Brown, M. R. Sim, M. J. Abramson and C. N. Gray, Concentrations of volatile organic compounds in indoor air - a review, *Indoor Air*, 1994, **4**, 123–134.
- 6 J. Zhang, P. J. Liou and Q. He, Characteristics of aldehydes: concentrations, sources, and exposures for indoor and outdoor residential microenvironments, *Environ. Sci. Technol.*, 1994, **28**, 146–152.
- 7 T. Salthammer, Emission of volatile organic compounds from furniture coatings, *Indoor Air*, 1997, **7**, 189–197.
- 8 T. Salthammer, A. Schwarz and F. Fuhrmann, Emission of reactive compounds and secondary products from wood-based furniture coatings, *Atmos. Environ.*, 1998, **33**, 75–84.
- 9 M. Makowski and M. Ohlmeyer, Influences of hot pressing temperature and surface structure on VOC emissions from OSB made of Scots pine, *Holzforschung*, 2006, **60**, 533–538.
- 10 Y. Liu, X. Zhu, X. Qin, W. Wang, Y. Hu and D. Yuan, Identification and characterization of odorous volatile organic compounds emitted from wood-based panels, *Environ. Monit. Assess.*, 2020, **192**, 348.
- 11 C. J. Weschler, A. T. Hodgson and J. D. Wooley, Indoor chemistry: ozone, volatile organic compounds, and carpets, *Environ. Sci. Technol.*, 1992, **26**, 2371–2377.
- 12 G. C. Morrison and W. W. Nazaroff, Ozone interactions with carpet: secondary emissions of aldehydes, *Environ. Sci. Technol.*, 2002, **36**, 2185–2192.
- 13 J. Bartsch, E. Uhde and T. Salthammer, Analysis of odour compounds from scented consumer products using gas chromatography-mass spectrometry and gas chromatography-olfactometry, *Anal. Chim. Acta*, 2016, **904**, 98–106.
- 14 P. Azimi, D. Zhao, C. Pouzet, N. E. Crain and B. Stephens, Emissions of ultrafine particles and volatile organic compounds from commercially available desktop three-dimensional printers with multiple filaments, *Environ. Sci. Technol.*, 2016, **50**, 1260–1268.
- 15 J. Gu, M. Wensing, E. Uhde and T. Salthammer, Characterization of particulate and gaseous pollutants emitted during operation of a desktop 3D printer, *Environ. Int.*, 2019, **123**, 476–485.
- 16 W. Zhang, Z. Bai, L. Shi, J. H. Son, L. Li, L. Wang and J. Chen, Investigating aldehyde and ketone compounds produced from indoor cooking emissions and assessing their health risk to human beings, *J. Environ. Sci.*, 2023, **127**, 389–398.
- 17 A. Wisthaler and C. J. Weschler, Reactions of ozone with human skin lipids: Sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air, *Proc. Natl. Acad. Sci. U. S. A.*, 2010, **107**, 6568–6575.
- 18 R. Otson and P. Fellin, A review of techniques for measurement of airborne aldehydes, *Sci. Total Environ.*, 1988, **77**, 95–131.
- 19 A. Calogirou, B. Larsen and D. Kotzias, Gas-phase terpene oxidation products: a review, *Atmos. Environ.*, 1999, **33**, 1423–1439.
- 20 T. Salthammer, S. Mentese and R. Marutzky, Formaldehyde in the indoor environment, *Chem. Rev.*, 2010, **110**, 2536–2572.
- 21 T. Salthammer, Formaldehyde sources, formaldehyde concentrations and air exchange rates in European housings, *Build. Environ.*, 2019, **150**, 219–232.
- 22 D. A. Sarigiannis, S. P. Karakitsios, A. Gotti, I. L. Liakos and A. Katsoyiannis, Exposure to major volatile organic compounds and carbonyls in European indoor environments and associated health risk, *Environ. Int.*, 2011, **37**, 743–765.
- 23 T. Salthammer, Acetaldehyde in the indoor environment, *Environ. Sci.: Atmos.*, 2023, **3**, 474–493.
- 24 W. Birmili, A. Daniels, R. Bethke, N. Schechner, G. Brasse, A. Conrad, M. Kolossa-Gehring, M. Debiak, J. Hurraß, E. Uhde, A. Omelan and T. Salthammer, Formaldehyde aliphatic aldehydes (C2–C11), furfural, and benzaldehyde in the residential indoor air of children and adolescents during the German Environmental Survey 2014–2017 (GerES V), *Indoor Air*, 2022, **32**, e12927.
