Environmental
Science

http://www.aimspress.com/journal/environmental

AIMS Environmental Science, 8(2): 135–147.
DOI: 10.3934/environsci.2021010
Received: 28 January 2021
Accepted: 25 March 2021
Published: 29 March 2021

Overview

Built environment and indoor air quality: The case of volatile organic compounds

Dimitrios Kotzias*

Former Sen. Official of the European Commission's Joint Research Centre, Ispra/Italy, present address: Bonn/Germany

* **Correspondence:** Email: dkotzias10@gmail.com.

Abstract: A large number of studies indicated the presence of volatile organic compounds (VOCs) of various chemical classes in indoor environments (public buildings, homes). VOCs affect the air quality indoors having an impact on human health and wellbeing. They are the result of infiltration of polluted outdoor air and emissions from various indoor sources, including building materials, consumer products (fragrances, air fresheners), activities of the occupants (cleaning) and smoking. On average, people spend a great part of their time (85 to 90%) in confined spaces (homes, office buildings and schools) exposed to a complex mixture of air contaminants at concentration levels that are often several times higher than outdoors. For many chemicals present in indoor air (and their mixtures) the risk for human health and comfort is almost unknown and difficult to predict because of the lack of toxicological data and information on the dose-response characteristics in humans or animal models.

Saving of energy for homes and public buildings becomes an additional and essential criterion for the overall quality of the built environment. The need to construct airtight buildings may lead to the accumulation of air contaminants indoors and thus changing the prevailing philosophy for a healthy indoor environmental quality. The necessity emerged, in particular, for low emitting construction and building materials along with the adaptation of appropriate ventilation regimes to ensure wellbeing and comfort for building occupants.

The paper provides an overview of indoor/outdoor air concentrations of volatile organic compounds in buildings. It discusses the methodological approaches and procedures applied so far to assess VOC's presence indoors and outdoors, notably benzene and formaldehyde as model compounds for indoor air quality emphasizing the needs for future research and action plans to ensure a healthy and occupant friendly indoor environment.

Keywords: indoor air quality, buildings, volatile organic compounds, carbonyls, benzene, formaldehyde

1. Introduction

Asthma, allergy, cardiovascular diseases, sensory irritation and neurological effects are often associated with poor Indoor Air Quality (IAQ); for some of the impact (in particular children's respiratory disease and mucous membrane irritation) relationships with exposure to indoor air pollution (IAP) are reported [1–6]. Indoor air pollution is an emerging environmental health issue because people spend most of their time indoors (approx. 85–90 %, at home, office buildings, schools, etc.) exposed to various air contaminants with often unknown health effects. On average, we inhale between 14–20 cubic meters of air daily, i.e. ca.15–18 kg of air per day 80–90% of which indoors. In comparison: adults consume 2 to 3 liters of liquids and 1 to 2 kilograms of food per day. The comparison between inhalation and ingestion is an approximation because the contact time of air/liquid/food with the body is different. So, the risk of exposure by inhalation or ingestion cannot be judged as fully equivalent. Because of the COVID-19 pandemic, people have changed their daily life behaviours and activities; they have to stay and work more time at home exposed for extended periods to indoor air contaminants.

Hazardous air pollutants (HAP) e.g. benzene, formaldehyde, CO, CO_2, NOx have many potential sources inside residential (homes) and work places (office buildings, schools). Given the time most people spend indoors, human exposure to hazardous air pollutants (HAP) is governed to a great extent by the presence of these compounds in indoor environments, rather than by their concentration in ambient air. In the last decades, research institutions and universities carried out substantial work in Europe through projects financially supported by the European Union and the Member States to identify and quantify the primary indoor air contaminants, to evaluate human exposure and assess the risk for human health and wellbeing and define strategies to facing contamination with air pollutants in indoor environments.

The current European Union (EU) policy and plans on urban air quality include that citizens are to be effectively protected from risks to health from air pollutants. EU legislation addresses, among others, air quality standards, national emission ceilings and emissions from vehicles and industries. The European Commission through its Environment and Health Strategy [7] and Action Plan [8] and, more recently, its Health and Consumer Protection Strategy [9] and the World Health Organization (WHO Guidelines, 2010) [10] significantly contributed to understanding of the impact of poor indoor air quality on human health and wellbeing, individuate pollutants with a potential risk for health and promote initiatives to reducing or eliminating air pollution indoors.

