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Chemicals in European residences – Part I: A review of emissions, concentrations and health effects of volatile organic compounds (VOCs)

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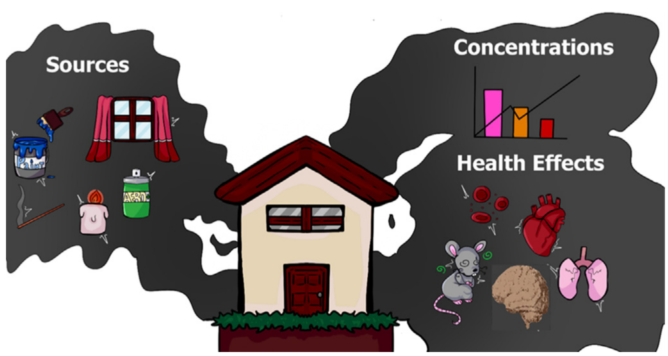
HIGHLIGHTS

- A systematic search was conducted designed to capture evidence on concentrations, emissions from indoor sources, and health effects for VOCs measured in European and UK residences.
- 65 individual VOCs were identified.
- Health end points from inhalation exposure to these VOCs were identified and discussed.
- Reported emission rates from indoor sources will provide a valuable source as input for modelling tools.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the more important classes of potentially toxic indoor air chemicals are the Volatile Organic Compounds (VOCs). However, due to a limited understanding of the relationships between indoor concentrations of individual VOCs and health outcomes, there are currently no universal health-based guideline values for VOCs within Europe including the UK. In this study, a systematic search was conducted designed to capture evidence on concentrations, emissions from indoor sources, and health effects for VOCs measured in European residences.

We identified 65 individual VOCs, and the most commonly measured were aromatic hydrocarbons (14 chemicals), alkane hydrocarbons (9), aldehydes (8), aliphatic hydrocarbons (5), terpenes (6), chlorinated hydrocarbons (4), glycol

Abbreviation: 1,4-DCB, 1,4-Dichlorobenzene; 4-AMCH, 4-Acetyl-1-methylcyclohexane; 4-OPA, 4-Oxopentanal; 6-MHO, 6-Methyl-5-hepten-2-one; ACN, acetonitrile; AM, Arithmetic means; BTX, Benzene, toluene, xylene; CEL, Critical exposure limit; CFU, Colony forming units; CI, Confidence Interval; CNS, Central nervous system; CV, Coefficient of Variation; CVD, Cardiovascular disease; DALY, Disability adjusted life years; DEHP, Diethylhexyl phthalate; DEP, Diethyl phthalate; DHC, Dihydrocarvone 2-methyl-5-isopropenyl-cyclohexan-1-one; DIBP, Diisobutyl phthalate; ECD, Electron capture detector; ECG, Electrocardiogram; EGBE, Ethylene glycol monobutyl ether; EH, Experimental House; Eo/B, Enhanced eosinophil/basophil; ETS, Environmental Tobacco Smoke; ETS, Environmental tobacco smoke; EU-LCI, EU-Lowest Concentration of Interest; FE, Field Experiment; FID, Flame ionization detector; FLEC, Field and Laboratory Emission Cell; GC/ECD, Gas chromatography/electron capture detector; GC/MS, Gas chromatography/ mass spectrometry; GC, Gas chromatography; GM, Geometric mean; GM-CSF, Granulocyte-macrophage colony-stimulating factor; GSD, Geometric standard deviation; HPLC, High-performance liquid chromatography; IAQ, Indoor Air Quality; IL-4, Interleukin-4; IOP, Isoprene oxidation products; IPOH, 3-Isopropenyl-6-oxo-heptanal; LOP, Limonene ozone reaction product; MEC, Miniature Emissions Chamber; NOEL, No Observed Effect Level; OMCTS, Octamethylcyclotetrasiloxane; OR, Odds Ratio; PBMC, Peripheral blood mononuclear cells; PFSs, Passive flux sampler; PGME, Propylene glycol methyl ether; PID, Photoionisation detector; RH, Relative humidity; SV, Sample Vessel; SVOCs, Semi volatile organic compounds; TB, Time of break; TC, Test Cell or Chamber; TE, Time of expiration; TI, Time of inspiration; TPDDIB, 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate / TXIB; TPDMIB, 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate/ texanol; TSP, Total suspended particles; TVOCs, Total volatile organic compounds; UV-VIS, Ultraviolet-visible spectroscopy; VD, Mid expiratory flow rate; VOCs, Volatile organic compounds; VT, Tidal Volume; WAGM, Weighted Average Geometric Mean.

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and glycol ethers (3) and esters (2). The pathway of interest was inhalation and 8 individual aromatic hydrocarbons, 7 alkanes and 6 aldehydes were associated with respiratory health effects. Members of the chlorinated hydrocarbon family were associated with cardiovascular neurological and carcinogenic health effects and some were irritants as were esters and terpenes. Eight individual aromatic hydrocarbons, 7 alkanes and 6 aldehydes identified in European residences were associated with respiratory health effects. Of the 65 individual VOCs, 52 were from sources associated with building and construction materials (e.g. brick, wood products, adhesives and materials for flooring installation etc.), 41 were linked with consumer products (passive, electric and combustible air fresheners, hair sprays, deodorants) and 9 VOCs were associated with space heating, which may reflect the relatively small number of studies discussing emissions from this category of sources.

A clear decrease in concentrations of formaldehyde was observed over the last few years, whilst acetone was found to be one of the most abundant but underreported species. A new approach based on the operational indoor air quality surveillance will both reveal trends in known VOCs and identify new compounds.

Contents

1. Introduction

Modern populations in developed countries both worldwide and in Europe spend approximately 90% of their time indoors and approximately 50% of their time at home (Dimitroulopoulou et al., 2017; Klepeis et al., 2001; Kornartit et al., 2010). Indoor air quality (IAQ) issues have been known since the 1970's, as a result of energy conservation measures, when, in 1973, the Arab Oil Embargo led to the tightening of building envelopes, which in turn reduced ventilation and deteriorated indoor air quality impacting human health. Over 2 million disability adjusted life years (DALY) were estimated to be annually lost in the European Union, as a result of exposure to indoor air pollution (Asikainen et al., 2016). In the decade of 2002–2012, IAQ received a significant interest and funding from the European Union as it was identified as a priority of European Environment and Health research and policy agenda (Settimo et al., 2020; Tuscano and Sinisi, 2012).

Volatile Organic Compounds (VOCs) are defined as organic compounds organic compound whose boiling point is in the range from (50 °C to 100 °C) to (240 °C to 260 °C) environments (ISO 16000-6:2011, 2011) and are key indoor pollutants. A common index of measuring them collectively is as TVOC (Total Volatile Organic Compounds). VOCs are found in both the outdoor and indoor environments; outdoors they are emitted by a variety of mechanisms and processes, (e.g. as by-products of industrial and commercial operations, road traffic exhaust gases), from biological metabolism and they play a significant role in the formation of ozone and particulates (Seinfeld and Pandis, 2006). Indoor VOC sources in the residential environment include construction and building materials (such as paints and glues, and furnishing), consumer products (such as detergents, cleaning and polishing products, air fresheners and personal care products) as well as emissions during the heating of indoor spaces using e.g. solid fuels (Paciência et al., 2016; Shrubsole et al., 2019).

With buildings in Europe becoming increasingly airtight to improve energy efficiency (Kovats and Brisley, 2021), high VOC concentrations will presumably become more common in residences. As an individual's exposure to VOCs is driven by the indoor environment (e.g. Wallace (1989), a reduction in residential VOC concentrations is likely to significantly reduce total exposures of the general public, and especially of vulnerable groups (e.g. children – RCPCH (2020)) that spend the most time in the residential environment.

Previous reviews on VOCs have often focused on sources and emission rates, reporting emissions as TVOCs, a metric that sometimes is used as an indicator of IAQ. (Yu and Crump, 1998), for example, reviewed the available information about the TVOCs emissions rates from polymeric materials widely used in construction, decorating and furnishing of homes, offices, schools and other non-industrial work-places (e.g. adhesives, sealants, furnishings and thermal insulants, wood-based products, household products and treatments for stone and masonry). Brown et al. (1994) reviewed TVOC source emission rates for construction materials and both “wet” (e.g. furniture spray polish) and “dry”(e.g. plywoods) household products.

It is far less common for reviews to report source, emission and concentration data for individual VOCs: Brown et al. (1994) summarised the concentrations of VOCs across several indoor environments with measurements from the US and Europe. This is a powerful summary, and provides a robust methodology for summarising concentrations, however, it is based on data that is nearly thirty years old and in the intervening years many new products and chemicals have entered the marketplace, several chemicals previously widespread in consumer products may now be subject to restrictions or bans and heating sources in households have changed. Destaillats et al. (2008) reviewed and evaluated detailed emissions of individual volatile and semi-volatile organic compounds (VOCs and SVOCs - a subgroup of VOCs that have boiling points of 260 °C–400 °C) from distributed office equipment (e.g. personal computers, printers), which are in close proximity to many users and are a potential source for exposure in the workplace. Similarly, Cacho et al. (2013) reviewed the emissions of air pollutants, including VOCs from electronic equipment in the office environment and concluded that office electronic equipment (i.e. computers, printers, photocopiers) emit variable quantities of VOCs, carbonyl compounds and particulate matter. With the increase of computing equipment (including laptops, tablets, PCs and game stations) in homes and also the current conditions of working from home, this is relevant also for the residential environment. However, the source apportionment for the majority of these pollutants in modern offices is quite difficult, due to the variety of sources. Sarigiannis et al. (2011) provided a more recent review of VOCs concentrations in European indoor environments and their impact on health, however, the chemicals studied were limited to nine VOCs (benzene, toluene, xylenes, styrene, formaldehyde acetaldehyde, limonene, naphthalene, a-pinene), identified by the European Commission's INDEX strategy report as the priority pollutants requiring regulation (Kotzias et al., 2005).

From a public health perspective, WHO (2021) identified 15 VOCs among 17 priority chemicals at schools in the framework of a screening tool for the assessment of the risk of combined exposure to hazardous chemicals, namely: formaldehyde, acetaldehyde, benzene, ethylbenzene, xylene (*o*, *m*, *p*,), styrene, toluene, 1,2,3 trimethylbenzene, 1,4 dichlorobenzene, butyl acetate, limonene, α-pinene, tetra- and tri-chloroethylene and naphthalene. These chemicals were identified by considering the likelihood of the presence of each chemical in indoor air in public settings for children, the availability of toxicological information on each chemical and their potential contribution to health risk at concentrations commonly observed in indoor air.

It is evident that many of these existing reviews are outdated, are focussing on multiple indoor environments, without, however, detailing the full range of VOCs present. Importantly, they are not specific to residential environments, and are not looking to identify collectively the sources, emissions and concentrations of the most frequently occurring and harmful VOCs.

The aim of this work is to identify literature, through means of a systematic review, on the concentrations of all individual VOCs measured in European residences, to look at their sources, and where possible, their emission rates, and to report the associated health effects from exposure to individual VOCs. To the best of our knowledge, such a detailed review of individual VOC concentrations in the indoor residential environment together with their emissions and associated health effects have not yet been reported. This is a continuation of our previous work (Shrubsole et al., 2019) that identified, but not systematically, the most abundant VOCs in homes and offices. The collected data will provide a valuable resource as an input for modelling tools both in terms of assessing exposure to individual VOCs in the home environment and also of providing information on sources-tracers for indoor air source apportionment studies.

Therefore, following a systematic literature review, this paper initially presents the VOCs measured in European, including UK, residences, along with a summary of their health effects and sources and a proposed ranking according to their health effects (Sections 3.1 and 3.2). Their health endpoints (effects on respiratory, nervous, and cardiovascular systems, allergenic sensitization and carcinogenicity) are then discussed in detail (Section 3.3), whereas the emission factors of individual VOCs emitted from construction materials, consumer products and during space heating are finally presented (Section 3.4).

2. Materials and methods

2.1. Search strategy: inclusion criteria and selection

The review followed the PRISMA methodology (Moher et al., 2009). A systematic search was conducted using the Global Health, Scopus and Environment Complete online databases. A search strategy was developed with key terms to explore the literature, restricted by publication language (English) and date (2000 – 2020). The search was designed to capture evidence on concentrations, emissions from indoor sources, and health effects for both VOCs and SVOCs (volatile and semi-volatile organic compounds respectively). This paper focusses on VOCs, with SVOCs being the focus of a forthcoming study (Part II) on indoor chemicals.

The search strategy was divided into three categories reflecting the following concepts:

- Identification of the individual VOCs and their concentrations in homes.
- Their health effects.
- Their indoor sources and emission rates.

Using this framework, an initial search was conducted, and further terms were identified and included in the final search. The exact search strings used are detailed in Appendix A.

To identify only literature relevant to the aims of this investigation, the following inclusion criteria were applied; the study must (a) contain monitoring or modelling studies on VOC concentrations, sources or emissions and health effects, in residential environments, but also in laboratory or environmental chambers, for estimating the emission rates and (b) the residential environment, laboratory or environmental chamber must be situated in a European country, to capture the impact of chemical strategies / policies in Europe. Residential environments were defined as houses or flats; other types of residences (e.g. care homes and student housing) were excluded. (c) papers presenting only TVOCs and not individual VOCs were excluded. As well as meeting the more general inclusion criteria, the selected papers needed to use an established measurement technique i.e. no low-cost measurements were considered. Note that terms related to tobacco smoke and vaping were not included in the final search string.

The search resulted in 4389 papers after duplicates were removed. The titles and abstracts were screened independently by four reviewers, and 3075 papers removed for not meeting the scope. The second round of abstract and title screening was conducted independently by four reviewers and removed an additional 914 papers. 400 full texts were examined and were divided into the three categories under consideration (concentrations, sources/emission rates and health effects, with some papers fitting into multiple categories). Once divided, the full text of each paper was screened; 92 papers were selected for further analysis and any useful information was extracted. Further details on the methodology followed is given below, whilst an overview of the methodology followed is given in Fig. 1.

The focus of this review is on inhalation exposure, following the WHO (2021) approach for schools. Dermal exposure and ingestion were considered out of scope for this work.

