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Exposure to volatile organic compounds in offices and in residential and educational buildings in the European Union between 2010 and 2023: A systematic review and health risk assessment

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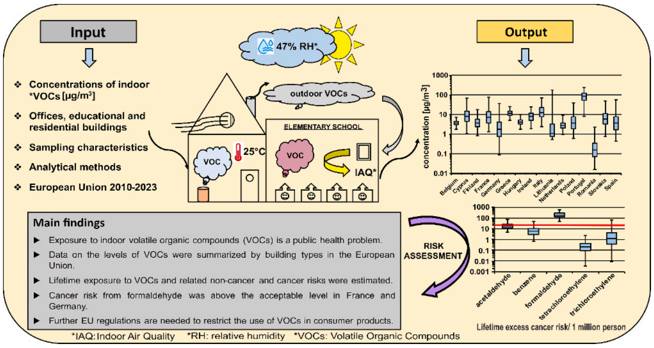
HIGHLIGHTS

- Exposure to indoor volatile organic compounds (VOCs) is a public health problem.
- Data on the levels of VOCs were summarized by building types in the European Union.
- Lifetime exposure to VOCs and related non-cancer and cancer risks were estimated.
- Cancer risk from formaldehyde was above the acceptable level in France and Germany.
- Further EU regulations are needed to restrict the use of VOCs in consumer products.

GRAPHICAL ABSTRACT



Main findings

- Exposure to indoor volatile organic compounds (VOCs) is a public health problem.
- Data on the levels of VOCs were summarized by building types in the European Union.
- Lifetime exposure to VOCs and related non-cancer and cancer risks were estimated.
- Cancer risk from formaldehyde was above the acceptable level in France and Germany.
- Further EU regulations are needed to restrict the use of VOCs in consumer products.

*IAQ: Indoor Air Quality *RH: relative humidity *VOCs: Volatile Organic Compounds

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ABSTRACT

Chronic exposure to indoor volatile organic compounds (VOCs) can result in several adverse effects including cancers. We review reports of levels of VOCs in offices and in residential and educational buildings in the member states of the European Union (EU) published between 2010 and 2023. We use these data to assess the risk to population health by estimating lifetime exposure to indoor VOCs and resulting non-cancer and cancer risks and, from that, the burden of cancer attributable to VOC exposure and associated economic losses. Our systematic review identified 1783 articles, of which 184 were examined in detail, with 58 yielding relevant data. After combining data on VOC concentrations separately for EU countries and building types, non-cancer and cancer risks were assessed in terms of hazard quotient and lifetime excess cancer risk (LECR) using probabilistic Monte Carlo Simulations. The LECR was used to estimate disability adjusted life years (DALYs) from VOC-related cancers and associated costs. We find that the LECR associated with formaldehyde exposure was above the acceptable risk level (ARL) in France and Germany and that of from exposure to benzene was also above the ARL in Spanish females. The sum of DALYs and related costs/1,000,000 population/year from exposure to acetaldehyde, benzene, formaldehyde, tetrachloroethylene, and trichloroethylene were 4.02 and €41,010, respectively, in France, those from exposure to acetaldehyde, benzene, carbon tetrachloride, formaldehyde, and

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trichloroethylene were 3.91 and €39,590 in Germany, and those from exposure to benzene were 0.1 and €1030 in Spain. Taken as a whole, these findings show that indoor exposure to VOCs remains a public health concern in the EU. Although the EU has set limits for certain VOCs, further measures are needed to restrict the use of these chemicals in consumer products.

1. Introduction

Volatile organic compounds (VOCs), with boiling points between 50 °C and 260 °C, comprise one of the most important groups of indoor air pollutants [González-Martín et al., 2021; Sarigiannis et al., 2011; World Health Organization (WHO), 2010]. They include acetaldehyde, benzene, formaldehyde, ethylbenzene, toluene, and xylene, all found in many widely-used building materials, including paints, thinners, and adhesives (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). Acetaldehyde, benzene and formaldehyde are also present in particleboard furniture and several wooden products such as plywood and laminate floorings (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). VOCs can also be released into the air from a variety of consumer products found indoors (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). For example, carpets can release benzene, ethylbenzene, formaldehyde, and styrene (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). Some household cleaning products are sources of formaldehyde, trichloroethylene, tetrachloroethylene, toluene, styrene, and xylene, while cosmetics can emit formaldehyde and toluene into the indoor environment (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). Electronic equipment, including computers and photocopiers, have been found to release formaldehyde and plastics can emit ethylbenzene and styrene (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). Although less of a problem since the widespread adoption of smoking bans, tobacco smoke has long been one of the most important sources of indoor benzene, toluene, ethylbenzene, xylene (abbreviated as BTEX) and formaldehyde (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010). Given their almost ubiquitous use, these VOCs can be found in many residential and educational buildings, and offices at non-trivial concentrations (González-Martín et al., 2021; Sarigiannis et al., 2011; WHO, 2010).

Several studies have linked long-term inhalation of VOCs to a range of toxic effects (WHO, 2010; Zhang and Smith, 2003) so chronic exposure is an important public health concern given the amount of time many people spend indoors (WHO, 2010). A previous study surveying 1427 subjects from seven regions of Europe reported that individuals spend an average of 13.95 h at home, 6.71 h at work and 1.67 h in other indoor environments (Schweizer et al., 2007). The most commonly reported adverse effects are central nervous system damage and associated symptoms, kidney dysfunction and elevated blood pressure (Chang et al., 2010; Chang et al., 2020; Gericke et al., 2001; Levin and Lilis, 2008; WHO, 2010). Long-time exposure to specific VOCs has also been identified as a risk factor for various cancers (WHO, 2010). Benzene and formaldehyde have been classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1), associated with increased incidence of myeloid leukaemia and nasopharyngeal cancer, respectively (IARC, 1987; IARC, 2012). Trichloroethylene is also a Group 1 carcinogen, linked to increased risk of kidney and liver cancers, and non-Hodgkin's lymphoma (IARC, 2014). Tetrachloroethylene is considered by IARC to be a probable human carcinogen (Group 2A) linked to bladder cancer (IARC, 2014), as is styrene, linked to cancers of the lymphohaematopoietic system (IARC, 2019). Acetaldehyde and ethylbenzene have been identified as possible human carcinogens (Group 2B) based on rat studies finding an increased incidence of nasopharyngeal carcinoma and renal tumours, respectively (Carreón-Valencia, 1999; IARC, 2000; National Toxicology Program, 1999).

One estimate of the disease burden in the 26 countries of the European Union (EU) in 2010 attributed 2.1 million disability adjusted life years (DALYs) to indoor air pollution of which 21,000 DALYs (1 %) were related to exposure to indoor VOCs in 2010 (Asikainen et al., 2016). One of the most extensive studies so far of the risks associated with indoor exposure to VOCs of public health concern in the EU covered the two decades prior to 2010 (Sarigiannis et al., 2011). However, it did not estimate the associated disease burden or economic losses (Sarigiannis et al., 2011). In addition, that study is now almost fourteen years old and a search using indoor air pollution and the name of each EU country separately as keywords yielded 3863 articles in the PubMed on 11th January 2023 (National Library of Medicine, PubMed Central database). These are expected to contain valuable data on recent concentrations of several VOCs, information that is important as exposures are likely to have changed. Consequently, our objective was to conduct a systematic review of data reported between 2010 and 2023 on the levels of the most relevant VOCs in residential buildings, educational buildings, and offices in the 27 countries that were members of the European Union in 2023. We used these data to conduct a comprehensive risk assessment in which we estimate lifetime exposure to VOCs and consequent non-cancer and cancer risks using a probabilistic Monte Carlo simulation, separately considering groups defined by sex and by differences in time spent in indoor environments. Finally, we calculated the cancer disease burden attributable to indoor VOC exposure and related economic losses.

2. Data and methods

2.1. Literature search

Of the VOCs present in indoor air, we selected for the literature search 18 aromatic hydrocarbons, including the most commonly detected BTEX and styrene, as well as the two most common aldehydes acetaldehyde and formaldehyde (González-Martín et al., 2021; Sarigiannis et al., 2011). All the VOCs included are listed in Supplementary Table 1. Systematic literature searches were conducted in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement in the PubMed (US National Library of Medicine, Bethesda, MD, USA), Web of Science (Thompson Reuters, Philadelphia, PA, USA) and Scopus (Elsevier B.V., Amsterdam, the Netherlands) databases (Page et al., 2021). The search strategy combined the chemical names of the selected VOCs, the names of the 27 countries that were members of the European Union in 2023, and the terms indoor, indoor air and indoor air quality. These were supplemented with words describing types of buildings, such as school, office, and house and their synonyms. Residential buildings were defined as dwellings, including houses, flats, and apartments intended to provide temporal or permanent private occupancy by individuals or families. Offices were defined as a room or sets of rooms in a building used for commercial, professional, or administrative purposes. Day-care centres, kindergartens, elementary and secondary schools, as well as universities were included in the category of educational buildings. The detailed strategy is described in Supplement 1. To be included, papers had to report data on indoor concentrations of the selected VOCs in residential, educational and office buildings published in English between January 2010 and January 2023. This generated 1783 articles, with 984 remaining after removing duplicates. Two authors then independently screened their titles and abstracts using Zotero reference management software version 6.0 (Coar and Sewell, 2010). We could not retrieve 42 conference proceedings (see Fig. 1 for more detail). This left 184 full text publications to be reviewed. Articles that reported indoor air concentrations of VOCs that had not been selected for inclusion, levels of total VOCs, or outdoor pollutants only were excluded, as were those that only reported data on mean, median, minimum, and maximum levels of VOCs, as well as those that reported indoor concentrations of VOCs in buildings other than residential, educational, or office buildings. To ensure comparability between studies, only those that used active or passive samplers and gas chromatography or high-performance liquid chromatography with various detectors were included while those that failed to report details of sample collection or analysis were excluded. This left 47 articles providing data that could be extracted. The reference lists of these articles were hand searched for further relevant papers, providing 11 further studies, making a total of 58. The flow chart describing this process and the list of studies meeting the inclusion criteria are shown in Fig. 1 and Supplement 2, respectively.