Saving of energy for homes and public buildings becomes an additional and essential criterion for the overall quality of the built environment. The need to construct airtight buildings to save energy often leads to accumulation of air contaminants (HAP, CO, NOx, CO_2) and has changed the prevailing philosophy for a healthy indoor environmental quality. The necessity emerged, in particular, for low emitting construction and building materials following Community directives or regulations along with the adaptation of appropriate ventilation regimes to ensure wellbeing and comfort of the building occupants. In this context, climate change will exert a substantial impact on indoor environmental quality due to changes in building construction practices associated with the consequences of the climate crisis such increased temperatures, humidity and changes in the chemical composition and chemistry of the atmosphere, of e.g. higher ambient ozone concentrations and other atmospheric components [11–13].

Although some issues remain open or under consideration, e.g. on energy-saving actions/solutions, suitable ventilation regimes and the development and use of low emitting construction and building materials, there are positive signs and approaches from science and policy. Substantial efforts made from the industry to adopt relevant regulations too. Besides, in the last years the awareness of consumers for ecologically friendly products has substantially increased.

The paper will provide an overview of indoor/outdoor and personal exposure concentrations of volatile organic compounds in buildings. It discusses the methodological approaches and procedures applied so far to assess the presence of VOCs indoors and outdoors, in particular of benzene and formaldehyde as model compounds for indoor air quality, emphasizing the need for targeted investigations on this subject to ensure a healthy and occupant friendly indoor environment.

2. Volatile organic compounds (VOCs) including carbonyls in residential and public buildings/schools

Volatile organic compounds, such as benzene, formaldehyde, toluene and acetaldehyde, have a major impact on indoor air quality and on human health and well-being [14–16]. In the last three decades several studies carried out worldwide to assess the presence of volatile organic compounds in confined environments and discuss and evaluate their impact on indoor air quality and the risk for human health [17–19]. The focus was on residential and office buildings of a different construction age and use.

In Europe, large-scale measuring campaigns carried out with the aim to individuate the main determinants of indoor air pollution, map them and explain their distribution at geographical and national level and evaluate their impact on wellbeing and human health. EXPOLIS is a study on air pollution exposure distributions of adult urban populations in Europe. It started in 1996, as a project within the 4th Framework Program for Research and Technological Development (RTD) (1994–1998) and was completed in 1998. One of the most relevant results of this project is a database, containing personal exposure data and home and work concentrations of main indoor pollutants (CO, PM 2.5, NO_2, VOCs). This represents a rich source of exposure related information and a basis for further research [20,21]. MACBETH (Monitoring of Atmospheric Concentrations of Benzene in European Towns and Homes) and the PEOPLE project followed the research line initiated by EXPOLIS and focused on European population exposure to benzene [22,23].

The European Indoor Air Monitoring and Exposure Assessment (AIRMEX) Study focused on the measurement of pollutants in various indoor environments and outdoor places in 11 European cities

(from Nicosia to Helsinki) in cold and warm seasons. Public buildings (offices), kindergartens and homes investigated during the years 2003–2008 [17,18]. SINPHONIE ((School indoor pollution and health: Observatory network in Europe) was a two-year (2010–2012) multidisciplinary project conducted in European schools, in which data on school children, parents/guardians, teachers, surrounding outdoor environments and indoor air quality of schools were collected using standardized and harmonized procedures and protocols [24].

A breakthrough in the area of indoor air quality was the EU-INDEX project (Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU) started in 2002 and concluded in 2005. The project was financially supported by the European Commission's Directorate General of Health and Consumer Protection (DG SANCO), coordinated and carried out by the European Commission's Joint Research Centre (JRC) in collaboration with leading European experts in the area of indoor air pollution. Scope of INDEX was to identify priorities for the measurement of air pollutants in indoor environments and assess the needs for a Community strategy and action plan in the area of indoor air pollution [25,26]. Typical micro-environmental and personal exposure concentrations, as summarized from population studies reviewed in the INDEX project, are given in Table 1. These data cover priority organic compounds, such as aromatics, aldehydes and terpenes, as well as classical pollutants, such as CO and NO_2. A comparative view of the summary results indicates that indoor air pollutant concentrations are often higher than outdoors, while personal exposure concentrations for some compounds are much higher than both. Work environment is generally characterized by slightly higher pollution levels than residential spaces, most likely due to the existence of strongly emitting sources in occupational settings.

As an outcome of the INDEX project (2005) five compounds-benzene, formaldehyde, carbon monoxide, nitrogen dioxide and naphthalene- selected as high priority pollutants for indoor environments based on risk characterization; they are also included in the WHO Guidelines for Indoor Air Quality-selected pollutants (2010) [10]. Even though a large body of data is now available on indoor and outdoor air concentrations of VOCs in Europe, very little convincing information exists about people's real exposure to these pollutants. While the quality of the data within each of the different studies carried out in Europe, through QA/QC procedures, is assured, the comparison is highly questionable for the data provided by different measuring campaigns because various methodological approaches applied to get analytical data used for exposure assessment. Measuring campaigns carried out at different periods and climatic conditions make it rather difficult and challenging to obtain an objective outcome on human exposure to hazardous VOCs and the evaluation of the overall risk for health.

