UK Health Security Agency

VOCs in European homes and schools

Prof. Sani Dimitroulopoulou

Principal Environmental Public Health Scientist - Indoor Environments,
Air Quality and Public Health, Environmental Hazards and Emergencies Dept, UK Health Security Agency
Visiting Professor, The Bartlett School, University College London
Chair, UK Indoor Environments Group

ASBP Healthy Building Conference and Expo 2024,
29 February 2024, London

Indoor air – Health effects

Exposure to indoor air pollutants, chemicals and biological contamination is associated with

- respiratory system
- nervous system
- cardiovascular system
- carcinogenicity
- respiratory irritation

RCPCH (2020) NICE (2020) WHO (2021)

Birth and infancy

- Respiratory problems – wheeze, rhinitis, atopic asthma, respiratory infections
- Low birthweight and pre-term birth

Pre-school

- Respiratory problems – wheeze, allergies, asthma, risk of respiratory diseases and pneumonia
- Eczema and atopic dermatitis
- Greater hyperactivity, impulsivity and inattention

School age

- Respiratory problems – wheeze, rhinitis, asthma, throat irritation, nasal congestion, dry cough
- Eczema, dermatitis, conjunctivitis, skin and eye irritation
- Reduced cognitive performance, difficulty sleeping

RCPCH (2020) https://www.rcpch.ac.uk/sites/default/files/2020-01/the-inside-story-report_january-2020.pdf

VOCs in European homes

- 65 individual VOCs
- Most commonly measured and health relevant VOCs in European homes (incl. UK) are:
  - aromatic hydrocarbons (14 chemicals)
  - alkanes (9)
  - aldehydes (8)
  - aliphatic hydrocarbons (5)
  - terpenes (6)
  - chlorinated hydrocarbons (4)
  - glycol and glycol ethers (3)
  - esters (2)

Science of the Total Environment 839 (2022) 156201

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

Christos H. Halios [a,1], Charlotte Landeg-Cox [a,1], Scott D. Lowther [a,1,2], Alice Middleton [a], Tim Marczylo [b], Sani Dimitroulopoulou [a,*]

[a] Air Quality & Public Health Group, Environmental Hazards and Emergencies Department, Radiation, Chemicals and Environmental Hazards, Science Group, UK Health Security Agency, Harwell Science and Innovation Campus, Chilton, UK

[b] Toxicology Department, Radiation, Chemicals and Environmental Hazards, Science Group, UK Health Security Agency, Harwell Science and Innovation Campus, Chilton, UK

HIGHLIGHTS

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

GRAPHICAL ABSTRACT

ARTICLE INFO

Editor: Philip K. Hopke

Keywords:
VOCs
Indoor
European residences
Emissions
Health effects

ABSTRACT

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

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

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

* Corresponding author.
E-mail address: Sani.Dimitroulopoulou@phe.gov.uk (S. Dimitroulopoulou).

[1] The first 3 authors contributed equally to this paper

[2] Now at Dyson, Environmental Care, RDD, Hullavington SN14 6GU, UK.

http://dx.doi.org/10.1016/j.scitotenv.2022.156201
Received 29 March 2022; Received in revised form 16 May 2022; Accepted 20 May 2022
Available online 24 May 2022

VOCs in European homes (Halios et al., 2022)

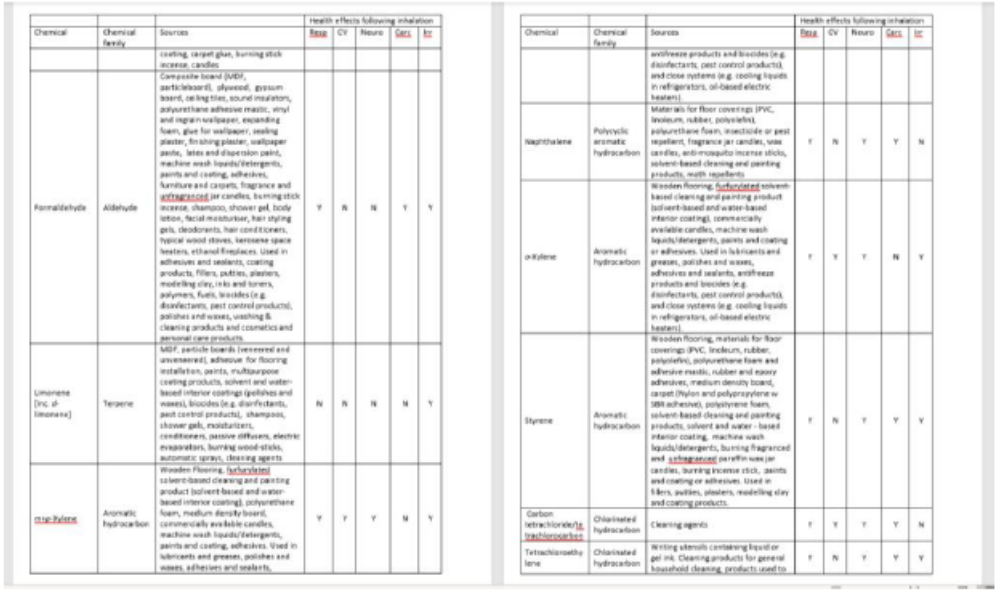
Table 1
Individual Volatile Organic Compounds (VOCs) identified through measurements in residences and their calculated Weighted Average Geometric Mean (*WAGM*).