- 25 A. Schieweck, E. Uhde and T. Salthammer, Determination of acrolein in ambient air and in the atmosphere of environmental test chambers, *Environ. Sci.: Processes Impacts*, 2021, **23**, 1729–1746.
- 26 P. Wolkoff, P. A. Clausen, C. K. Wilkins and G. D. Nielsen, Formation of strong airway irritants in terpene/ozone mixtures, *Indoor Air*, 2000, **10**, 82–91.
- 27 T. Salthammer and F. Fuhrmann, Release of acetic acid and furfural from cork products, *Indoor Air*, 2000, **10**, 133–134.
- 28 W. Liu, J. Zhang, L. Zhang, B. J. Turpin, C. P. Weisel, M. T. Morandi, T. H. Stock, S. Colome and L. R. Korn, Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States, *Atmos. Environ.*, 2006, **40**, 2202–2214.
- 29 M. Sleiman, J. M. Logue, V. N. Montesinos, M. L. Russell, M. I. Litter, L. A. Gundel and H. Destailats, Emissions from electronic cigarettes: Key parameters affecting the release of harmful chemicals, *Environ. Sci. Technol.*, 2016, **50**, 9644–9651.
- 30 H. Fromme, *Luftverunreinigungen in Innenräumen*, Ecomed Medizin, Landsberg, 2021.
- 31 T. Salthammer, Very volatile organic compounds: an understudied class of indoor air pollutants, *Indoor Air*, 2016, **26**, 25–38.
- 32 T. Salthammer, M. Bednarek, F. Fuhrmann, R. Funaki and S.-I. Tanabe, Formation of organic indoor air pollutants



- by UV-curing chemistry, *J. Photochem. Photobiol., A*, 2002, **152**, 1–9.
- 33 P. Harb, N. Locoge and F. Thevenet, Emissions and treatment of VOCs emitted from wood-based construction materials: Impact on indoor air quality, *Chem. Eng. J.*, 2018, **354**, 641–652.
 - 34 T. Salthammer, Y. Zhang, J. Mo, H. M. Koch and C. J. Weschler, Assessing Human Exposure to Organic Pollutants in the Indoor Environment, *Angew. Chem., Int. Ed.*, 2018, **57**, 12228–12263.
 - 35 ISO 16000-3, *Indoor air – Part 3: Determination of formaldehyde and other carbonyl compounds in indoor and test chamber air – active sampling method*, International Organization for Standardization, Geneva, 2022.
 - 36 EN 717-1, *Wood-based panels – Determination of formaldehyde release – Part 1: Formaldehyde emission by the chamber method*, Beuth Beuth Verlag, Berlin, 2004.
 - 37 ISO 16000-6, *Indoor air – Part 6: Determination of organic compounds (VOC, VOC, SVOC) in indoor and test chamber air by active sampling on sorbent tubes, thermal desorption and gas chromatography using MS or MS FID*, International Organization for Standardization, Geneva, 2021.
 - 38 A. Schieweck, J. Gunschera, D. Varol and T. Salthammer, Analytical procedure for the determination of very volatile organic compounds (C3–C6) in indoor air, *Anal. Bioanal. Chem.*, 2018, **410**, 3171–3183.
 - 39 J. Yu, R. C. Flagan and J. H. Seinfeld, Identification of products containing -COOH, -OH, and -CO in atmospheric oxidation of hydrocarbons, *Environ. Sci. Technol.*, 1998, **32**, 2357–2370.
 - 40 V. Y. Seaman, M. J. Charles and T. M. Cahill, A sensitive method for the quantification of acrolein and other volatile carbonyls in ambient air, *Anal. Chem.*, 2006, **78**, 2405–2412.
 - 41 S. E. Anderson, L. G. Jackson, J. Franko and J. R. Wells, Evaluation of dicarbonyls generated in a simulated indoor air environment using an in vitro exposure system, *Toxicol. Sci.*, 2010, **115**, 453–461.
 - 42 A. Streitwieser, C. H. Heathcock and E. M. Kosower, *Introduction to Organic Chemistry*, Macmillan Publishing Co. Ltd, New York, 1992.
 - 43 A. D. Buckingham, D. A. Ramsay and J. Tyrrell, Electric dipole moment of formaldehyde in the first 3A_2 excited state, *Can. J. Phys.*, 1970, **48**, 1242–1253.
 - 44 N. J. Turro, V. Ramamurthy and J. C. Scaiano, *Modern Molecular Photochemistry of Organic Molecules*, University Science Books, Sausalito, CA, 2010.