There is currently no general agreement in the way investigations in confined environments (homes, public buildings) for the sampling and measurement of VOCs should be undertaken. There is no agreement on harmonized occupant's survey methods, sampling and analytical techniques to measure VOCs indoors/outdoors and for human exposure estimates. As a consequence, various methodological approaches used for sampling and analysis often yield varying concentrations of VOCs present in indoor and outdoor air.

On April 4–5, 2011 a meeting took place in the premises of WHO in Bonn/Germany with the aim to develop (among others) a recommendation on a methodology of monitoring exposure to formaldehyde and nitrogen dioxide (NO_2) as core pollutants in classrooms. The meeting was cosponsored by the Joint Research Centre of the European Commission (Ispra/Italy). This was a first attempt for the harmonization of measurement procedures to facilitate new data collection and to ensure synergies with ongoing and forthcoming international data collection and reporting mechanisms [27].

Table 1. Typical European micro-environmental and exposure concentrations (μg/m^3, except for CO in mg/m^3) summarized from population based studies reviewed in the INDEX report [25].

Organic compounds		Indoor	Workplace	Outdoor	Personal
Aromatics	Benzene	2–13	4–14	1–21	3–23
	Naphthalene	1–90	2–8	1–4	2–46
	Styrene	1–6	3–7	1–2	1–5
	Toluene	15–74	25–69	3–43	25–130
	m&p-Xylenes	4–37	25–121	2–23	25–55
	o-Xylene	2–12	7–29	1–8	8–15
Aldehydes	Acetaldehyde	10–18	3	1–2	8
	Formaldehyde	7–79	12	2–4	21–31
Terpenes	a- Pinene	11–23	1–17	1–7	7–18
	Limonene	6–83	11–23	5–9	19–56
Classical pollutants	CO	0.5–1	1	2	0.8–1.7
	NO_2	13–62	27–36	24–61	25–43

3. Sources of VOCs indoors

a) Activities of the occupants (cleaning, cooking, air fresheners and smoking) lead to the emission of individual compounds and/or mixtures of compounds b) Emissions from building or construction materials indoors (paints, furniture, adhesives) c) Chemical reactions between indoor ozone and terpenes as constitutes of e.g. cleaning liquids and aerosol sprays for personal care may produce formaldehyde and other compounds, partly present as secondary organic aerosols (SOA) in indoor air, with unknown toxicological effects for humans [28,29]. Up to 90% of all investigated confined environments the indoor air concentrations of VOCs are in the μg/m^3 range. In many cases, indoor air concentrations for individual VOCs exceeding the air concentrations outdoors were measured [30].

4. Benzene and formaldehyde as model compounds for the air quality indoors-Benzene

In the frame of EXPOLIS, MACBETH, AIRMEX and SINPHONIE studies field campaigns carried out at pan-European level to measure indoor/outdoor concentrations for benzene (among other pollutants) which is classified by IARC as a known human carcinogen (Group 1) and to relate them to personal exposure estimates. Preliminary evidence indicates that in most of the investigated buildings the concentration of total volatile organic compounds are high, which reveals the presence of strong indoor sources [17].

Ambient air concentrations for benzene substantially vary between the northern and the southern part of Europe; with higher ambient air levels measured in the cities of Southern Europe. This is mainly due to climatic conditions (higher temperature, low wind speed regimes), heavy traffic and often the lack of infrastructure needed to facilitate the movement of the citizens from/ into the city.

Table 2. Indoor, Outdoor and Personal Exposure concentrations of VOCs and benzene in European cities [17].

Compounds	Environment	Sampling time (days)	Number of samples (n)	Concentration (μg/m^3)		
				Minimum	Maximum	Arithmetic Mean
VOC[t] in	Public Buildings	7	111	7.7	281.8	48.6
	Schools	7	60	7.8	192.7	41.3
VOC[t] out	Public Buildings	7	57	7.5	153.7	32.7
	Schools	7	47	3.6	240.5	19.3
VOC[t] P	Public Buildings	3	91	9.2	478.7	96.3
	Schools	3	52	16.4	216.8	65.7
Benzene [in]	Public Buildings	7	111	0.7	63.7	5.5
	Schools	7	60	0.8	10.7	3.0
Benzene [out]	Public Buildings	7	57	0.7	15.2	3.8
	Schools	7	47	0.4	6.9	2.5
Benzene [P]	Public Buildings	3	91	0.7	26.4	5.8
	Schools	3	52	1.0	12.3	3.9

Notes: In=indoors, Out =outdoors, P=personal exposure, VOC [t] = the sum of VOCs (without the carbonyl compounds) measured in this study.

