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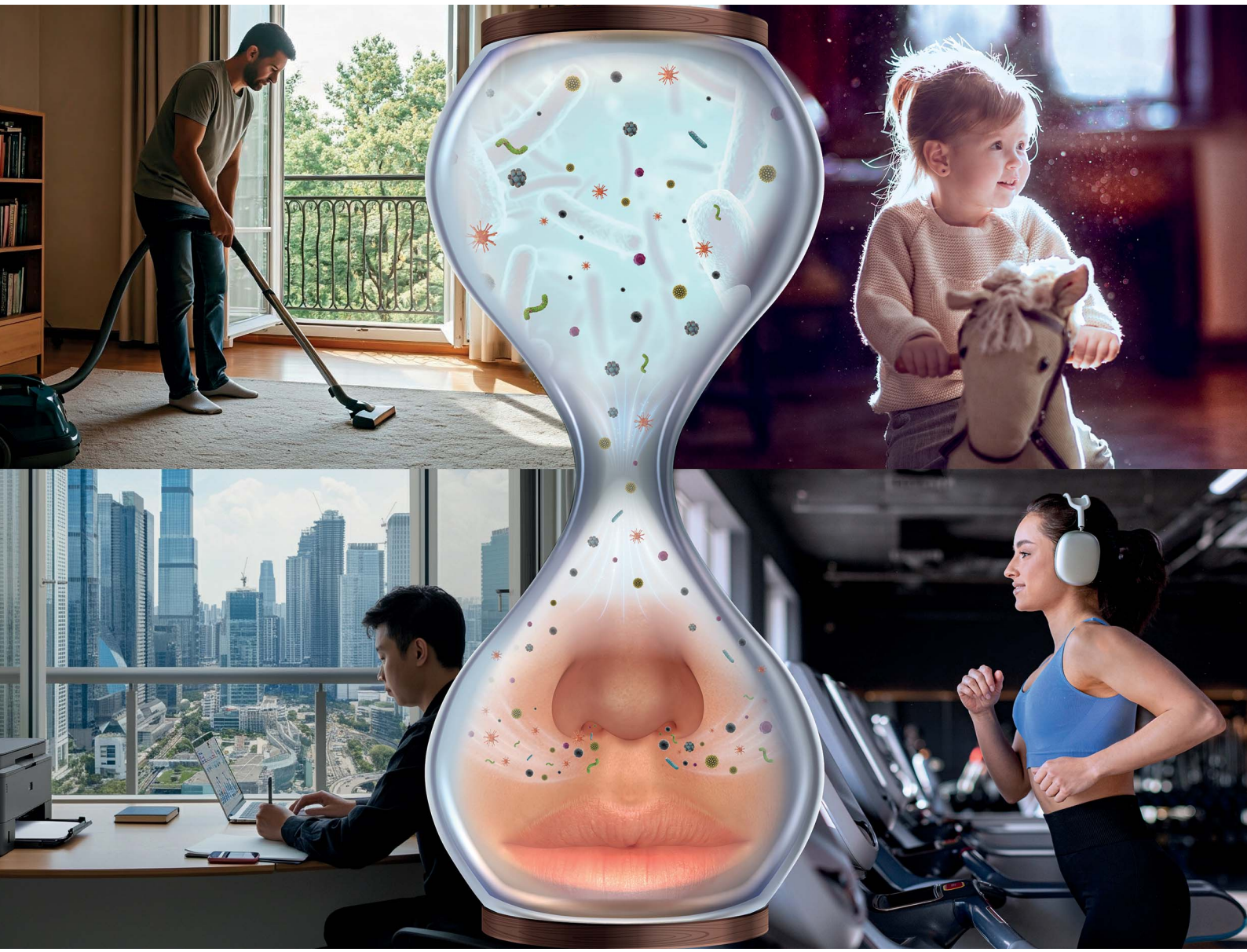

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CRITICAL REVIEW
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Towards developing an indoor emissions inventory for the UK: challenges and future directions

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The global attention on indoor air quality is progressively increasing as people spend *ca.* 80 to 90% of their lives indoors. Therefore, a substantial fraction of exposure to air pollution occurs in different indoor environments. However, there is a lack of information on how different time and activity dependent sources and built environment characteristics affect air pollutant emissions and their distribution. There is an urgent need to develop indoor emissions inventories to estimate the contribution of multiple and time-dependent sources and activities to air pollutant emissions. This paper reviews the current state-of-the-art of indoor air pollution research in the UK, categorises the published literature according to pollutant types, built environments and activities, provides an overview of typical levels of indoor air pollutants with a focus on UK-specific measurements and identifies the research gaps and future directions to progress towards developing indoor emission inventories. In the UK, researchers have investigated indoor air quality since the nineties producing many studies from different perspectives. However, a cohesive methodological approach is lacking in most of the studies. Several important sources/species are not represented, ancillary information relating to environment characteristics (volumes and ventilation) and occupants' behaviours during the measurements is not reported and too little information on the indoor–outdoor continuum is provided. Despite the gaps identified, the existing evidence base on indoor air pollution in the UK can be categorised in an easy-to-use database of indoor air pollutant concentrations and characteristic emission rates for specific activities, pollutants and environments. This will provide a platform for designing standardised approaches for indoor air quality measurements and the development of activity-based indoor emission inventories, which will be a step-change in indoor air pollution research in the UK and globally.

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Environmental significance

This review article stems from the Metoffice/UKRI Clean Air Programme Strategic Priorities Fund through the grant for "Indoor Air Quality Emissions and Modelling System" and synthesizes the current state of the art on indoor air pollutant levels in the UK, categorising pollutant types, built environments, and activities, with a view to highlight key research gaps, discuss the challenges and identify the future direction for the development of an indoor air pollution emission inventory for the UK. Indoor air pollution poses a significant environmental risk to public health due to prolonged exposure to a variety of pollutants in different indoor environments such as residential, occupational, transportation, and recreational spaces. The relationship between indoor and outdoor air quality is complex and affected by a range of factors including outdoor environmental conditions, indoor design and construction and how occupants use and manage indoor spaces. This article is timely due to the growing focus on estimating exposure to air pollutants across the indoor–outdoor continuum. To advance the understanding of the emission dynamics, exposure profiles and resultant health impacts of air pollutants across the indoor–outdoor continuum in different built environments, a comprehensive and quantitative evidence base of indoor pollutant levels in different indoor settings is required. There is an urgent need to develop indoor emission inventories for different environments to understand the contribution of multiple and time-dependent sources and activities to air pollutant emissions and to inform intervention strategies.

1 Introduction

Indoor air pollution is a major public health concern due to the amount of time spent in different indoor environments (residential, occupational, transport and recreational spaces) and overall exposure to diverse air pollutants.[1] Whilst indoors humans can be exposed to a cocktail of pollutants, such as aerosols (including bioaerosols), and gaseous pollutants. These pollutants can originate from indoor sources as well as from outdoor sources that penetrate the indoor environment. The indoor–outdoor air quality relationship is complex and affected by a range of factors in outdoor environments as well as building design, construction, use and management. Occupant activities (*e.g.*, cooking, heating, cleaning, personal care and ventilation behaviour) also play a key role in indoor air pollution

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levels. For instance, smoke and fumes produced during fuel burning for cooking and heating activities can lead to the release of harmful air pollutants. In particular, the use of wood stoves and fireplaces can result in high levels of indoor air pollution.[2] Similarly, cleaning activities contribute to the complex mixtures of volatile and semi-volatile organic compounds. Finally, building materials, furnishings and ventilation systems are additional parameters that strongly influence mechanisms of dispersion and deposition of indoor air pollutants, so that even modest emission levels may result in high and often harmful pollutant concentrations.