 - 45 J. D. Rogers, Ultraviolet absorption cross sections and atmospheric photodissociation rate constants of formaldehyde, *J. Phys. Chem.*, 1990, **94**, 4011–4015.
 - 46 R. D. Martinez, A. A. Buitrago, N. W. Howell, C. H. Hearn and J. A. Joens, The near U.V. absorption spectra of several aliphatic aldehydes and ketones at 300 K, *Atmos. Environ.*, 1992, **26**, 785–792.
 - 47 J. G. Calvert and J. N. Pitts, *Photochemistry*, John Wiley & Sons Inc., New York, NY, 1966.
 - 48 B. J. Finlayson-Pitts and J. N. Pitts, *Chemistry of the upper and lower atmosphere*, Academic Press, San Diego, 2000.
 - 49 H. C. Hsieh and W. C. Ermler, Ab initio vibrational transition dipole moments and intensities of formaldehyde, *J. Comput. Chem.*, 1988, **9**, 95–106.
 - 50 T. Nakanaga, S. Kondo and S. Saeki, Infrared band intensities of formaldehyde and formaldehyde-d₂, *J. Chem. Phys.*, 1982, **76**, 3860–3865.
 - 51 R. Brückner, *Advanced Organic Chemistry – Reaction Mechanisms*, Harcourt/Academic Press, San Diego, CA, 2002.
 - 52 A. Vairavamurthy, J. M. Roberts and L. Newman, Methods for determination of low molecular weight carbonyl compounds in the atmosphere: A review, *Atmos. Environ.*, 1992, **26**, 1965–1993.
 - 53 T. Nash, The colorimetric estimation of formaldehyde by means of the Hantzsch reaction, *Biochem. J.*, 1953, **55**, 416–421.
 - 54 S. Belman, The fluorimetric determination of formaldehyde, *Anal. Chim. Acta*, 1963, **29**, 120–126.
 - 55 T. Salthammer, Photophysical properties of 3,5-diacetyl-1,4-dihydrolutidine in solution: application to the analysis of formaldehyde, *J. Photochem. Photobiol., A*, 1993, **74**, 195–201.
 - 56 S. Dong and P. K. Dasgupta, Fast fluorometric flow injection analysis of formaldehyde in atmospheric water, *Environ. Sci. Technol.*, 1987, **21**, 581–588.
 - 57 J. R. Lakowicz, *Principles of fluorescence spectroscopy*, Springer Science+Business Media LLC, New York, NY, 2006.
 - 58 EN 717-1, *Wood-based panels – determination of formaldehyde release. Part 1: formaldehyde emission by the chamber method*, Beuth Verlag, Berlin, 2005.
 - 59 T. Kleindienst, P. Shepson, C. Nero, R. Arnts, S. Tejada, G. Mackay, L. Mayne, H. Schiff, J. Lind, G. Kok, A. Lazrus, P. Dasgupta and S. Dong, An intercomparison of formaldehyde measurement techniques at ambient concentration, *Atmos. Environ.*, 1988, **22**, 1931–1939.
 - 60 M. Risholm-Sundman, A. Larsen, E. Vestin and A. Weibull, Formaldehyde emission – comparison of different standard methods, *Atmos. Environ.*, 2007, **41**, 3193–3202.
 - 61 T. Salthammer and S. Mentese, Comparison of analytical techniques for the determination of aldehydes in test chambers, *Chemosphere*, 2008, **73**, 1351–1356.
 - 62 E. Roffael, *Formaldehyde in nature, in wood and in wood-based panels*, DRW-Verlag, Leinfelden-Echterdingen, 2017.
 - 63 S. Dugheri, D. Massi, N. Mucci, G. Marrubini, G. Cappelli, A. Speltini, M. C. Bonferoni and G. Arcangeli, Exposure to airborne formaldehyde: Sampling and analytical methods – A review, *Trends Environ. Anal. Chem.*, 2021, **29**, e00116.
 - 64 C. Hak, *et al.*, Intercomparison of four different *in situ* techniques for ambient formaldehyde measurements in urban air, *Atmos. Chem. Phys.*, 2005, **5**, 2881–2900.
 - 65 U. Riess, U. Tegtbur, C. Fauck, F. Fuhrmann, D. Markewitz and T. Salthammer, Experimental setup and



- analytical methods for the non-invasive determination of volatile organic compounds, formaldehyde and NO in exhaled human breath, *Anal. Chim. Acta*, 2010, **669**, 53–62.