The papers identified through the search string were reviewed to identify health effects from the identified compounds. Epidemiological, in vitro and in vivo (both human and animal) studies were identified within papers for some of the compounds however not for all. Therefore, grey literature sources were used to inform potential health impacts from inhalation

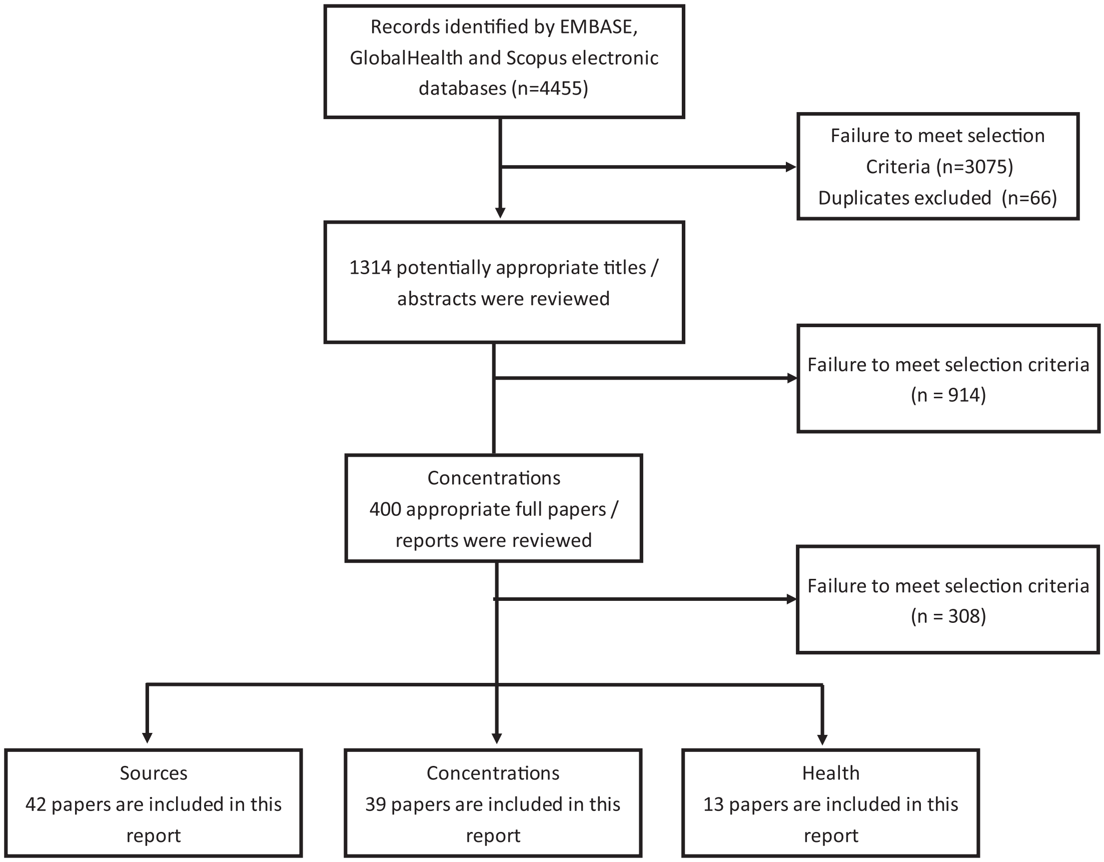

Fig. 1. PRISMA diagram of the search process.

studies including respiratory, cardiovascular, neurological, carcinogenic and irritant effects. Sources of the grey literature included toxicological profiles and summaries that have been used to develop guideline values and critical endpoints from recognised international organisations, such as: the WHO (2010) IAQ Guidelines, the Agency for Toxic Substances and Disease Registry (ATSDR), US Environmental Protection Agency (Integrated Risk information System (IRIS), Public Health England's IAQ Guidelines for Selected VOCs (PHE, 2019) and Compendium of Chemical Hazards (PHE), Health Canada (2017), European Chemical Agency (ECHA), and European Commission EU-LCI values for building materials, INDEX for consumer products (Kotzias et al., 2005).

For each paper identified by the systematic review that fitted into the sources/emissions category, the methods of analysis used for the identification/ quantification of the VOC emissions were considered to address reproducibility and robustness concerns. To establish a greater range of possible VOC sources occurring in the residential environments, data from the following organisations were also utilized to support the information given in the papers: European Chemicals Agency (ECHA), the World Health Organization (WHO), United States Environmental Protection Agency (US EPA), the National Institute for Public Health and the Environment (RIVM, Netherlands).

2.2. Defining a metric for the VOCs concentrations

Measured VOCs in European residences were identified (see Section 3) and their average concentrations were estimated by combining the results extracted from different sources. Brown et al. (1994) provides a robust methodological framework for calculating a Weighted Average Geometric Mean (*WAGM*) concentration, which allows for many measurements to be condensed into a single metric. Being harmonised in this way, this metric enables their ranking, in terms of their abundance, i.e. concentration levels.

Using the Brown et al. (1994) methodology, it is first necessary to convert the statistical values of the reported concentrations into a comparable format. Concentrations are typically reported as geometric means (*GM*), arithmetic means (*AM*), unspecified means or medians. For this type of analysis, geometric means are the most useful, as they are less skewed by outliers than arithmetic means. VOC concentrations below the limit of detection were not included. All the extracted concentrations were converted to geometric means where necessary. Medians were used as an estimate of geometric means. Arithmetic means (including unspecified means which were assumed to be arithmetic means) were converted to geometric means using the following formula:

$$GM = \left(\frac{AM}{\sqrt{1 + CV^2}}\right) \quad (1)$$

where CV is the Coefficient of Variation assigned with a value of 1.53, which was estimated from the assumption that VOC concentrations are log normally distributed with a Geometric Standard Deviation (GSD) of 3.0, (Brown et al. (1994); Jia et al. (2008); Yang et al. (2020)):

$$\log_e GSD = \sqrt{\log_e(1 + CV^2)}$$

Once converted to geometric means, the average for individual VOCs were weighted based on the number of samples (or repeats, as named within the papers) collected. Therefore, the *WAGM* concentration can be calculated as follows:

$$\log_e WAGM = \frac{\sum N_i \log_e GM_i}{\sum N_i} \quad (2)$$

with GM_i being the estimated or extracted GM from study i and N_i being the number of samples collected from study i.

It should be noted that this analysis allows for collating measurements from different countries, residence types, and years, which introduces some uncertainty that is not accounted for here.

3. Results and discussion

Following the methodology described in Section 2.1, 39 papers on measured concentrations, 42 papers on sources/emissions and 13 papers on health effects were finally selected. The studies that were selected for each one of the above three categories under consideration are presented in detail in Supplementary Material, as follows: details of studies on measuring VOC concentrations in Table S1, description of epidemiological, in-vivo and in vitro studies in Table S2, and studies on VOC sources/emissions Table S3.

3.1. Identification of the VOCs measured in European residences: Their concentrations, sources and health effects

The largest investigations in this analysis, used for the identification of VOCs measured in European residences, were Schlink et al. (2004) and Rehwagen et al. (2003) in Germany, Raw et al. (2004) in the UK and Kirchner et al. (2008) in France with 2103, 1499, 876 and 567 samples collected, respectively. By country, across all studies the most samples were collected in Germany (4200), the UK (1900) and France (1638 – Table S1). In detail, seven studies were conducted in UK and France, 6 in Germany, 4 in Finland, 2 in Italy, Greece/Cyprus, Poland, Sweden and Lithuania, and 1 study in Portugal, Romania and Switzerland. 2 studies reported samples collected in several European countries (The Netherlands, Greece, Belgium, Hungary, Ireland, Finland, Germany, Italy, Cyprus and Turkey). The AIRMEX (Geiss et al., 2011) and EXPOLIS (Jantunen et al., 1998) databases represent the two largest European campaigns to measure VOCs indoors. As seen in Table S1, the studies typically used passive samplers with a duration from 24 h to several weeks. For shorter sampling times <24 h, studies used active sampling, where a pump draws air through the sampler. The VOC concentrations in the samples were typically analyzed using gas chromatography with flame ionization (FID), electron capture (ECD) or mass spectrometry (GC–MS) detection.

Sixty-five individual VOCs were identified through measurements in European residences and are presented in Table 1 along with the calculated Weighted Average Geometric Mean (*WAGM)* (calculated as described in Section 2.2). The most commonly identified/measured VOCs were aromatics (14 compounds), alkanes (9), aldehydes (8), terpenes (6), chlorinated (4), and aliphatic (5) hydrocarbons, glycol and glycol ethers (3) and esters (2). Alicyclic hydrocarbons, aliphatic alcohols, chloroethanes, heterocyclics, hydrocarbons, ketones, polycyclic aromatic hydrocarbons and aromatic heterocyclics were also identified in European homes but occur less frequently. *WAGM* concentrations ranged between 92 μg m^{-3} (ethanol) and 0.1 μg m^{-3} (3-ethenylpyridine). 9 chemicals (ethanol, formaldehyde, toluene, limonene, hexaldehyde, α-pinene, butane, acetone and acetaldehyde) were found to be the most abundant in European residences having *WAGM* more than 10 μg m^{-3}, whereas 16 had *WAGM* less than 1 μgm^{-3} (3-ethyltoluene, 2-ethyltoluene, acrolein, styrene, propylbenzene, tetrachlorocarbon, trichloroethane, *p*-isopropyltoluene, trichloroethylene, naphthalene, chlorobenzene, methylbenzoate, 1,3,5- Trimethylbenzene, pyridine, 1,3-butadiene, 3-ethenylpyridine). In some studies, the following VOCs were reported below the limit of detection: *p*-isopropyltoluene and 1,4-dichlorobenzene (Kim et al., 2001), 1-octanol, phenol, cyclohexane, hexane, trichloroethene, tetrachloroethene, 1,1,2-trichloroethane, 1-methyl-2-pyrrolidinone (Edwards et al., 2001; Lai et al., 2004), naphthalene, *o*-xylene, styrene, 1-butanol, 2-methyl-1-propanol, 2-ethyl-1-hexanol, 2-butoxy-ethanol, (Lai et al., 2004), 2-butoxy-ethylacetate, 1-methoxy-2-propylacetate (Kirchner et al., 2008; Billionnet et al., 2011). In Baya et al., (2004) 50% of trichloroethylene concentrations were low or below the detection limit in most air samples.

For the 65 identified VOCs, we looked at the health effects following inhalation of the VOCs reported in the papers presented in Table S2. Using both human and animal studies, the adverse effects are: respiratory (related to impacts on the lungs including coughing), irritation (eyes or upper respiratory tract), cardiovascular, neurological and carcinogenic. These are the same adverse effect endpoints as used in the WHO (2021) work for schools. For each of the 65 identified VOCs, the health effects reported in animal and human inhalation studies in acute, short-term, sub-chronic and chronic timeframes are summarised in (Table S4). Whilst undertaking indoor VOC

Table 1
Individual Volatile Organic Compounds (VOCs) identified through measurements in residences and their calculated Weighted Average Geometric Mean (*WAGM*).

VOC	*WAGM* (μg/m³)	VOC	WAGM (μg/m³)	VOC	*WAGM* (μg/m³)
Ethanol	92.00	Isobutane	4.01	1-Methoxy-2-propanol/propylene glycol methyl ether (PGME)	1.35
Formaldehyde	18.04	2-Ethylhexanol	3.70	4-Ethyltoluene	1.33
Toluene	15.90	Dodecane/*n*-dodecane	3.69	2-Butoxyethanol	1.26
Limonene [inc. D-limonene]	13.65	Hexane/*n*-hexane	3.66	2-Carene	1.10
Hexanal/hexaldehyde/hexanaldehyde	13.30	Heptane/*n*-heptane	3.45	Methyl-cyclopentane	1.04
α-pinene	12.10	Trimethylbenzene (including 1,2,4- Trimethylbenzene)	3.22	Isopropanol	1.00
Butane	12.00	Cyclohexane	2.99	3-Ethyltoluene	0.98
Acetone	11.40	2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (tpddib/TXIB)	2.94	2-Ethyltoluene	0.94
Acetaldehyde	10.14	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (tpdmib/texanol)	2.78	Acrolein	0.92
2-Methyl-1-propanol	8.20	Tetracholorethane	2.68	Styrene	0.82
2-Methylbutane	7.80	Methyl-cyclohexane	2.68	Propylbenzene	0.80
1-Butanol	6.16	Tetrachloroethylene/tetrachloroethene	2.24	Tetrachlorocarbon	0.80
Butylbenzene	5.72	Nonane	2.21	Trichloroethane	0.73
Decane/n-decane	5.27	Benzene	1.99	*p*-Isopropyltoluene/*p*-cymene	0.56
m + *p*-Xylene	4.57	Ethylbenzene	1.84	Trichloroethene/trichloroethylene	0.53
Undecane/n-undecane	4.38	Propanal/proprionaldehyde	1.80	Naphthalene	0.50
3-Carene	4.38	Tridecane	1.77	Chlorobenzene	0.42
Pentanal	4.34	Pentane	1.69	Methylbenzoate	0.33
2,2,4 Trimethylpentane	4.33	*o*-Xylene	1.57	1,3,5- Trimethylbenzene	0.33
Octanal	4.30	*α*-Pinene	1.56	Pyridine	0.12
Ethyl acetate	4.30	Benzaldehyde	1.55	1,3-Butadiene	0.11
p-Dichlorobenzene	3.90	Octane	1.54	3-Ethenylpyridine/3-vinylpyridine	0.06

measurements, several papers (Clarisse et al., 2003; Dallongeville et al., 2016; Dassonville et al., 2009) asked inhabitants to complete questionnaires. The questionnaires primarily focused on characteristics and content of the building and activities undertaken (e.g. cleaning, heating, smoking). However, some of the papers included questions on symptoms and perceived air quality and these have also been included in Table S4.

Chemical families with the most identified health effects are the most represented in the list of VOCs measured in European residences (Tables 2 and S6): thus for example, aromatic hydrocarbons, a chemical family with 14 individual VOCs measured in European residences, has the most singly identified health effects from all categories (Table S4). As the pathway of interest was inhalation several chemicals were expected to be associated with respiratory health effects: this was confirmed for 8 individual aromatic hydrocarbons, 7 alkanes and 6 aldehydes measured in European residences. On the other hand, some chlorinated hydrocarbons (tetrachloroethylene and trichloroethylene), esters (ethyl acetate, methylbenzoate), some terpenes (α- and β-pinene, limonene), acetone, 2-butoxyethanol, pyridine, and ethenylpyridine were found to be irritants. Some chlorinated hydrocarbons were also associated with cardiovascular (trichloroethylene and trichloroethane), neurological (tetrachloroethylene, tetrachloroethane, trichloroethylene and trichloroethane), and carcinogenic effects (tetrachloroethylene, tetrachloroethane and trichloroethylene). Trichloroethylene was the only chemical identified to have health effects in all five health end-points. In Section 3.3 the association of health effects with individual VOCs are discussed in greater detail.