2.2. Database development

Mean concentrations of VOCs in residential, educational, and office buildings, with their standard deviations, medians, minimums, maximums, and percentile values were extracted from the selected studies. The name of the first author, title of the article, country and settlement concerned, date of publication and sampling, type of environment (urban, suburban, rural), number of buildings investigated, sampling conditions (air temperature and humidity), sampling and analytical methods were also recorded. To ensure comparability, concentrations of VOCs expressed in ppm were converted to μg/m^3.

2.3. Determination of country specific distribution of VOCs

As only aggregated data on concentrations of VOCs were reported, the “goodness of fit test” could not be used to determine distributions (Liu et al., 2022). However, several studies have demonstrated that levels of VOCs have a log-normal distribution in indoor environments (Brown et al., 1994; Jia et al., 2008; Liu et al., 2022; Sarigiannis et al., 2011; Zhang et al., 2020), which we apply in our analysis. The data extracted from each study were used to determine the distribution parameters for each VOC separately applying @Risk for Excel software, version 8.1 (Palisade Corporation, Ithaca, NY, USA). The resulting distributions of concentrations of individual VOCs were grouped by country and then weighted by the number of buildings studied and VOCs were combined using probabilistic Monte Carlo simulations with 10,000

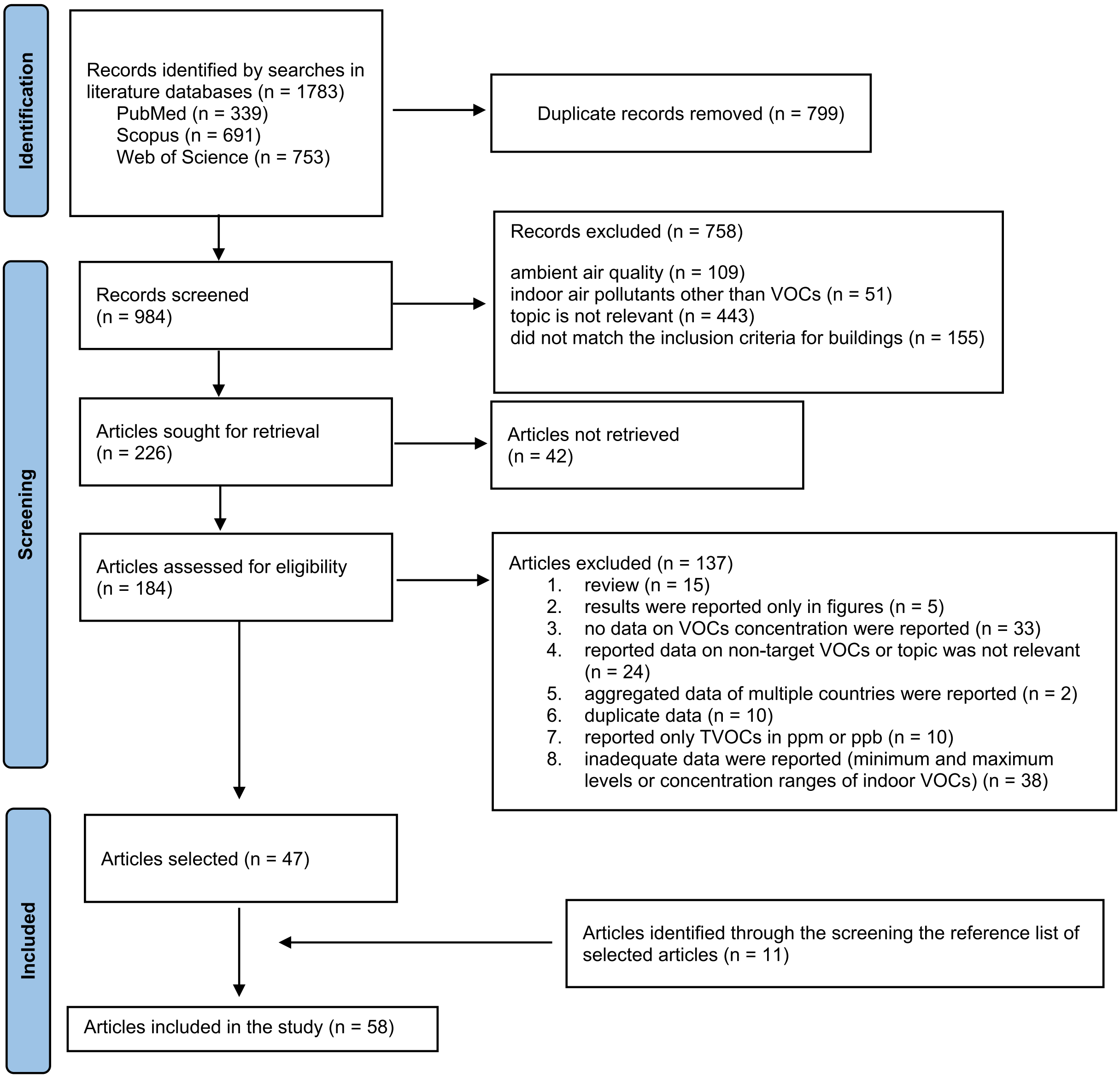

Fig. 1. Flowchart of literature search.

iterations, Latin Hypercube sampling, and the Mersenne Twister random number generator (Pál et al., 2022). The combined VOC concentration distributions (CVCDs) obtained were used to assess cancer and non-cancer risks. The number of buildings by types, countries, and VOCs included in our study are reported in Supplementary Tables 2–4.

2.4. Estimation of VOC–related cancer and non-cancer risks

A realistic health risk assessment requires data on VOC concentrations measured in a large enough number of buildings. To select the CVCDs to be used for cancer and non-cancer risk assessments, the minimum number of buildings from which concentration data were for health risk estimations was calculated using the Yamane-type Eq. (1):

$$n = \frac{N}{\left[1 + N(e)^2\right]} \tag{1}$$

where, n is the minimum number of buildings required, N is the number of residential, office and educational buildings in a country, and e is the margin of error (Yamane, 1967). To estimate n, data on the number of residential and educational buildings in the member states of the European Union were extracted from the EU Building Stock Observatory Database (European Commission, 2023). Since this does not include numbers of offices, they were estimated by multiplying the share of offices in non-residential buildings by the number of non-residential buildings. Data on the share of offices in the building stock were obtained from "The European Building Stock Analysis (Gevorgian et al., 2021). The margin of error was considered to be 0.05. The result of the Yamane-type equation indicated that we would require concentrations from at least 400 each of residential, office, and educational buildings separately for our health risk assessment. These were only available for French, German and Spanish residential buildings and used for cancer and non-cancer risk estimations. Consequently, we did not have sufficient data to include office and educational buildings in our estimation of cancer and non-cancer risk estimates. The final list of VOCs included in our analysis is in Supplementary Table 1.

The distributions of lifetime excess cancer risks (LECRs) were estimated using the following formula (2):

$$\text{LECR} = \text{EC x IUR} \tag{2}$$

where EC is the distribution of exposure to VOCs expressed in concentrations as µg/m^3 over a lifetime. IUR is the inhalation unit risk as (µg/m^3)$^{-1}$ (US EPA, 2009). The IUR values were obtained from the United States Environmental Protection Agency and are shown in Table 1 (US EPA, 2023). Since a range of IUR (2.2×10^{-6}–7.8×10^{-6}) was reported for benzene, in this case a uniform distribution of IUR was assumed in LECR estimations (US EPA, 2023). EC was determined as follows (3):

$$\text{EC} = \frac{\text{CVCDs x ETx EF x ED}}{\text{AT}} \tag{3}$$

where, ET is the distribution of life–stage specific exposure time (hours/day) assuming normal distribution, EF is the exposure frequency (365 day), ED is the exposure duration, i.e. the number of years spent in each life–stage multiplied by 365 days, (365 days x number of years spent in the specific life–stage), AT is the averaging time (365 days x number of years spent in the specific life–stage). Zeghnoun and Dor (2010), Brasche and Bischof (2005), and Gershuny et al. (2020) reported life-stage specific time spent indoors (LSTSI) values for the French, German, and Spanish populations respectively for residential buildings. These data were used to determine the average LSTSI ± standard deviation (SD). To obtain ET, these values were applied in probabilistic Monte Carlo simulations. The exposure duration (ED) was determined separately for French, German, and Spanish males and females using the life–stage categories and life expectancies at birth in 2021: 79.3 years for French males, 85.5 years for French females, 78.4 years for German males, 83.3 years for German females, 80.4 years for Spanish males, and 86.2 years for Spanish females (Eurostat, 2023). The life-stage categories are shown in Table 2. We assumed that people were exposed to a single indoor air pollutant during their lifetime. The results were expressed in LECR/1,000,000 population. The acceptable risk level (ARL) for VOCs classified as known or suspected carcinogens, including agents in IARC Group 1, 2A and 2B, has been defined as the range from 1×10^{-6} to 1×10^{-4} (IARC, 2023; US EPA, 2020). Risks below 1×10^{-6} (1 additional cancer per 1,000,000 population) are generally not a cause for public health concern. However, risk levels exceeding 1×10^{-4} (100 additional cancer per 1,000,000 population) are considered unacceptable (US EPA, 2020).

Table 1
Inhalation unit risks and reference concentrations of volatile organic compounds included in this study.

Name of compound	Inhalation unit risk[a] [µg/m^3]	Reference concentration [µg/m^3]	IARC group[g]
acetaldehyde	2.2×10^{-6}	100[b]	2B
benzene	$2.2\text{-}7.8 \times 10^{-6}$	30[a]	1
2-butanone	–	5000[c]	–
butyl acetate	–	100[d]	–
cyclohexane	–	6000[a]	–
chloroform	–	300[e]	2B
carbon tetrachloride	6×10^{-6}	100[a]	2B
1,4-dichlorobenzene		800[a]	2B
ethylbenzene	–	1000[a]	2B
formaldehyde	1.3×10^{-5}	100[b]	1
n-hexane	–	700[a]	–
styrene	–	250[f]	2A
tetrachloroethylene	2.6×10^{-7}	40[a]	2A
toluene	–	300[b]	3
trichloroethylene	4.1×10^{-6}	2[a]	1
xylenes	–	100[a]	3

The data presented in Table 1 were obtained from the following sources:

[a] United States Environmental Protection Agency, 2023. Integrated Risk Information System Assessments. https://iris.epa.gov/AtoZ/?list_type=alpha (accessed 16 January 2024).