- 66 N. Aldag, J. Gunschera and T. Salthammer, Release and absorption of formaldehyde by textiles, *Cellulose*, 2017, **24**, 4509–4518.
 - 67 E. Sawicki, T. R. Hauser, T. W. Stanley and W. Elbert, The 3-methyl-2-benzothiazolone hydrazone test. sensitive new methods for the detection, rapid estimation, and determination of aliphatic aldehydes, *Anal. Chem.*, 1961, **33**, 93–96.
 - 68 A. P. Altshuller and L. J. Leng, Application of the 3-methyl-2-benzothiazolone hydrazone method for atmospheric analysis of aliphatic aldehydes, *Anal. Chem.*, 1963, **35**, 1541–1542.
 - 69 R. Goebel, A. Krug and R. Kellner, Spectrophotometric flow injection analysis of formaldehyde in aqueous solutions using 3-methyl-2-benzthiazolinone hydrazone, *Fresenius' J. Anal. Chem.*, 1993, **347**, 491–494.
 - 70 K. Toda, K.-I. Yoshioka, K. Mori and S. Hirata, Portable system for near-real time measurement of gaseous formaldehyde by means of parallel scrubber stopped-flow absorptiometry, *Anal. Chim. Acta*, 2005, **531**, 41–49.
 - 71 S. Huang, W. Wei, L. B. Weschler, T. Salthammer, H. Kan, Z. Bu and Y. Zhang, Indoor formaldehyde concentrations in urban China: Preliminary study of some important influencing factors, *Sci. Total Environ.*, 2017, **590–591**, 394–405.
 - 72 W. H. Chan, S. Shuang and M. M. F. Choi, Determination of airborne formaldehyde by active sampling on 3-methyl-2-benzothiazolinone hydrazone hydrochloride-coated glass fibre filters, *Analyst*, 2001, **126**, 720–723.
 - 73 R. Giesen, T. Schripp, D. Markewitz, B. Meyer, H. Schwab, E. Uhde and T. Salthammer, Comparison of methods for the determination of formaldehyde in air, *Anal. Lett.*, 2016, **49**, 1613–1621.
 - 74 R. Feldbrügge, K. P. Rindt and A. Borchert, in *Advances in Molecular and Cell Biology*, ed. E. E. Bittar, B. Danielsson and L. Bülow, JAI Press Inc., Greenwich, CT, 1996, vol. 15B, pp. 451–459.
 - 75 A. Monkawa, T. Gessei, Y. Takimoto, N. Jo, T. Wada and N. Sanari, Highly sensitive and rapid gas biosensor for formaldehyde based on an enzymatic cycling system, *Sens. Actuators, B*, 2015, **210**, 241–247.
 - 76 EN 16516, *Construction products: Assessment of release of dangerous substances – Determination of emissions into indoor air*, European Committee for Standardization, Brussels, 2017.
 - 77 M. Aiello and R. McLaren, Measurement of airborne carbonyls using an automated sampling and analysis system, *Environ. Sci. Technol.*, 2009, **43**, 8901–8907.
 - 78 U. Karst, N. Binding, K. Cammann and U. Witting, Interferences of nitrogen dioxide in the determination of aldehydes and ketones by sampling on 2,4-dinitrophenylhydrazine-coated solid sorbent, *Fresenius' J. Anal. Chem.*, 1993, **345**, 48–52.
 - 79 R. R. Arnts and S. B. Tejada, 2,4-Dinitrophenylhydrazine-coated silica gel cartridge method for determination of formaldehyde in air: identification of an ozone interference, *Environ. Sci. Technol.*, 1989, **23**, 1428–1430.
 - 80 J. Williams, H. Li, A. B. Ross and S. P. Hargreaves, Quantification of the influence of NO₂, NO and CO gases on the determination of formaldehyde and acetaldehyde using the DNPH method as applied to polluted environments, *Atmos. Environ.*, 2019, **218**, 117019.
 - 81 V. G. Berezkin and Y. S. Drugov, *Gas chromatography in air pollution analysis*, Elsevier Science Publishers B.V., Amsterdam, 1991.
 - 82 S. S. H. Ho, K. Ho, W. Liu, S. Lee, W. Dai, J. Cao and H. Ip, Unsuitability of using the DNPH-coated solid sorbent cartridge for determination of airborne unsaturated carbonyls, *Atmos. Environ.*, 2011, **45**, 261–265.