Of the 65 individual VOCs commonly found in European residential microenvironments (Table 1), 52 (80%) were identified to have sources associated with building and construction materials (e.g. brick, wood products, adhesives and materials for flooring installation etc.). 41 (63%) individual VOCs were linked with consumer products (passive, electric and combustible air fresheners, hair sprays, deodorants) with 19 of these VOCs specifically associated with candle and incense burning (Fig. 2). Nine VOCs (14%), were associated with space heating, reflecting the relatively few studies discussing emissions from this category of sources (Table S3). All source categories (i.e. construction and building products, consumer products and space heating) emit aldehydes and ketones, whilst particular VOC families abundant in the residential microenvironments are more associated with specific source categories, e.g. cleaning materials with halogenated organic compounds.

3.2. Ranking of individual VOCs based on their health effects

Given the large number of individual VOCs, and in the interest of space we will discuss here the 17 most health relevant VOCs (Table S4), according to their adverse-effect endpoints (i.e. respiratory, irritation of the upper airway system and eyes, cardiovascular, neurological and carcinogenic – Section 3.3) and the number of studies reporting their concentrations (Table S5). These chemicals are: trichloroethylene which is associated with health effects in all five categories of adverse-effect endpoints; tetrachloroethylene, 2-methylbutane, tetrachlorocarbon, benzene, ethylbenzene, $m + p$-xylene, o-xylene, styrene, toluene, trimethylbenzene, acetone, associated with health effects in four of the adverse-effect categories; acetaldehyde, formaldehyde and naphthalene associated with health effects in three adverse-effect categories. α–pinene and limonene are included in this list: even though they are only associated with irritation, they are clearly characterized as high priority chemicals by a number of studies summarised in Shrubsole et al. (2019).

Table 2 summarizes the above identified individual 17 VOCs, their sources (derived from Table S3) and the associated health end-points (derived from Table S4). We also considered in this summary the sources and health effects reported by various organisations and databases (as discussed in Section 2.1). The remaining VOCs, their sources and health effects are presented in the Supplementary Material (Table S6 - complementary to Table 2).

Widely used building and construction materials (e.g. composite boards, paints and coatings) are included in the sources found for eleven of these chemicals (benzene, ethylbenzene, xylenes, styrene, toluene, acetone, acetaldehyde, formaldehyde, trimethylbenzene, naphthalene, α-pinene and limonene); and very commonly used consumer products, other than burning candles and incenses, such as cleaning agents are the sources for acetone, formaldehyde, naphthalene, α-pinene, limonene, trichlorocarbon, benzene, ethylbenzene and xylenes. 5 of the 17 chemicals included in this list are emitted from all four categories of indoor sources: benzene, toluene, acetone, acetaldehyde and formaldehyde.

The following sections discuss more explicitly the results for the above VOCs, in terms of concentrations and health effects, as well as emissions and their sources.

3.2.1. Results and discussion on the selected VOC concentrations

Fig. 3 illustrates the ranked WAGM concentrations and minimum and maximum geometric mean values across the samples and studies for the 17 selected VOCs. Of these, formaldehyde had the highest *WAGM* (17.4 $\mu g\ m^{-3}$) and naphthalene the lowest (0.5 $\mu g\ m^{-3}$). Formaldehyde, toluene, limonene, α-pinene and acetone were found to be the most abundant chemicals in European residences with concentrations higher than 10 $\mu g\ m^{-3}$, whilst styrene, tetrachlorocarbon, trichloroethylene and naphthalene were the least abundant with concentrations less than 1 $\mu g\ m^{-3}$. Specific chemicals demonstrate a broad range of geometric mean concentrations across studies e.g. minimum and maximum values cover almost two orders of magnitude for limonene (3.40 $\mu g\ m^{-3}$ and 197.8 $\mu g\ m^{-3}$) and α-pinene (0.8 $\mu g\ m^{-3}$ and 157 $\mu g\ m^{-3}$). These results should be treated with some caution as the magnitude of the range to some extent depends on the number of samples included in the calculation – and therefore on the number of studies included in this review: weak but statistically significant ($p < 0.01$) correlations (r) exist between the calculated concentration's range, the number of studies ($r = 0.29$) and the number of samples ($r = 0.38$) included in the calculations. No-significant correlations were found between the *WAGM* and number of samples ($r = -0.08$) and studies (($r = 0.05$).

The results found in the present study for benzene, toluene, xylenes, styrene, formaldehyde acetaldehyde, limonene, naphthalene, and α-pinene were compared with the values found in Sarigiannis et al. (2011). The methodology described in Section 2.2 was applied on data from residences reported in this latter study and the calculated *WAGM* are shown in Fig. 3. Higher *WAGMs* for toluene, α-pinene, acetaldehyde, benzene, styrene, naphthalene, $m + p$- and o-xylene were found in the present study compared to Sarigiannis et al. (2011) values corresponding to an average increase of 17%. A 14.4% decrease in formaldehyde *WAGMs* was observed, potentially reflecting its classification as a human carcinogen in the National Toxicology Program 12th Report on Carcinogens (2011). This is further confirmed by a moderate negative correlation ($r = -0.393, p < 0.01$) between formaldehyde concentrations and time of publication (Fig. 4), indicating a clear negative trend for formaldehyde concentrations during the last 20 years. A decrease of 11% was observed for limonene *WAGMs*, probably also reflecting concerns raised on its presence above certain levels in some products. For example the European Cosmetics Directive requires manufacturers of cosmetics and personal care products to indicate the presence of certain “allergenic” substances: when Limonene concentration exceeds 0.001% in leave-on the skin products or 0.01% in products that are rinsed off the skin it must be indicated in the list of ingredients (European Parliament, 2009).

The data utilized in Sarigiannis et al. (2011) were published between 1990 and 2008 and the data reviewed here between 2000 and 2020. It could be argued therefore that at least to some extend the results presented above, reflect changes in the concentrations of the abovementioned pollutants in European residences during the last few decades. In general, this conclusion should be treated with caution however, as papers published during 2000–2008 were included both in Sarigiannis et al. (2011) and the present study.

The list presented in Table 2 and Fig. 3 includes all 15 VOCs that were identified by WHO (2021) as priority chemicals within the framework of a screening tool for assessment of the risk of combined exposure to hazardous chemicals in schools. Following the discussion in Section 3.2, it is

Table 2
Most health relevant and commonly measured VOCs identified in European residences: their sources and health effects.

Chemical	Chemical family	Sources	Health effects following inhalation				
			Resp	CV	Neuro	Carc	Irr
Acetaldehyde	Aldehyde	Concrete/screed with and without PVC covering, wooden flooring and battens, composite board (MDF, chipboard), plywood, skirting board, expanding foam, finishing plaster, ceiling tiles, gypsum, plaster, vinyl and ingrain wallpaper, polyurethane adhesive mastic, wallpaper paste, latex and dispersion paints, Carpet (nylon with PVC backing), fragranced and unfragranced jar candles, burning stick incense, typical domestic wood stoves, kerosene space heaters, ethanol fireplaces	Y	N	N	Y	Y
Acetone	Ketone	Solid wood (pine, oak, beech), plywood, composite board (MDF, chipboard, OSB), fireboards from coriander biorefinery, glue for wallpaper, finishing plaster, linoleum, silicone, expanding foam, ceiling tile, gypsum board, veneered particle board (UV curing lacquer), surface sprays, glues, burning stick incense, electric air fresheners, kerosene space heaters, ethanol fireplaces, cleaning agent, cosmetics, flea sprays	Y	Y	Y	N	Y
Benzene	Aromatic hydrocarbon	Gypsum board, commercially-available floor coverings (made of PVC or with polypropylene or polyamide fibres), low density polyethylene, polyurethane foam, carpet glue, scatter rugs, solvent-based cleaning and painting products (acrylic and water based paints, matt emulsion), burning fragrance jar candles and burning stick incense, kerosene space heaters, fireplaces with liquids, wood-burning fireplaces	N	Y	Y	Y	Y
Ethylbenzene	Aromatic hydrocarbon	Materials for floor coverings (PVC, linoleum, rubber, polyolefin), gypsum board, Carpet, plywood, polyurethane foam and adhesive mastic, solvent-based cleaning and painting products, solvent and water based interior coating, carpet glue, burning stick incense, candles	Y	N	Y	Y	Y
Formaldehyde	Aldehyde	Composite board (MDF, particleboard), plywood, gypsum board, ceiling tiles, sound insulators, polyurethane adhesive mastic, vinyl and ingrain wallpaper, expanding foam, glue for wallpaper, sealing plaster, finishing plaster, wallpaper paste, latex and dispersion paint, machine wash liquids/detergents, paints and coating, adhesives, furniture and carpets, fragrance and unfragranced jar candles, burning stick incense, shampoo, shower gel, body lotion, facial moisturizer, hair styling gels, deodorants, hair conditioners, typical wood stoves, kerosene space heaters, ethanol fireplaces. Used in adhesives and sealants, coating products, fillers, putties, plasters, modelling clay, inks and toners, polymers, fuels, biocides (e.g. disinfectants, pest control products), polishes and waxes, washing & cleaning products and cosmetics and personal care products.	Y	N	N	Y	Y
Limonene [inc. D-limonene]	Terpene	MDF, particle boards (veneered and unveneered), adhesive for flooring installation, paints, multipurpose coating products, solvent and water-based interior coatings (polishes and waxes), biocides (e.g. disinfectants, pest control products), shampoos, shower gels, moisturizers, conditioners, passive diffusers, electric evaporators, burning wood-sticks, automatic sprays, cleaning agents	N	N	N	N	Y
m + *p*-Xylene	Aromatic hydrocarbon	Wooden Flooring, furfurylated solvent-based cleaning and painting product (solvent-based and water-based interior coating), polyurethane foam, medium density board, commercially available candles, machine wash liquids/detergents, paints and coating, adhesives. Used in lubricants and greases, polishes and waxes, adhesives and sealants, antifreeze products and biocides (e.g. disinfectants, pest control products), and close systems (e.g. cooling liquids in refrigerators, oil-based electric heaters).	Y	Y	Y	N	Y
Naphthalene	Polycyclic aromatic hydrocarbon	Materials for floor coverings (PVC, linoleum, rubber, polyolefin), polyurethane foam, insecticide or pest repellent, fragrance jar candles, wax candles, anti-mosquito incense sticks, solvent-based cleaning and painting products, moth repellents	Y	N	Y	Y	N
o-Xylene	Aromatic hydrocarbon	Wooden flooring, furfurylated solvent-based cleaning and painting product (solvent-based and water-based interior coating), commercially available candles, machine wash liquids/detergents, paints and coating or adhesives. Used in lubricants and greases, polishes and waxes, adhesives and sealants, antifreeze products and biocides (e.g. disinfectants, pest control products), and close systems (e.g. cooling liquids in refrigerators, oil-based electric heaters).	Y	Y	Y	N	Y
Styrene	Aromatic hydrocarbon	Wooden flooring, materials for floor coverings (PVC, linoleum, rubber, polyolefin), polyurethane foam and adhesive mastic, rubber and epoxy adhesives, medium density board, carpet (Nylon and polypropylene w SBR adhesive), polystyrene foam, solvent-based cleaning and painting products, solvent and water - based interior coating, machine wash liquids/detergents, burning fragranced and unfragranced paraffin wax jar candles, burning incense stick, paints and coating or adhesives. Used in fillers, putties, plasters, modelling clay and coating products.	Y	N	Y	Y	Y
Carbon tetrachloride/tetrachlorocarbon	Chlorinated hydrocarbon	Cleaning agents	Y	Y	Y	Y	N
Tetrachloroethylene [Tetrachloroethylene]	Chlorinated hydrocarbon	Writing utensils containing liquid or gel ink. Cleaning products for general household cleaning, products used to clean glass, mirrors, and windows. Paint or stain related products. Leave-on masks or peels for treatment of the face. Shampoos, including dual shampoo/conditioner products. Metal cleaning and degreasing agents, dry cleaning, polyester and PVC heating bags.	Y	N	Y	Y	Y
Toluene	Aromatic hydrocarbon	Materials for floor coverings (PVC, Linoleum, Rubber, Polyolefin), carpet backing, polyurethane foam, vinyl flooring, carpet backing, gypsum board, medium density board, polishes (e.g. nail polish), synthetic fragrances, paints, adhesives, sealants, anti-freeze products, carpet backing, vinyl flooring,	Y	Y	Y	N	Y

(continued on next page)

Table 2 (*continued*)

Chemical	Chemical family	Sources	Health effects following inhalation Resp	CV	Neuro	Carc	Irr
		non-metal surface treatment products, carpets, general furnishing, biocides (e.g. disinfectants, pest control products), textile treatment products and dyes, leather treatment products, cellulose fiber and fibrous glass, machine wash liquids/detergents, burning stick incense and candles, inks and toners. Used in close systems like cooling liquids in refrigerators, oil-based electric heaters					
Trichloroethylene	Chlorinated hydrocarbon	Refrigerant and heat-exchange liquid; fumigant; cleaning and drying electronic parts; diluent in paints and adhesives; textile processing. Used as household cleaner; with trichloroethane it is used in most typewriter correction fluid.	Y	Y	Y	Y	Y
Trimethylbenzene [1,2,4-Trimethylbenzene + 1,3,5-Trimethylbenzene]	Aromatic hydrocarbon	Materials for flooring coverings (PVC, linoleum, rubber, polyolefin)	Y	ND	Y	N	Y
α – Pinene	Terpene	MDF, chipboard (both veneered and unveneered), adhesives for flooring installation, nylon carpet PVC, solvent-based interior coatings, passive diffusers, burning wood-sticks, automatic sprays, electric air fresheners, perfumes, cleaning products and deodorants.	N	N	N	N	Y
2-Methylbutane [isopentane]	Alkane	Fuels, perfumes, fragrances. Cosmetics and personal care products. Other release to the indoor environment: machine wash liquids/detergents, paints and coating or adhesives, air fresheners, in close systems with minimal release (e.g. cooling liquids in refrigerators, oil-based electric heaters).	Y	Y	Y	ND	Y

Y: Health effects associated with the VOCs have been reported for this end-point; **N**: It has been reported that no health effects are associated with the VOC for this end-point.
ND: No health effects related with this end-point have been reported for this VOC.
Resp: Respiratory effects; **CV**: Cardiovascular effects; **Neuro**: Neurological effects; **Carc:** Carcinogenic risk; **Irr:** irritant effects.

perhaps not surprising that the most well studied VOCs, based on the number of studies reporting their concentrations (Table S5), are included in the list of 17 VOCs in the present study: e.g. benzene, toluene, m + p-xylene, and formaldehyde are mentioned in 23, 23, 22 and 21 papers, respectively. Of the three VOCs in the present study that were not included in the WHO list of priority chemicals, 2-methylbutane and tetrachlorocarbon are reported in only one paper (Yang et al. (2020) and Sakai et al. (2004), respectively), and acetone only in four papers (Bartzis et al., 2008; Geiss et al., 2011; Jurvelin et al., 2003; Yang et al., 2020) Tetrachlorocarbon *WAGM* concentrations were low (0.8 μg m^{-3}), but high values were observed for 2-methylbutane and acetone (7.8 μg m^{-3} and 11.4 μg m^{-3}, respectively). These VOCs are discussed in the following paragraphs.