Improving indoor air quality (IAQ) requires sustained investments in scientific and engineering research and active collaboration with stakeholders and policymakers to inform solutions in IAQ measurements, modelling, control and management.[2] In the UK, 80 to 90% of time is spent in different indoor environments (private, public and commercial buildings) and around 60% in homes.[3,4] Hence the knowledge of IAQ is critical to calculate the total human exposure to various air pollutants across the indoor–outdoor continuum. In the UK, the current air quality regulation framework is a mixture of domestic, EU and international policies that do not provide regulations or limits to indoor air pollution.[5] In 2019, Public Health England (PHE) published IAQ guidelines for a selected group of volatile organic compounds in the UK.[6] Additionally, there are several regulations aimed at reducing specific emissions from indoor environments in the UK. Some of these regulations apply specifically to workplaces and focus on the use of hazardous substances[7] or specific chemicals[8] and their health impact. Other measures are complementary to outdoor mitigation policies for those emissions related to particular activities such as domestic combustion,[9] varnishing and painting[10] or building construction.[11]

Indoor air pollution has been a topic of research in the UK since the nineties and accounts for a large number of studies investigating the topic from different perspectives. Early research focused on the residential environment using passive sampling techniques to analyse the average levels of air pollution in various residential settings. These studies focused on one or more pollutants and generally averaged over long time periods, such as. monthly, seasonal or annual periods.[12–18] Other studies investigated the impact of specific activities such as cooking, heating, and smoking, as well as specific fuel types such as solid fuel combustion, gas, and electricity, on IAQ.[19,20]

Subsequently, public, environments were investigated. Several occupational environments (*e.g.*, offices, schools and hospitals) have been studied. Schools have been investigated to quantify the exposure levels of pupils to gaseous pollutants (NO_2, CO_2, O_3, VOCs), aerosols (including bioaerosols such as fungi and bacteria) and polybrominated diphenyl ethers (PBDEs) in dust.[21–29] The impacts of building construction and ventilation rates were also investigated in relation to concentration levels in UK classrooms.[23,28,30–32] Indoor air pollution levels were also monitored during working hours in offices focusing on levels of $PM_{2.5}$, NO_2 and VOCs related to cleaning and smoking activities[33,34] or to ventilation rates in natural and mechanically ventilated working places.[35,36]

Indoor air pollutants were also investigated inside different types of transport vehicles. A major part of this work focused on concentrations and exposure levels of particulate matter (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) and total suspended particles (TSP) during journeys.[37–39] Other studies focused on the impact that different types of filters in cars can have on exposure levels of NO_2.[40] Train and London underground levels of air pollution were also objects of investigation. The focus was on the quantification of pollutant levels during journeys, in driver's cabs, on the platforms and in stations.[41–43] Studies were also conducted in other indoor environments, *e.g.* to quantify the levels of CO and $PM_{2.5}$ from shisha smoking activities in restaurants[44] or the levels of synthetic cannabinoids in UK prisons.[45]

The interest in indoor air pollution and the wide range of variables contributing to the levels of pollutants indoors led to significant research investment focused on numerical simulations of IAQ. The modelling approach allowed to better understand the contributions of different emission sources, building structures and occupant activities on the resulting levels of air pollutants. Early studies focused on aerosols using outdoor/indoor measurements to assess the model's performance.[17,46] Later, other works considered air exchange rates between communicating rooms and outdoor ventilation.[47] Finally, physical processes started to be coupled with more complex chemical transformations, focusing the attention on secondary aerosol formation,[48] and reactive gaseous species related to particular activities and their impact on health.[49–51] A recent report from the Royal Society of Chemistry identifies challenges and opportunities associated with a better understanding of the impact of chemistry on indoor air pollution.[52]

Despite the research conducted on indoor air pollution in the UK, there is a lack of information on how different sources, built environment characteristics and occupants' activities affect air pollutants across the indoor–outdoor continuum. A comprehensive and quantitative evidence base of the levels of indoor pollutants in different indoor environments in the UK is therefore urgently needed and a prerequisite to a better understanding of the emission dynamics, exposure profiles and resultant health impacts of air pollutants across the indoor–outdoor continuum in different built environments.

There is an urgent need to develop indoor emission inventories for different environments to understand the contribution of multiple and time-dependent sources and activities to air pollutant emissions and to inform and constrain numerical modelling. Similarly to outdoor air pollution, national authorities should make use of numerical simulations using updated emission inventories created using extensive observational data collected over time (*e.g.*, the National Atmospheric Emission Inventory[53] for outdoors); this has not been possible for the indoor air pollution case so far which is a major omission also highlighted by recent studies.[54]

In this paper we synthesize the current state of the art on indoor air pollutant levels in the UK, categorising pollutant types, built environments, and activities, with a view to highlight key research gaps, discuss the challenges and identify the future direction for the development of an indoor air pollution emission inventory for the UK.

2 State of the art

A literature review was conducted to examine the state of the art on indoor air pollution in the UK. To identify relevant literature, databases such as Google Scholar, Scopus and ResearchGate were searched using keywords including "indoor air pollution," "UK," and "air quality" published in the period from 1995 to 2023. The identified studies were then categorized by the type of macro-environment in which the measurements were taken (residential, occupational, recreational, and transport). In each macro-environment, the review examined specific micro-environments (*e.g.*, living rooms, schools, cars) and analysed the duration and timing of the measurements, sampling methods, activities, and pollutant concentrations. The selection of studies prioritized those that provided detailed descriptions of indoor environment characteristics and related activities. Additionally, advancements in numerical modelling techniques for indoor air quality were reviewed to provide a comprehensive understanding of both empirical data and simulation-based approaches.

The literature published in the UK on indoor air pollution, albeit spanning from 1995 to 2023, is limited compared to outdoor air. The studies are very diverse, covering a vast range of pollutant characteristics from various indoor environments. However, they often lack information on indoor environment characteristics and activities. The distribution of the articles published in the UK highlights that most of the research was focused on domestic indoor environments (40 papers), followed by non-domestic environments[27] including occupational environments (hospitals, offices, schools), recreational environments (pubs, restaurants, museums) and transport environments (private cars, taxis, buses, trains, underground and over ground trains). A similar amount of literature was found for intercomparisons of different environments[19] and for numerical modelling simulations of indoor air pollution.[22] Finally, several reports have been published from 2003 to 2022 on the topic of indoor air pollution.[12]

The studies were grouped into four main macro-environments where the measurements took place: residential, occupational, recreational and transport environments. Each of these environments provides detailed information relating to particular micro-environments:

- Residential: living room, kitchen, bedroom and bathroom.
- Occupational: office, school and hospital.
- Transportation: private cars, trains (underground, overground), taxis and buses.
- Recreational: pubs, restaurants, libraries and museums.