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

Halios CH, Landeg-Cox, Lowther SD, Middleton A., Marczylo T, Dimitroulopoulou S. (2022). Chemicals in European Residences – Part I: a review of emissions, concentrations, and health effects of Volatile Organic Compounds (VOCs). Science of the Total Environment, 156201 https://doi.org/10.1016/j.scitotenv.2022.156201

Results:

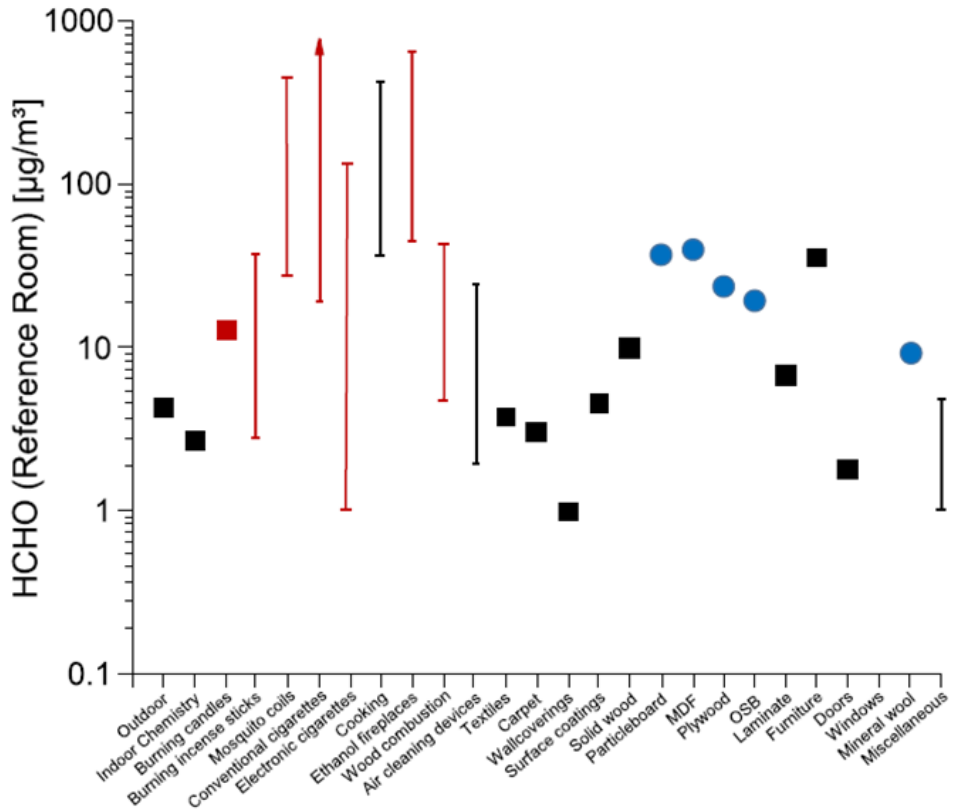
			Health effects following inhalation				
Chemical	Chemical family	Sources	Resp	CV	Neuro	Carc	Irr
Acetaldehyde	Aldehyde	Concrete/screed with and without PVC covering, wooden flooring and battens, composite board (MDF, chipboard), plywood, skirting board, expanding foam, finishing plaster, ceiling tiles, gypsum, plaster, vinyl and ingrain wallpaper, polyurethane adhesive mastic, wallpaper paste, latex and dispersion paints, Carpet (nylon with PVC backing), fragranced and unfragranced jar candles, burning stick incense, typical domestic wood stoves, kerosene space heaters, ethanol fireplaces	Y	N	N	Y	Y
Acetone	Ketone	Solid wood (pine, oak, beech), plywood, composite board (MDF, chipboard, OSB), fireboards from coriander biorefinery, glue for wallpaper, finishing plaster, linoleum, silicone, expanding foam, ceiling tile, gypsum board, veneered particle board (UV curing lacquer), surface sprays, glues, burning stick incense, electric air fresheners, kerosene space heaters, ethanol fireplaces, cleaning agent, cosmetics, flea sprays	Y	Y	Y	N	Y
Benzene	Aromatic hydrocarbon	Gypsum board, commercially-available floor coverings (made of PVC or with polypropylene or polyamide fibres), low density polyethylene, polyurethane foam, carpet glue, scatter rugs, solvent-based cleaning and painting products (acrylic and water based paints, matt emulsion), burning fragrance jar candles and burning stick incense, kerosene space heaters, fireplaces with liquids, wood-burning fireplaces	N	Y	Y	Y	Y
Ethylbenzene	Aromatic hydrocarbon	Materials for floor coverings (PVC, linoleum, rubber, polyolefin), gypsum board, Carpet, plywood, polyurethane foam and adhesive mastic, solvent-based cleaning and painting products, solvent and water based interior	Y	N	Y	Y	Y