The Yang et al. (2020) study reported measurements conducted in 169 energy-efficient dwellings in Switzerland, and it was suggested that 2-methylbutane concentrations infiltrated indoors from the attached garages. Indoor tetrachlorocarbon values reported in Sakai et al., 2004, were slightly higher than outdoors (geometric mean 0.83 μg m^{-3} and 0.67 μg m^{-3} respectively, $p < 0.01$), but it was unclear what indoor sources contribute to tetrachlorocarbon in this case.

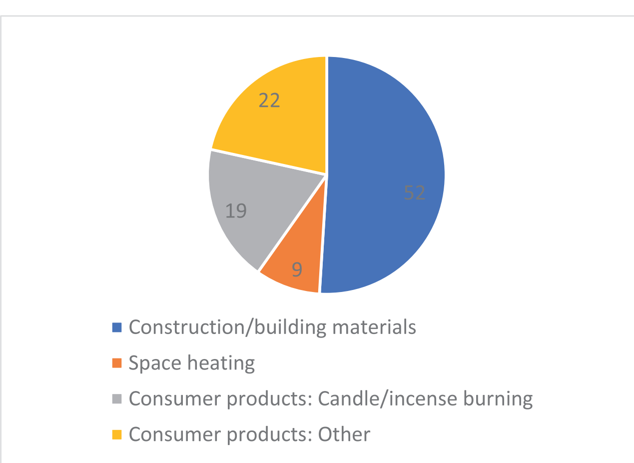

Fig. 2. Categorization of sources for the 65 identified VOCs in the European residences.

Abundant acetone concentrations were reported in Yang et al. (2020) (in 169 houses in Switzerland), Jurvelin et al. (2003) (in 15 houses in Helsinki metropolitan area), and Bartzis et al. (2008) (in 2 houses in Greece and Cyprus); In Geiss et al. (2011) study acetone was found to be the most abundant chemical among 23 VOCs measured in 88 houses across Europe and similar results were obtained in a recent study (published in 2021, and therefore not included in this review), where acetone was among the most abundant VOCs measured in 60 houses in UK (Heeley-Hill et al., 2021). Given that acetone is emitted from a variety of building and construction materials (solid wood, composite boards, finishing plaster, linoleum, silicone, expanded foam, ceiling tiles, surface sprays, glues), consumer products (burning incense sticks, electric air fresheners, cleaning agents, cosmetics, flea sprays), kerosene space heaters and ethanol fireplaces commonly used in residences, high residential acetone concentrations are to be expected.

3.3. Health effects of the individual VOCs

3.3.1. Respiratory

Two studies (Venn et al., 2003; Madureira et al., 2016) focused on the relationships between infant/child exposures to specific VOCs and associated respiratory health effects. In a UK case control study that reported on traffic pollution and wheezing in children (Venn et al., 2003), the risk of wheezing (a) was found to significantly increase with damp levels (OR = 1.32 (95% confidence interval 1.00 to 1.75) and (b) was unrelated to other measured exposures. However, the frequency of the reported night-time wheezing symptoms was significantly associated with formaldehyde levels and damp in the bedroom, kitchen and living room. The effects of formaldehyde and living room mould were increased for atopic cases, but no effect was observed in non-atopic cases. There was no evidence of associations between persistent wheeze and either the total VOC or formaldehyde concentrations. Moreover, in a study conducted in children's bedrooms where formaldehyde and acetaldehyde concentrations were measured below the WHO guidelines in Portugal, Madureira et al. (2016) no differences were found between VOC exposures in two groups of asthmatic and non-asthmatic children. Interestingly, higher D-limonene concentrations were measured in the dwellings of the non-asthmatic children, which was attributed to using less of limonene-emitting cleaning products in the homes of asthmatic children or higher flow rate of outdoor air as there was no significant statistical difference in the cleaning frequency.

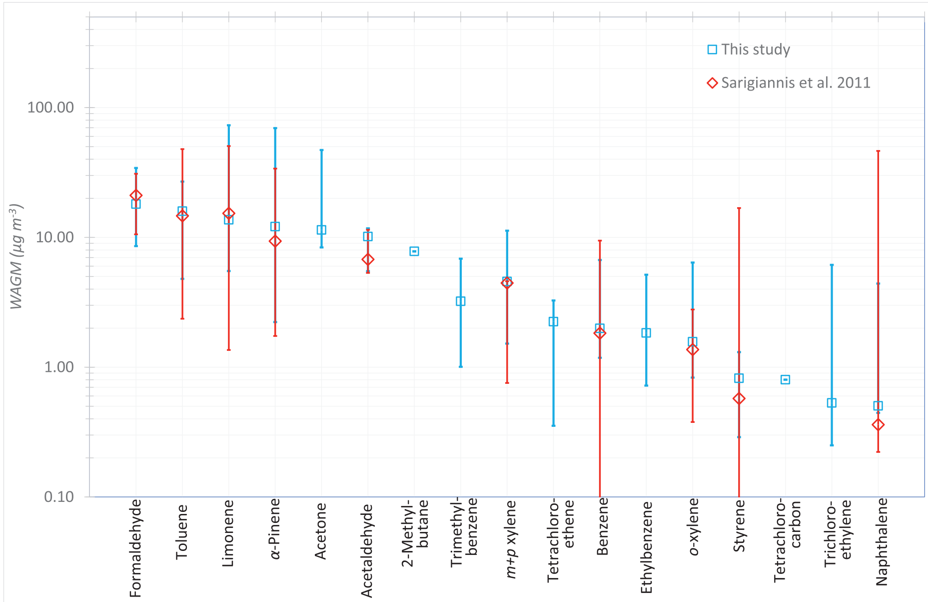

Fig. 3. Concentrations of selected VOCs in residences, with each point representing a weighted average geometric mean concentration (μg m^{-3}). Error bars indicate geometric mean concentrations' minimum and maximum values. Note that vertical axis is presented on a logarithmic scale.

Some studies reported links between exposure to individual VOCs, as a result of DIY and decorating activities, and respiratory outcomes (Franck et al., 2014; Lehmann et al., 2002; Tuomainen et al., 2003). An analysis that was conducted within the framework of the LINA study (Lifestyle and Environmental Factors and their influence on Newborn Allergy risk birth cohort study - Franck et al. (2014)), focused on the association of respiratory outcomes with VOCs exposures during prenatal and postnatal decoration of a child's nursery. It was found that exposure to increased styrene, ethylbenzene, tridecane, *o*-xylene, octane and 1-butanol concentrations during pregnancy contributed to physician-treated wheeze. During pregnancy and the first year of life, no association was found with bronchitis. However, both the replacement of flooring and the use of dispersion paint during pregnancy were related to an increased risk for obstructive bronchitis (OR 4.39, 95% CI 1.01–19.05; OR 5.46, 95%CI 1.09–27.20, respectively). Installation of new flooring (laminate, wall-to-wall carpet and PVC flooring) placed during pregnancy was found to be associated with physician-treated wheeze (OR 5.20 95% CI 1.77–15.25) especially for children with an atopic disposition.

In another study Lehmann et al. (2002) the relationships between elevated VOC concentrations in, and, associated with activities from painting infants' bedrooms, fitting new carpets, smoking during pregnancy and house restoration was investigated. Significant associations were found between concentrations of hexane, dodecane, tridecane, methylcyclopentane, trichloroethylene and tetrachloroethylene and an elevation or reduction in cytokine producing cord-blood T cells. It was noted that although this study offers evidence that maternal exposure could be associated with altered

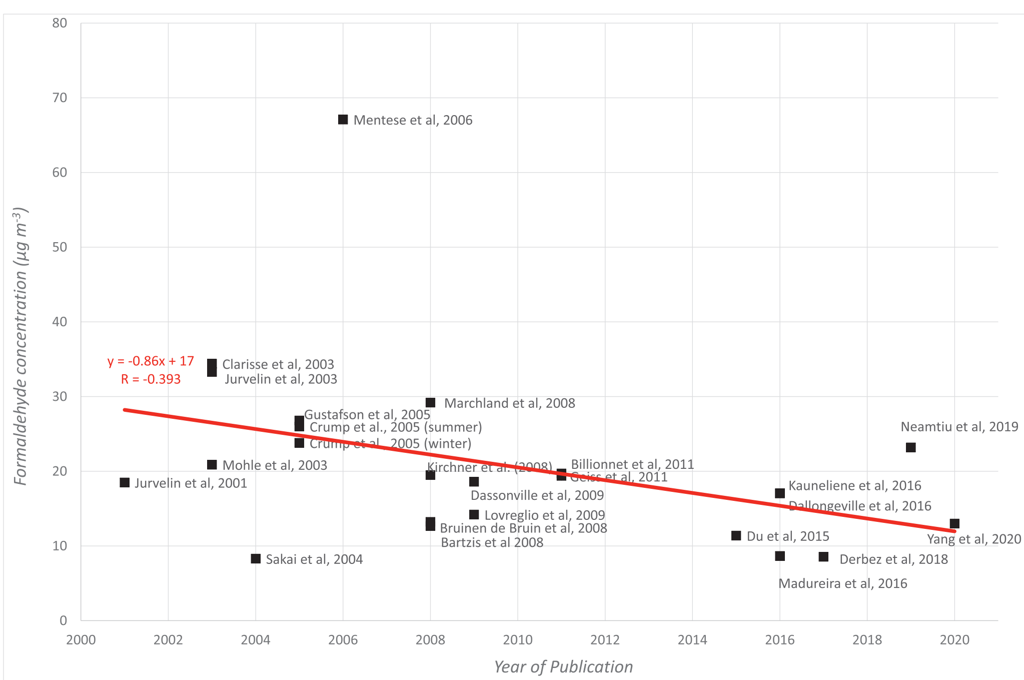

Fig. 4. Reported formaldehyde concentrations (2000–2020). Trend line is also reported.

cytokine secretion profile of cord blood T cells, its clinical relevance is currently unknown.

More generally, the association between symptoms in asthmatic occupants and VOC concentrations measured before, and, 5, 12, 24 and 36 months after the occupancy of a case and a control building was studied in Tuomainen et al. (2003). The case building was built for occupants with respiratory diseases and conformed to the Finnish Classification of Indoor Climate, Construction and Finishing Materials; the control building was built using conventional building materials. The questionnaire completed by occupants included self-reporting of 23 different symptoms (e.g. headache, irritation -nasal, cough and skin - and four questions on allergenic symptoms). It was noted that before moving to the case building, 60% of asthmatics and their families reported upper respiratory symptoms and fatigue. The prevalence of symptoms decreased distinctly among the asthmatic occupants after relocation to the case building: during the first year, only fatigue was reported by asthmatic occupants and their families, and nasal symptoms by the asthmatics alone. Symptoms of the asthmatic occupants in the case building increased in the second and third year with 33–56% reporting symptoms associated with nasal, cough, fatigue, skin and eye. This was only observed in asthmatic occupants. In comparison 22–42% of occupants in the control building reported similar symptoms.

In a review, Dallongeville et al. (2016) noted that several studies report respiratory outcomes (asthma and allergies) as associated to the frequently reported aldehydes within dwellings; and also to compounds such as benzene, 1,2,4-trimethylbenzene, dichlorobenzene, styrene and *n*-undecane. Wheezing was associated with formaldehyde concentrations above 16 $\mu g m^{-3}$, which accounted for 87% of the dwellings monitored. Studies that Dallongeville et al. (2016) discusses include McGwin et al. (2010) and Billionnet et al. (2011). McGwin et al. (2010) noted an association between an increase of 10 $\mu g m^{-3}$ of formaldehyde and childhood asthma. In a national cross-sectional survey of 1013 inhabitants in France, Billionnet et al. (2011) reported a significant association between (a) concentrations of *n*-undecane and 1,2,4-trimethylbenzene above 12.2 and 6.6 μgm⁻3 and prevalence of asthma and (b) ethylbenzene, trichloroethylene, *m/p* and *o*-xylene and rhinitis.

Trantallidi et al. (2015), within the framework of the EU EPHECT project (Emissions, Exposure Patterns and Health Effects of Consumer Products in the EU), referenced several epidemiological studies that were reporting an association between exposure to cleaning and personal care products and respiratory effects. Irritative and respiratory effects were considered during an acute (30 min) and 24 h inhalation exposure to five selected pollutants (acrolein, formaldehyde, naphthalene, limonene and α-pinene) emitted from consumer products used in households. In their assessment, they identified critical effects and derived health based Critical Exposure Limit (CEL) values.

A greater number of infant Eo/B (eosinophils and basophils, blood cells that responds to allergenic inflammation) colony forming units was found in the peripheral blood in children with wheeze that were exposed to environmental pollution (VOCs, tobacco smoke and disinfection products) as part of the LINA study, Hörnig et al. (2016). However, these results do not distinguish the health effects from exposures to VOCs alone, and it was reported that a larger cohort would be required to verify the results.

Wolkoff et al. (2013), used breathing pattern analysis to investigate the exposure effects of terpene reaction products inhaled by eight naïve inbred BALB/cA (an albino immunodeficient laboratory bred strain of house mouse) male mice in an exposure chamber. A baseline respiratory parameters period was 15 min followed by 60-min exposure and a 30-min recovery period. Observations were made of the 'time of break' (TB: the time between inhalation finishing and exhalation starting), and an elongated gap was found to act as a specific marker of sensory irritation. Other associated parameters are the time of inspiration (TI, ms), time of expiration (TE, ms) and mid expiratory flow rate (VD, mL/s) and are used for evaluating airflow limitations which may be due to bronchial constriction, mucous accumulation or inflammation of the conducting airways.