Information included in each macro-environment covers different measurement durations in different years and seasons. Moreover, a variety of sampling methods were used for measurements, and these are analysed in this review as well as the concentration levels of indoor air pollutants related to particular activities. In addition to the review of field experiments and sampling measurements of indoor air pollution, a brief presentation of the advances in the numerical modelling of indoor air pollution is also provided.

2.1 Measurements of indoor air pollutants

Measurements of indoor air pollution in the UK cover a wide range of contaminants, including gaseous pollutants (NO, NO_2, CO, CO_2, O_3), aerosols (PM_{10}, $PM_{2.5}$, $PM_{1.0}$, ultra-fine particles (UFPs), bioaerosols) and 52 different volatile organic compounds (VOCs).

The different measurement techniques adopted in the field sampling research articles have been grouped by pollutant. The macro-categories adopted for this analysis divide the measurement techniques into active sampling (*i.e.*, air pumps, canisters, impactors, optical counters, sensors, chemiluminescence UV, infrared and gravimetric methods) and passive sampling (*i.e.*, sorbent tubes, diffusive filters). The type of sampler is highly variable and depends on the pollutant and type of analysis. Aerosol species (PM_{10}, $PM_{2.5}$, $PM_{1.0}$) measurements were carried out mainly using active sampling techniques, with only a small number of articles using passive samplers.[23–25] Gravimetric sampling was used for indoor air measures[55,56] and for personal exposure studies.[57] Optical counters were widely used for aerosol measurements in personal exposure studies[20,37,39,58] and indoor air.[16,41] Other works employed aerosol spectrometers,[59] small inertial impactors[60] or multi-orifice cascade particle sizing samplers.[61] Ultrafine particles (UFPs) were monitored using scanning mobility particle sizers.[19]

Gaseous pollutants, including CO_2, CO, NO_2 and O_3 show more variability in the measurement techniques with a higher number of passive samplers often used for long-term sampling campaigns over a large number of sampling dwellings. The majority of these experiments uses diffusion tubes.[12,13,20,55,56,61,62] Active sampling of gaseous pollutants was carried out using data loggers,[20,62,63] chemiluminescence,[19] infrared spectrometry[24] and airflow test meters.[20,36,61]

Measurements of Volatile Organic Compounds (VOCs) reported these compounds either as a group of several VOCs (Total Volatile Organic Compounds, TVOCs) or apportioning the individual species. The techniques adopted for the measurements include different types of sorbent tubes as passive samplers.[24,25,55,64–66] Active sampling of TVOCs and individual VOCs included air canisters[67] and high-volume air samplers.[36,55,68] Finally, bacteria and fungi were monitored using single or multi-stage cascade impactors[55,69] or portable air samplers[36] to measure the concentration and size distribution of culturable bacteria and fungi.

To conclude, the existing evidence base of indoor air pollutant concentrations stems from a range of sampling and analysis methods ranging from passive to active sampling and consequent analysis by analytical chemistry techniques (*e.g.*, gas chromatography). While a wide range of methods has been applied to a range of pollutants, a gap can be identified in the harmonization of the methods used to provide enough precision in the comparison of the results from different environments. Moreover, the time frame in which the measurements took place represents another element of big uncertainty in the final concentrations, monitored both during the time of a particular activity (*e.g.*, minutes of cooking activity of a particular dish[19]) and over long periods as an average of

several possible activities not specified in the original article (*e.g.*, seasonal periods[13,14]).

2.2 Macro- and micro-environments of indoor air pollutants

The dynamics of indoor air pollutants are related to the characteristics of environments and the occurrence of human activities in a particular environment. Some air pollutants are in common between outdoor and indoor environments, with concentrations in the latter environments may be strongly influenced by outdoor levels unless unusually strong indoor sources are presented. For example, nitrogen oxides in indoor environments are influenced by cooking activities (if gas fuel is used in the kitchen), but can be impacted by outdoor concentrations, if the residential dwelling where the measurements take place is in an urban traffic area. In other cases, pollutants less common outdoors can be more relevant in indoor environments due to accumulation: this is the case for carbon monoxide (CO) from incomplete combustion and formaldehyde from building material among others. Some pollutants are almost absent in outdoor environments and found only in indoor environments, such as specific VOCs from paints, carpets, and cleaning products or brominated fire retardants in modern furniture.[70] Finally, the ventilation and hygrothermal variables of micro-environments contribute to the build-up of indoor air pollutants, such as in the case of bioaerosols (bacteria and fungi), particularly in damp and overcrowded indoor conditions.[71]

Table 1 illustrates the links between typical indoor activities, indoor micro-environments and air pollutants. It is evident from the current literature that the high variability in the sources and types of pollutants make it challenging to systematically categorise all sources and pollutants contributing to indoor air pollution levels thus providing a clear motivation for further, more systematic and methodologically consistent studies.

In the review of the UK literature on indoor air pollution concentrations, we found a big difference in the type and number of pollutants monitored by macro- and micro-environment. The transportation macro-environment provides the smallest number of pollutants monitored. Studies on the quantification of per-journey exposure to indoor air pollutants focused, in fact, only on aerosols (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$). Private cars have been analysed in individual journeys of different lengths and in different periods of the year[37–39,42,57] while only one paper analysed the concentrations of $PM_{2.5}$ for taxi driver exposure[86] and on public buses.[57] Finally, particulate matter (PM_{10} and $PM_{2.5}$)

Table 1 Common human activities in different micro-environments and air pollutants measured

Indoor activity/emission	Typical air pollutants	Indoor micro-environments
Cleaning (washing, toilets/bathrooms), emission from surfaces (carpets/furnishes), house dust, pets, human expiratory activities, air conditioning/HVAC systems	Bioaerosols,[72–74] VOCs[75]	All indoor environments Dwellings Care home School/nursery Gym/indoor sports centres
Cooking – food emission, from oil, foodstuffs *etc.*	VOCs, particulate matter (PM)[76,77]	Dwellings Care home
Cooking – Gas stove	CO_2, NO_x, CO[78,79]	Dwellings Care home
Cooking – H_2 stove	CO_2, NO_x	Dwellings Care home
Building surface emissions – carpets, furniture, paints, floors	VOCs, formaldehyde, di-2-ethylhexyl phthalate (DEHP)[75]	Dwellings School/nursery Care home Gym/indoor sport centres
People	CO_2, VOCs, bioaerosols[80]	All indoor environments
Personal care product use (*e.g.*, refreshers)	VOCs[81]	Dwellings Care home
Cleaning activities	VOCs, PM[75,82]	All indoor environments
Wet surfaces	Bioaerosols[83,84]	All indoor environments
Heating – gas (minor indoor emission – majority vented externally)	CO_2, NO_x, CO[80]	Dwellings School/nursery Care home
Heating – H_2 (minor indoor emission – majority vented externally)	CO_2, NO_x	Dwellings School/nursery Care home
Heating – biomass/coal (minor indoor emission – majority vented externally)	CO_2, NO_x, VOCs, PM, CO[80]	Dwellings School/nursery Care home
Recreational indoor burning – wood/coal/candles	CO_2, NO_x, VOCs, PM, CO[85]	Dwellings School/nursery Care homes

levels have been monitored in train and underground stations, platforms and in trains to evaluate passengers' and drivers' exposure during both journey and waiting times.[41–43,57]