 - 83 S. S. H. Ho, H. S. S. Ip, K. F. Ho, L. P. T. Ng, W. Dai, J. Cao, C. S. Chan and L. B. Ho, Evaluation of hazardous airborne carbonyls on a university campus in southern China, *J. Air Waste Manage. Assoc.*, 2014, **64**, 903–916.
 - 84 F. Villanueva, I. Colmenar, R. Mabilia, C. Scipioni and B. Cabañas, Field evaluation of the Analyst® passive sampler for the determination of formaldehyde and acetaldehyde in indoor and outdoor ambient air, *Anal. Methods*, 2013, **5**, 516–524.
 - 85 Y. Chi, Y. Feng, S. Wen, H. Lü, Z. Yu, W. Zhang, G. Sheng and J. Fu, Determination of carbonyl compounds in the atmosphere by DNPH derivatization and LC-ESI-MS/MS detection, *Talanta*, 2007, **72**, 539–545.
 - 86 Y.-L. Feng and J. Zhu, Separation and determination of carbonyl compounds in indoor air using two-step gradient capillary electrochromatography, *Anal. Sci.*, 2004, **20**, 1691–1695.
 - 87 X. Zhang, Y. Kong, J. Cao, H. Li, R. Gao, Y. Zhang, K. Wang, Y. Li, Y. Ren and W. Wang, A sensitive simultaneous detection approach for the determination of 30 atmospheric carbonyls by 2,4-dinitrophenylhydrazine derivatization with HPLC-MS technique and its preliminary application, *Chemosphere*, 2022, **303**, 134985.
 - 88 H.-J. Hübschmann, *Handbook of GC/MS: Fundamentals and Applications*, WILEY-VCH, Weinheim, 2015.
 - 89 F. W. McLafferty and F. Turecek, *Interpretation of mass spectra*, University Science Books, Mill Valley, CA, 1993.
 - 90 O. Wilke, W. Horn, M. Richter and O. Jann, Volatile organic compounds from building products - results from six round robin tests with emission test chambers conducted between 2008 and 2018, *Indoor Air*, 2021, **31**, 2049–2057.
 - 91 T. Salthammer, TVOC-Revisited, *Environ. Int.*, 2022, **167**, 107440.
 - 92 E. Woolfenden, Sorbent-based sampling methods for volatile and semi-volatile organic compounds in air, *J. Chromatogr. A*, 2010, **1217**, 2674–2684.
 - 93 P. A. Clausen and P. Wolkoff, Degradation products of Tenax TA formed during sampling and thermal desorp-



- tion analysis: Indicators of reactive species indoors, *Atmos. Environ.*, 1997, **31**, 715–725.
- 94 J. G. Klenø, P. Wolkoff, P. A. Clausen, C. K. Wilkins and T. Pedersen, Degradation of the adsorbent Tenax TA by nitrogen oxides, ozone, hydrogen peroxide, OH radical, and limonene oxidation products, *Environ. Sci. Technol.*, 2002, **36**, 4121–4126.
 - 95 M. Richter, E. Juritsch and O. Jann, Determination of recovery rates of adsorbents for sampling very volatile organic compounds (C1–C6) in dry and humid air in the sub-ppb range by use of thermal desorption gas chromatography-mass spectrometry, *J. Chromatogr. A*, 2020, **1626**, 461389.
 - 96 M. Even, E. Juritsch and M. Richter, Measurement of very volatile organic compounds (VVOs) in indoor air by sorbent-based active sampling: Identifying the gaps towards standardisation, *TrAC, Trends Anal. Chem.*, 2021, **140**, 116265.
 - 97 R. Schulte-Ladbeck, R. Lindahl, J.-O. Levin and U. Karst, Characterization of chemical interferences in the determination of unsaturated aldehydes using aromatic hydrazine reagents and liquid chromatography, *J. Environ. Monit.*, 2001, **3**, 306–310.
 - 98 U.S. Environmental Protection Agency, *Method TO-15A: Determination of volatile organic compounds (VOCs) in air collected in specially prepared canisters and analyzed by gas chromatography-mass spectrometry (GC-MS)*, U.S. EPA Office of Research and Development, Washington, D.C., 2019.
 - 99 E. Uhde and T. Salthammer, Impact of reaction products from building materials and furnishings on indoor air quality - a review of recent advances in indoor chemistry, *Atmos. Environ.*, 2007, **41**, 3111–3128.
 - 100 C. D. Forester and J. R. Wells, Yields of carbonyl products from gas-phase reactions of fragrance compounds with OH radical and ozone, *Environ. Sci. Technol.*, 2009, **43**, 3561–3568.