Ambient air concentrations for benzene substantially vary between the northern and the southern part of Europe; with higher ambient air levels measured in the cities of Southern Europe. This is mainly due to climatic conditions (higher temperature, low wind speed regimes), heavy traffic and often the lack of infrastructure needed to facilitate the movement of the citizens from/ into the city.

While for Athens, Murcia, Milan outdoor (mean) concentrations for benzene reach values up to 21 μg/m^3, in Copenhagen, Helsinki, Rouen and Prague outdoor (mean) concentrations for benzene up to 5 μg/m^3 measured. In indoor environments, mean benzene concentrations ranged from 2.2–13.2 μg/m^3 [20–22]. There is clear evidence that even at ambient air concentrations of about 5 μg/m^3 (the limit value-annual mean-set by the European Commission), human exposure to benzene is often twice as high the ambient air concentrations. Northern/Central European cities have higher exposure/outdoor (E/O) and indoor/outdoor (I/O) concentration ratios, than cities in Southern Europe (Table 3).

In the AIRMEX field campaign indoor benzene concentrations varied from 0.7 to 63.7 μg/m^3, with the highest levels measured in cities of Southern Europe. Outdoor benzene concentrations ranged from 0.4 to 15.2 μg/m^3. The mean personal exposure concentration for benzene was 4.7 μg/m^3 and the 95th percentile (all volunteers, all sites) was 13.6 μg/m^3. Indoor/outdoor concentration of VOCs in kindergartens and schools followed a similar trend as found in public buildings. Concentrations of benzene inside and outside schools and kindergartens were in most cases lower compared to that measured at public buildings (17). The selected schools/kindergartens were mainly located out-side heavy traffic zones. So, the impact of (benzene rich) outdoor air was generally lower. In the frame of the German Environmental Survey of children and teenagers (GerES IV), Ullrich et al., (2002), reported personal exposure (mean) concentrations for benzene of 2.5 μg/m^3, lower to those obtained in other cities of Central Europe (Prague, Antwerp, Basel). Assuming a 24 hours exposure to this concentration a daily intake of 60 μg of benzene is estimated. Gonzalez-Flesca et al., (1999) reported personal exposure concentrations in the city of Nancy ranging from 9.9–55.5 µg/m^3, with a mean value of 23.8 µg/m^3. This is significantly higher than the (mean) indoor and outdoor concentrations of 10.8 and 4.4 µg/m^3, respectively [31,32].

Table 3. Personal exposure, outdoor/indoor concentrations (in µg/m^3) and ratios exposure/outdoor (E/O) and indoor/outdoor (I/O) for benzene in European cities [20,22].

City	Personal	Indoor	Outdoor	I/O	E/O
Athens (1)	18	11	11	1	1.6
Basel	5.6	3.1	1.5	2	3.7
Helsinki	3.4	2.2	1.6	1.3	2.3
Milan	16	13.2	10	1.3	1.6
Prague	12	12	5.2	2.3	2.3
Athens (2)	18.8	10.1	20.7	0.5	0.9
Padua	10.6	7	8	0.9	1.3
Rouen	13.4	9.5	4.7	2	2.8
Copenhagen	6.6	4.5	3.1	1.4	2.1
Murcia	23.1	12.3	11.7	1	1.9
Antwerp	12.2	9.4	4.4	2.1	2.8

Note: (1) EXPOLIS study; (2) MACBETH study.

In UK ambient air concentrations of benzene are generally in the range of 1–6 µg/m^3. Mean indoor air concentrations were estimated up to 8 µg/m^3 for homes. However, non-occupational exposed adults receive very high daily doses of 74–528 µg of benzene, which corresponds to an average range of benzene in air of 3.7–26.4 µg/m^3, an amount significantly higher than the mean outdoor air benzene concentration (Duarte-Davidson R et al. (1999) [33].

Crump et al. (1999) reported that the mean personal exposure for individuals in Hertfordshire, England was 183.9 µg/m^3.24h. Using the mean outdoor air concentration near homes to predict personal exposures a value of 92.6 µg/m^3.24 h has been obtained [34].

From all data available until now personal exposure cannot be estimated from ambient air concentrations. Reducing benzene emissions from mobile sources will have a relatively limited effect on total human air exposure to this compound. This observation has been made elsewhere too [35].