[b] German Environment Agency, 2023. Guide values for the concentration of specific substances in indoor air. https://www.umweltbundesamt.de/en/gallery/guide-values-for-the-concentration-of-specific (accessed 16 January 2024).

[c] Agency for Toxic Substances and Disease Registry of U.S. Department of Health and Human Services, 2020. Toxicological Profile for 2-Butanone. https://www.atsdr.cdc.gov/ToxProfiles/tp29.pdf (accessed 16 January 2024).

[d] Ordinance of the Minister of Health and Social Welfare of Poland on indoor air pollutants, 1996. https://isap.sejm.gov.pl/isap.nsf/download.xsp/WMP19960190231/O/M19960231.pdf (accessed 16 January 2024).

[e] California Environmental Protection Agency, 2000. Chronic toxicity summary on chloroform. https://oehha.ca.gov/media/downloads/crnr/16chrel.pdf (accessed 16 January 2024).

[f] Kotzias et al., 2005. The INDEX Project - Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU. https://publications.jrc.ec.europa.eu/repository/handle/JRC31622 (accessed 16 January 2024).

[g] International Agency for Research on Cancer, 2023. Agents classified by the IARC Monographs. https://monographs.iarc.who.int/list-of-classifications (accessed 16 January 2024).

Non-cancer risks were assessed by determining the distribution of hazard quotient (HQ) for each CVCDs as follows (4):

$$\text{HQ} = \frac{\text{EC}}{\text{RFC}} \tag{4}$$

where, RFC is the reference concentration of a VOC. If the ratio of EC and RFC is less than or equal to 1.0 the hazard is considered to be negligible, while values above 1.0 indicate an increased non-cancer risk (US EPA, 2009). The RFC values were selected according to the criteria described previously (De Brouwere and Cornelis, 2016; Szabados et al., 2021). They were obtained from the Agency for Toxic Substances and Disease Registry (2020), California Environmental Protection Agency (2000), German Environment Agency (2023), Kotzias et al. (2005), Ministry of

Table 2

Life-stage specific time spent in residential buildings in France, Germany, and Spain.

France[a]			Germany[b]			Spain[c]		
life-stages [years]	time spent by females in residential buildings [mean hours ± SD*]	time spent by males in residential buildings [mean hours ± SD]	life-stages [years]	time spent by females in residential buildings [mean hours ± SD]	time spent by males in residential buildings [mean hours ± SD]	life-stages [years]	time spent by females in residential buildings [mean hours ± SD]	time spent by males in residential buildings [mean hours ± SD]
0–4	17.7 ± 0.8	17.2 ± 0.6	<7	17.9 ± 2.9	17.3 ± 3.6	10–20	16.6 ± 3.9	16.3 ± 4.2
5–9	16.2 ± 0.5	14.1 ± 1.3	7–16	14.8 ± 3.2	14.7 ± 2.6	21–30	16.0 ± 4.8	15.3 ± 4.7
10–14	15.1 ± 0.8	15.7 ± 0.5	17–24	12.9 ± 3.6	12.4 ± 3.2	31–40	16.8 ± 4.3	15.0 ± 4.5
15–19	14.7 ± 0.6	14.4 ± 1.1	25–34	14.7 ± 4.5	11.9 ± 3.1	41–50	17.1 ± 4.3	15.1 ± 4.4
20–29	15.2 ± 0.9	14.6 ± 0.7	35–44	15.7 ± 4.0	12.4 ± 2.4	51–60	17.9 ± 4.3	15.7 ± 4.3
30–39	17.2 ± 0.4	14.3 ± 0.6	45–54	15.8 ± 3.7	13.0 ± 3.7	61–70	19.6 ± 3.4	17.6 ± 3.9
40–49	16.9 ± 0.4	15.1 ± 0.5	55–64	17.5 ± 3.9	15.8 ± 4.6	71–80	20.8 ± 2.8	19.2 ± 3.1
50–59	17.0 ± 0.6	14.4 ± 0.6	64 <	19.9 ± 2.9	19.0 ± 3.3	80<	21.7 ± 2.9	20.4 ± 3.0
60 <	19.3 ± 0.3	17.1 ± 0.9						

Life-stage specific time spent in residential buildings was calculated using data obtained from:

[a] Zeghnoun and Dor, 2010. Description du budget espace-temps et estimation de l'exposition de la population française dans son logement. Saint-Maurice (Fra): Institut de veille sanitaire, 37. www.invs.sante.fr (accessed 8 February 2024).

[b] Brasche and Bischof, 2005. Daily time spent indoors in German homes – baseline data for the assessment of indoor exposure of German occupants Int. J. Hyg. Environ. Health, 208, 247–253.

[c] Gershuny et al., 2020. Multinational Time Use Study. Centre for Time Use Research, UCL IOE, University College London. https://www.timeuse.org/survey-data (accessed 8 February 2024).

[*] SD: standard deviation.

Health and Social Welfare of Poland (1996) and US EPA (2023).

2.5. Estimating disease burden and costs associated with cancer risks from exposure to VOCs

First, the LECRs for residential VOC exposure were multiplied by the number of males and females living in France, Germany and Spain to calculate the total number of cancers for each VOC separately. Population numbers were obtained from World Bank data (Word Bank, 2023a). Second, to determine the disability adjusted life years (DALYs) from VOC-related cancers, the results were multiplied by the ratio of DALYs attributable to cancer/year and the number of new cancer cases in the selected countries. Third, to obtain the costs of VOC-related cancers, DALYs from VOC-related cancers were multiplied by the cost of one cancer-related DALY. Data on DALYs and cancer incidence were from the Global Burden of Disease (GBD) Study (2020) whereas the cost of one cancer-related DALY (US$ 9150) was taken from a publication by Garlasco et al., 2022. All monetary values were adjusted for inflation and expressed in 2022 euros (European Central Bank, 2022; World Bank, 2023b).

3. Results

The CVCDs in offices, residential and educational buildings in EU member states are presented in Figs. 2–6, respectively. Fig. 2 shows that the distribution of tetrachloroethylene in France [panel G; median: 11.3 μg/m^3, interquartile range (IQR): 4.3–29.9 μg/m^3, 1st and 99th percentile: 0.4 and 323.9 μg/m^3], trichloroethylene in Greece (panel I; median: 0.2 μg/m^3, IQR: 0.1–0.5 μg/m^3, 1st and 99th percentile: 0.02 and 2.8 μg/m^3), and xylenes in the Netherlands (panel J; median: 2.6 μg/m^3, IQR: 1.4–5.8 μg/m^3, 1st and 99th percentile: 0.2 and 108.2 μg/m^3) exceeded the RFC in office buildings. As shown in Figs. 3 and 4, the distribution of acetaldehyde in Romania (Fig. 3, panel A, median: 68.6 μg/m^3, IQR: 42.2–112.2 μg/m^3, 1st and 99th percentile: 16.1 and 362.3 μg/m^3), benzene in Cyprus (Fig. 3 panel B, median: 3.4 μg/m^3, IQR: 1.6–7.2 μg/m^3, 1st and 99th percentile: 0.3 and 44.5 μg/m^3), formaldehyde in Romania (Fig. 4 panel B, median: 89.4 μg/m^3, IQR: 55.2–124.5 μg/m^3, 1st and 99th percentile: 8.8 and 247.1 μg/m^3), trichloroethylene in France (Fig. 4 panel G, median: 0.4 μg/m^3, IQR: 0.1–1.4 μg/m^3, 1st and 99th percentile: 0.004 and 24.1 μg/m^3), and Lithuania (Fig. 4 panel G, median: 6.9 μg/m^3, IQR: 5.9–8.1 μg/m^3, 1st and 99th percentile: 3.8 and 11.9 μg/m^3), and xylenes in Lithuania (Fig. 4 panel H, median: 1.1 μg/m^3, IQR: 0.79–3.4 μg/m^3, 1st and 99th percentile: 0.5 and 177.6 μg/m^3) and Portugal (Fig. 4 panel H, median: 89.4 μg/m^3, IQR: 55.2–124.1 μg/m^3, 1st and 99th percentile: 8.3 and 246.5 μg/m^3) were above the RFC in residential buildings. Considering CVCDs in educational buildings, our results showed that the distribution of benzene in Germany (Fig. 5, panel B, median: 3.3 μg/m^3, IQR: 1.9–6.4 μg/m^3, 1st and 99th percentile: 0.5 and 36.0 μg/m^3) and trichloroethylene in France (Fig. 6, panel F. median: 12.8 μg/m^3, IQR: 12.3–13.9 μg/m^3, 1st and 99th percentile: 12.1 and 24.6 μg/m^3) and Romania (Fig. 6, panel F. median: 3.6 μg/m^3, IQR: 2.3–5.4 μg/m^3, 1st and 99th percentile: 0.7 and 8.8 μg/m^3) were higher than the RFC.

The distributions of LECRs from exposure to VOCs in residential buildings among French, German, and Spanish males and females are shown in Fig. 7. The distribution of LECR associated with formaldehyde exposure was above the upper limit of the ARL of 1×10^{-4} in the French and German male (France: median: 170.4/1 million population, IQR: 115.3–246.8/1 million population, 1st and 99th percentile: 40.8 and 510.7/1 million population; Germany: median: 189.9/1 million population, IQR: 127.7–278.9/1 million population, 1st and 99th percentile: 43.7 and 699.2/1 million population) and female (France: median: 191.2/1 million population, IQR: 129.1–277.0/1 million population, 1st and 99th percentile: 45.4 and 575.1/1 million population; Germany: median: 214.5/1 million population, IQR: 144.7–312.3/1 million population, 1st and 99th percentile: 52.1 and 744.9/1 million population) population (Fig. 7, panels A-D). The LECR among Spanish females (median: 5.4/1 million population, IQR: 2.7–11.9/1 million population, 1st and 99th percentile: 0.09 and 106.3/1 million population) exposed to benzene also exceeded the upper limit of the ARL (Fig. 7, panel F). As presented in Fig. 8 the distribution of HQ values of trichloroethylene exposure among French males (median: 0.13, IQR: 0.04–0.45, 1st and 99th percentile: 9.7×10^{-4} and 7.5) and females (median: 0.15, IQR: 0.04–0.5, 1st and 99th percentile: 9.8×10^{-4} and 8.3) was above 1 (panels A and B).