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

Formaldehyde emission rates (Salthammer, 2019)

Product	function	Emission factor
burning candles * (both scented and unscented)	log-normal	GM=192.5 µg/h, σ_g=1.42 µg/h
burning incense sticks *	uniform	Min=3 µg/m³, Max=39 µg/m³
burning mosquito coils *	uniform	Min=0.54 mg/h, Max=7.52 mg/h
tobacco smoking	uniform	Min=20 µg/m³, Max >1000 µg/m³
electronic cigarettes	uniform	Min=1 µg/m³, Max=135 µg/m³
decorative fireplaces (during the burning phase, with different type of fuel: ethanol and gel-type) *	uniform	Min=698 µg/h, Max=10637 µg/h
wood-burning fireplaces *	uniform	Min=5 µg/m³, Max=48 µg/m³
cooking	normal	µ=700 µg/h, σ=100 µg/h
air cleaning devices *	uniform	Min=2 µg/m³, Max=25 µg/m³
textile	log-normal	GM=1.9 µg/(m² h), σg=1.38 µg/(m² h)
carpet	log-normal	GM=3.9 µg/(m² h), σg=1.65 µg/(m² h)
surface coatings	log-normal	GM=2.3 µg/(m² h), σg=1.56 µg/(m² h)
wallcoverings	log-normal	GM=0.5 µg/(m² h), σg=2.23 µg/(m² h)
solid wood	normal	µ=4 µg/(m² h), σ=1 µg/(m² h)
particleboard	log-normal - normal	GM=79 µg/(m² h), σg=1.37 µg/(m² h)
OSB (Oriented strand board)	log-normal - normal	GM=39 µg/(m² h), σg=1.96 µg/(m² h)
MDF	n.a.	GM=80 µg/(m² h)
plywood	n.a.	GM=48 µg/(m² h)
laminate	log-normal	GM=8.5 µg/(m² h), σg=1.8 µg/(m² h)
furniture	log-normal - normal	GM=17.8 µg/(m² h), σg=2.54 µg/(m² h)
doors	log-normal	GM=18.2 µg/(m² h), σg=2.7 µg/(m² h)
mineral wool	n.a.	GM=31.0 µg/(m² h)



Formaldehyde in European homes (Halios et al., 2022)