5. Formaldehyde

Formaldehyde is classified as a known human carcinogen (Group 1) by IARC and is one of the most common pollutants in indoor non-industrial environments. A large body of data exists on measurements for formaldehyde in homes and buildings in Europe. Indoor average concentration levels for formaldehyde in public buildings range from 8 up to 27 µg/m^3, while mean outdoor concentrations of up to 6 µg/m^3 were measured. Table 4 shows minimum, maximum and mean concentrations for public buildings and schools at European level, including all cities under investigation in the AIRMEX project [17]. Public buildings and schools/kindergarten mean concentrations all across Europe show almost similar values for indoor/outdoor and personal exposure concentrations. In the frame of the SINPHONIE project personal exposures to formaldehyde concentrations in schools range from 15 µg/m^3(mean) to 50 µg/m^3(99th percentile); to benzene concentrations from 5–33 µg/m^3(mean-99th percentile) [24]. These values are similar to the values measured during the AIRMEX campaign (Table 4).

Table 4. Indoor, Outdoor and Personal exposure concentrations of carbonyls (CARB [t]) in European cities [17].

Compounds	Environment	Sampling time (days)	Number of samples (n)	Concentration (µg/m3)		
				Minimum	Maximum	Arithmetic Mean
CARB [t] in	Public Buildings	7	112	7.0	245.5	44.1
	Schools	7	57	6.8	144.0	48.2
CARB [t] out	Public Buildings	7	57	2.1	13.7	6.5
	Schools	7	47	1.2	12.0	5.6
CARB [t] P	Public Buildings	3	24	32.1	126.5	61.8
	Schools	3	18	30.9	76.6	52.4
FORM [in]	Public Buildings	7	112	1.7	34.5	16.7
	Schools	7	57	1.5	49.7	17.4
FORM [out]	Public Buildings	7	57	1.0	7.3	2.9
	Schools	7	47	0.6	4. 6	2.4
FORM [P]	Public Buildings	3	24	7.4	29.9	16.3
	Schools/	3	18	10.0	25.6	15.3

Notes: In = indoors. Out = outdoors. P = personal exposure, CARB[t] = the sum of CARBs measured in this study. FORM = Formaldehyde

In air pollution episodes formaldehyde concentrations reach values up to 80 µg/m^3, at locations far from emission sources [36]. However, in almost all measurements formaldehyde indoor concentrations exceed by several times (5–10 times) the outdoor levels, indicating strong emission sources inside buildings and homes. The evidence is strong that exposure to formaldehyde is particularly dominated by the indoor environment at home and in workplaces. A daily intake up to 50 µg (HCHO) results from the exposure to ambient air, while exposure to indoor and workplace concentrations has been estimated to amount to about 0.3–0.5 mg/day.

6. Indoor/Outdoor concentrations and exposure estimates for benzene and formaldehyde in the US and in some Asiatic locations.

During the last twenty years several studies were carried out in the US to determine indoor/outdoor air concentration levels for priority pollutants and to assess personal exposure estimates. They have shown higher indoor than outdoor concentrations for the main pollutants.

Indoor (mean) concentrations for benzene range from 8.2 to17 µg/m^3. For formaldehyde mean indoor concentrations reach values up to 92 µg/m^3, while "typical values" for outdoor air concentrations of 4 µg/m^3 are reported. Daily exposure estimates are based on the assumption that people spend about 90% of its time in indoor environments and 10% outdoors. For benzene daily personal exposures vary between 108–177 µg/m^3, about 20% lower than the mean exposures estimated for European citizens. For the formaldehyde personal exposures range from

380–2000 μg/m^3; rather similar to European exposure estimates [37–39]. Kinney PL et al. (2002) reported for benzene (mean) values of 5.9 (homes), 2.5 (outdoors) and 4.7 μg/m^3 for personal exposure, in New York City, respectively. The corresponding values for the formaldehyde are: 12.1, 2.1 and 11.5 μg/m^3, respectively [40].

In Asiatic cities (Hong Kong, Bangkok) mean values for benzene in office buildings of 8.1 μg/m^3 for Hong Kong and 8.8 μg/m^3 for Bangkok were reported [41,42], while for Singapore high mean values for benzene of 88.1 μg/m^3 were measured [43]. In Bangkok mean values for formaldehyde in office buildings of 35.5 μg/m^3 are reported [42].