The incidence, total number of cases/year, DALYs, and cost of DALYs associated with cancer from exposure to specific VOCs in residential buildings among the French, German, and Spanish male and female population are reported in Tables 3, 4 and 5. The incidence and the total number of cancer cases were higher in males than in females for each of the VOCs investigated (Tables 3, 4, and 5). In contrast, cancer-related DALYs and associated costs were higher for males than for females in these countries (Tables 3, 4 and 5). Tables 3 and 4 also show that exposure to formaldehyde was responsible for the greatest incidence,

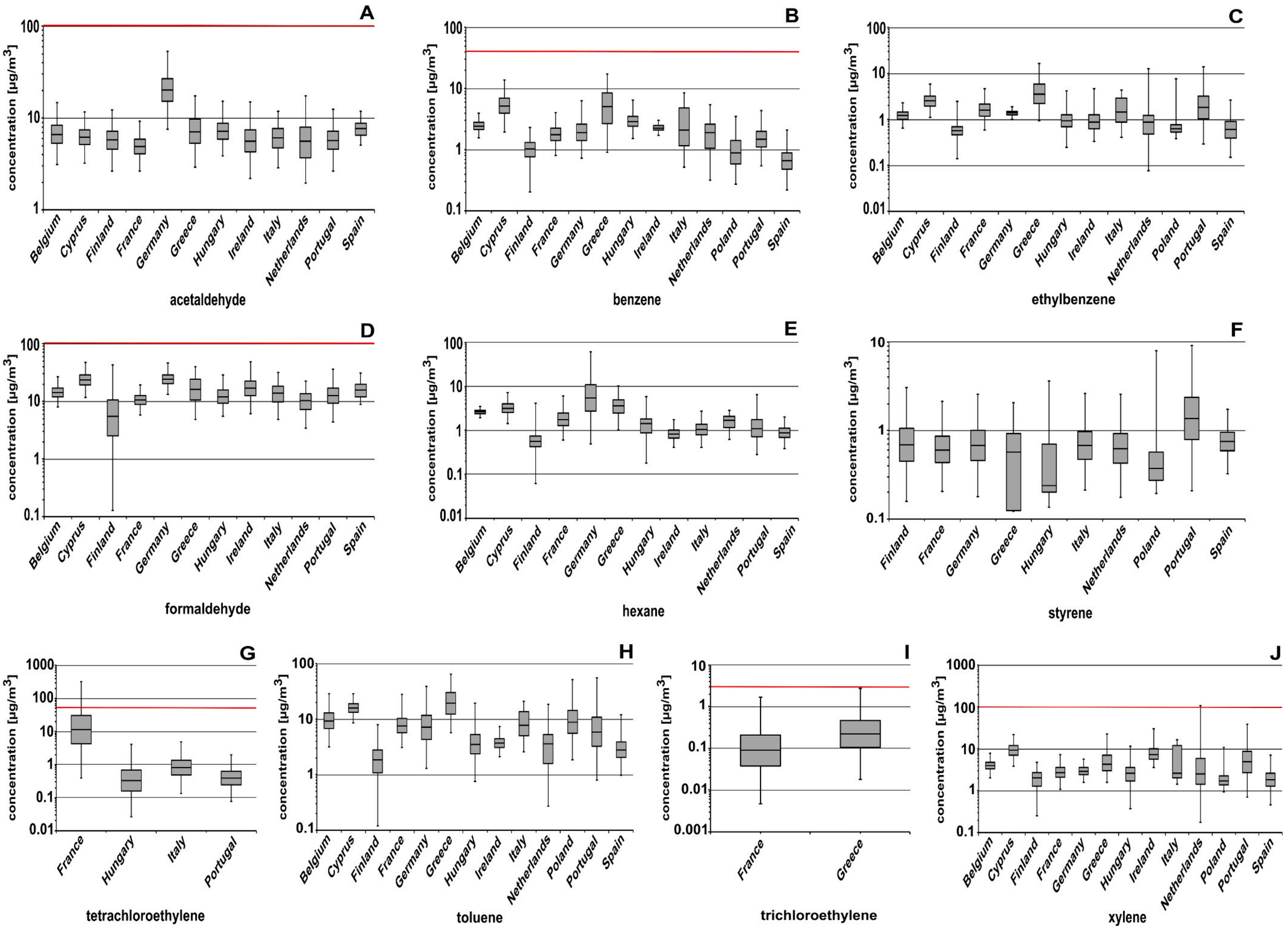

Fig. 2. Combined volatile organic compound concentration distributions in offices in the member states of the European Union.
Data on the concentrations of volatile organic compounds (VOCs) were obtained from the articles identified by literature search. The data extracted from each study were used to determine the concentration distribution for each VOC separately. The resulting concentration distributions were grouped by country then weighted by the number of buildings studied and combined by VOCs using probabilistic Monte Carlo simulations. Panels: A: acetaldehyde, B: benzene, C: ethylbenzene, D: formaldehyde, E: hexane, F: styrene, G: tetrachloroethylene, H: toluene, I: trichloroethylene, J: xylene. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the reference concentration (RFC) of VOCs. The RFC is not shown for those VOCs where it was above the maximum of the y-axis.

total number of cases/year, DALYs, and cost of DALYs for men and women both in France and Germany. Of the VOCs measured in Spanish residential buildings, it was only possible to estimate disease burden and costs associated with cancer risks for benzene (Table 5). The results obtained were similar to those found in the French and German population with cancer incidence and total number of cases due to benzene exposure being higher among Spanish females, while the costs of DALYs were greater among Spanish males (Table 5).

4. Discussion

Although there are many studies that have measured the concentration of VOCs in indoor air in offices and in residential and educational buildings, very few have estimated the health risks from chronic exposure to these chemicals in member states of the EU (Halios et al., 2022; Sarigiannis et al., 2011; Szabados et al., 2021) and those that have either use data derived from a small number of indoor spaces or have combined measurements from different types of buildings, neither of which may reflect realistic exposures. To overcome these shortcomings, we have combined data on indoor VOC levels separately for studies of offices and residential and educational buildings in different EU member states. We have also used a comprehensive, population-based approach to assess the related cancer and non-cancer risks. To reduce the effect of unrepresentative outliers, we only included data for each VOC where it was derived from at least 400 buildings. This criterion was fulfilled by CVCDs containing data on VOC levels in French, German, and Spanish residential buildings. We have also taken account of the distribution of population and age specific exposure time as well as life expectancy at birth separately for males and females in these countries.

In contrast to previous investigations, our study has allowed us to compare the combined concentration distributions of VOCs in offices and in residential and educational buildings of these EU countries with the corresponding RFC. Considering all three building types, we show that the concentration distributions of 6 out of the 18 VOCs (acetaldehyde, benzene, formaldehyde, tetrachloroethylene, trichloroethylene, xylene) were higher than the recommended RFCs in 8 EU member states (Cyprus, France, Germany, Greece, Lithuania, the Netherlands, Portugal, Romania; see Fig. 2–6). A recent, well-designed systematic review reported weighted averages of residential VOC concentrations falling within the interquartile range of CVCDs determined in our study (Halios et al., 2022). For example, the authors found that the mean levels of acetaldehyde, benzene, and formaldehyde in European homes were 10.14, 1.99, and 18.04 µg/m^3, respectively. In our study, the interquartile range of concentration distributions for acetaldehyde,

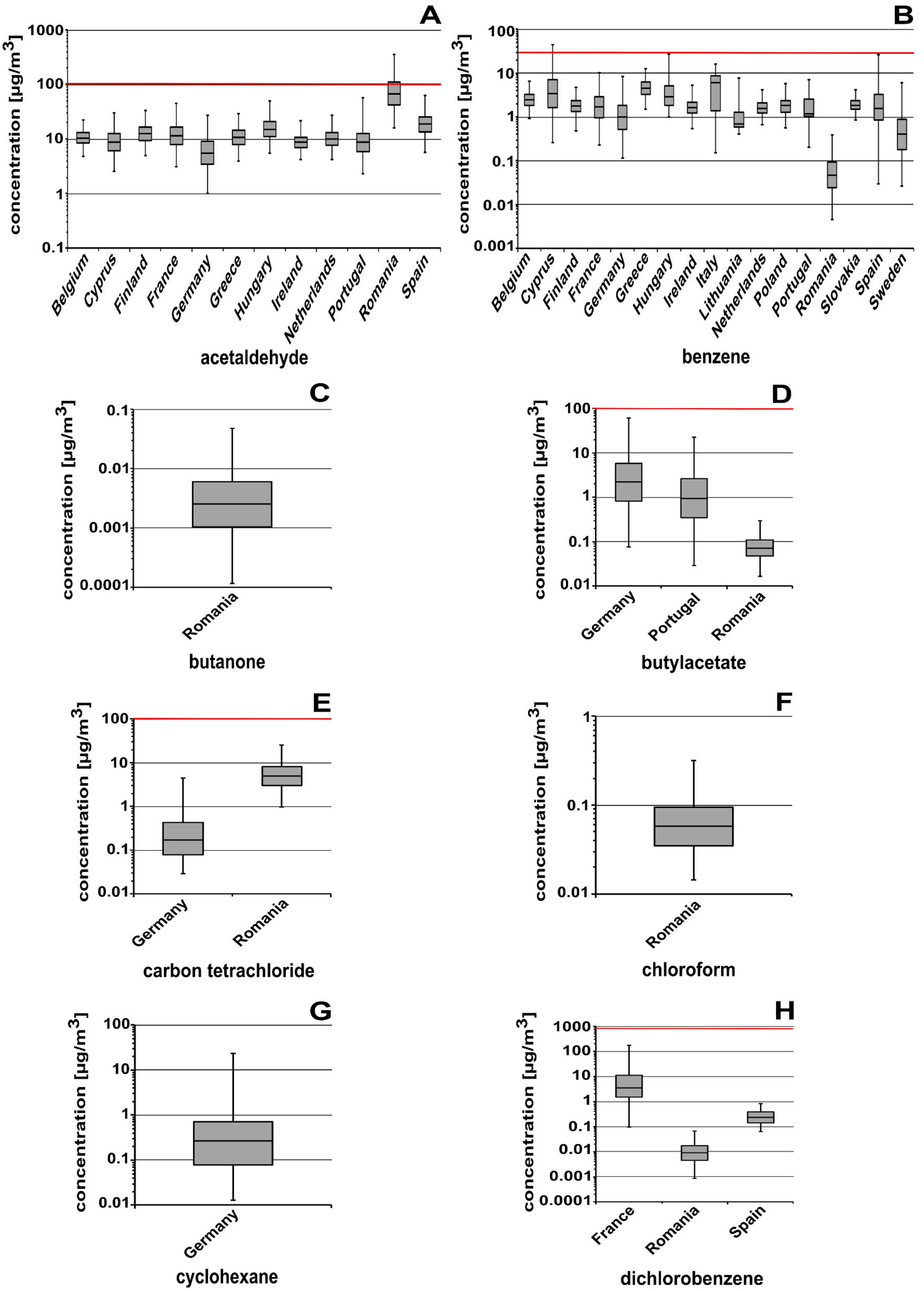

Fig. 3. Combined volatile organic compound concentration distributions in residential buildings in the member states of the European Union.
Data on the concentrations of volatile organic compounds (VOCs) were obtained from the articles identified by literature search. The data extracted from each study were used to determine the concentration distribution for each VOC separately. The resulting concentration distributions were grouped by country then weighted by the number of buildings studied and combined by VOCs using probabilistic Monte Carlo simulations. Panels: A: acetaldehyde, B: benzene, C: butanone, D: butylacetate, E: carbon tetrachloride, F: chloroform, G: cyclohexane, H: dichlorobenzene. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the reference concentration (RFC) of VOCs. The RFC is not shown for those VOCs where it was above the maximum of the y-axis.