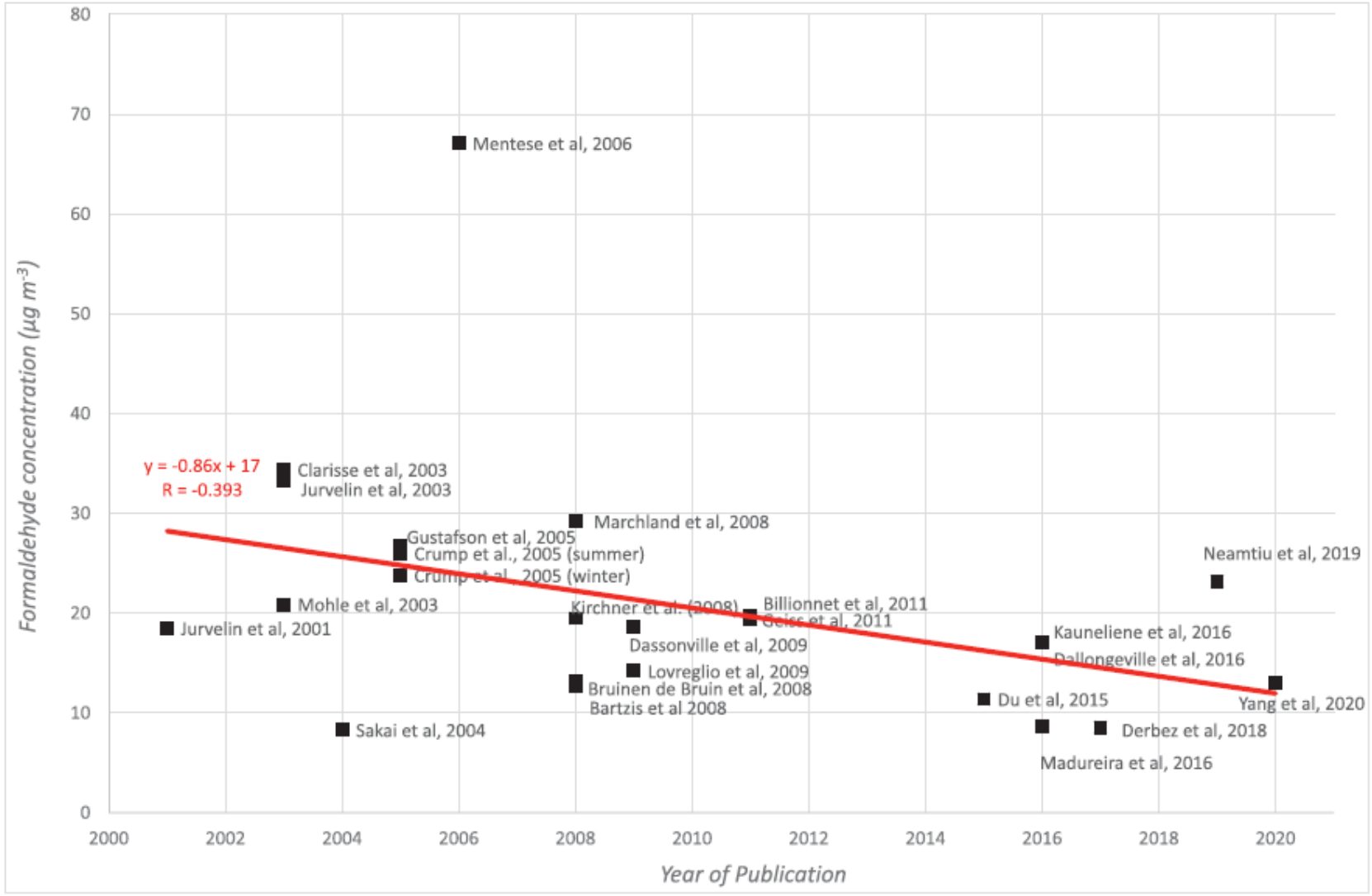
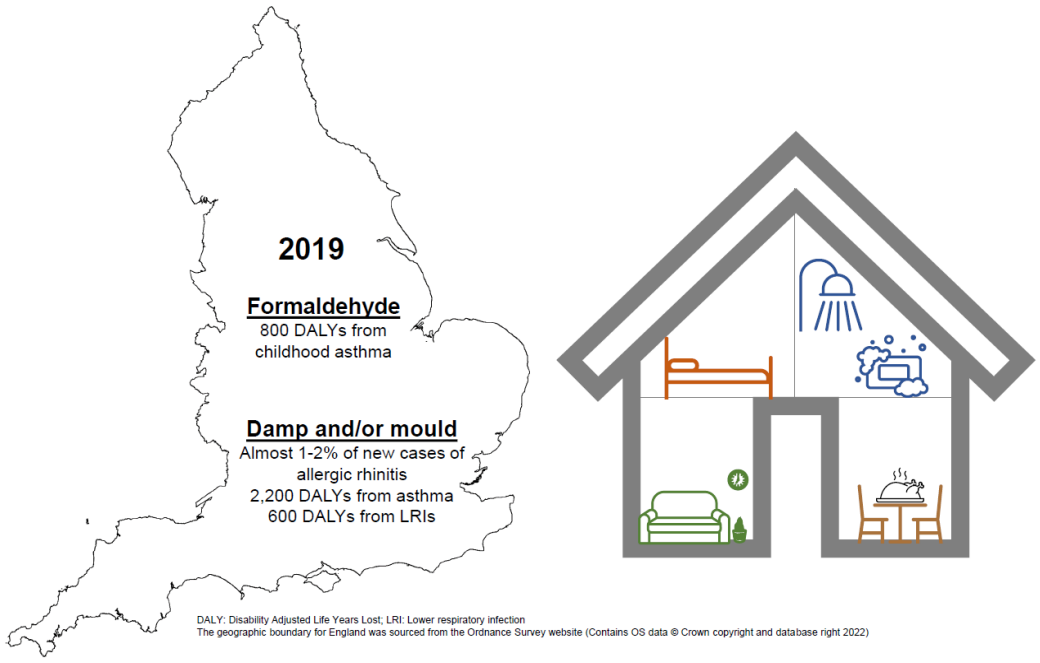


Fig. 4. Reported formaldehyde concentrations (2000–2020). Trend line is also reported.