7. Methodological approach discussion

The methodological approaches and techniques applied for the measuring campaigns differ from one study to another. In the EXPOLIS (1996–1998) study sampling for volatile compounds (including benzene) carried out using active sampling (pumps) for a period of 48 hours, while in the MACBETH (1997–1998) study the diffusion technique (passive sampling) used for benzene over a period of five consecutive days/per month, within a study period of one year. A similar methodological approach (passive sampling) applied during the measuring campaigns in the frame of the AIRMEX (2003–2008) and SINPHONIE (2011–2012) for the measurement of VOCs in homes, public buildings, schools and outdoors. In other local studies sampling for VOCs made using personal pumps, four or two times per day in weekly measuring campaigns, carried out in different seasons of the year. Table 2 shows the various sampling and analytical techniques applied for the measurement of VOCs in selected investigations in Europe.

Table 5. Devices, sampling time, sampling treatment and analytical techniques (GC-FID and GC-MS) reported in the selected studies for the measurement of benzene and other VOCs indoors/outdoors.

Studies	Devices, sampling time, sampling treatment and analytical techniques
EXPOLIS	Active sampling (pumps-Tenax tubes), 48 hours, thermal desorption, Gas chromatographic analysis (GC)
MACBETH	Passive sampling (Radiello), 5 days, CS2 elution, GC
AIRMEX	Passive sampling (Radiello), 7 days, CS2 elution, GC
SINPHONIE	Passive sampling (Radiello), 5 days, CS2 elution, GC
Ullrich et al.	Passive sampling (OVM), 1–4 weeks, CS2 elution, GC
Crump et al.	Passive sampling (Tenax tubes), 28 days, thermal desorption, GC, partly active sampling (pumps-Tenax tubes) was used, GC
Lahaniati et al.	Active sampling (pumps-Tenax tubes), 4 times/day over one week, thermal desorption, GC
Maggos et.al	Active sampling (pumps-Tenax tubes), 2 times a day, thermal desorption, GC
Chatzis et al.	Passive sampling (radiello), 5 days, CS2 elution, GC

Notes: C = Gas chromatographic analysis with FID as detector, or with mass spectrometry.

The lack of a standard procedure as regards the representativeness of sampling location and season, measuring time and analytical techniques, micro-environmental activities and subset of population selected for investigation leads to a diversification of the data obtained and finally results to analytical measurements and exposure estimates of rather indicative value. An example is the city of Athens/Greece where different values for the outdoor concentration of benzene are reported, although the measuring campaigns carried out in almost the same time period (from 1996–2001). The mean outdoor benzene concentrations varied between 9.6 and 31.4 μg/m ^{3}[44]. In a study carried out in 2005 in Athens at two different locations (open road, street canyon) benzene concentrations of 5.2 and 15.4 μg/m ^{3}were measured, respectively [45]. In another study carried out between Sept. 1997–Sept.1998 urban levels for benzene varied between 15.4 and 27.9 μg/m^3 (annual mean, 20.4 μg/m^3) [46]. Also, in the case of formaldehyde a harmonized methodological approach for the sampling time (seasonal variation), location and analysis is missing. The results from all these campaigns show that sampling time and sampling technique, location and season are essential to derive representative values for the urban pollution in a city. The differences between the reported values partly caused due to the application of different methodological approaches regarding sampling location and techniques (passive, active) and sampling periods. In the assessment of indoor air quality, regarding its impact on human health and wellbeing, the seasonal variation of the pollutant concentrations is an essential criterion. Indeed, the improved quality of fuel i.e. the reduction of the benzene content of gasoline, the introduction of the automobile catalyst converter in the last three decades as well as the removal of volatile organic compounds, e.g. toluene in solvents used for building and household products are additional reasons for a better outdoor and indoor air quality.

8. Conclusions

The analysis of the existing data on indoor/outdoor air concentrations and exposure estimates for benzene and formaldehyde in European cities shows, that indoor air concentration levels and the time spent indoors clearly determine human air exposure. However, there is a need to harmonize measuring protocols and techniques and the assessment of personal exposure to air pollutants. This assessment requires a broad consensus on harmonized methodological approaches for sampling and analytical measurement techniques and exposure estimates for a reliable evaluation of human health risk.

Besides, to obtain reliable human air exposure estimates, personal monitoring over a more extended period i.e. weekly monitoring (once per month) over a period of one year should be carried out. This can be done by applying suitable sampling and analytical technique/sensors at low costs, in parallel with indoor/outdoor air concentration measurements. Such a procedure would be more appropriate instead of exposure estimates and indoor/outdoor measurements during short field campaigns, often at different seasons. Comparing the data from both European and US studies indicates that for benzene and formaldehyde, the data for indoor and outdoor are similar. Personal exposure estimates for benzene calculated to be lower in the US than in Europe, while similar values obtained for formaldehyde. As a very positive step to improve the indoor air quality in buildings/schools and ameliorate occupants' wellbeing and comfort could be introducing the indoor air quality (IAQ) certificate of buildings in analogy to energy performance certificate proposed by the European Union (EU) and implemented in the majority of the EU-Member States. The IAQ certificate for buildings would motivate and stimulate architects and engineers to use the right products for new and the renovation of old buildings, for the wellbeing of the residents and at the same time for maintaining the value of the buildings.