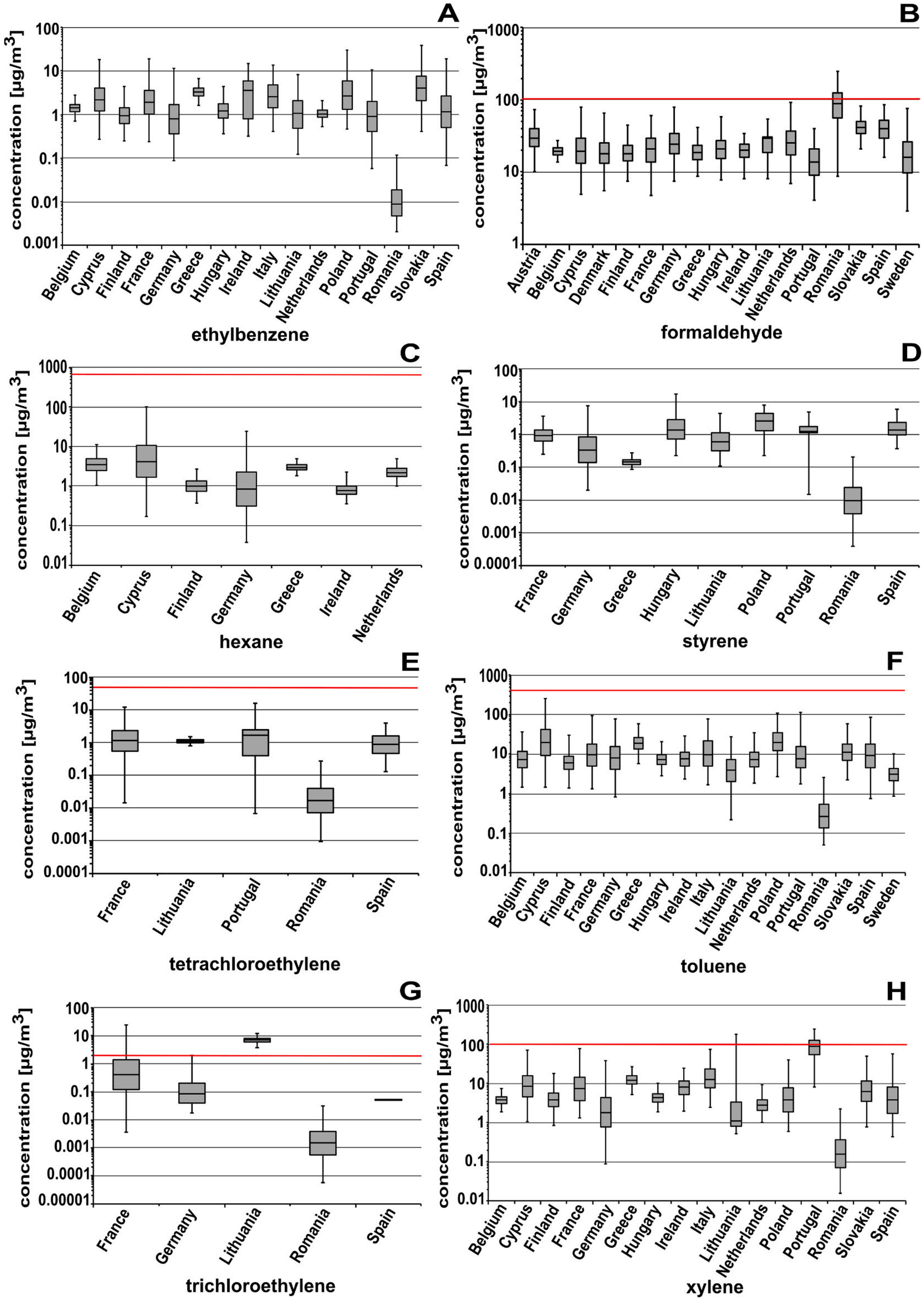

Fig. 4. Combined volatile organic compound concentration distributions in residential buildings in the member states of the European Union.
Data on the concentrations of volatile organic compounds (VOCs) were obtained from the articles identified by literature search. The data extracted from each study were used to determine the concentration distribution for each VOC separately. The resulting concentration distributions were grouped by country then weighted by the number of buildings studied and combined by VOCs using probabilistic Monte Carlo simulations. Panels: A: ethylbenzene, B: formaldehyde, C: hexane, D: styrene, E: tetrachloroethylene, F: toluene, G: trichloroethylene, H: xylene. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the reference concentration (RFC) of VOCs. The RFC is not shown for those VOCs where it was above the maximum of the y-axis.

benzene, and formaldehyde for residential buildings in 8 (Belgium, Cyprus, Finland, France, Greece, Ireland, the Netherlands, Portugal; see Fig. 3, panel A), 12 (Belgium, Cyprus, Finland, France, Hungary, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Spain; see Fig. 3, panel B), and 12 (Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, the Netherlands, Portugal, Sweden; see Fig. 4, panel B) EU countries included these values, respectively. However, due to methodological differences, the results of the two studies are difficult

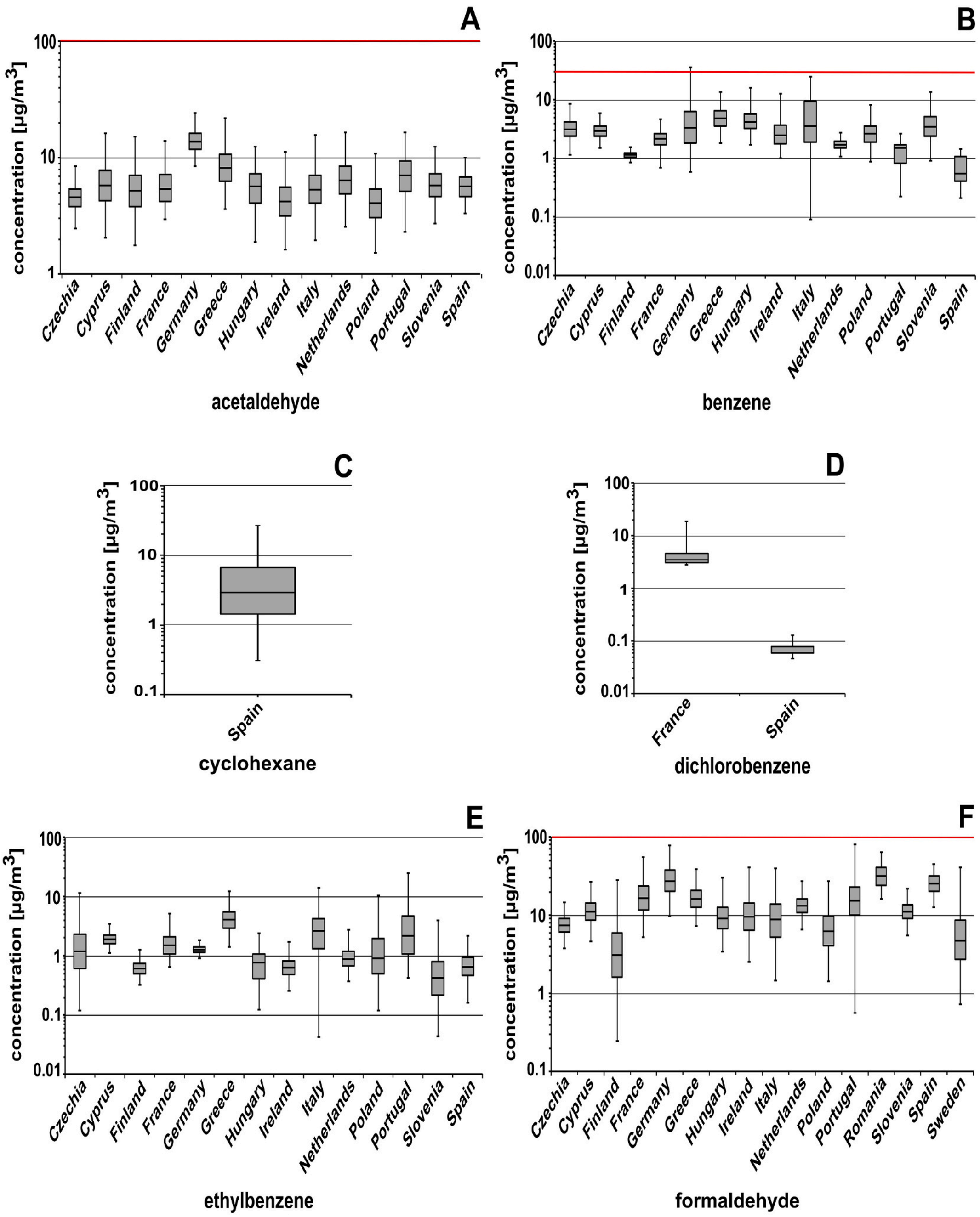

Fig. 5. Combined volatile organic compound concentration distributions in educational buildings in the member states of the European Union.
Data on the concentrations of volatile organic compounds (VOCs) were obtained from the articles identified by literature search. The data extracted from each study were used to determine the concentration distribution for each VOC separately. The resulting concentration distributions were grouped by country then weighted by the number of buildings studied and combined by VOCs using probabilistic Monte Carlo simulations. Panels: A: acetaldehyde, B: benzene, C: cyclohexane, D: dichlorobenzene, E: ethylbenzene, F: formaldehyde. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the reference concentration (RFC) of VOCs. The RFC is not shown for those VOCs where it was above the maximum of the y-axis.