Higher variability in the measurements was found in the recreational macro-environments where pubs and restaurants have been investigated for aerosols and gaseous pollutants. These studies focused on the effect of smoking activities in shisha premises of pubs and restaurants and relative effects on CO and $PM_{2.5}$ (ref. 44) or on the carcinogenic potential of polycyclic aromatic hydrocarbon (PAH) mixtures in restaurants, libraries and museums.[87]

A larger number of micro-environments and pollutants have been investigated in the occupational macro-environment. Average concentrations of NO_2, O_3 and VOCs have been measured long-term in hospitals in the UK[66] analysing the indoor–outdoor ratios and showing how few VOCs (*e.g.*, benzene and formaldehyde) exceeded the World Health Organization or the Public Health England guideline values during the monitoring. A higher number of studies have focused on indoor air pollution in schools. Gaseous pollutants (CO, CO_2, NO_2, O_3), aerosols (PM_{10} and $PM_{2.5}$) and VOCs have been monitored during the lessons in heating and non-heating periods. These studies are particularly detailed and also provide complementary information on the size of the classroom where the sampling took place and the ventilation rates measured before the monitoring.[22–25,27,60,66] Finally, a large number of research has investigated the average concentrations of gaseous pollutants (CO, CO_2, NO_2, O_3), aerosols ($PM_{10,}$ $PM_{2.5}$ and $PM_{1.0}$), VOCs and bioaerosols in offices of different dimensions, sited on different floors and subjected to different types of ventilation.[36,55,64–66]

The macro-environment that provided the highest number of studies by pollutant type and by micro-environment is the residential environment. Gaseous pollutants and aerosols (including bioaerosols) have been monitored according to different criteria: as average over seasons in different types of households in a range of building archetypes (mid-, end-terraced, semi-detached and detached houses), flats and bungalows according to the dwelling sizes and ventilation systems[62] or according to particular activities taking place in specific micro-environments. Some studies investigated the concentrations emitted during cooking activities using different fuel types[12–14] while others focused on the quantification of the concentrations from a particular type of cooking method (*e.g.*, frying, boiling, baking).[19] Aerosol concentrations were monitored with a particular focus on heating and cooking fuel types (wood, coal, peat) and smoking activities.[20,59] Finally, VOCs concentrations have been monitored in particular to dwelling activities in rooms of different sizes and providing the ventilation rates and the activity times.[88] It is of note that most of the studies monitored the average concentrations of pollutants in indoor environments. However, some studies provide detailed information about activity durations, room sizes, and ventilation rates. These works are important because they help quantify concentration levels and emission rates for specific activities. This information has relevance both for quantification of the emission rates attributable to representative activities in macro- and micro-environments and as input data for modelling work aimed at simulating dispersion and chemical transformation of air pollutants in the indoor environment.

2.3 Activity-based measurements of indoor air pollutants

The analysis of the literature published in the UK on indoor air pollution highlights how indoor air pollution measurements were carried out. On the one hand, the aim was to quantify average concentrations across a large number of dwellings to obtain representative average values for each pollutant. On the other hand, many articles investigated the net concentrations generated by particular activities in specific macro-environments, or the different impact that a particular pollutant could have in different macro-environments. The activity-based measurements carried out in the UK provide a fingerprint of the actual concentrations during human activity and provide higher precision for the quantification of exposure levels in different macro- and micro-environments. The average observed values of indoor air pollutants have been categorised into four macro-environments (residential, occupational, transport and recreational environments) for all pollutants. Gaseous pollutants and aerosols have been divided according to the activity type (Table 2), while individual VOCs and bioaerosols (fungi, bacteria) have been divided according to macro- and micro-environment (Tables 3 and 4, respectively).

Information on outdoor concentrations during indoor activity-based measurements in specific locations is critical to understanding the indoor–outdoor relationship of different air pollutants and quantifying the contribution from indoor sources. However, studies published in the UK on indoor air quality measurements do not always provide this. Outdoor concentrations have been included in Tables 2 and 3 if they are reported in the studies.

2.3.1 Gaseous pollutants and aerosols. Main gaseous pollutants (CO, CO_2, NO, NO_2 and O_3) and aerosols (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) are the species whose indoor measurements have been linked to particular types of human activities. Representative concentrations measured in the UK for these pollutants are reported in Table 2. Across the four macro-environments, the residential one is the sector providing the highest number of activities for which measurements are available: 10 from cooking, 4 from heating and 2 from other activity types. The species with the highest representativity are NO_2 and $PM_{2.5}$. The former was measured during a total of 12 different activities (7 cooking activities, 4 heating activities and 1 smoking activity), while the latter during a total of 10 activities (5 from cooking, 4 from heating and 1 from smoking). The second most investigated pollutant in the residential environment was CO, measured for 8 different types of activities (3 from cooking, 4 types of fuel used for heating and 1 measurement from smoking activity), followed by NO measured in 4 different activities related to residential cooking. The other species are less well represented: PM_{10} and $PM_{1.0}$ were measured for a total of 5 different activities (2 from cooking, 2 from heating and once from smoking) while CO_2 was measured only in relationship to people occupancy (breathing activity).

Table 2 Activity-based observations of indoor gaseous air pollutants and aerosols in different indoor environments (residential, transport, occupational and recreational)

Observed indoor concentrations by activity								
Environment/activity	CO[a]	CO_2	NO_2[a]	O_3[a]	NO	PM_{10}[a]	$PM_{2.5}$[a]	$PM_{1.0}$
Residential (cooking)								
Generic cooking (gas)	0.54 mg m^{-3} (ref. 13)		52.8 μg m^{-3} 39.69 μg m^{-3}[b] (ref. 14) 38.9 μg m^{-3} (ref. 13) 48.4 μg m^{-3} (ref. 12)		0.65 μg m^{-3} (ref. 19)	30 μg m^{-3} (ref. 59)	8.6 μg m^{-3} (ref. 20)	5.0 μg m^{-3} (ref. 59)
Baking (gas)			0.37 μg m^{-3} (ref. 19)		0.68 μg m^{-3} (ref. 19)			
Roasting (gas)			0.30 μg m^{-3} (ref. 19)		0.72 μg m^{-3} (ref. 19)			
Frying (gas)			0.09 μg m^{-3} (ref. 19)		0.09 μg m^{-3} (ref. 19)			
Boiling (gas)			0.18 μg m^{-3} (ref. 19)		0.32 μg m^{-3} (ref. 19)			
Oven (gas)	0.76 mg m^{-3} (ref. 13)		42.3 μg m^{-3} (ref. 13)					
Generic cooking (electric)	0.46 mg m^{-3} (ref. 13)		19.5 μg m^{-3} (ref. 12)			61 μg m^{-3} (ref. 59)	51 μg m^{-3} (ref. 59)	44 μg m^{-3} (ref. 59)
Generic cooking (peat)							15.6 μg m^{-3} (ref. 58)	
Generic cooking (coal)							8.9 μg m^{-3} (ref. 58)	
Generic cooking (wood)							7.7 μg m^{-3} (ref. 58)	
Residential (heating)								
Gas	0.25 mg m^{-3} (ref. 62)		27.3 μg m^{-3} 33.14 μg m^{-3}[b] (ref. 62)			32 μg m^{-3} (ref. 59)	11 μg m^{-3} (ref. 59)	6.0 μg m^{-3} (ref. 59)
Coal	0.12 mg m^{-3} (ref. 20)		8.0 μg m^{-3} (ref. 20)				8.9 μg m^{-3} (ref. 20)	
Peat	0.12 mg m^{-3} (ref. 20)		7.0 μg m^{-3} (ref. 20)				15.6 μg m^{-3} (ref. 20)	
Wood	0.001 mg m^{-3} (ref. 20)		5.0 μg m^{-3} (ref. 20)			203 μg m^{-3} (ref. 59)	191 μg m^{-3} (ref. 59)	185 μg m^{-3} (ref. 59)
Residential (others)								
Smoking	0.66 mg m^{-3} (ref. 13)		13.0 μg m^{-3} (ref. 20)			35 μg m^{-3} 30 μg m^{-3}[b] (ref. 59)	28.50 μg m^{-3} 18 μg m^{-3}[b] (ref. 59) 143.1 μg m^{-3} (ref. 20)	23.75 μg m^{-3} 12 μg m^{-3}[b] (ref. 59)