Conflict of interest

There is no conflict of interest.

References

1. WHO (World health report 222), Geneva: World Health Organization 2002; URL http://www.who.int/whr/2002.
2. Janson C, Anto J, Burney P, et al. (2001) The European Community Respiratory Survey: what are the main results so far? *Eur Respir J* 18: 598–611.
3. Strachan D, Sibbald B, Weiland S, et al. (1997) Worldwide variations in prevalence of symptoms of allergic rhinoconjunctivitis in children; the International Study of Asthma and Allergies in Childhood (ISAAC). *Pediatr Allergy Immunol* 8: 161–174.
4. Bousquet J. (2000) Global initiative for asthma (GINA) and its objectives. *Clin Exp Allergy* 30 (Suppl. 1): 2–5.
5. Bornehag CG, Sundell J, Weschler CJ, et al. (2004) Association between asthma and allergic symptoms in children and phthalates in house dust: a nested case-control study. *Environ Health Perspectives* 112: 1393–1397.
6. Franchi M, Carrer P, Kotzias D, et al. (2006) Working towards healthy air in dwellings in Europe. Allergy 6: 864.
7. European Commission (2003) Communication from the European Commission on the European Environment and Health Strategy. COM (2003) 338 final.
8. European Commission (2004) Communication from the European Commission on the European Environment and Health Action Plan 2004–1010. COM (2004) 416 final.
9. European Commission (2005) Communication from the European Commission on a Health and Consumer Protection Strategy. Proposal for a Decision of the European Parliament and of the Council establishing a Programme of Community action in the field of Health and Consumer Protection 2007–2013. COM (2005) 115 final.
10. World Health Organization-Regional office for Europe-WHO Guidelines for Indoor Air Quality-selected pollutants (2010).
11. The recast Directive on Energy Performance of Buildings (EPBD) 31/2010
12. Directive amending the Energy Performance of Buildings Directive (2018/844/EU).
13. Levin, Hal (2008) Indoor climate and global climate change: Exploring connections, Indoor Air 2008 conference, Copenhagen, August 18.
14. Rumchev K, Spickett J, Bulsara M, et al. (2004) Association of domestic exposure to volatile organic compounds with asthma in young children. *Thorax* 59: 746–751.
15. Rumchev K, Brown H, and Spickett J. (2007) Volatile Organic Compounds: Do they present a risk to our health? *Reviews Environ Health* 22: 39–55.