Mice were exposed to varying concentrations of 3-Isopropenyl-6-oxoheptanal (IPOH), 4-Acetyl-1-methylcyclohexane (4-AMCH), 4-Oxopentanal (4-OPA), Methyl-5-hepten-2-one (6-MHO) and dihydrocarvone (2-methyl-5-isopropenyl-cyclohexan-1-one, DHC).They concluded that most of these ozone-initiated terpene reaction products should not contribute to symptoms of sensory irritation or pulmonary effects in an indoor environment. However, IPOH may contribute as a sensory irritant and conditions that encourage the formation of 4-OPA should be avoided.

Airway inflammation was not observed in Wolkoff et al. (2012), in cases where mice were exposed to either limonene alone, ozone alone (0.1 ppm) or limonene ozone reaction product (LOP). The details of this study are provided in the irritation section below due to the reporting of irritation. However, Clausen et al. (2001) and Wolkoff et al. (2012) reported that exposure to VOC oxidation products can irritate the upper respiratory tract of mice.

3.3.2. Irritation of the upper airway system and eyes

Several animal and human studies have reported on sensory irritation related to exposure to terpenes and terpene oxidation products. Wolkoff et al. (2012) used nine or ten naïve inbred BALB/cA male mice and studied the sensory irritation of eyes and airways from repeated low-level indoor air exposure to limonene (52 ppm), ozone (0.1 ppm), and LOP reaction mixtures of limonene (52 ppm) with ozone (0.5 ppm, 2.5 ppm and 3.9 ppm) for 1 h/day over 10 consecutive days. The study did not observe consistent effects on the respiratory rate following exposure to either limonene or ozone alone, however, for the mixtures cases the respiratory rate decreased concentration-dependently with an extrapolated no effect level of ~0.3 ppm admixing of ozone; however, rapid sensory irritation and slow air flow limitation (limonene admixed 3.9 ppm ozone) were reported. An earlier study by Clausen et al. (2001) noted a reduced respiration rate by 33 +/− 3% (95% confidence limits) when four male BALB/ca mice were exposed to a mixture of ozone and limonene; sensory irritation was the dominating effect of the mixture. They had used a mouse bioassay to evaluate the respiratory patterns in the formation of irritating substances when male mice were exposed to a reaction mixture of limonene and ozone; the analysis demonstrated that sensory irritation was the dominant effect of the limonene and ozone mixture. They reported that although exposure to VOCs caused a strong sensory irritation effect, it was fully reversible after the exposure had ended; in Wolkoff et al. (2012), a decrease of the TB was reported following the repeated exposure to 52 ppm limonene alone. Strong sensory irritation was observed in mice exposed to the reaction mixture.

Klenø and Wolkoff (2004) measured eye blinking frequency in a human volunteer study on 8 adult males (aged between 30 and 63 years with a mean of 48 years) who were exposed to limonene oxidation products at 0.22 ppm limonene admixed with 0.13 ppm ozone for 20 min over several sessions. A significant ($p < 0.0001$) increase in the eye blinking compared to the baseline (exposure to parts per billion levels) was reported. Nørgaard et al. (2014) investigated the formation of ozone-initiated reaction products by undertaking near realistic user conditions of two common household products (kitchen cleaning agent and plug-in air freshener) in a 20m^2 walk-in climate chamber. Even at high (50 ppb) ozone test concentrations, acute airway effects were not expected from the short term use of the kitchen cleaning agent, however, possible sensory irritation (eyes and upper airways) from formaldehyde and airflow limitation in the airways by 4-OPA was reported, using thresholds in Wolkoff et al. (2013) from the plug-in air freshener, possibly due to the longer term and constant emitting source. It concluded that further realistic assessments should be undertaken to obtain acute and longer-term exposure data.

Jensen et al. (2001) researched toxicological databases and focused on the health evaluation of 84 individual VOCs emitted from 23 wood and wood-based materials. Predominant chemicals included aldehydes, (mainly acetaldehyde), propanol, butanal, pentanal, hexanal, and acetone. Formaldehyde was the predominant single emittant from urea-formaldehyde glued panels, while pine emissions included terpenes (α- and β-pinene, limonene). It was concluded that sensory and mucous membrane effects are most likely the critical effects at the low formaldehyde exposures experienced (Jensen et al., 2001). Exposure to acetaldehyde led to higher mucous membrane irritation levels than formaldehyde. The relevant

Table 3a
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Adhesives (μg m^{-2} h^{-1})		Ceiling (μg m^{-2} h^{-1})				
		General	Mastic (polyurethane)	General	Tiles	0 months□	6 months□	12 months□
Acetaldehyde	Plaisance et al. (2017) **TC**		1.9[3]					
	Plaisance et al. (2014b) **TC**			<1.3[3]				
Acetone	Plaisance et al. (2014b) **TC**			<1[3]				
α-Pinene	Järnström et al. (2008) **FLEC**	1 (1,6)[3,1]						
Ethyl benzene	Plaisance et al. (2017) **TC**		995[3]					
Formaldehyde	Gunschera et al. (2013) **TC**				22 (20, 55)[3, 1]			
	Järnström et al. (2007) **FLEC**					42 (5, 96)[2]	42 (14, 109)[2]	28 (13, 46)[2]
	Plaisance et al. (2017) **TC**		11.6[3]					
	Plaisance et al. (2014b) **TC**				99[3]			
m + *p*- Xylenes	Plaisance et al. (2017) **TC**		2447[3]					
Styrene	Plaisance et al. (2017) **TC**		9.9[3]					
Toluene	Plaisance et al. (2017) **TC**		2.6[3]					

TC: Test Cell or Chamber; **FLEC**: Field and Laboratory Emission Cell.
[1] Median, min max.
[2] Average, min max.
[3] Sample value.
□ Period after the structure was finished.

health effects reported in the toxicological sheets of the Lowest Concentration of Interest (Jensen et al., 2001) for the chemicals emitted from construction products have been included in Table 2. Jensen et al. (2001) concluded that even though wood is an important renewable resource and the perception of wood odour is positive to the public, this odour could be caused by irritative substances and have an impact on health.

3.3.3. Cardiovascular

No cardiovascular studies were identified within the reviewed papers; therefore, we considered the grey literature and the following toxicological reports and databases were reviewed: Health Canada (2017); WHO Indoor Air Guidelines (WHO); PHE Indoor Air Quality Guidelines for selected Volatile Organic Compounds (PHE, 2019); Integrated Risk information System (IRIS) (US Environmental Protection Agency); Agency for Toxic Substances and Disease Registry (ATSDR); PHE Compendium of Chemical Hazards (PHE); EU-Lowest Concentration of Interest (EU-LCI) Values, European Chemical Agency (ECHA) (European Commission, 2021).

The commonly measured VOCs identified in European residences that are reported to have cardiovascular effects are benzene, xylenes, tetrachlorocarbon, toluene and trichloroethylene (details are outlined in Table 2). Health effects associated with exposure to the above chemicals include tachycardia (xylene) and ventricular arrythmia (benzene, toluene). Other VOCs identified in the studies that have reported cardiovascular effect from inhalation include 2-methylbutane (isopentane), trichloroethane and effects are outlined in Table S4.

3.3.4. Neurological

The impact of formaldehyde exposure on the nervous system was examined in one in vitro and one animal study. In an inhalation animal study forty Wistar rats (21 male and 19 female about 16 weeks old with a body weight of 180-200 g for the females and 250–280 g for the males) were exposed to different concentrations of formaldehyde. Fourteen days prior to the experiment commencing the rats had a 14-day training period in a maze. A petri dish was placed in a closed vitreous chamber and was filled with water for the control group and an aqueous formaldehyde solution (0.25% and 0.7%); rats entered the chamber 5 min later and ambient air was measured for formaldehyde concentrations. For 90 days the rats were exposed for 10 min a day, 7 days a week and after the 90 days the rats had to re-enter the maze every 10th day over a 30 day observation period (Pitten et al., 2000). A statistically significant difference was observed between the rats exposed to formaldehyde and the group that was not exposed ($p < 0.05$) in terms of time required to complete a task and mistakes made. Even though effects continued to be observed through the post-trial observation period, the authors noted that further studies were required to determine if the effects were reversible.

In Tuomainen et al. (2003) mentioned above, occupants of both buildings were asked to complete a self-reporting questionnaire, including

Table 3b
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Area-specific emission rate (μg m^{-2} h^{-1})							
	Study	Chipboard	Fireboard	Composite board	Finishing plaster	Floor covering (parquet)		
						0 months*	6 months*	12 months*
Acetaldehyde	Plaisance et al. (2014b) **TC**	7.25 (3.4 11.1)[3,1]		<1.3[3]	147.3 (1.3500)[3,1]			
	Simon et al. (2020) **TC**	6.29[3]	31.39[3]					
Acetone	Plaisance et al. (2014b) **TC**	<1[3]		3.9[3]	86.5 (1241)[3,1]			
	Simon et al. (2020) **TC**	34.26[3]	<0.4[3]					
Formaldehyde	Järnström et al. (2007) **FLEC**					7 (5, 10)[2]	5 (5, 6)[2]	5 (5, 8)[2]
	Plaisance et al. (2017) **TC**							
	Plaisance et al. (2014a)	282.8[3]			682[3]			
	Plaisance et al. (2014a) **PFS**							
	Plaisance et al. (2014b) **TC**	224 (203, 245)[3,1]		4[3]	38 (26.7413)[3,1]			
	Simon et al. (2020) **TC**	83.87[3]	<0.14[3]					

TC: Test Cell or Chamber; **PFS**: Passive Flux Sampler; **FLEC**: Field and Laboratory Emission Cell.
[1] Median, min max.
[2] Average, min max.
[3] Sample value.
* Period after the structure was finished.

Table 3c
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Floor covering				Foam	Furnishing plaster	Glass wool
		Various	PVC: 0 months	PVC: 6 months	PVC: 12 months			
Acetaldehyde	Plaisance et al. (2017) **TC**						3.2[a,3]	7.25 [a,3]
	Plaisance et al. (2014b) **TC**					1.6 [a,3]		
Acetone	Plaisance et al. (2014b) **TC**					<1[a,3]		
Benzene	Marć et al. (2017) **MEC**	1.48 (0.059,11.1)[b,1]						
	Marć et al. (2017) **PFS**	3.6 (0.32,36.1) [b,1]						
Ethylbenzene	Marć et al. (2017) **MEC**	3.055 (0.38,21.4) [b,1]						
	Marć et al. (2017) **PFS**	2.4 (0.29,8.1)[b,1]						
Formaldehyde	Järnström et al. (2007) **FLEC**		9 (5,18) [a,2]	5 (5, 10)[a, 2]	7 (6, 10) [a,2]			
	Plaisance et al. (2017) **TC**						17.5[a,3]	1.505[a,3]
	Plaisance et al. (2014b) **TC**					<3.9[a,3]		
p,m-Xylene	Marć et al. (2017) **PFS**	6.75 (0.55,24.3)[b,1]						
	Marć et al. (2017) **MEC**	19.35 (2.36,75.1) [b,1]						
Styrene	Marć et al. (2017) **MEC**	5.375 (0.64,16.7)[b,1]						
	Marć et al. (2017) **PFS**	2.155 (0.26,10.3)[b,1]						
Toluene	Marć et al. (2017) **MEC**	20.75 (1.38,344)[b,1]						
	Marć et al. (2017) **PFS**	12.2 (1.1,63)[b,1]						

TC: Test Cell or Chamber; **MEC**: Miniature Emissions Chamber; **PFS**: Passive Flux Sampler; **FLEC**: Field and Laboratory Emission Cell.
[a] $\mu g\ m^{-2}\ h^{-1}$ (area-specific emission rates).
[b] $\mu g\ m^{-2}$.
[1] Median, min max.
[2] Average, min max.
[3] Sample value.

symptoms such as headaches (feeling heavy headed, headache, dizziness, difficulties in concentrating). The air inside the apartments were analyzed for TVOC, formaldehyde and acetaldehyde. There was a reduced reporting of headaches after one and three years of occupancy in the case building when compared to headaches prior to moving into the case building.

As only these two studies were identified regarding neurological outcomes of VOCs exposure, the information on neurological outcomes included in Table 2 and Table S4 also includes data from toxicological reports from the following sources: Health Canada (2017); WHO Indoor Air Guidelines (WHO, 2010); PHE Indoor Air Quality Guidelines for selected Volatile Organic Compounds (PHE, 2019); Integrated Risk Information System (US Environmental Protection Agency); Agency for Toxic Substances and Disease Registry (ATSDR); PHE Compendium of Chemical Hazards (PHE); Lowest Concentration of Interest Values, European Chemical Agency (European Commission, 2021).

The commonly measured VOCs identified in European residence that are reported to have neurological effects are formaldehyde, benzene, ethylbenzene, xylenes, styrene, toluene, tetrachloroethylene and trichloroethylene and are outlined in Table 2. Other VOCs identified in the studies that have reported neurological effect from inhalation are outlined in Table S4.

Health effects resulting from chronic exposure to tetrachloroethylene (including occupational and residential settings) have suggested effects on colour vision, visual contrast sensitivity and additional neurobehavioral effects (ATSDR, 2019). Chronic styrene inhalation exposure health effects include impairment of the vestibular-oculomotor system, impaired hearing, decreased colour discrimination, altered performance on behavioural tests. Other neurological symptoms reported include dizziness (toluene) and headaches (formaldehyde, trichloroethylene).

3.3.5. Carcinogenic

No specific carcinogen studies were identified from the literature search and therefore the toxicological reports from IRIS, IARC and US-EPA Carcinogen Category were reviewed and populated in Table 2 and S4.