Table 2 (*Contd.*)

Observed indoor concentrations by activity								
Environment/activity	CO[a]	CO_2	NO_2[a]	O_3[a]	NO	PM_{10}[a]	$PM_{2.5}$[a]	$PM_{1.0}$
Occupancy (breathing)		1984.3 mg m^{-3} (ref. 62) 1743.94 mg m^{-3} (ref. 63)						
Transport (journey time)								
Train						62.25 μg m^{-3} (ref. 42)	16 μg m^{-3} (ref. 42)	10.25 μg m^{-3} (ref. 42)
Car			26.3 μg m^{-3} (ref. 40)			192.4 μg m^{-3} (ref. 42)	8 μg m^{-3} (ref. 42) 15 μg m^{-3} (ref. 38) 34.3 μg m^{-3} (ref. 57)	
SUV			34.3 μg m^{-3} (ref. 40)					
Van			44.6 μg m^{-3} (ref. 40)					
Underground (train)						1200 μg m^{-3} (ref. 41)	80.38 μg m^{-3} (ref. 43)	
Underground (platform)							346.6 μg m^{-3} (ref. 41)	
Underground (driver's cab)							130.0 μg m^{-3} (ref. 41)	
Overground							29 μg m^{-3} (ref. 57)	
Bus							38.5 μg m^{-3} (ref. 57)	
Taxi							33.0 μg m^{-3} (ref. 86)	
Occupational								
Office	0.1 mg m^{-3} (ref. 36)	1011.6 mg m^{-3} (ref. 36)	29.6 μg m^{-3} (ref. 65) 11.3 μg m^{-3} (ref. 66)	4.0 μg m^{-3} (ref. 25)		20.87 μg m^{-3} (ref. 55)		
School		1768.8 mg m^{-3} (ref. 24) 2185.5 mg m^{-3} (ref. 25) 1954.8 mg m^{-3} (ref. 27)	24.4 μg m^{-3} (ref. 24) 19.1 μg m^{-3} (ref. 25) 22.1 μg m^{-3} (ref. 66)	7.8 μg m^{-3} (ref. 24) 11.9 μg m^{-3} (ref. 25) 11.1 μg m^{-3} (ref. 66)		59.0 μg m^{-3} (ref. 24) 51.0 μg m^{-3} (ref. 25)	25.6 μg m^{-3} (ref. 60) 39.3 μg m^{-3} (ref. 24) 32.3 μg m^{-3} (ref. 25)	37.3 μg m^{-3} (ref. 24) 30.3 μg m^{-3} (ref. 25)
Hospital			20.4 μg m^{-3} (ref. 66)	13.8 μg m^{-3} (ref. 25)				

Table 2 (*Contd.*)

Observed indoor concentrations by activity								
Environment/activity	CO[a]	CO_2	NO_2[a]	O_3[a]	NO	PM_{10}[a]	$PM_{2.5}$[a]	$PM_{1.0}$
Recreational								
Shisha premises	7.12 mg m^{-3} (ref. 44)						270.66 μg m^{-3} (ref. 44)	
Restaurant/Pub	0.71 mg m^{-3} (ref. 44)						23.0 μg m^{-3} (ref. 44)	

[a] Species for which the World Health Organisation published guidelines values in 2021 (World Health Organization 2021); SO_2 is also part of this list, but it is absent from measurements in the UK.
[b] Represents outdoor concentration for a pollutant where available.

The occupational macro-environment represents the most represented sector in terms of the number of gaseous pollutants[4] and aerosols.[3] The highest number of measurements are for NO_2 and O_3 levels, monitored in all three environments (schools, hospitals and offices) followed by CO_2 monitored in schools and offices only. Few articles focused on the levels of aerosols with different size distributions in schools, 2 of them analysed PM_{10} and $PM_{1.0}$ and 3 of them analysed $PM_{2.5}$, while only PM_{10} was measured in office environments. Finally, CO measurements were taken only in an office and represented only in one article.

The transport macro-environment provides the most information in relation to $PM_{2.5}$ measured in trains, cars, underground trains, buses and taxis. Other aerosols (PM_{10} and $PM_{1.0}$) were measured in train and the underground (inside the trains, drivers' cabs and on the platforms) and cars (PM_{10} only). Finally, detailed NO_2 measurements were performed in different types of on-road vehicles (SUVs and vans) using different types of air filter technologies at different usage durations (from new to 12 months of usage).[40] The least represented macro-environment is the recreation sector. For this environment, only one article was found providing measurements of CO and $PM_{2.5}$ from restaurant dining spaces and from shisha premises attached to the restaurants.

To summarise, gaseous pollutants measured in UK indoor environments cover a total of 16 activities related to the residential macro-environment, 3 different types of occupational environments, 10 types of transport-related measurements and two recreational environments. Among these NO_2 is measured 70% of the time, $PM_{2.5}$ and NO 50%, CO, PM_{10} and $PM_{1.0}$ 20% and no measurements of O_3 were found. Among the four types of fuels used for residential heating, CO, NO_2 and $PM_{2.5}$ were measured for all 4 categories while PM_{10} and $PM_{1.0}$ were measured only in 2 of the 4 categories (gas and wood). Finally, concerning the other activities, smoking was monitored for 63% of the species (CO, NO_2, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$). The transport sector showed higher representativity among the different transport micro-environments in $PM_{2.5}$ (70%) followed by PM_{10} and NO_2 (30%), and finally $PM_{1.0}$ (10%). There were no measurements of CO_2, CO and O_3 in transport environments. The occupational macro-environment is the most represented sector among the different species taken into account. The school micro-environment covered 75% of the pollutants (6 of a total of 8) followed by the office micro-environment covered by 63% (5 of 8) of pollutants and hospitals only by 25% (2 of 8). Finally, the recreational macro-environment is the least represented sector showing the smallest percentage of representation of pollutants (CO and $PM_{2.5}$) and for the number of environments (restaurants, pubs and shisha premises).