 - 101 J. Wells and J. E. Ham, A new agent for derivatizing carbonyl species used to investigate limonene ozonolysis, *Atmos. Environ.*, 2014, **99**, 519–526.
 - 102 J. Herrington, L. Zhang, D. Whitaker, L. Sheldon and J. J. Zhang, Optimizing a dansylhydrazine (DNSH) based method for measuring airborne acrolein and other unsaturated carbonyls, *J. Environ. Monit.*, 2005, **7**, 969–976.
 - 103 S. S. H. Ho and J. Z. Yu, Determination of airborne carbonyls: comparison of a thermal desorption/GC method with the standard DNPH/HPLC method, *Environ. Sci. Technol.*, 2004, **38**, 862–870.
 - 104 J. Li, Y. L. Feng, C. J. Xie, J. Huang, J. Z. Yu, J. L. Feng, G. Y. Sheng, J. M. Fu and M. H. Wu, Determination of gaseous carbonyl compounds by their pentafluorophenyl hydrazones with gas chromatography/mass spectrometry, *Anal. Chim. Acta*, 2009, **635**, 84–93.
 - 105 X. Pang, A. C. Lewis and J. F. Hamilton, Determination of airborne carbonyls via pentafluorophenylhydrazine derivatisation by GC-MS and its comparison with HPLC method, *Talanta*, 2011, **85**, 406–414.
 - 106 M. A. Ullah, K.-H. Kim and J. E. Szulejko, The effect of solvent selection in the gas chromatographic analysis of carbonyls in air samples after derivatization with pentafluorophenyl hydrazine, *Atmos. Res.*, 2015, **166**, 101–109.
 - 107 D. Bourdin and V. Desauziers, Development of SPME on-fiber derivatization for the sampling of formaldehyde and other carbonyl compounds in indoor air, *Anal. Bioanal. Chem.*, 2014, **406**, 317–328.
 - 108 H. Lan, K. Hartonen and M.-L. Riekkola, Miniaturised air sampling techniques for analysis of volatile organic compounds in air, *TrAC, Trends Anal. Chem.*, 2020, **126**, 115873.
 - 109 M. Glowania, F. Rohrer, H.-P. Dorn, A. Hofzumahaus, F. Holland, A. Kiendler-Scharr, A. Wahner and H. Fuchs, Comparison of formaldehyde measurements by Hantzsch, CRDS and DOAS in the SAPHIR chamber, *Atmos. Meas. Tech.*, 2021, **14**, 4239–4253.
 - 110 A. Wisthaler, E. C. Apel, J. Bossmeyer, A. Hansel, W. Junkermann, R. Koppmann, R. Meier, K. Müller, S. J. Solomon, R. Steinbrecher, R. Tillmann and T. Brauers, Technical Note: Intercomparison of formaldehyde measurements at the atmosphere simulation chamber SAPHIR, *Atmos. Chem. Phys.*, 2008, **8**, 2189–2200.
 - 111 B. Hanoune, T. LeBris, L. Allou, C. Marchand and S. L. Calvé, Formaldehyde measurements in libraries: Comparison between infrared diode laser spectroscopy and a DNPH-derivatization method, *Atmos. Environ.*, 2006, **40**, 5768–5775.
 - 112 K. H. Michaelian, *Photoacoustic IR Spectroscopy*, WILEY-VCH, Weinheim, 2010.
 - 113 C. B. Hirschmann, J. Lehtinen, J. Uotila, S. Ojala and R. L. Keiski, Sub-ppb detection of formaldehyde with cantilever enhanced photoacoustic spectroscopy using quantum cascade laser source, *Appl. Phys. B*, 2013, **111**, 603–610.
 - 114 A. Gratien, B. Picquet-Varrault, J. Orphal, E. Perraudin, J.-F. Doussin and J.-M. Flaud, Laboratory intercomparison of the formaldehyde absorption cross sections in the infrared (1660–1820 cm⁻¹ and ultraviolet (300–360 nm) spectral regions, *J. Geophys. Res.*, 2007, **112**, D05305.
 - 115 EN 16738, *Emission safety of combustible air fresheners – Test methods*, European Commission for Standardization, Brussels, 2015.
 - 116 T. Salthammer, J. Gu, S. Wientzek, R. Harrington and S. Thomann, Measurement and evaluation of gaseous and particulate emissions from burning scented and unscented candles, *Environ. Int.*, 2021, **155**, 106590.