Of the commonly measured VOCs identified in European residences, formaldehyde, acetaldehyde, benzene, ethylbenzene, tetrachloroethylene, trichloroethylene and styrene are reported to have carcinogenic effects. Other VOCs identified in the studies that have reported carcinogenic effects

Table 3d
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Glue for wallpaper	Gypsum board	Linoleum	MDF	Noise protection panel	OSB
Acetaldehyde	Plaisance et al., 2017 **TC**		5.9[a,2]			4.1 [a, 2]	6.05[a,2]
	Plaisance et al., 2014b **TC**	1.3[a,2]	1.9[a,2]	<1.3[a,2]	3.55 (1.6 12.5)[a,2,1]		10.6 (6.5 14.7)[a,2,1]
	Simon et al., 2020 **TC**				2.27[a,2]		
Acetone	Plaisance et al., 2014b **TC**	92[a,2]	14.1[a,2]	<1[a,2]	15.85 (1 38.2)[a,2,1]		548.9 (26.81071)[a,2,1]
	Simon et al., 2020 **TC**				2.68[a,2]		
α-Pinene	Plaisance et al., 2017 **TC**						1.9[a,2]
D-Limonene	Plaisance et al., 2017 **TC**						0.72[a,2]
Formaldehyde	Plaisance et al., 2017 **TC**		2.6[a,2]			5.15[a,2]	19.95[a,2]
	Plaisance et al., 2014a **PFS**						16.4[a,2]
	Plaisance et al., 2014a **PFS**				133.3 (92.5, 135.5)[a,2,1]		
	Plaisance et al., 2014b **TC**	5[a,2]	15.5[a,2]	<3.9[a,2]	193 (92255)[a,2,1]		26.15 (21.3 31)[a,2,1]
	Risholm-Sundman et al., 2007 **PM**				3.5[b,2]		
	Risholm-Sundman et al., 2007 **TC**				4.4[a,2]		
	Simon et al., 2020 **TC**				42.09[a,2]		
Styrene	Plaisance et al., 2017 **TC**						0.79[a,2]

TC: Test Cell or Chamber; **PFS**: Passive Flux Sampler; **PM**: Perforator Method.
[a] $\mu g\ m^{-2}\ h^{-1}$ (area-specific emission rates).
[b] mg per 100 g
[1] Median, min max.
[2] Sample value.

Table 3e
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Paints				Particle board	
		General	Alkyd resin (high airflow rates)	Alkyd resin (low airflow rates)	Latex on concrete and polyester substrate	E0	E1
Acetaldehyde	Plaisance et al., 2017 **TC**	38.5[a,1]					
D-Limonene	Plaisance et al., 2017 **TC**	5.75[a,1]					
Ethyl benzene	Plaisance et al., 2017 **TC**	3.5[a,1]					
Formaldehyde	Plaisance et al., 2017 **TC**	88[a,1]					
	Risholm-Sundman et al., 2007 **FM**					2[b,1]	4[b,1]
	Risholm-Sundman et al., 2007 **PM**					2–3[c,1]	4.6[c,1]
	Risholm-Sundman et al., 2007 **TC**					0.8[a,1]	2[a,1]
m + *p*-Xylenes	Plaisance et al., 2017 **TC**	1.55[a,1]					
Styrene	Plaisance et al., 2017 **TC**	7.2[a,1]					

TC: Test Cell or Chamber; **FM**: Flask Method; **PM**: Perforator Method.
[a] $\mu g\ m^{-2}\ h^{-1}$ (area-specific emission rates).
[b] $mg\ kg^{-1}$.
[c] mg per 100 g.
[1] Sample value.

from inhalation are outlined in Table S4. More specifically: the International Agency for Research on Cancer (IARC) used evidence from epidemiological studies and animal data to classify chemicals and their carcinogenicity, and concluded that from the most commonly measured VOCs identified in European residences, formaldehyde, benzene and trichloroethylene have been classified as known human carcinogens (Group 1), while styrene and tetrachloroethylene have been classified as possible or probable carcinogens for humans (Group 2A and Group 2B, respectively). Formaldehyde causes cancer of the nasopharynx and leukaemia and benzene can trigger chromosomal aberrations and causes an effect in the blood and bone marrow, a critical health outcome being acute myeloid leukaemia (WHO, 2010).

The EPA toxicological review (ATSDR, 2019) reports a pattern of association between tetrachloroethylene exposure and increased incidence of liver tumours (inhalation and oral exposure in mice) and kidney and mononuclear cell leukaemia (inhalation exposure in rats). Naphthalene is considered a non-genotoxic carcinogen in the rodent respiratory tract (WHO, 2010), trichloroethylene is positively associated with cancer of the liver, kidney and non-Hodgkin lymphoma (WHO, 2010) and styrene exposure is reported to be possibly associated with an increased risk of leukaemia and lymphoma. There is a suggested association of tetrachlorocarbon with non-Hodgkins lymphoma and animal studies have reported liver tumours; however, the former was studied in an occupational study and not possible to be attributed solely to tetrachlorocarbon exposure. Ethylbenzene had no excess of cancer incidence in human studies, however, in mice there was an increased incidence of lung and liver adenomas (IARC IAfroC, 2000). The EPA has classified acetaldehyde as a probable human carcinogen (B2) based on nasal tumours in rats and laryngeal tumours in hamsters.(US-EPA, 1988).

Several identified VOCs had insufficient data from human and animal studies and therefore are reported as not detected or determined.

3.4. Emissions

We report emission factors defined as weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (EPA: Basic Information of Air Emissions Factors and Quantification). The most commonly used is the emission rate of the emitting material and it is measured as emitted mass per unit time and area. We do not report emissions in terms of concentrations. We present emissions that were quantified in the relevant papers; approximate values presented in figures in papers were not included.

Emission factors presented in the same paper and obtained with the same methodology (e.g. test chamber) have been merged and their statistical values (median, min and max) are reported. This method was deemed sufficient for the needs of this study, as results of each study were processed separately and not combined with data from other studies. In cases where two or more different methods are used in the same paper, results are

Table 3f
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Plywood						
		General	Exterior	Exterior (22 mm)	exterior (8 mm)	Interior	Interior (22 mm)	Interior (8 mm)
Acetaldehyde	Plaisance et al., 2014b **TC**	18.4 (4.8 32)[a,2,1]						
Acetone	Plaisance et al., 2014b **TC**	15.4 (1 29.8)[a,2,1]						
Formaldehyde	Bohm et al., 2012 **TC**			between 0.36 ± 0.02 and 0.85 ± 0.03[a,2]	between 0.13 ± 0.01 and 0.72 ± 0.07[a,2]		between 1.47 ± 0.19 and 2.65 ± 0.17[a,2]	between 1.24 ± 0.04 and 1.66 ± 0.04[a,2]
	Plaisance et al., 2014b **TC**	8.3[a,2]						
	Risholm-Sundman et al., 2007 **FM**		1.4[b,2]			32[b,2]		
	Risholm-Sundman et al., 2007 **TC**		0.2[a,2]			5.5[a,2]		

TC: Test Cell or Chamber; **FM**: Flask Method.
[a] $\mu g\ m^{-2}\ h^{-1}$ (area-specific emission rates).
[b] $mg\ kg^{-1}$.
[1] Median, min max.
[2] Sample value.

Table 3g
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Area-specific emission rates (μg m^{-2} h^{-1}) PVC Only	PVC Adhesives	Sealing plaster	Silicone	Skirting board	Vapour barriers	Varnish on various substrates
Acetaldehyde	Plaisance et al., 2017 **TC**					4[2]	2.4 [2]	
	Plaisance et al., 2014b **TC**				14.4[2]			
α-Pinene	Järnström et al., 2008 **FLEC**	1 (1,1)[2,1]	3 (1,9)[2,1]					
Acetone	Plaisance et al., 2014b **TC**				12.2[2]			
	Plaisance et al., 2017 **TC**					17.8[2]	1.805[2]	
Formaldehyde	Plaisance et al., 2014a			43.4[2]				
	Plaisance et al., 2014b **TC**				<3.9[2]			
	Plaisance et al., 2014b **TC**				1.7[2]			

TC: Test Cell or Chamber; **FLEC**: Field and Laboratory Emission Cell.
[1] Median, min max.
[2] Sample value.

presented separately. An exception is the study of Afshari et al. (2003), where similar emission rates were measured with different test chambers and were therefore merged together.

Characterizing emissions from sources in residential environments can be challenging due to the diversity of available materials and processes, and the variability in environmental and real-life conditions. Unavoidably, studies designed to investigate emissions are limited to a rather narrow spectrum of conditions, chemicals and environmental conditions. A large variability in reported emission levels is expected to be observed. Therefore, for reasons of clarity, in this review sources have been separated in the following three categories: construction and building materials, consumer products and space heating. Consequently, emission factors for the most commonly measured and health relevant individual VOCs are reported for these three categories separately in Tables 3a–3h, 4a–4c and 5, respectively; for all the other VOCs, similar data are reported in the Supplementary materials (Tables S7 and S8). We discuss key elements of experiments reported in the current literature: facilities where the measurements took place (emission chambers etc), and sensitivity of results due to measuring methods and conditions.

Emission factors can be used to estimate the "pollution load" (the summation of products of emission areas times the emission factor of source surfaces). Lack of reliable methods to estimate pollutant load in the way heating/cooling in residential buildings loads are routinely estimated, is a major obstacle to integrating energy and Indoor Air Quality (IAQ) strategies (IEA, 2020).

3.4.1. Construction and building materials

VOC emission factors from construction and building materials were reported in 13 studies (Afshari et al., 2003; Böhm et al., 2012; de Gennaro et al., 2015; Gunschera et al., 2013; Järnström et al., 2007; Järnström

Table 3h
Most health relevant and commonly measured VOCs identified in European residences: emissions from building and construction materials.

VOC	Study	Area-specific emission rates (μg m^{-2} h^{-1}) Walls 0 months*	Walls 12 months*	Walls 6 months*	Solid wood	Wood stain Solvent based	Wood stain Water based	Wooden battens and studs	Wooden flooring
Acetaldehyde	Plaisance et al., 2017 **TC**							0.63[3]	4.2[3]
	Plaisance et al., 2014b **TC**				Between 5.4 and 57[3]				
Acetone	Plaisance et al., 2014b **TC**				<1[3]				
α-Pinene	De Gennaro et al., 2015 **ECM**					96.6[3]			
	Plaisance et al., 2017 **TC**							6.35[3]	1.6[3]
Benzene	De Gennaro et al., 2015 **ECM**					185.3[3]	10.8[3]		
D-Limonene	Plaisance et al., 2017 **TC**							3.4[3]	0.59[3]
	De Gennaro et al., 2015 **ECM**					180.6[3]	56.8[3]		
Ethylbenzene	De Gennaro et al., 2015 **ECM**					93.4[3]	26.6[3]		
Formaldehyde	Bohm et al., 2012 **TC**				Between 0.014 ± 0.001 and 0.084 ± 0.009[1]				
	Järnström et al., 2007 **FLEC**	7 (5, 11)[2]	9 (5, 20)[2]	13 (5, 37)[2]					
	Plaisance et al., 2017 **TC**							2.26[3]	134[3]
	Plaisance et al., 2014b **TC**				Between 3.9 and 14[3]				
Styrene	De Gennaro et al., 2015 **ECM**					286.2[3]	83[3]		
Styrene	Plaisance et al., 2017 **TC**								0.88[3]
Toluene	De Gennaro et al., 2015 **ECM**					303.4[3]	39.5[3]		
	Plaisance et al., 2017 **TC**								0.78[3]
Xylenes	De Gennaro et al., 2015 **ECM**					145.7[3]	40.2[3]		

TC: Test Cell or Chamber; **ECM**: Emission Chamber and Model; **FLEC**: Field and Laboratory Emission Cell.
[1] Average, SD.
[2] Average, min max.
[3] Sample value.
* Period after the structure was finished.

Table 4a
Most health relevant and commonly measured VOCs identified in European residences: emissions from consumer products.

VOC	Study	Combustible AF					Conditioner
		General	Fragranced candles	Unfragranced candles	High flow rates*	Low flow rates**	
Acetaldehyde	Derudi et al., 2012 **TC**	1.12[d,1]					
	Manoukian et al., 2016 **TC**		62.8 (13.6, 167)[b,1]	167 (3, 25.7)[b,1]			
	Manoukian et al., 2013 **EH**	4910 (11)[e,2]			1046 (104)[d,2]	418 (34)[d,2]	
Acetone	Manoukian et al., 2016 **TC**				644 (28)[d, 2]	222 (34)[2]	
	Manoukian et al., 2013 **EH**	251 (6)[e,2]					
Benzene	Derudi et al., 2012 **TC**	0.13[d,1]					
	Derudi et al., 2014 **TC**	Between 0.02 ± 0.01 and 0.37 ± 0.07[d,2]					
	Manoukian et al., 2016 **TC**				1718 (94)[d,2]	800 (128)[d,2]	
	Manoukian et al., 2013 **EH**	937 (5)[e,2]					
	Petry et al., 2013 **TC**	1 (0.4, 1.3)[e,3,1]					
	Petry et al., 2014 **TC**		21.1 (1.8, 72)[b,3,1]	72 (0.9, 25.7)[b,3,1]			
Ethylbenzene	Derudi et al., 2014 **TC**	Between 0.02 ± 0.01 and 0.11 ± 0.04[d,2]					
	Manoukian et al., 2016 **TC**				736 (376)[d,2]	152 (42)[d,2]	
	Manoukian et al., 2013 **EH**	940 (49)[e,2]					
Formaldehyde	Derudi et al., 2012 **TC**	2.91[d,1]					
	Manoukian et al., 2016 **TC**				2304 (226)[d,2]	822 (66)[d,2]	
	Manoukian et al., 2013 **EH**	1206 (17)[e,2]					
	Petry et al., 2013 **TC**	25.8 (17, 38.1)[e,3,1]					
	Petry et al., 2014 **TC**		280 (73, 372.2)[b,3,1]	22.65 (19.6, 25.7)[b,3,1]			
Limonene	Petry et al., 2014 **TC**		83.5 (45, 122)[b,3,1]				
Limonene (sum of monoterpenes)	Yeoman et al., 2020 **SV**						1.6 (0.51 7.6)[a,1]
Naphthalene	Derudi et al., 2014 **TC**	Between 0.016.7 ± 0.002.5 and 0.123 ± 0.045.3[d,2]					
	Manoukian et al., 2013 **EH**	217 (4)[e,2]					
	Orecchio et al., 2011 **FE**	0.94 (0.18,15)[c,3,1]					
	Petry et al., 2014 **TC**		3.24 (0.5, 56.5)[b,3,1]	56.5 (0.2, 0.72)[b,3,1]			
o-Xylene	Derudi et al., 2014 **TC**	Between 0.03 ± 0.01 and 0.05 ± 0.01[d,2]					
p + *m* -Xylene	Derudi et al., 2014 **TC**	Between 0.02 ± 0.01 and 0.11 ± 0.02[d,2]					
Styrene	Manoukian et al., 2013 **EH**	726 (7)[e,2]					
	Petry et al., 2014 **TC**		20.7 (1.8, 80.6)[b,3,1]	80.6 (0.2, 25.7)[b,3,1]			
Toluene	Derudi et al., 2012 **TC**	0.23[d,1]					
	Derudi et al., 2014 **TC**	Between 0.03 ± 0.01 and 0.46 ± 0.12[d,2]					
	Manoukian et al., 2016 **TC**				1164 (28)[d,2]	470 (48)[d,2]	
	Manoukian et al., 2013 **EH**	770 (7)[e,2]					
	Petry et al., 2014 **TC**		12.9 (2.6, 84.8)[b,3,1]	84.8 (0.3, 25.7)[b,3,1]			
Xylenes	Derudi et al., 2012 **TC**	0.04[d,1]					
	Petry et al., 2014 **TC**		8.95 (2.4, 29.6)[b,3,1]	29.6 (0.5, 25.7)[b,3,1]			

TC: Test Cell or Chamber; **SV**: Sample Vessel; **FE**: Field Experiment. **EH**: Experimental House.
[a] $\mu g\ s^{-1}\ g[product]^{-1}$.
[b] $mg\ h^{-1}$.
[c] $\mu g\ kg^{-1}$.
[d] $\mu g\ g^{-1}$.
[e] $\mu g\ h^{-1}$.
[1] Median, min max.
[2] Average, SD.
[3] Sample value.
* Air exchange rate 0.25 h^{-1}.
** Air exchange rate 1.5 h^{-1}.