The representativity of the measurements carried out in the UK shows a heterogeneous picture of the available data and highlights the presence of gaps in the representation of gaseous pollutants in particular. We recall that the number and type of pollutants chosen for the analysis have been defined based on the available measurements and that important species may be missing because they may never have been measured in the UK at the time of writing. Similarly, the number and type of

Table 3 Individual VOC observations from indoor macro- and micro-environments (residential, transport, occupational and recreational)

	Residential	Occupational			Recreational		
	Multiple	Hospital	School	Workplace	Library/ museum	Pub	Restaurant
1,2,4-Trimethylbenzene	2.3 μg m^{-3} (ref. 64)			1.3 μg m^{-3} (ref. 64)			
1,3,5-Trimethylbenzene	0.61 ng m^{-3} (ref. 64)			0.26 ng m^{-3} (ref. 64)			
1,3-Butadiene	0.24 ng m^{-3} (ref. 64)			0.08 ng m^{-3} (ref. 64)			
3-Carene	2.3 μg m^{-3} (ref. 65)			2.8 μg m^{-3} (ref. 65)			
3-Ethenylpyridine	0.1 ng m^{-3} (ref. 64)			0.07 ng m^{-3} (ref. 64)			
Acenaphthalene				0.08 ng m^{-3} (ref. 87)	0.74 ng m^{-3} (ref. 87)	1.46 ng m^{-3} (ref. 87)	0.65 ng m^{-3} (ref. 87)
Acenaphthene	19.1 ng m^{-3}, 1.04 ng m^{-3}[b] (ref. 68)		23.82 ng m^{-3} 0.75 ng m^{-3}[b] (ref. 68)	0.25 ng m^{-3} (ref. 87)	0.87 ng m^{-3} (ref. 87)	0.41 ng m^{-3} (ref. 87)	0.85 ng m^{-3} (ref. 87)
Acetaldehyde[a]	16 μg m^{-3} (ref. 89)						
Anthracene	1.14 ng m^{-3}, 1.3 ng m^{-3}[b] (ref. 68)		1.9 μg m^{-3} (ref. 68)	0.06 ng m^{-3} (ref. 87)	0.29 ng m^{-3} (ref. 87)	0.16 ng m^{-3} (ref. 87)	0.06 ng m^{-3} (ref. 87)
a-Pirene[a]	3.13 μg m^{-3} (ref. 62) 7.56 μg m^{-3} (ref. 88) 115.5 μg m^{-3} (ref. 67)	3.8 μg m^{-3} (ref. 66)	25.5 μg m^{-3} (ref. 24) 9.2 μg m^{-3} (ref. 25) 5.6 μg m^{-3} (ref. 66)	18.4 μg m^{-3} (ref. 65) 136.3 μg m^{-3} (ref. 66)			
Benzaldehyde	5.2 μg m^{-3}, 3.0 μg m^{-3}[b] (ref. 65)			3.8 μg m^{-3} (ref. 65)			
Benzene[a]	0.5 μg m^{-3} (ref. 62) 2.6 μg m^{-3}, 2.3 μg m^{-3}[b] (ref. 65) 2.8 μg m^{-3} (ref. 75) 1.97 ng m^{-3} (ref. 64) 13 μg m^{-3} (ref. 67)	0.8 μg m^{-3} (ref. 66)	0.9 μg m^{-3} (ref. 24) 0.68 μg m^{-3} (ref. 25) 1.4 μg m^{-3} (ref. 66)	4.5 μg m^{-3} (ref. 65) 1.18 μg m^{-3} (ref. 66) 11.8 ng m^{-3} (ref. 64)			
Benzo[a]anthracene	0.71 ng m^{-3}, 0.46 ng m^{-3}[b] (ref. 68)		1.68 ng m^{-3} (ref. 68)	0.06 ng m^{-3} (ref. 87)	0.04 ng m^{-3} (ref. 87)	0.63 ng m^{-3} (ref. 87)	0.09 ng m^{-3} (ref. 87)

Table 3 (*Contd.*)

	Residential	Occupational			Recreational		
	Multiple	Hospital	School	Workplace	Library/ museum	Pub	Restaurant
Benzo[*a*]pyrene	0.04 ng m^{-3}, 0.3 ng m^{-3}[b] (ref. 68)		0.31 ng m^{-3} (ref. 68)	0.09 ng m^{-3} (ref. 87)	0.05 ng m^{-3} (ref. 87)	0.62 ng m^{-3} (ref. 87)	0.16 ng m^{-3} (ref. 87)
Benzo[*b*]anthracene	0.03 ng m^{-3}, 0.26 ng m^{-3}[b] (ref. 68)		0.86 ng m^{-3} (ref. 68)				
Benzo[*b*]fluoranthene				0.2 ng m^{-3} (ref. 87)	0.12 ng m^{-3} (ref. 87)	0.92 ng m^{-3} (ref. 87)	0.35 ng m^{-3} (ref. 87)
Benzo[*g*,*h*,*i*]perylene			0.63 ng m^{-3} (ref. 68)	0.01 ng m^{-3} (ref. 87)	0.09 ng m^{-3} (ref. 87)	0.64 ng m^{-3} (ref. 87)	0.3 ng m^{-3} (ref. 87)
Benzo[*k*]fluorantene			0.09 ng m^{-3} (ref. 68)	0.12 ng m^{-3} (ref. 87)	0.11 ng m^{-3} (ref. 87)	0.82 ng m^{-3} (ref. 87)	0.3 ng m^{-3} (ref. 87)
Chrisene	0.32 ng m^{-3}, 0.37 ng m^{-3}[b] (ref. 68)		1.24 ng m^{-3} (ref. 68)	0.16 ng m^{-3} (ref. 87)	0.34 ng m^{-3} (ref. 87)	2.0 ng m^{-3} (ref. 87)	0.47 ng m^{-3} (ref. 87)
Coronene			0.08 ng m^{-3} (ref. 68)	0.09 ng m^{-3} (ref. 87)	0.02 ng m^{-3} (ref. 87)	0.2 ng m^{-3} (ref. 87)	0.12 ng m^{-3} (ref. 87)
Decanale	1.53 μg m^{-3} (ref. 62)			8.8 μg m^{-3} (ref. 65)			
Dibenzo[*a*,*c*]anthracene	4.9 μg m^{-3}, 2.7 μg m^{-3}[b] (ref. 65)						
Dibenzo[a,h] anthracene				0.03 ng m^{-3} (ref. 87)		0.15 ng m^{-3} (ref. 87)	0.05 ng m^{-3} (ref. 87)
D-Limonene[a]	15.7 μg m^{-3} (ref. 62)	14.3 μg m^{-3} (ref. 66)	15.9 μg m^{-3} (ref. 24)	10.7 μg m^{-3} (ref. 65)			
	8.0 μg m^{-3}, 2.0 μg m^{-3}[b] (ref. 65)		16.1 μg m^{-3} (ref. 25)				
	160.5 μg m^{-3} (ref. 88)		3.3 μg m^{-3} (ref. 66)	46.7 μg m^{-3} (ref. 66)			
	728.5 μg m^{-3} (ref. 67)						
Decamethylcyclo pentasiloxane (DMCPS)	106.3 μg m^{-3} (ref. 90)						
Ethylbenzene	1.6 μg m^{-3}, 1.6 μg m^{-3}[b] (ref. 65)			1.23 ng m^{-3} (ref. 64)			
	1.7 ng m^{-3} (ref. 64)						
	20.4 μg m^{-3} (ref. 67)						