 - 117 ISO 12460-3, *Wood-based panels - Determination of formaldehyde release. Part 3: gas analysis method*, International Organization for Standardization, Geneva, 2020.
 - 118 A. M. Ellis and C. A. Mayhew, *Proton Transfer Reaction Mass Spectrometry: Principles and Applications*, John Wiley & Sons, Chichester, 2013.
 - 119 R. S. Blake, P. S. Monks and A. M. Ellis, Proton-transfer reaction mass spectrometry, *Chem. Rev.*, 2009, **109**, 861–896.



- 120 D. M. Lunderberg, P. K. Misztal, Y. Liu, C. Arata, Y. Tian, K. Kristensen, R. J. Weber, W. W. Nazaroff and A. H. Goldstein, High-resolution exposure assessment for volatile organic compounds in two California residences, *Environ. Sci. Technol.*, 2021, **55**, 6740–6751.
- 121 Y. Liu, P. K. Misztal, C. Arata, C. J. Weschler, W. W. Nazaroff and A. H. Goldstein, Observing ozone chemistry in an occupied residence, *Proc. Natl. Acad. Sci. U. S. A.*, 2021, **118**, e2018140118.
- 122 N. Zannoni, P. S. J. Lakey, Y. Won, M. Shiraiwa, D. Rim, C. J. Weschler, N. Wang, L. Ernle, M. Li, G. Bekö, P. Wargocki and J. Williams, The human oxidation field, *Science*, 2022, **377**, 1071–1077.
- 123 N. Wang, L. Ernle, G. Bekö, P. Wargocki and J. Williams, Emission rates of volatile organic compounds from humans, *Environ. Sci. Technol.*, 2022, **56**, 4838–4848.
- 124 D. Smith and P. Španěl, Selected ion flow tube mass spectrometry (SIFT-MS) for on-line trace gas analysis, *Mass Spectrom. Rev.*, 2005, **24**, 661–700.
- 125 T. Schripp, S. Etienne, C. Fauck, F. Fuhrmann, L. Märk and T. Salthammer, Application of proton-transfer-reaction-mass-spectrometry for indoor air quality research, *Indoor Air*, 2014, **24**, 178–189.
- 126 E. P. L. Hunter and S. G. Lias, Evaluated gas phase basicities and proton affinities of molecules: an update, *J. Phys. Chem. Ref. Data*, 1998, **27**, 413–656.
- 127 A. Hansel, W. Singer, A. Wisthaler, M. Schwarzmair and W. Lindinger, Energy dependencies of the proton transfer reactions, *Int. J. Mass Spectrom. Ion Processes*, 1997, **167–168**, 697–703.
- 128 T. Schripp, C. Fauck and T. Salthammer, Interferences in the determination of formaldehyde via PTR-MS: What do we learn from m/z 31?, *Int. J. Mass Spectrom.*, 2010, **289**, 170–172.
- 129 P. Španěl, Y. Ji and D. Smith, SIFT studies of the reactions of H_3O^+ , NO^+ and O_2^+ with a series of aldehydes and ketones, *Int. J. Mass Spectrom. Ion Processes*, 1997, **165–166**, 25–37.
- 130 C. Warneke, J. A. de Gouw, W. C. Kuster, P. D. Goldan and R. Fall, Validation of atmospheric VOC measurements by proton-transfer-reaction mass spectrometry using a gas-chromatographic pre-separation method, *Environ. Sci. Technol.*, 2003, **37**, 2494–2501.
- 131 D. Pagonis, K. Sekimoto and J. de Gouw, A library of proton-transfer reactions of H_3O^+ ions used for trace gas detection, *J. Am. Soc. Mass Spectrom.*, 2019, **30**, 1330–1335.
- 132 J. W. Einax, H. W. Zwaninger and S. Geiß, *Chemometrics in Environmental Analysis*, VCH Verlag, Weinheim, 1997.
- 133 L. Cappellin, T. Karl, M. Probst, O. Ismailova, P. M. Winkler, C. Soukoulis, E. Aprea, T. D. Märk, F. Gasperi and F. Biasioli, On quantitative determination of volatile organic compound concentrations using proton transfer reaction time-of-flight mass spectrometry, *Environ. Sci. Technol.*, 2012, **46**, 2283–2290.
- 134 T. Su, Parametrization of kinetic energy dependences of ion–polar molecule collision rate constants by trajectory calculations, *J. Chem. Phys.*, 1994, **100**, 4703–4703.
- 135 T. Salthammer, U. Hohm, M. Stahn and S. Grimme, Proton-transfer rate constants for the determination of organic indoor air pollutants by online mass spectrometry, *RSC Adv.*, 2023, **13**, 17856–17868.