Table 4b
Most health relevant and commonly measured VOCs identified in European residences: emissions from consumer products.

VOC	Study	Electric AF	Heating bag				Liquid Foundation
			Heating mode, polyester coverage	Heating mode, PVC coverage	Not-heating mode, polyester coverage	Not-heating mode, PVC coverage	
1,2,3-Trimethylbenzene	Palmisani et al., 2020 **TC**		6.3[c,2]	Between 0.25 and 0.4[c,2]	0.21[c,2]	Between 0.018 and 0.020[c,2]	
1,2,4-Trimethylbenzene	Palmisani et al., 2020 **TC**		7.22[c,2]	Between 0.3 and 0.43[c,2]	0.38[c,2]	Between 0.020 and 0.024[c,2]	
1,3,5-Trimethylbenzene	Palmisani et al., 2020 **TC**		1.5[c,2]	Between 0.21 and 0.32[c,2]	0.083[c,2]	0.019[c,2]	
Benzene	Palmisani et al., 2020 **TC**		0.2[b,2]	Up to 0.11[c,2]	0.018[c,2]	Up to 0.015[c,2]	
Ethylbenzene	Palmisani et al., 2020 **TC**		0.42[c,2]	Between 0.29 and 0.95[c,2]	0.038[c,2]	Between 0.029 and 0.038[c,2]	
Limonene (sum of monoterpenes)	Yeoman et al., 2020 **SV**						0.019 (0.016 0.3)[a,1]
Naphthalene	Palmisani et al., 2020 **TC**		630.9[c,2]	Between 0.03 and 11.2[c,2]	9.013[c,2]	Between 0.010 and 0.133[c,2]	
o-Xylene	Palmisani et al., 2020 **TC**		1.6[c,2]	Between 0.24 and 0.49[c,2]	0.133[c,2]	Between 0.024 and 0.029[c,2]	
p + *m* -Xylene	Palmisani et al., 2020 **TC**		0.43[c,2]	Between 0.29 and 0.71[c,2]	0.048[c,2]	Between 0.032 and 0.047[c,2]	
Styrene	Palmisani et al., 2020 **TC**		0.7[c,2]	Between 0.34 and 2.2[c,2]	0.07 [c, 2]	Between 0.038 and 0.057[c,2]	
Tetrachloroethylene	Palmisani et al., 2020 **TC**			Up to 0.26[c,2]		Up to 0.033[c,6]	
Toluene	Palmisani et al., 2020 **TC**		6.79[c,2]	Between 1.09 and 2.57[c,2]	0.485[c,2]	Between 0.121 and 0.171[c,2]	

TC: Test Cell or Chamber; **SV**: Sample Vessel.
[a] $\mu g\ s^{-1}\ g[product]^{-1}$.
[b] $\mu g\ h^{-1}$.
[c] $ng\ h^{-1}$.
[1] Median, min max.
[2] Sample value.

et al., 2008; Marć et al., 2017; Plaisance et al., 2014a; Plaisance et al., 2014b; Plaisance et al., 2017; Risholm-Sundman et al., 2007; Silva et al., 2003; Simon et al., 2020). Forty four VOCs were shown to be emitted from a wide range of materials (adhesives, chipboard, fireboard, gypsum boards, plywood, Oriented Strand Board, Medium Density Fireboard, finishing plaster, paints, wood stains, wood and wooden batten and studs, materials used in ceilings and flooring – e.g. tiles, PVC, wood). Results are presented in Tables 3a–3h and Tables S7a-h.

Ten studies reported measurements from test chambers or cells, compliant with established methodologies (e.g. ISO-16000 series: (Böhm et al., 2012; Gunschera et al., 2013; Järnström et al., 2007; Järnström et al., 2008; Plaisance et al., 2014b; Plaisance et al., 2017; Simon et al., 2020)), while in two more studies emission rates were calculated by inputting test chamber measurements to a double exponential model (de Gennaro et al., 2015; Silva et al., 2003). Passive Flux Sampler techniques were used in two studies (Marć et al., 2017; Plaisance et al., 2014a).

Comparison between different methods and protocols have been assessed in some of the selected studies. Afshari et al. (2003), compared emission rates of several VOCs (pentanal, hexanal, octanal and decanol) obtained from three different test chamber methods: a 50 L environmental test chamber (CLIMPAQ), the Field and Laboratory Emission Cell (FLEC: a microchamber for testing VOCs in field and lab, and a 1 m^3 test chamber. All three chambers gave similar emission rates within the uncertainty used in the experiments. In Risholm-Sundman et al. (2007), the standard test chamber method for formaldehyde emissions (gas analysis method:

Table 4c
Most health relevant and commonly measured VOCs identified in European residences: emissions from consumer products.

VOC	Study	Moisturizer	Passive AF	Shampoo	Shower Gel	Spray	Toys	
							Acrylonitrile butadiene styrene	Polyamide
α-Pinene	Uhde and Schulz_2015 **TC**					552[b,2]		
Benzene	Marć et al., 2015 **MEC**						0.21 (1.35, 0.044)[c,1]	0.41 (1.36, 0.058)[c,1]
Ethylbenzene	Marć et al., 2015 **MEC**						2 (44.5, 0.25)[c,1]	0.86 (4.3, 0.04)[c,1]
Limonene	Uhde and Schulz_2015 **TC**					9132[b,2]		
Limonene (sum of monoterpenes)	Yeoman et al., 2020 **SV**	0.53 (0.029 5.8)[a,1]		25 (1.6 70)[a,1]	11 (1.4120)[a,1]			
p + *m* -Xylene	Marć et al., 2015 **MEC**						1 (4, 0.19)[c,1]	0.75 (23.3, 0.16)[c,1]
Styrene	Marć et al., 2015 **MEC**						22 (210, 0.5)[c,1]	3.4 (38.7, 0.14)[c,1]
Toluene	Marć et al., 2015 **MEC**						2.3 (6.5, 0.44)[c,1]	2.6 (12.4, 0.6)[c,1]

TC: Test Cell or Chamber; **MEC**: Miniature Emissions Chamber; **SV**: Sample Vessel.
[a] $\mu g\ s^{-1}\ g[product]^{-1}$.
[b] mg/(unit*h).
[c] $ng\ h^{-1}$
[1] Median, min max.
[2] Maximum values.

Table 5
Volatile Organic Compound emission factors (μg g^{-1}: mean value ± standard deviation) during space heating in the residential environment (Carteret et al., 2012).

VOC	Heater	
	Wick	Injection
Formaldehyde	Between 10.2 ± 7.8 and 17.7 ± 2.2	Between 6.0 ± 3.1 and 10.1 ± 2.3
Acetaldehyde	Between 2.5 ± 2.2 and 4.9 ± 0.3	Between 2.4 ± 0.5 and 3.8 ± 3.7
Acetone	Between 3.9 ± 2.6 and 31.2 ± 35.8	Between 3 ± 1.9 and 24.2 ± 39.1

EN 717-2) was employed whereby a test piece of known surface area is placed in a chamber with controlled temperature, relative humidity, airflow and pressure was compared against the perforator method (EN 120: formaldehyde is extracted from test wood pieces by means of boiling toluene and then transferred into water) and the flask method (EN 717-3: test pieces of known mass are suspended over water in a closed container at constant temperature). It was concluded that variations between the results from different methods can partly be explained by differences in test conditions, with conditioning of the sample before the test and test temperature having the largest effect on the final emission result. In Marć et al. (2017), it was found that monoaromatic hydrocarbon emissions with a home-made PFSs were nearly 10 times higher than those obtained using a micro-chamber/thermal extractor (m-CTE™250) system.

3.4.2. Consumer products

Emissions from consumer products are presented in Tables 5a-c and Tables S8a-c. Eleven studies reported VOC emission factors from consumer products and 8 from burning combustible air fresheners (Derudi et al., 2014; Derudi et al., 2012; Manoukian et al., 2016; Manoukian et al., 2013; Orecchio, 2011; Petry et al., 2014; Petry et al., 2013; Uhde and Schulz, 2015)); 2 from polymer-based items (heating bags, Palmisani et al. (2020), and small toys placed in chocolate food products, Marć et al. (2015)); one from non-aerosol personal care products (shampoo, shower get, moisturizer, conditioner and liquid foundation, Yeoman et al. (2020); and another one from fragranced products (electric, passive and combustible air fresheners and sprays; (Uhde and Schulz, 2015). Most of the detected VOCs (40) have been measured from burning combustible air fresheners -apparently reflecting the larger number of studies focused on combustible air fresheners emissions. Interestingly, even though only one study examined VOCs emissions from sprays (an automatic spray mechanism which scents the room at pre-set timing intervals, and a conventional room spray advertised for use in schools, (Uhde and Schulz (2015)) 29 individual VOCs have been detected. It should be pointed out that the dispersion in combustible air fresheners (candles, burning incense sticks) is achieved by flame/heating whilst in other air fresheners by diffusion (e.g. passive diffusers) or evaporation (e.g. electric evaporators, automatic sprays).

Most studies have been conducted in test chambers. Exceptions are the studies by Manoukian et al. (2013), Orecchio (2011) and Yeoman et al. (2020) that were carried out in an Experimental House (Riberon and O'Kelly (2002)), a medium sized room and a 10- mL volume stainless steel gas-tight sample vessel, respectively.

In six studies, measurements took place in environments (e.g. test chambers) where the environmental conditions of temperature, relative humidity and air flow or air change rates were controlled or measured (Manoukian et al., 2016; Manoukian et al., 2013; Palmisani et al., 2020; Petry et al., 2013; Petry et al., 2014; Uhde and Schulz, 2015). Two studies do not report environmental measurements (Orecchio, 2011; Yeoman et al., 2020), two report only control of the airflow (Derudi et al., 2014; Derudi et al., 2012), and in one (Marć et al., 2015) temperature and airflow were measured but not the relative humidity.

The effect of environmental conditions on the measured emission rates in test chambers has been examined in two papers. In Petry et al. (2013), a comparison was made between different laboratories maintaining the same environmental conditions (temperature, relative humidity), and it was concluded that when the laboratories were able to control the chamber parameters within the suggested defined boundaries (chamber temperature and relative humidity not exceeding 30 °C and 75% RH), reproducible emissions were determined.

3.4.3. Space heating

Even though several studies were found to report VOCs emitted from activities related with space heating (see Appendix B), only one study was found to specifically report VOC emission factors during space heating in particular for formaldehyde, acetaldehyde and acetone (Carteret et al., 2012). Emissions during space heating are presented in Table 5.

4. Summary and conclusions

In this systematic literature review, data were collected on the concentrations of all individual VOCs measured in European residences, to look at their sources, and where possible, their emission rates, and report the associated health effects.

The results may be summarised as follows:

- 65 individual VOCs were identified in European homes.; the most commonly measured VOCs were aromatic hydrocarbons (14 compounds), alkane hydrocarbons (9), aldehydes (8), aliphatic hydrocarbons (5), terpenes (6), chlorinated hydrocarbons (4), glycol and glycol ethers (3) and esters (2). Alicyclic hydrocarbons, aliphatic alcohols, chloroethanes, heterocyclic compounds, hydrocarbons, ketones, polycyclic aromatic hydrocarbons and aromatic - heterocyclics were also measured.
- The Weighted Average Geometric Mean (WAGM) concentrations ranged between 92 μg m^{-3} (ethanol) and 0.1 μg m^{-3} (3-ethenylpyridine). 8 chemicals (ethanol, formaldehyde, toluene, limonene, hexaldehyde, *α*-pinene, butane, acetone) were found to be the most abundant in residences having *WAGM* more than 10 μgm^{-3}, and 14 the least abundant with *WAGM* less than 1 μgm^{-3} (2-ethyltoluene, styrene, propylbenzene, tetrachlorocarbon, acrolein, 1,1,1-trichloroethane, *p*-isopropyltoluene, trichloroethylene, naphthalene, chlorobenzene, methylbenzoate, pyridine, 1,3-butadiene, 3-ethenylpyridine).
- Aromatic hydrocarbons (8 compounds), alkanes (7 compounds) and aldehydes (6 compounds) measured in European residences are associated with respiratory health effects. Certain chlorinated hydrocarbons are associated with cardiovascular (trichloroethylene and trichloroethane), neurological (tetrachloroethylene, tetrachloroethane, trichloroethylene and trichloroethane) and carcinogenic (tetrachloroethylene, tetrachloroethane and trichloroethylene)., whereas some chlorinated hydrocarbons (tetrachloroethylene and trichloroethylene), esters (ethyl acetate, methylbenzoate), terpenes (*α*- and *β*- pinene, limonene), acetone, 2-butoxyethanol, pyridine, and ethenylpyridine are found to be irritants. Trichloroethylene was the only chemical identified to have health effects in all five categories.
- 80% of the 65 individual VOCs commonly found in European residential microenvironments were identified to have sources associated with building and construction materials (e.g. brick, wood products, adhesives and materials for flooring installation etc.), whereas63% of them were emitted from consumer products (passive, electric and combustible air fresheners, hair sprays, deodorants) and some of them were specifically associated with candle and - incense burning. 14%, were associated with space heating, reflecting the relatively small number of studies discussing emissions from this category of sources. Aldehydes and ketones are emitted by all source categories (i.e. construction and building products, consumer products and space heating), whilst particular VOC families abundant in the residential microenvironments are more associated with specific source categories, e.g. cleaning materials with halogenated organic compounds.
- Although cetone, 2-methylbutane and tetrachlorocarbon are of most health relevant, and acetone is one of the most abundant species in European residences, they are reported in a small number of studies. More monitoring is needed to establish their levels and sources in European residences.