to compare. Halios et al. (2022) averaged data from measurements performed in various EU and non-EU countries but most data on VOC concentrations were obtained from studies conducted in France, Germany, and the United Kingdom and published before 2010. Looking ahead, there is a strong case for harmonisation of approaches to measurement of VOC concentrations within the EU. In addition, large differences can be observed in the levels of indoor air pollutants worldwide. For example, Chang et al. (2019) reported that the average indoor level of benzene in Taiwanese residential buildings was 7.0 µg/m^3 which was above the 99th percentile of the concentration distribution of benzene in 8 of 17 EU member states included in our study (see Fig. 3, panel B). Similarly, a Chinese investigation has reported a mean formaldehyde level of 175 µg/m^3 in households (Zhang et al., 2020). This exceeded the 99th percentile of the distribution of formaldehyde concentrations in all of the 17 EU member states investigated (see Fig. 4, panel B). In contrast, Cheng et al. (2022) reported a median benzene level of 1.57 µg/m^3 in a Taiwanese university campus that was considerably lower than the concentrations of this chemical in educational buildings in 11 of the 14 EU member states (see Fig. 5, panel B). The observed differences in the concentration of benzene and formaldehyde may be attributed to a number of factors including alterations in the number of samples, location of the sampling site, the level of ambient air

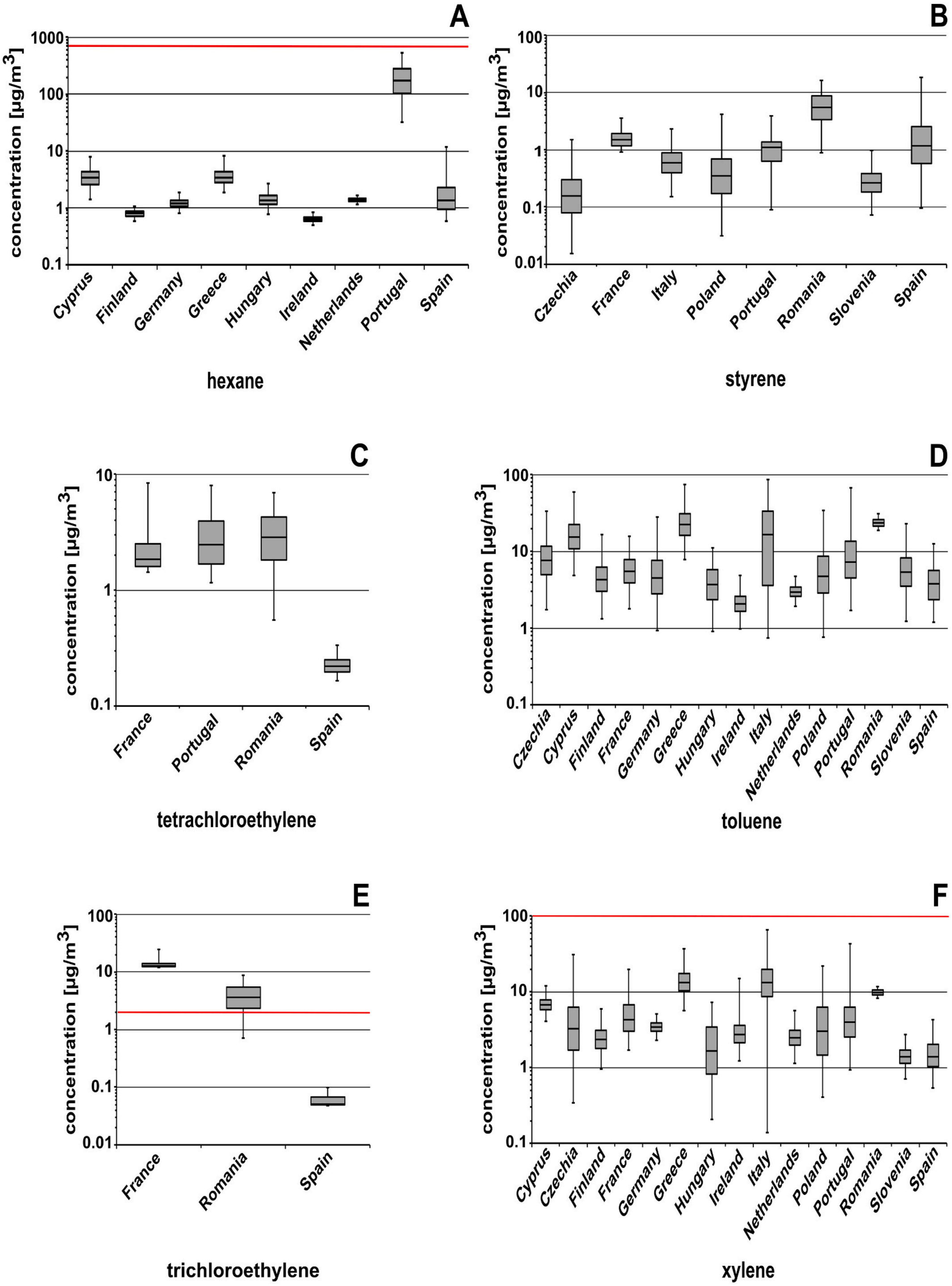

Fig. 6. Combined volatile organic compound concentration distributions in educational buildings in the member states of the European Union.
Data on the concentrations of volatile organic compounds (VOCs) were obtained from the articles identified by literature search. The data extracted from each study were used to determine the concentration distribution for each VOC separately. The resulting concentration distributions were grouped by country then weighted by the number of buildings studied and combined by VOCs using probabilistic Monte Carlo simulations. Panels: A: hexane, B: styrene, C: tetrachloroethylene, D: toluene, E: trichloroethylene, F: xylene. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the reference concentration (RFC) of VOCs. The RFC is not shown for those VOCs where it was above the maximum of the y-axis.

pollution, and variations in the emissions of VOCs from building materials and consumer products. These data show that indoor VOC concentrations measured in different regions of the world can vary significantly.

Cancer risk from exposure to VOCs in the indoor environment was estimated in a previous study (Sarigiannis et al., 2011) that extracted data from articles published between 1990 and 2008. In that study, Sarigiannis et al. (2011) showed that exposure to acetaldehyde, benzene, and formaldehyde exceeded the acceptable cancer risk by 1 to 2 orders of magnitude in each European country examined. However, the authors also noted that this result depends on the IUR used in the risk assessment. Since Sarigiannis et al. (2011) and our study only used the

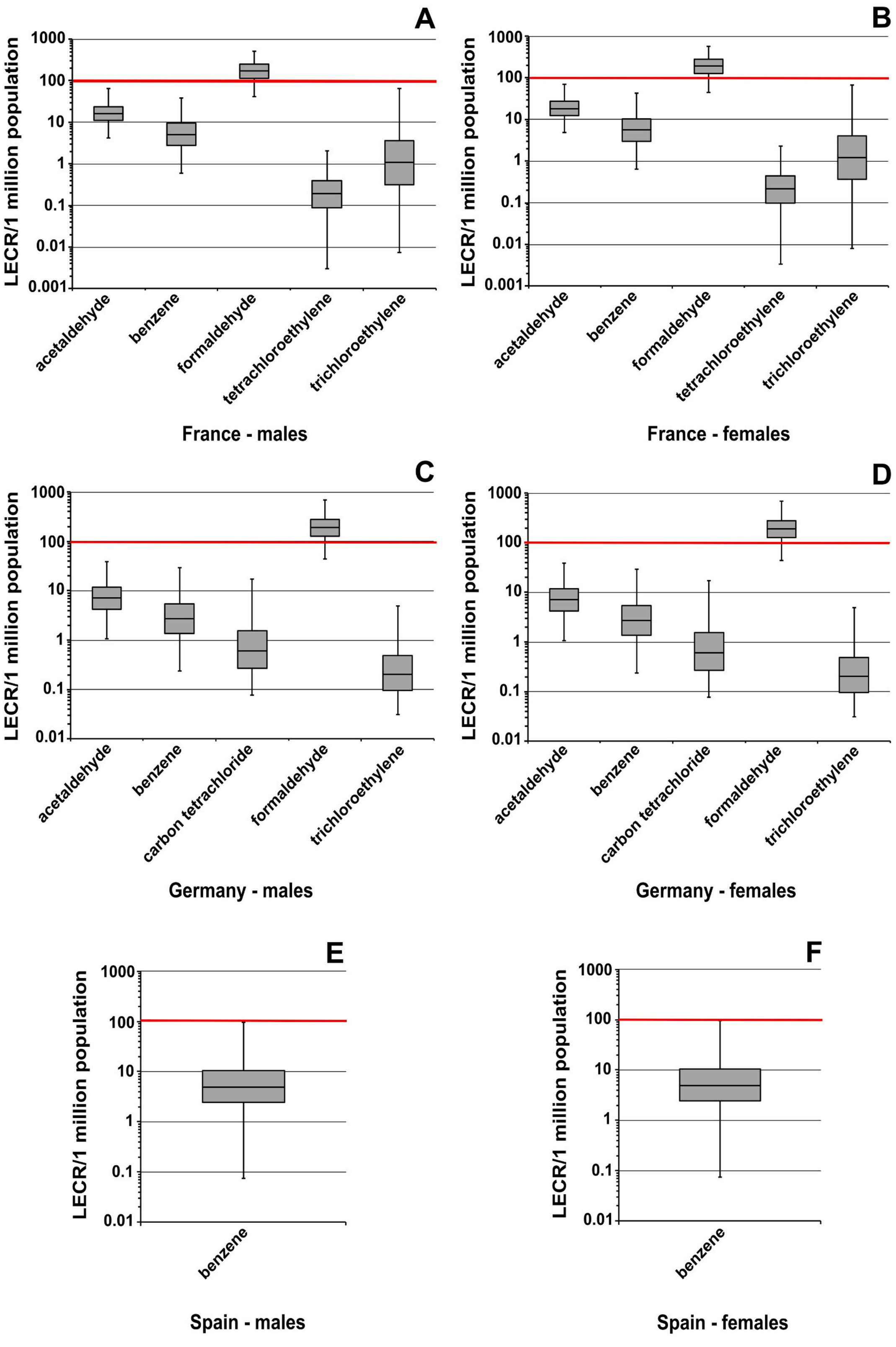

Fig. 7. Distributions of lifetime excess cancer risk from exposure to volatile organic compounds in residential buildings among French, German, and Spanish males and females.