Burden of Disease - Formaldehyde in English homes (Clark et al., 2023)

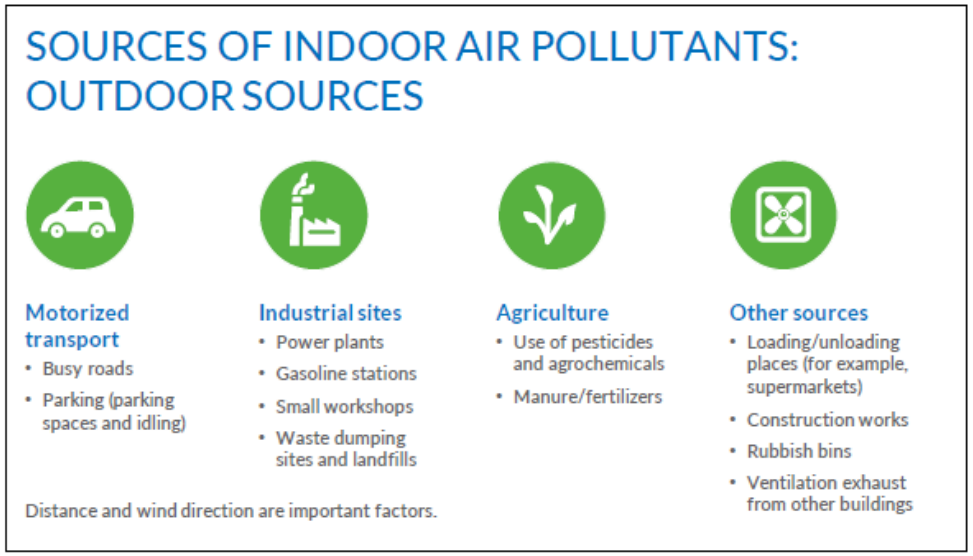


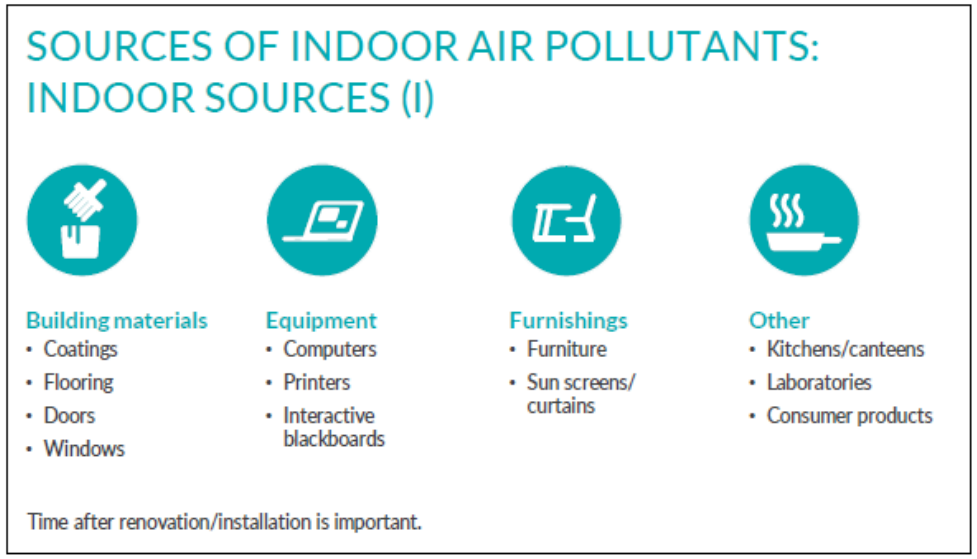
- We estimated the burden of disease from asthma associated with residential formaldehyde concentrations, among children in England, using the most up-to-date epidemiological evidence available