- 136 R. Barth, *The chemistry of beer*, John Wiley & Sons Inc., Hoboken, NJ, 2022.
- 137 G. A. Eiceman, Z. Karpas and H. H. Hill Jr., *Ion mobility spectrometry*, CRC Press, Boca Raton, FL, 2014.
- 138 R. Cumeras, E. Figueras, C. E. Davis, J. I. Baumbach and I. Gràcia, Review on Ion Mobility Spectrometry. Part 1: current instrumentation, *Analyst*, 2015, **140**, 1376–1390.
- 139 R. Cumeras, E. Figueras, C. E. Davis, J. I. Baumbach and I. Gràcia, Review on Ion Mobility Spectrometry. Part 2: hyphenated methods and effects of experimental parameters, *Analyst*, 2015, **140**, 1391–1410.
- 140 C. Tiebe, H. Miessner, B. Koch and T. Hübner, Detection of microbial volatile organic compounds (MVOCs) by ion-mobility spectrometry, *Anal. Bioanal. Chem.*, 2009, **395**, 2313–2323.
- 141 V. Ruzsanyi, P. Mochalski, A. Schmid, H. Wiesenhofer, M. Klieber, H. Hinterhuber and A. Amann, Ion mobility spectrometry for detection of skin volatiles, *J. Chromatogr. B: Anal. Technol. Biomed. Life Sci.*, 2012, **911**, 84–92.
- 142 P. C. Moura and V. Vassilenko, Gas Chromatography – Ion Mobility Spectrometry as a tool for quick detection of hazardous volatile organic compounds in indoor and ambient air: A university campus case study, *Eur. J. Mass Spectrom.*, 2022, **28**, 113–126.
- 143 J. E. Szulejko and K.-H. Kim, Derivatization techniques for determination of carbonyls in air, *TrAC, Trends Anal. Chem.*, 2015, **64**, 29–41.
- 144 E. Pibiri, A. Omelan, E. Uhde and T. Salthammer, Effect of surface covering on the release of formaldehyde, acetaldehyde, formic acid and acetic acid from particleboard, *Build. Environ.*, 2020, **178**, 106947.
- 145 O. Toyinbo, L. Hägerhed, S. Dimitroulopoulou, M. Dudzinska, S. Emmerich, D. Hemming, J.-H. Park and U. Haverinen-Shaughnessy, Open database for international and national indoor environmental quality guidelines, *Indoor Air*, 2022, **32**, e13028.
- 146 ASTM D5197-21, *Standard Test Method for Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology)*, American Society for Testing and Materials, West Conshohocken, PA, 2022.
- 147 B. Yuan, A. R. Koss, C. Warneke, M. Coggon, K. Sekimoto and J. A. de Gouw, Proton-transfer-reaction mass spectrometry: applications in atmospheric sciences, *Chem. Rev.*, 2017, **117**, 13187–13229.
- 148 K. Buhr, S. van Ruth and C. Delahunty, Analysis of volatile flavour compounds by Proton Transfer Reaction-Mass Spectrometry: fragmentation patterns and discrimination between isobaric and isomeric compounds, *Int. J. Mass Spectrom.*, 2002, **221**, 1–7.
- 149 Y. L. Pham, W. Wojnowski and J. Beauchamp, Online volatile compound emissions analysis using a microchamber/



- thermal extractor coupled to proton transfer reaction-mass spectrometry, *Anal. Chem.*, 2022, **94**, 17354–17359.
- 150 D. Pagonis, D. J. Price, L. B. Algrim, D. A. Day, A. V. Handschy, H. Stark, S. L. Miller, J. de Gouw, J. L. Jimenez and P. J. Ziemann, Time-resolved measurements of indoor chemical emissions, deposition, and reactions in a university art museum, *Environ. Sci. Technol.*, 2019, **53**, 4794–4802.
- 151 C. J. Weschler and W. W. Nazaroff, Human skin oil: a major ozone reactant indoors, *Environ. Sci.: Atmos.*, 2023, **3**, 640–661.
- 152 N. Beauval, M. Verri  le, A. Garat, I. Fronval, R. Dusautoir, S. Anth  rieu, G. Gar  on, J.-M. Lo-Guidice, D. Allorge and N. Locoge, Influence of puffing conditions on the carbonyl composition of e-cigarette aerosols, *Int. J. Hyg. Environ. Health*, 2019, **222**, 136–146.