Table 3 (*Contd.*)

	Residential	Occupational			Recreational		
	Multiple	Hospital	School	Workplace	Library/ museum	Pub	Restaurant
Fluoranthere	5.76 ng m^{-3}, 5.8 ng m^{-3}[b] (ref. 68)		7.9 ng m^{-3} (ref. 68)	0.42 ng m^{-3} (ref. 87)	2.15 ng m^{-3} (ref. 87)	1.78 ng m^{-3} (ref. 87)	0.85 ng m^{-3} (ref. 87)
Fluorene	39.4 ng m^{-3}, 2.93 ng m^{-3}[b] (ref. 68)		57.4 ng m^{-3} (ref. 68)	0.04 ng m^{-3} (ref. 87)	0.02 ng m^{-3} (ref. 87)	0.29 ng m^{-3} (ref. 87)	0.58 ng m^{-3} (ref. 87)
Formaldehyde[a]	26.3 μg m^{-3} (ref. 62) 12.41 μg m^{-3} (ref. 55) 15.31 μg m^{-3} (ref. 88)	4.0 μg m^{-3} (ref. 66)	17.5 μg m^{-3} (ref. 24) 15.9 μg m^{-3} (ref. 25) 3.5 μg m^{-3} (ref. 66)	16.9 μg m^{-3} (ref. 55) 16.4 μg m^{-3} (ref. 66)			
Hexanal	1.6 μg m^{-3} (ref. 65)						
Hexane				15.3 μg m^{-3} (ref. 65)			
Indeno[1,2,3-*c*,*d*]pyrene				0.1 ng m^{-3} (ref. 87)	0.09 ng m^{-3} (ref. 87)	0.35 ng m^{-3} (ref. 87)	0.19 ng m^{-3} (ref. 87)
Isoprene	16.5 μg m^{-3} (ref. 67)						
m/*p*-Xylene[a]	4.8 μg m^{-3}, 3.9 μg m^{-3}[b] (ref. 65) 41.2 μg m^{-3} (ref. 67)			8.4 μg m^{-3} (ref. 67)			
m-Xylene[a]	4.14 ng m^{-3} (ref. 64)			3.2 ng m^{-3} (ref. 64)			
Naphtalene[a]	0.79 ng m^{-3} (ref. 64)	0.4 μg m^{-3} (ref. 66)	0.52 μg m^{-3} (ref. 24) 0.89 μg m^{-3} (ref. 25) 0.5 μg m^{-3} (ref. 66)	0.4 μg m^{-3} (ref. 66) 0.37 ng m^{-3} (ref. 64)			
n-Hexane	2.9 ng m^{-3} (ref. 64)			1.03 ng m^{-3} (ref. 64)			
Nonane	2.3 μg m^{-3}, 1.4 μg m^{-3}[b] (ref. 65)			4.8 μg m^{-3} (ref. 65)			
o-Xylene[a]	2.02 ng m^{-3} (ref. 64)			1.26 ng m^{-3} (ref. 64)			

Table 3 (*Contd.*)

	Residential	Occupational			Recreational		
	Multiple	Hospital	School	Workplace	Library/ museum	Pub	Restaurant
	2054 μg m^{-3} (ref. 67)						
Phenanthrene	62.01 ng m^{-3}, 98.66 ng m^{-3}[b] (ref. 68)		81.7 ng m^{-3}	0.22 ng m^{-3} (ref. 87)	1.13 ng m^{-3} (ref. 87)	0.6 ng m^{-3} (ref. 87)	0.22 ng m^{-3} (ref. 87)
p-Isopropyltoluene	1.03 ng m^{-3} (ref. 64)			0.47 ng m^{-3} (ref. 64)			
Propylbenzene	1.2 μg m^{-3}, 1.0 μg m^{-3}[b] (ref. 65)			3.3 μg m^{-3} (ref. 65)			
p-Xylene	1.7 ng m^{-3} (ref. 64)			1.2 ng m^{-3} (ref. 64)			
Pyrene	3.11 ng m^{-3}, 2.35 ng m^{-3}[b] (ref. 68)		3.56 ng m^{-3} (ref. 68)	0.27 ng m^{-3} (ref. 87)	0.85 ng m^{-3} (ref. 87)	1.07 ng m^{-3} (ref. 87)	0.48 ng m^{-3} (ref. 87)
Pyridine	0.15 ng m^{-3} (ref. 64)			0.11 ng m^{-3} (ref. 64)			
Styrene[a]	0.86 ng m^{-3} (ref. 64)	0.4 μg m^{-3} (ref. 66)	1.75 μg m^{-3} (ref. 66)	0.55 ng m^{-3}[64] 1.5 ng m^{-3} (ref. 66)			
Tetrachloroethylene [4]		0.45 μg m^{-3} (ref. 66)	0.45 μg m^{-3} (ref. 24) 0.30 μg m^{-3} (ref. 25) 0.55 μg m^{-3} (ref. 66)	0.56 μg m^{-3} (ref. 66)			
Texanol	10.8 μg m^{-3} (ref. 62)						
Toluene[a]	1.6 μg m^{-3} (ref. 62) 12.1 μg m^{-3}, 7.6 μg m^{-3}[b] (ref. 65) 17.5 μg m^{-3} (ref. 64) 27.37 μg m^{-3} (ref. 67)	1.73 μg m^{-3} (ref. 66)	27.1 μg m^{-3} (ref. 65) 2.52 μg m^{-3} (ref. 66) 4.31 μg m^{-3} (ref. 64)	3.17 μg m^{-3} (ref. 24) 4.33 μg m^{-3} (ref. 25) 1.62 μg m^{-3} (ref. 66)			
Trichloroethylene		0.35 μg m^{-3} (ref. 66)	0.1 μg m^{-3} (ref. 24) 0.32 μg m^{-3} (ref. 25)	0.46 μg m^{-3} (ref. 66)			

Table 3 (*Contd.*)

	Residential	Occupational			Recreational		
	Multiple	Hospital	School	Workplace	Library/ museum	Pub	Restaurant
			0.45 μg m^{-3} (ref. 66)				
Trimethilbenzene	4.2 μg m^{-3}, 2.9 μg m^{-3}[b] (ref. 65)			8.9 μg m^{-3} (ref. 65)			
Undecanale	3.4 μg m^{-3} (ref. 62) 3.4 μg m^{-3}, 1.5 μg m^{-3}[b] (ref. 65)			4.2 μg m^{-3} (ref. 65)			

[a] Species for which indoor threshold limits are reported at national level by the Public Health of England.[6] [b] Represents outdoor concentration for a pollutant where available.

activities/environments chosen to fill the sub-categories within the four macro-environments were defined on the basis of the available measurements and there is lack of representativity of important activities related to indoor air pollution. One example is the lack of measurements of ammonia (NH_3) or of sulphur dioxide (SO_2). Both species have been included in the National Atmospheric Emission Inventory[91] for key indoor emission sectors. For NH_3 around 895 tons come from residential heating (specifically from anthracite, coal, coke and wood), 970 tons from cleaning products, 580 tons from adult breath and sweating, 100 tons from cigarette smoking and 20 from infant emissions.[91] Similarly, SO_2 emissions have been quantified to be 43 000 tons per year and were related to different types of fuels for residential heating namely anthracite, burning oil, coal, gas oil, LPG, natural gas, petroleum coke, secondary solid fuels (SSF), wood, peat and charcoal). Indoor measurements of these pollutants are absent from the literature adding to the lack of the other pollutants in key sectors. While some species are highly represented among the four macro-environments (*e.g.*, NO_2 and $PM_{2.5}$) others are less represented despite their relevance in indoor environments due to the accumulation and harmfulness when considering human exposure (*e.g.*, CO).