Combined concentration distributions of volatile organic compounds (VOCs) containing data from a minimum of 400 buildings were used to estimate lifetime excess cancer risk due to exposure to VOCs in French, German, and Spanish residential buildings. Panels: A: France-males, B: France-females, C: Germany-males, D: Germany-females, E: Spain-males, F: Spain-females. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the upper limit of the US Environmental Protection Agency acceptable risk level of 1×10^{-4}.

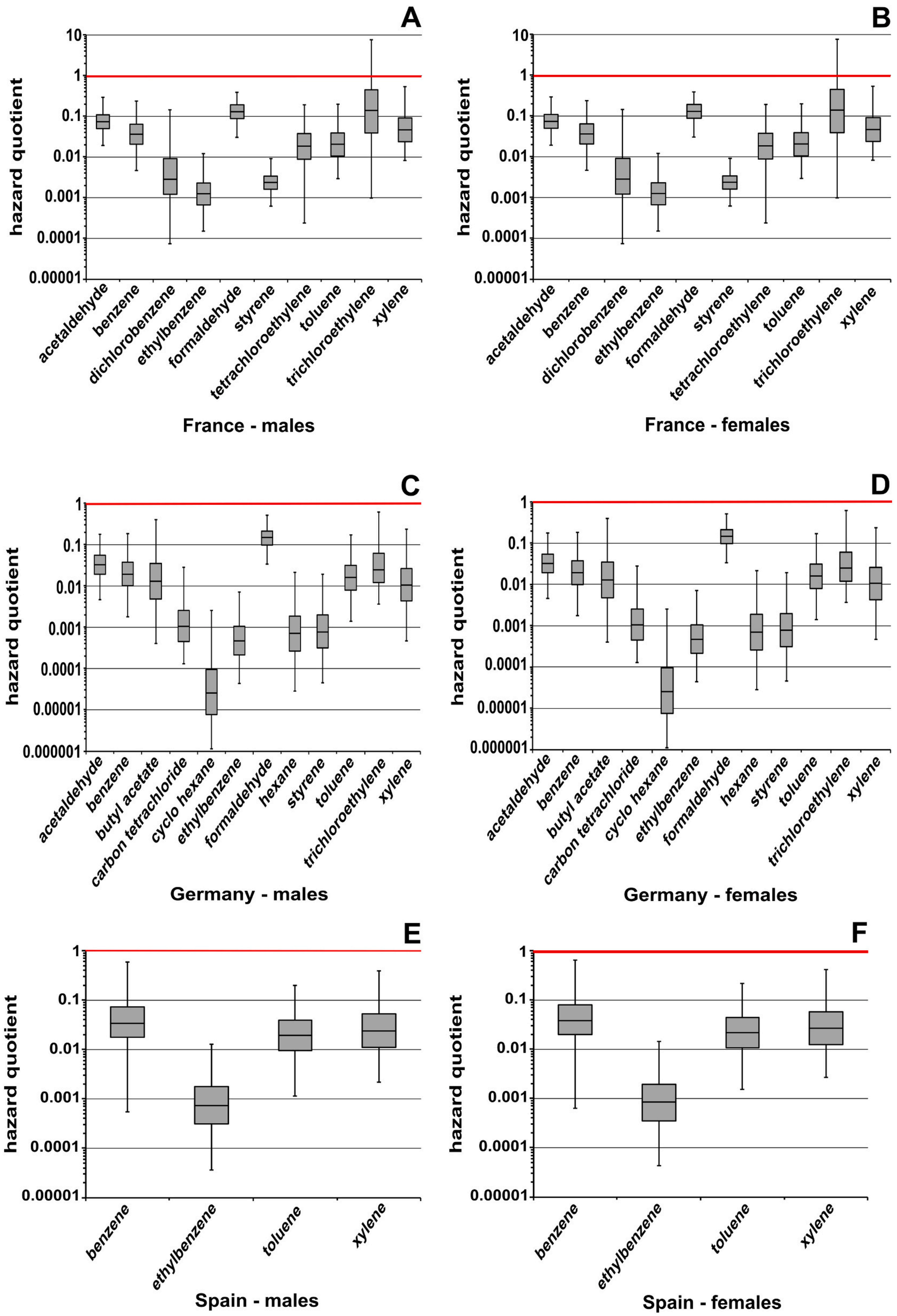

Fig. 8. Distributions of hazard quotient from exposure to volatile organic compounds in residential buildings among French, German, and Spanish males and females.

Combined concentration distributions of volatile organic compounds (VOCs) containing data from a minimum of 400 buildings were used to estimate hazard quotient (HQ) due to exposure to VOCs in French, German, and Spanish residential buildings. Panels: A: France-males, B: France-females, C: Germany-males, D: Germany-females, E: Spain-males, F: Spain-females. Median values, their interquartile ranges, 1st and 99th percentiles are presented. The red line indicates the HQ limit of 1.

Table 3
Incidence, disease burden and costs of cancers related to VOC exposure in residential buildings in France.

Country	Sex	VOC[*]	Cancer incidence [cases/1 million persons/year]	Total number of cancer cases [cases/year]	Disability adjusted life years due to VOC related cancers [DALYs[**]/1 million persons/year]	Disability adjusted life years due to VOC related cancers [DALYs/year]	Costs due to VOC related cancers [1000 euro/year]	Costs due to VOC related cancers [1000 euro/1 million persons/year]
France	Male	Acetaldehyde	0.20 (0.05–0.81)	6.68 (1.75–26.64)	0.21 (0.05–0.84)	6.93 (1.81–27.63)	70.15 (18.35–279.72)	2.14 (0.56–8.54)
		Benzene	0.06 (0.01–0.49)	2.10 (0.24–15.95)	0.06 (0.007–0.51)	2.18 (0.25–16.55)	22.08 (2.56–167.49)	0.67 (0.08–5.11)
		Formaldehyde	2.15 (0.51–6.44)	70.37 (16.83–210.90)	2.22 (0.53–6.68)	73.01 (17.47–218.81)	739.0 (176.79–2214.41)	22.56 (5.39–67.62)
		Trichloroethylene	0.014 (9.53×10^{-5}-0.82)	0.46 (0.003–26.75)	0.014 (9.88×10^{-5}-0.84)	0.47 (0.003–27.76)	4.80 (0.03–280.97)	0.15 (9.16×10^{-4}-8.58)
		Tetrachloroethylene	0.002 (3.81×10^{-5}-0.026)	0.08 (0.001–0.84)	0.002 (3.95×10^{-5}-0.026)	0.08 (0.001–0.87)	0.84 (0.013–8.83)	0.03 (3.97×10^{-4}-0.27)
		Sum			2.51 (0.59–8.9)	82.67 (19.53–291.62)	863.87 (197.74–2951.42)	25.55 (6.03–90.12)
	Female	Acetaldehyde	0.21 (0.05–0.82)	7.40 (1.93–29.0)	0.12 (0.03–0.49)	4.46 (1.18–17.49)	45.20 (11.98–177.08)	1.29 (0.34–5.06)
		Benzene	0.06 (0.007–0.51)	2.3 (0.26–17.92)	0.04 (0.004–0.31)	1.41 (0.16–10.81)	14.26 (1.59–109.41)	0.41 (0.05–3.13)
		Formaldehyde	2.24 (0.53–6.73)	78.27 (18.58–235.34)	1.34 (0.32–4.06)	47.21 (11.21–141.95)	477.85 (113.47–1436.87)	13.66 (3.24–41.07)
		Trichloroethylene	0.04 (9.49×10^{-5}-0.78)	0.50 (0.003–27.58)	0.009 (5.73×10^{-5}-0.48)	0.30 (0.002–16.64)	3.08 (0.20–168.44)	0.08 (0.005–4.82)
		Tetrachloroethylene	0.002 (3.98×10^{-5}-0.02)	0.08 (0.001–0.94)	0.001 (2.40×10^{-5}-0.02)	0.05 (0.0008–0.57)	0.54 (0.009–5.76)	0.02 (2.57×10^{-4}-0.16)
		Sum			1.51 (0.35–5.36)	53.43 (12.55–187.46)	540.93 (127.25–1896.69)	15.46 (3.64–54.24)
		Both sexes			4.02 (0.94–14.26)	136.1 (32.08–479.08)	1377.8 (324.99–4848.11)	41.01 (9.67–144.36)

Median values, 1st and 99th percentiles (in brackets) are demonstrated.

[*] VOC: volatile organic compounds.

[**] DALYs: disability-adjusted life years.

Table 4
Incidence, disease burden and costs of cancers related to VOC exposure in residential buildings in Germany.