16. Wolkoff P. (2013) Indoor air pollutants in office environments: Assessment of comfort, health, and performance. *Int J Hyg Environ Health* 216: 371–394.
17. Kotzias D, Geiss O, Tirendi S, et al. (2009) Exposure to multiple air contaminants in public buildings, schools a kindergartens- The European indoor air monitoring and exposure assessment study. *Fresenius Environ Bull* 18: 671–681.
18. Otmar G, Giannopoulos G, Tirendi S, et al. (2011) The AIRMEX study-VOC measurements in public buildings and schools/kindergartens in eleven European cities: Statistical analysis of the data. *Atmospheric Environ* 45: 3676–3684.
19. Cacho C, VenturaSilva G, Martins A, et al. (2013) Air pollutants in office environments and emissions from electronic equipment. A review. *Fresenius Environ Bull* 22: 2488–2497.
20. EXPOLIS project. http://www.ktl.fi/expolis
21. Künzli N, Jantunen MJ, Bayer-Oglesby L, et al. (2004) EXPOLIS- INDEX Human Exposure Patterns for Health Risk Assess- ment: Indoor Determinants of Personal Exposures in the European EXPOLIS Population in Athens. Basel. Grenoble. Milan. Helsinki, Oxford and Prague. Final Report to CEFIC contract NMALRI-A3.3UBAS-0207 BIS.
22. Cocheo V, Boaretto C, Sacco P, et al. (2000) Urban benzene and population exposure-The Macbeth project. *Nature* 404: 141–2.
23. Pérez Ballesta P, Field RA, Connolly R, et al. (2006) Population exposure to benzene: one day cross-sections in six European cities. *Atmos Environ* 40: 3355–3366.
24. Munir Baloch R, Maesano CN, Christoffersen J, et al. (2020) Indoor air pollution, physical and comfort parameters related to schoolchildren's health: Data from the European SINPHONIE study. *Sci Total Environ* 739: 139870.
25. Kotzias D, Koistinen K, Kephalopoulos S, et al. (2005) The INDEX project: Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU. EUR 21590 EN.
26. Koistinen K, Kotzias D, Kephalopoulos S, et al. (2008) The INDEX project: executive summary of a European Union project on indoor air pollutants. *Allergy* 63: 810–819.
27. WHO/JRC Methods for monitoring indoor air quality in schools. Report of the meeting 4–5, April, 2011 in Bonn/Germany.
28. Calogirou A, Larsen BR, Kotzias D (1999) Gas-phase terpene oxidation products, A review. *Atmospheric Environ* 33: 1423–1439.
29. Weschler CJ (2004) Chemical reactions among indoor pollutants: what we've learned in the new millennium. *Indoor Air* 14: 184–194.
30. Rovelli S, Cattaneo A, Fazio A, et al. (2019) VOCs Measurements in Residential Buildings: Quantification via Thermal Desorption and Assessment of Indoor Concentrations in a Case-Study. *Atmosphere* 10: 57.
31. Ullrich D, Gleue C (2002) Indoor Air, Proceedings, 9th International Conference on Indoor Air Quality and Climate, Monterey, California, June 30–July 5
32. Gonzalez-Flesca N, Cicolella A, Bates M, et al. (1999) Pilot Study on Personal, Indoor and Outdoor Exposure to Benzene, Formaldehyde and Acetaldehyde. *Environ Sci Pollut Res* 6: 95–102.
33. Duarte-Davidson R, Courage C, et al. (1999) General Population Exposure to Environmental Levels of Benzene in the UK. Proceedings of the 8th International Conference on Indoor Air Quality and Climate, Indoor Air 99. 5: 333–334.

34. Crump DR, Bland BH, Mann HS, et al. (1999) Personal Exposure to Air Pollutants in Hertfordshire, England, Proceedings of the 8th International Conference on Indoor Air Quality and Climate. *Indoor Air 99* 5:288–293.
35. Levsen K, Ilgen E, Angerer J,et al. (1999) Human's Exposure to Benzene and other Aromatic Hydrocarbons: Indoor and outdoor Sources, Proceedings of the 8th International Conference on Indoor Air Quality and Climate. Indoor Air 99 5: 312–316.
36. Amanatidis G, Viras LG, Kotzias K, et al. (1997) Carbonyl Levels in Athens during a Winter Air Pollution Episode. *Fresenius Environ Bull* 372–377.
37. Mendell MJ, Mirer A, Lei-Gomez Q (2007) Contaminants in buildings and occupied spaces as risk factors for occupant symptoms in US offices. EPA BASE Study. Ernest Orlando Lawrence Berkley National Laboratory Report. Berkeley, CA (US).
38. US-EPA-Inside IAQ report (1998). A Comparison of Indoor and Outdoor Concentrations of Hazardous Air Pollutants, Spring/Summer.
39. US-EPA (2012); http://www.epa.gov/iaq/base/index.html
40. Kinney PL, Chillrud SN, Ramstrom S, et al. (2002) Exposure to multiple air toxics in New York City. *Environ Health Perspect* 110: 539–546.
41. Chao CY, Chang GY (2001) Quantification of indoor VOCs in twenty mechanically ventilated buildings in Hong Kong. *Atmos Environ* 35: 5894–5913.
42. Ongwandee M, Moonrinta R, Panyametheekul S, et al. (2010) Investigation of volatile organic compounds in office buildings in Bangkok, Thailand: Con- centrations, sources and occupant symptoms. *Build Environ* 45: 1512–1522.
43. Zuraimi MS, Roulet CA, Tham KW et al. (2006) A comparative study of VOCs in Singapore and European office buildings. *Build Environ* 41: 316–329.
44. Lahaniati M, Maggos T, Hatzianestis J, et al. (2001). Concentration Levels of Volatile Organic Compounds in the Greater Athens Area. *Fresenius Environ Bull* 10: 609–614.
45. Maggos T, Bartzis J, Kotzias D, et al. (2006). Traffic related air pollution measurements in two streets with different geometry in Athens, Greece. Fresenius Envir. Bulletin. 15: 910–915.
46. Chatzis C, Alexopoulos EC, Linos A (2005) Indoor and outdoor personal exposure to benzene in Athens, Greece. *Sci Total Environ* 349: 72–80.

AIMS Press