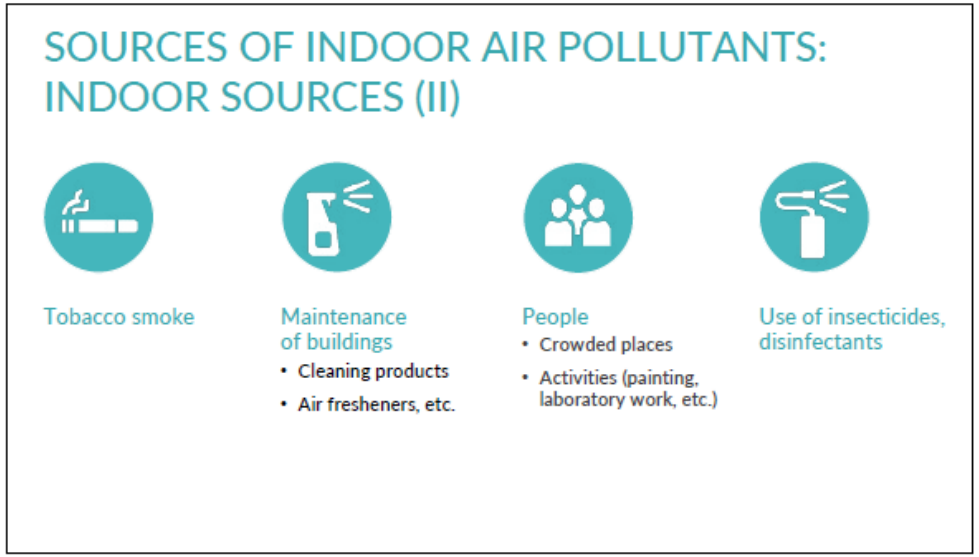
- In 2019, exposure to formaldehyde in England was associated with approximately:
  - 4,000 cases of asthma

Clark, S.N.; Lam, H.C.Y.; Goode, E.-J.; Marczylo, E.L.; Exley, K.S.; Dimitroulopoulou, S (2023). The Burden of Respiratory Disease from Formaldehyde, Damp and Mould in English Housing. Environments, 10(8), 136. https://doi.org/10.3390/environments10080136

Sources of IA pollutants - schools

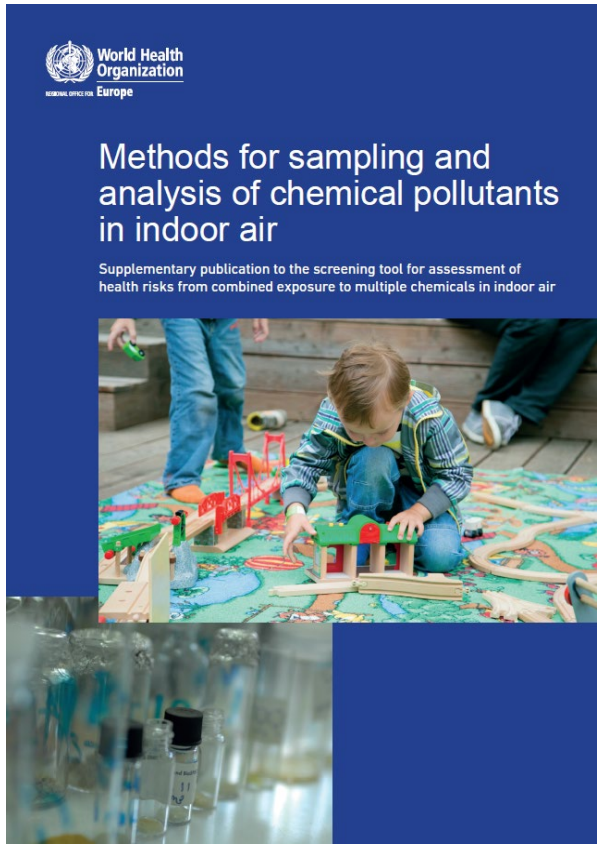




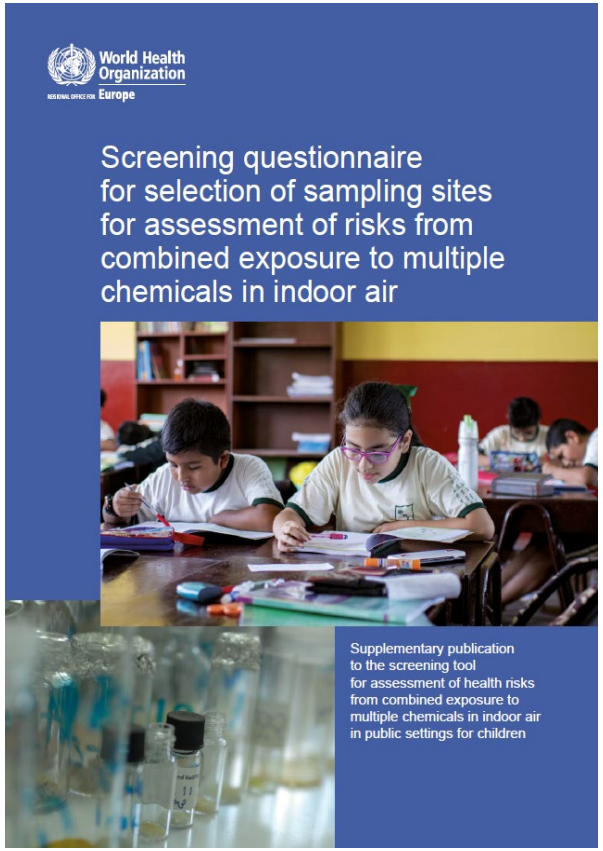


WHO (2021) Educational course
Chemical pollution of indoor air and its risk for children's health
[9789289055628-eng.pdf (who.int)]