Country	Sex	VOC[*]	Cancer incidence [cases/1 million persons/ year]	Total number of cancer cases [cases/year]	Disability adjusted life years due to VOC related cancers [DALYs[**]/1 million persons/year]	Disability adjusted life years due to VOC related cancers [DALYs/year]	Costs due to VOC related cancers [1000 euro/year]	Costs due to VOC related cancers [1000 euro/1 million persons/year]
Germany	Male	Acetaldehyde	0.09 (0.01–0.49)	3.67 (0.55–19.74)	0.08 (0.01–0.44)	3.27 (0.49–17.62)	33.12 (4.94–178.34)	0.82 (0.12–4.45)
		Benzene	0.04 (0.003–0.37)	1.41 (0.12–14.94)	0.03 (0.002–0.33)	1.26 (0.11–13.34)	12.70 (1.09–135.01)	0.32 (0.02–3.37)
		Formaldehyde	2.42 (0.56–8.92)	97.01 (22.30–357.11)	2.16 (0.49–7.96)	86.58 (19.9–318.72)	876.39 (201.45–3226.27)	21.89 (5.03–80.58)
		Trichloroethylene	0.003 (0.0004–0.06)	0.10 (0.02–2.55)	0.002 (0.0003–0.05)	0.09 (0.01–2.28)	0.94 (0.14–23.04)	0.02 (0.003–0.58)
		Carbon tetrachloride	0.008 (0.001–0.22)	0.31 (0.04–8.75)	0.007 (0.0008–0.19)	0.28 (0.03–7.81)	2.82 (0.35–79.02)	0.07 (0.008–1.97)
		Sum			2.28 (0.50–8.97)	91.48 (20.54–359.77)	925.97 (207.97–3641.68)	23.12 (5.18–90.95)
	Female	Acetaldehyde	0.10 (0.02–0.52)	4.08 (0.65–22.01)	0.06 (0.009–0.31)	2.44 (0.39–13.18)	24.73 (3.92–133.40)	0.59 (0.09–3.16)
		Benzene	0.04 (0.003–0.39)	1.56 (0.14–16.21)	0.02 (0.002–0.23)	0.93 (0.09–9.71)	9.44 (0.86–98.25)	0.22 (0.02–2.33)
		Formaldehyde	2.58 (0.63–8.94)	108.42 (26.33–376.47)	1.54 (0.37–5.35)	64.91 (15.75–225.38)	657.04 (159.53–2281.40)	15.59 (3.79–54.16)
		Trichloroethylene	0.003 (0.0004–0.07)	0.12 (0.02–2.83)	0.002 (0.0003–0.04)	0.07 (0.01–1.69)	0.70 (0.11–17.13)	0.02 (0.002–0.41)
		Carbon tetrachloride	0.008 (0.001–0.23)	0.35 (0.05–9.69)	0.005 (0.0007–0.14)	0.21 (0.03–5.8)	2.12 (0.28–58.73)	0.05 (0.006–1.39)
		Sum			1.63 (0.38–6.07)	68.56 (16.27–255.76)	694.03 (164.70–2588.91)	16.47 (3.91–61.45)
		Both sexes			3.91 (0.89–15.04)	160.04 (36.81–615.53)	1620 (372.67–6230.59)	39.59 (9.09–152.4)

Median values, 1st and 99th percentiles (in brackets) are demonstrated.

[*] VOC: volatile organic compounds.

[**] DALYs: disability-adjusted life years.

Table 5
Incidence, disease burden and costs of cancers related to VOC exposure in residential buildings in Spain.

Country	Sex	VOC*	Cancer incidence [cases/1 million persons/ year]	Total number of cancer cases [cases/year]	Disability adjusted life years due to VOC related cancers [DALYs**/1 million persons/year]	Disability adjusted life years due to VOC related cancers [DALYs/year]	Costs due to VOC related cancers [1000 euro/year]	Costs due to VOC related cancers [1000 euro/1 million persons/ year]
Spain	Male	Benzene	0.07 (0.001–1.36)	1.59 (0.02–31.57)	0.07 (0.001–1.29)	1.51 (0.02–29.95)	15.28 (0.24–303.19)	0.66 (0.01–13.05)
	Female	Benzene	0.07 (0.001–1.38)	1.70 (0.03–33.28)	0.03 (0.0006–0.71)	0.89 (0.01–17.33)	8.97 (0.15–175.43)	0.37 (0.006–7.26)
		Both sexes	0.14 (0.002–2.74)	3.29 (0.05–64.85)	0.1 (0.001–2.0)	2.4 (0.03–47.28)	24.25 (0.39–478.62)	1.03 (0.01–20.31)

Median values, 1st and 99th percentiles (in brackets) are demonstrated.

[*] VOC: volatile organic compounds.

[**] DALYs: disability-adjusted life years.

same IUR for acetaldehyde (2.2×10^{-6} cases/μg/m^3) and formaldehyde (1.3×10^{-5} cases/μg/m^3) to estimate cancer risk, we can only compare these chemicals. We estimated a lower median cancer risk from exposure to acetaldehyde in Germany and from exposure to formaldehyde in France and Germany then Sarigiannis et al. (2011). A possible explanation for this discrepancy may be that we included only data on VOC concentrations in residential buildings, whereas they combined data on indoor air pollutant concentrations in various types of buildings (Sarigiannis et al., 2011). Another plausible reason for this difference may be the finding, reported in a recent analysis (Halios et al., 2022) that concentrations of formaldehyde have fallen in European residential buildings between 2000 and 2020. This likely reflects the impact of the EU Directive on reducing VOCs, which came into force in 2001 (The Council of the European Union, 1999), and was implemented by national measures in each member state (Ministére de L'Écologie, Du Dévelopment Durable, des Transports et du Logement, 2011; German Institute for Building Technology, 2019). However further studies are needed to understand the reasons for the difference in estimates of cancer risk associated with acetaldehyde and formaldehyde exposure.

Hänninen and Asikainen (2013) estimated that 53.0 DALYs/ 1,000,000 population could be attributed to indoor exposure to VOCs in the EU, with 48.0, 51.0, and 45.0 DALYs/1,000,000 population in France, Germany, and Spain respectively, the countries included in our disease burden analysis. We showed that the combined DALYs for both sexes from exposure to acetaldehyde, benzene, formaldehyde, tetrachloroethylene, and trichloroethylene were 4.02/1,000,000 population in France, those from exposure to acetaldehyde, benzene, carbon tetrachloride, formaldehyde, and trichloroethylene were 3.9/1,000,000 population in Germany, and those from exposure to benzene were 0.1/ 1,000,000 population in Spain. Although our DALY values were lower than those estimated previously, there is no contradiction between the two sets of findings. Hänninen and Asikainen (2013) considered both malignant and non-malignant disorders when calculating DALYs and used a point estimate of total VOC (TVOC) concentration. In contrast, we took into account the distribution of specific VOCs and estimated only DALYs from malignant diseases. DALYs attributable to neoplasms as a share of those from all causes in France, Germany, and Spain has been reported to be 0.212, 0.195, and 0.196, respectively. By multiplying these by the corresponding DALYs of 48.0, 51.0, and 45.0/1,000,000 population, we calculated the number of DALYs/1,000,000 from TVOC-related cancer as 10.1 in France, 9.9 in Germany, and 8.8 in Spain. These data are comparable to the figures from our study which considered exposure to five and six specific VOCs for French (4.02/1,000,000) and German (3.9/1,000,000) populations, respectively. As explained in Section 2.4, we were able to include only the distribution of benzene concentrations to estimate the burden of cancer-related diseases in the Spanish population. As a result, the DALY values that we calculated differed from those published by Hänninen and Asikainen (2013). In France, 91.2 % of the VOC-related DALYs were associated with exposure to formaldehyde and benzene, while this figure was 96.1 % in Germany. Consequently, of among the VOCs studied these two pollutants can be considered as the greatest concern.

Looking at residential buildings, the estimated annual cost of DALYs attributable to neoplasms caused by exposure to the selected VOCs was €41,010 per 1 million population in France and €39,590 per 1 million population in Germany. Multiplying these costs by the total EU population of 447 million in 2022 (World Bank, 2023a) gives costs that vary from €18.33 million to €17.69 million per year. However, it is important to note that this estimate does not cover the total economic loss because exposure to VOCs can lead to a range of health issues beyond malignant tumours, such as respiratory, cardiovascular, and neurological diseases (González-Martín et al., 2021). Furthermore, our assessment only considered exposure to certain VOCs in residential buildings and excludes indoor air pollutants other than VOCs.

5. Strengths and limitations

Data on VOC concentrations in residential and educational buildings and offices were obtained from 58 articles published in the last 13 years. The combined distribution of VOC levels in each EU member state and in different building types was compared with the corresponding reference concentrations. A comprehensive probabilistic Monte Carlo simulation was conducted to assess the cancer and non-cancer risks from residential exposure to VOCs separately for males and females. Another strength is that age and country specific exposure time were also considered in our risk assessment. DALYs from cancer and related costs were also estimated. A limitation of our study is that we were only able to carry out cancer and non-cancer risk assessments for certain VOCs and for the French, German and Spanish populations. Additionally, our study assessed health risks only from exposure to VOCs in residential buildings and could not take account of those in offices and educational buildings. In addition, another limitation of this study is that our risk assessment does not consider the cancer risk that could arise from the antagonistic or synergistic interactions among VOCs when exposed simultaneously. This could result in an under- or overestimation of cancer risk in our study. Therefore, further toxicological studies are needed to determine the interactions between VOCs to provide more precise health risk assessments. Our estimation could also not consider the effect of environmental factors influencing the levels of indoor VOCs. As described previously, indoor concentrations of VOCs can rise significantly with increasing temperature and relative humidity (Liang et al., 2016; Lin et al., 2009; Markowicz and Larsson, 2015; Xiong et al., 2016; Wang et al., 2022). Consequently, the health risk from exposure to VOCs may be higher at elevated temperatures and humidity levels. Some assumptions had to be made and these will increase the uncertainty of the results obtained.

6. Conclusion

Our findings show that indoor exposure to VOCs has remained a public health concern in many EU member states over the past decade. In addition to providing an updated summary of indoor VOC concentrations, our results identify formaldehyde and benzene as posing the highest cancer risk among the VOCs studied in France and Germany. Compared to other environmental hazards, this risk is lower but not negligible. Although threshold values for the emission of certain VOCs have been introduced in EU member states, further measures are needed to restrict the use of these chemicals in building materials and furnishings. Since limited data on VOC concentrations have been reported from most European countries, to carry out a more accurate risk assessment, EU-wide programmes using a common methodology are required to determine the concentration of indoor air pollutants in representative samples of residential and educational buildings and offices and to calculate the associated health risks. This is especially timely given the focus on indoor air quality more generally as a result to widespread recognition of the role of airborne transmission of respiratory viruses since the COVID-19 pandemic.

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CRediT authorship contribution statement

László Pál: Writing – original draft, Supervision, Investigation, Data curation, Conceptualization. **Szabolcs Lovas:** Visualization, Data curation. **Martin McKee:** Writing – review & editing. **Judit Diószegi:** Data curation. **Nóra Kovács:** Data curation. **Sándor Szűcs:** Writing – original draft, Supervision, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors report no conflict of interest. The authors alone are responsible for the content and writing of the paper.

Data availability

The dataset and information obtained from the original research articles are available on Mendeley Data: https://doi.org/10.17632/x4887snd8j.1

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