- A clear negative trend was observed for formaldehyde concentrations during the last 20 years, in line with European regulations (e.g. REACH, regulations on cosmetic products).

The residential VOC concentrations and emission rates reported in this review are expected to contribute to the parameterisation and validation of modelling tools that predict population exposure to indoor VOCs s.

5. Recommendations

5.1. Measurements

Through this literature review, we have identified a limited number of individual VOC measurements in Europe but even less, especially recently, in the UK. A systematic approach is needed to characterise indoor air both for chemical and biological contamination. This approach would aim beyond research derived evidence, to systematic and operational surveillance of the indoor air, akin to outdoor air, aiming to show trends in known VOCs and identify any new compounds. Most of the current research focusses only on targeted analysis, that determines quantitively a specific number of target compounds, usually the priority chemicals, as required by the funding source, for which the analysis is undertaken. It is recommended to report non-target compounds together with a list of target chemicals - either qualitatively or quantitatively with some level of quantification (e.g. toluene equivalent amount); this would enable us to identify new chemical exposures indoors which may require further investigation.

5.2. Emissions

There is a wide range of sources and emissions of VOCs to indoor air. High-quality and comprehensive emission data and resulting determination of chemical concentrations in indoor air are critical for human health impact assessments. However, this review shows that emission data are currently scattered, frequently having unclear quality and structure, are not easily publicly available and consequently do not allow for exposure assessment. Improvement in collection, analysis and storage of chemical emission samples would be an important step forward.

The "Lowest Concentration of Interest" is a scientific approach based on toxicological and epidemiological data, which links emissions from construction products with indoor concentrations of chemicals and is used to harmonise emission testing and evaluate and control VOC emissions. Given that regulating the emissions of chemicals in the indoor environments are of utmost importance, it was adopted and further developed in European Labelling Schemes (e.g., the German AgBB and the French ANSES), aiming for a wider application across Europe. This approach might inform the development of voluntary labelling schemes in the UK.

5.3. Health

Following the PHE (2019) indoor air quality guidelines for selected VOCs, more work is needed in this area based on the outcome from the current review, which would further support future policy developments. Although this review focusses on homes, collection of chemical data from other indoor environments, such as schools, through citizen science and across different socio-economic status groups would help us to assess chemical exposures, especially of vulnerable populations. Even longitudinal observational studies, measuring indoor chemicals and assessing exposure to indoor pollutants versus self-reported health status and symptoms would be of a great benefit, but certainly clinical trials and biomarker studies would be the right step to this direction.

CRediT authorship contribution statement

Conceptualization, S.D., C.L.-C.;
Methodology, S.D., C.L.-C.;
Data Curation, C.L.-C., A.M., C.H.H., S.L.;
Writing - Original Draft Preparation, S. L., C.H.H., C.L.-C., S.D.;
Writing - Review and Editing, S.D., T.M.;
Supervision, S.D.;
Project Administration, S.D.
All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

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Appendix A. Search strategy

Table A1
Embase search strategy.

1 exp. volatile organic compound/ (18094)
2 "volatile organic compound*".tw. (13103)
3 VOC.tw. (7711)
4 VOCs.tw. (8322)
5 "semi volatile organic compound*".tw. (452)
6 "semi volatile compound*".tw. (201)
7 SVOC.tw. (230)
8 SVOCs.tw. (400)
9 exp. dust/ (32383)
10 dust.tw. (51330)
11 exp. benzene/ (20487)
12 benzene.tw. (32874)
13 exp. formaldehyde/ (52127)
14 formaldehyde.tw. (24148)
15 exp. toluene/ (20526)
16 toluene.tw. (23764)
17 exp. styrene/ (6823)
18 styrene.tw. (11964)
19 exp. acetaldehyde/ (9604)
20 acetaldehyde.tw. (10691)
21 exp. pinene/ (6202)
22 a-pinene.tw. (178)
23 exp. limonene/ (7504)
24 D-Limonene.tw. (989)
25 exp. naphthalene/ (8809)
26 naphthalene.tw. (13488)
27 exp. tetrachloroethylene/ (3352)
28 tetrachloroethylene.tw. (1342)
29 exp. trichloroethylene/ (10791)
30 trichloroethylene.tw. (4340)
31 m-xylene.tw. (930)
32 p-xylene.tw. (1501)
33 o-xylene.tw. (1189)
34 exp. ethylbenzene/ (3758)
35 ethylbenzene.tw. (2865)
36 exp. "benzo[*a*]pyrene"/ (16794)
37 benzopyrene.tw. (427)
38 exp. carbon monoxide/ (36477)
39 carbon monoxide.tw. (31459)
40 exp. nitrogen dioxide/ (12837)
41 nitrogen dioxide.tw. (6589)
42 exp. ozone/ (28082)
43 ozone.tw. (28382)
44 exp. phthalic acid diethyl ester/ (1400)
45 Diethyl phthalate.tw. (933)

46 Diisobutyl phthalate.tw. (217)
47 di-n-butyl phthalate.tw. (976)
48 exp. galaxolide/ (444)
49 galaxolide.tw. (331)
50 tonalide.tw. (239)
51 exp. acenaphthene/ (807)
52 acenaphthene.tw. (682)
53 exp. acenaphthylene/ (1222)
54 acenaphthylene.tw. (476)
55 exp. phenanthrene/ (6371)
56 phenanthrene.tw. (6344)
57 exp. anthracene/ (4917)
58 anthracene.tw. (12647)
59 exp. “benz[*a*]anthracene”/ (2927)
60 exp. “benzo[*b*]fluoranthene”/ (1638)
61 exp. “benzo[*k*]fluoranthene”/ (1665)
62 exp. “benzo[*e*]pyrene”/ (640)
63 exp. “benzo[*ghi*]perylene”/ (1502)
64 benzo.tw. (27099)
65 exp. chrysene/ (2762)
66 chrysene.tw. (1612)
67 exp. “dibenz[*a*,*h*]anthracene”/ (1646)
68 exp. “dibenzo[*a*,*l*]pyrene”/ (266)
69 dibenz*.tw. (18662)
70 exp. fluoranthene/ (3605)
71 fluoranthene.tw. (2928)
72 exp. fluorene/ (2780)
73 fluorene.tw. (2865)
74 indenol.tw. (27)
75 exp. pyrene/ (7711)
76 pyrene.tw. (25167)
77 exp. phenol/ (26475)
78 phenol*.tw. (113770)
79 exp. plasticizer/ (15969)
80 plastici?er*.tw. (6491)
81 or/1–80 (530745)
82 exp. fragrance/ (22341)
83 air freshener*.tw. (186)
84 exp. antiinfective agent/ (3479324)
85 antimicrobial.tw. (201609)
86 exp. antioxidant/ (220297)
87 antioxidant*.tw. (257737)
88 exp. biocide/ (2507)
89 biocide.tw. (2328)
90 exp. building material/ (5693)
91 building material*.tw. (2776)
92 cable*.tw. (9264)
93 candle*.tw. (1451)
94 carpet*.tw. (3328)
95 exp. domestic chemical/ (17080)
96 cleaning agent*.tw. (933)
97 coalescing agent*.tw. (7)
98 combustion byproduct*.tw. (73)
99 decoration*.tw. (3300)
100 exp. deodorant agent/ (841)
101 deodorant*.tw. (680)
102 deod?ri?er.tw. (87)
103 diffuser*.tw. (1505)
104 exp. disinfectant agent/ (463296)
105 disinfectant*.tw. (11349)
106 exp. electronics/ (67201)
107 electronic component*.tw. (794)
108 exp. emulsifying agent/ (45452)
109 emulsifying agent*.tw. (503)
110 exp. essential oil/ (25078)
111 essential oil*.tw. (24260)
112 fixture*.tw. (3001)
113 exp. flame retardant/ (10748)
114 flame retardant*.tw. (5146)
115 floor covering*.tw. (205)
116 exp. fungicide/ (33568)
117 fungicide*.tw. (11108)
118 furnish*.tw. (14287)
119 exp. furniture/ (28093)
120 furniture.tw. (2616)
121 heat transfer fluid*.tw. (99)
122 exp. herbicide/ (52986)
123 herbicide*.tw. (21519)
124 exp. glue/ (2952)
125 glue.tw. (14203)
126 exp. incense/ (290)
127 incense.tw. (669)
128 internal source*.tw. (470)
129 exp. nonionic surfactant/ (46702)
130 nonionic surfactant*.tw. (3673)
131 (oil adj3 repellent*).tw. (157)
132 (water adj3 repellent*).tw. (443)
133 exp. paint/ (5498)
134 paint.tw. (7036)
135 exp. perfume/ (1921)
136 perfume*.tw. (2390)
137 exp. cosmetic/ (111657)
138 cosmetic*.tw. (68259)
139 personal care product*.tw. (3256)
140 exp. pesticide/ (342808)
141 pesticide*.tw. (58120)
142 exp. plastic/ (22926)
143 plastic*.tw. (220771)
144 polishes.tw. (146)
145 exp. preservative/ (293754)
146 preservative*.tw. (13739)
147 renovation*.tw. (2231)
148 exp. sealant/ (2208)
149 sealant*.tw. (7630)
150 exp. surfactant/ (239494)
151 surfactant.tw. (59026)
152 stain repellent*.tw. (22)
153 termiticide*.tw. (122)
154 terpene oxidation product*.tw. (13)
155 vinyl floor*.tw. (100)
156 wallpaper.tw. (208)
157 water disinfection product*.tw. (4)
158 exp. wax/ (4311)
159 waxes.tw. (1731)
160 exp. wood protecting agent/ (404)
161 wood preservative*.tw. (540)
162 or/82–161 (4589020)
163 indoor.tw. (34435)
164 exp. indoor air pollution/ (13379)
165 exp. ambient air/ (25496)
166 dwelling.tw. (39796)
167 domestic.tw. (83261)
168 exp. home/ (8083)
169 home.tw. (306935)
170 homes.tw. (51676)
171 exp. household/ (38767)
172 exp. building/ (7510)
173 ((new or green or sick) adj build*).tw. (2002)
174 “low carbon”.tw. (1476)
175 exp. home environment/ (4806)
176 “home environment*”.tw. (7143)
177 “sick building syndrome*”.tw. (739)
178 ventilation.tw. (173638)
179 “energy efficien*”.tw. (6943)
180 airtight*.tw. (1064)
181 “air permeability”.tw. (276)
182 exp. air conditioning/ (22678)
183 air conditioning.tw. (2510)
184 carbon neutral.tw. (329)
185 decay.tw. (74309)
186 or/163–185 (792951)
187 emission*.tw. (258318).
188 emission rate*.tw. (3662).
189 environmental chamber*.tw. (1369)
190 exp. measurement/ (1728870)
191 exp. monitoring/ (598505)
192 exp. exposure/ (613219)
193 “decay rate*”.tw. (4615)
194 exp. concentration ratio/ (1234)
195 exp. health impact assessment/ (4784)
196 (health adj (impact* or assessment* or effect*)).tw. (63034)
197 or/187–196 (3010795)
198 81 and 162 and 186 and 197 (4988)
199 limit 198 to english language (4680)
200 limit 199 to conference abstract (543)
201,199 not 200 (4137)
202 limit 201 to yr = “2000 -Current” (3511)

Table A2
Scopus and Environmental Complete search strategy:

TITLE-ABS-KEY("volatile organic compound*" or VOC or VOCs or "semi volatile organic compound*" or "semi volatile compound*" or SVOC or SVOCs or dust or benzene or formaldehyde or toluene or styrene or acetaldehyde or a-pinene or D--Limonene or naphthalene or tetrachloroethylene or trichloroethylene or m-xylene or p-xylene or o-xylene or ethylbenzene or benzopyrene or "carbon monoxide" or "nitrogen dioxide" or ozone or "Diethyl phthalate" or "Diisobutyl phthalate" or "di-n-butyl phthalate" or galaxolide or tonalide or acenaphthene or acenaphthylene or phenanthrene or anthracene or benzo or chrysene or dibenz* or fluoranthene or fluorene or indenol or pyrene or phenol* or plasticizer* or plasticizer*) AND TITLE-ABS-KEY(fragrance or "air freshener*" or antimicrobial or antioxidant* or biocide or "building material*" or cable* or candle* or carpet* or "cleaning agent*" or "coalescing agent*" or "combustion byproduct*" or decoration* or deodorant* or deodoriser* or deodorizer* or diffuser* or disinfectant* or "electronic component*" or "emulsifying agent*" or "essential oil*" or fixture* or "flame retardant*" or "floor covering*" or fungicide* or furnish* or furniture or "heat transfer fluid*" or herbicide* or glue or incense or "internal source*" or "nonionic surfactant*" or "oil repellent*" or "water repellent*" or paint or perfume* or cosmetic* or "personal care product*" or pesticide* or plastic* or polishes or preservative* or renovation* or sealant* or surfactant or "stain repellent*" or termiticide* or "terpene oxidation product*" or "vinyl floor*" or wallpaper or "water disinfection product*" or wax or waxes or "wood protecting agent" or "wood preservative*") AND TITLE-ABS-KEY (indoor or "indoor air pollution" or "ambient air" or dwelling or domestic or home or homes or household or building* or "low carbon" or "home environment*" or "sick building syndrome*" or ventilation or "energy efficien*" or airtight* or "air permeability" or "air conditioning" or "carbon neutral" or decay) AND TITLE-ABS-KEY(emission* or "emission rate*" or "environmental chamber*" or measurement or monitoring or exposure* or "decay rate*" or "concentration ratio" or "health impact*" or "impact assessment*" or "health assessment*" or "health effect*") AND PUBYEAR AFT 2000.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156201.

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