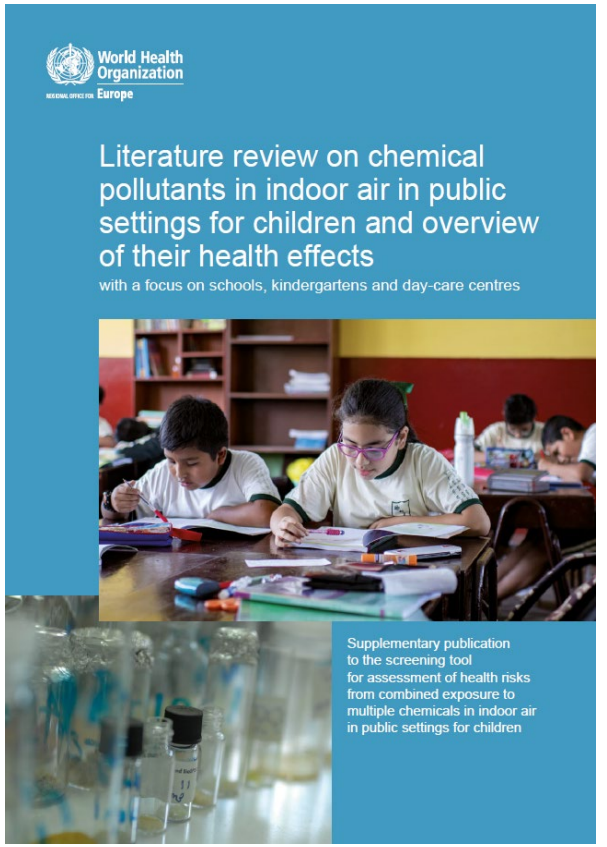
WHO – tool to assess combined exposure to chemicals in schools



WHO (2020)
https://apps.who.int/iris/bitstream/handle/10665/334389/9789289055239-eng.pdf



WHO (2021)
https://apps.who.int/iris/handle/10665/341466



WHO (2021)
https://iris.who.int/handle/10665/341467

Priority chemicals in European schools

No.	Chemical family		Substances	Chemical Abstracts Services (CAS) number
1	**Oxygenated volatile organic compounds (oxy-VOCs)**	Aldehydes	Formaldehyde	50-00-0
2			Acetaldehyde	75-07-0
3	**Volatile organic compounds (VOCs)**	Aromatic hydrocarbons	Benzene	71-43-2
4			Ethylbenzene	100-41-4
5			xylene (o-, m-, p-)	95-47-6 108-38-3/106-42-3
6			Styrene	100-42-5
7			Toluene	108-88-3
8			1,2,3-trimethylbenzene	526-73-8
9			1,4-dichlorobenzene	106-46-7
10		Esters	Butyl acetate	123-86-4
11		Terpenes	Limonene	138-86-3
12			α-pinene	80-56-8
13		Chlorinated hydrocarbons	Tetrachloroethylene	127-18-4
14			Trichloroethylene	79-01-6
15		Polycyclic aromatic hydrocarbons (PAHs)	Naphthalene	91-20-3
16	**Semi-volatile organic compounds (SVOCs)**	PAHs	Benzo(a)pyrene	50-32-8
17	**Inorganic compounds**	Nitrogen dioxide (NO_2)	NO_2	10102-44-0

No.	Chemical family	Substances
1	**Particulate matter**	Particulate matter with an aerodynamic diameter below 10 µm (PM_{10})
2		Particulate matter with an aerodynamic diameter below 2.5 µm ($PM_{2.5}$)
3	**Inorganic compounds**	Carbon monoxide (CO)
4		Ozone (O_3)
5	**Phthalates**	Diethyl phthalate (DEP)
6		Diisobutyl phthalate (DiBP)
7		Di-n-butyl phthalate (DnBP)
8	**Musks**	Galaxolide
9		Tonalide
10	**PAHs**	Acenaphthene
11		Acenaphthylene
12		Phenantrene
13		Anthracene
14		Benz[a]anthracene
15		Benzo[b]fluoranthene
16		Benzo[j]fluoranthene
17		Benzo[e]pyrene
18		Benzo[ghi]perylene
19		Benzo[k]fluoranthene
20		Chrysene
21		Dibenz[a,h]anthracene
22		Dibenzo[a,l]pyrene
23		Fluoranthene
24		Fluorene
25		Indeno[1,2,3-cd]pyrene
26		Pyrene
27	**Brominated flame retardants (BFRs)–polybrominated diphenyl ethers (PBDEs)**	2,4,4'-tribromodiphenyl ether (BDE 28)
28		2,2',4,4'-tetrabromodiphenyl ether (BDE 47)
29		2,2',4,4',5-pentabromodiphenyl ether (BDE 99)
30		2,2',4,4',6-pentabromodiphenyl ether (BDE 100)
31		2,2',4,4',5,5'-hexabromodiphenyl ether (BDE 153)
32		2,2',3,4,4',5',6-heptabromodiphenyl ether (BDE 183)
33		2,2',3,3',4,4',5,5',6,6'-decabromodiphenyl ether (BDE 209)
34		1,2-dibromo-4-(1,2-dibromoethyl)cyclohexane (DBE-DBCH)
35	**Organophsophate flame retardants (OPFRs)**	Tributyl phosphate (TBP)
36		Tris(2-butoxyethyl) phosphate (TBEP)
37		Tris(1-chloropropan-2-yl) phosphate (TCPP)
38		Tris(2-chloroethyl) phosphate (TCEP)
39	**Chlorinated paraffins (CPs)**	Short-chain CPs (SCCPs) (C_{10-13})
40		Medium-chain CPs (MCCPs) (C_{14-17})
41		Long-chain CPs (LCCPs) (C_{18-30})

WHO, 2020. Methods for sampling and analysis of chemical pollutants in indoor air: supplementary publication to the screening tool for assessment of health risks from combined exposure to multiple chemicals in indoor air, ISBN 978 92 890 5523 9. https://apps.who.int/iris/bitstream/handle/10665/334389/9789289055239-eng.pdf

Table 2. Source control of pollutant emissions from indoor sources (based on WHO, 2022)

Potential indoor sources	Pollutants	Source control / mitigation measures
Furniture and wooden products (for example, pressed board, plywood, particle board, fibreboard furniture, flooring, panelling, doors)	formaldehyde, acetaldehyde, benzene, α-pinene	Choose certified, eco-labelled materials with low VOC emissions for floor/wall/ceiling coverings and furniture
Flooring materials (e.g., PVC flooring with adhesive, carpet backings)	formaldehyde, acetaldehyde, benzene, ethylbenzene, xylenes, styrene, toluene	- Implement renovations and refurbishments in the first month of the summer holiday - Use woven or knotted textile carpets instead of synthetic ones
Wall paints, solvent-based (water-resistant)	benzene, xylenes, styrene, toluene	Implement renovations and refurbishments in the first month of the summer holiday - Use water-based paints
DIY products (for example, solvents, paints, wallpapers, glues, adhesives, varnishes, lacquers)	formaldehyde, acetaldehyde, benzene, ethylbenzene, trimethylbenzene, xylenes, styrene, toluene, tetrachloroethylene trichloroethylene, n-butyl-acetate, naphthalene, benzo(a)pyrene	- Implement renovations and refurbishments in the first month of the summer holiday - Use smaller quantities of or green alternatives to paints, solvents, adhesives and science laboratory chemicals - Increase ventilation, e.g., open windows when working with chemicals
Painted or varnished coatings	benzene, ethylbenzene, xylenes, toluene, dichlorobenzene, n-butyl-acetate	Choose certified, eco-labelled materials Limit the use of chemical products
Paint and varnish removers stain removers, wood cleaners	α-pinene, tetrachloroethylene, trichloroethylene	Choose certified, eco-labelled materials Limit the use of chemical products
Electronic equipment (e.g., photocopy machines)	formaldehyde, acetaldehyde	Place photocopiers and printers in separately ventilated rooms
Plastics	trimethylbenzene, styrene	
New books, magazines, newspapers	formaldehyde, toluene	Locate in dedicated rooms /library, well ventilated
Cleaning products and disinfectants	formaldehyde, trimethylbenzene, toluene, limonene, α-pinene, trichloroethylene naphthalene	Use fragrance-free cleaning materials,
Dry-cleaned textiles, curtains, carpets	tetrachloroethylene	Use washable textiles for classrooms instead of textiles that require dry-cleaning
Air fresheners	dichlorobenzene, limonene	Do not use air fresheners in classrooms,
Human activities (cooking)	formaldehyde, acetaldehyde, benzo(a) pyrene	Install extractor fans in kitchens to be on during cooking activity

Let’s work together

to reduce our exposure to indoor air pollution

Thank you!

www.gov.uk/ukhsa

Sani.Dimitroulopoulou@ukhsa.gov.uk