2.3.2 Volatile organic compounds (VOCs). Measurements of volatile organic compounds (VOCs) in UK environments cover a total of 52 species divided across three main macro-environments (residential, occupational and recreational) and in a total of seven individual micro-environments (1 in residential and 3 each in occupational and recreational spaces). Representative concentrations of measured VOCs have been grouped and are displayed in Table 3.

Among the different macro-environments and relative micro-environments, the highest representativity of measurements comes from the occupational environment represented by 84% of the species (44 of 52) and the residential environment by 82% of the species (43 of 52). For the same macro-environment, measurements of VOCs in schools cover 42% of the total species (22 of 52) and only 17% of species were monitored in hospitals (9 of 52). The recreational environment is represented by 28 and 30% of the total species (15 species for library/museums and 16 species for pubs and restaurants), respectively.

Measurements of VOCs were performed in research experiments aimed to quantify the concentrations of a variable number of individual species in different environments, but these measurements were not related to particular activities, but were calculated over long time periods *e.g.*, monthly[67] or annual averages.[92,93] The reactivity of VOCs is highly variable, and the concentration of these species can vary according to the presence of individual or combined activities acting in a particular indoor environment. The potential impact of VOCs related to different activities has been highlighted by the Air Quality Expert Group in their recent report on indoor air pollution[5] that pointed out how a large number of species, emitted by a variable and high number of sources and with high reactivity make it difficult to quantify the emission rates by source. Measurements made in a sample of 25 UK homes of

Table 4 Measurements of bioaerosols (bacteria, fungi) from residential and occupational macro-environments divided by micro-environment type[a]

	Bacteria	Fungi
Residential		
Room in shared house	2721.3 CFU m^{-3} (ref. 69)	1217.3 CFU m^{-3} (ref. 69)
Flat	1581 CFU m^{-3} (ref. 69)	509.6 CFU m^{-3} (ref. 69)
	2459.4 CFU m^{-3} (ref. 55)	253.5 CFU m^{-3} (ref. 55)
Detached house	4836 CFU m^{-3} (ref. 69)	4129 CFU m^{-3} (ref. 69)
Occupational		
Office	265 CFU m^{-3} (ref. 55)	558 CFU m^{-3} (ref. 55)
Office's kitchen	375 CFU m^{-3} (ref. 55)	5 CFU m^{-3} (ref. 55)
Atrium	825 CFU m^{-3} (ref. 55)	30 CFU m^{-3} (ref. 55)
Stairs	165 CFU m^{-3} (ref. 55)	50 CFU m^{-3} (ref. 55)
Cellular	4510 CFU m^{-3} (ref. 55)	
Open plan office	915.33 CFU m^{-3} (ref. 55)	

[a] CFU: Colony forming unit.

varying design, age and occupancy behaviour highlighted the high variability in the measurements of monoterpenes in particular with concentrations *e.g.* of D-limonene varying from 18 to 1400 μg m^{-3} as the highest peak reported in the literature so far.[67] The authors of this study observed that the variability in measurements was linked to the occupants' behaviour and in particular with the frequency of the use of cleaning products and with fragranced materials. This demonstrates the intricate nature of indoor air pollution affected by various time-dependent sources and activities, posing challenges to quantifying emissions and resultant exposure levels in different indoor environments.

Moreover, measurements of activity-based VOCs showed that in addition to the emissions related to indoor activities such as cooking or cleaning, the highest emission rates of VOCs originated from furnishings[94] and personal care and toiletries.[95,96] This highlights the need for further development of activity-based measurements for this class of pollutant. Micro-environments where VOCs are widely used and for which no evidence has been found in the UK literature are those related to construction and building products (*e.g.*, painting, varnishes, waxes and solvents) and in occupational environments in relation to the use of particular devices (*e.g.*, photocopiers and printers).

For the former example, the NAEI emission inventory quantifies the emissions related to the use of decorative paints, domestic adhesives and paint thinner to be 12 200, 4300 and 5500 tons per year. For the latter, emission rates have been measured in environmental chambers studies and used for modelling studies focusing in intercomparing office air quality in different European cities.[97,98] The use of desktop PCs, monitors and notebooks generated around 180 μg h^{-1} per device while the use of inkjet or laser printers generated between 300 and 1400 ppbv of TVOCs.[97]

In addition to the lack of comprehensive information about VOC levels in different macro-environments, microenvironments and relative activities, another important factor to take into account is the VOCs' reactivity and formation of secondary products. Primary VOCs are emitted in indoor environments by multiple activities depending on occurrence and frequency of occupants' behaviours, but the final concentrations measured at the receptors is affected by ozone-initiated chemistry mainly involving terpenes and their degradation pathways.[99,100] The health impact of VOCs from indoor air pollution has been highlighted both at international and at national level by The World Health Organisation (WHO) and Public Health England (PHE). PHE published guidelines and concentrations thresholds for selected VOCs in indoor environments.[75] All species reported in this PHE report are represented by at least one experimental study (see Table 3).

2.3.3 Biological aerosols. The concentrations of bioaerosols (bacteria and fungi) that have been measured in the UK are provided in Table 4. The macro-environments that have been investigated were residential and occupational spaces. In the first case, the presence of biological aerosols was investigated in three different types of private dwellings: a room in a shared house, a flat and a detached house while in the second case, different office spaces were investigated: office kitchen, atrium, corridor, cellular (desks are arranged in small groups). Airborne bacteria are the most investigated bioaerosols represented in all the mentioned dwelling types and macro-environments, followed by fungi represented in 70% of the environments.

2.4 Indoor air pollution modelling in the UK

UK researchers started to focus on modelling indoor air pollutants at the beginning of the 2000s focusing on aerosol particles (PM_{10}, $PM_{2.5}$, $PM_{1.0}$). Outdoor/indoor measurements in a range of buildings (offices and private houses) were used to assess the performance of the models.[17,46] Subsequently, the basis of the first models was used to extend the analysis from aerosol particles (treated as passive scalar) to reactive gaseous species, accounting for air exchange rates between communicating rooms of a particular dwelling and with outdoor ventilation.[47] Besides the measurements of indoor air pollution,

emission rates and sources started to be taken into account as well as the physical processes of dispersion, ventilation and deposition. A further step forward from these models represented the ability to combine individual emission rates of pollutants from different activities and let the particles interact in different indoor building types (*e.g.* rooms with different sizes and ventilation rates).[101]

These three steps formed the basis of the evolution of indoor air pollution modelling in the UK. Since then, the number of studies in this field has increased, mainly since 2012. Physical processes started to be coupled with more complex chemical transformations, focusing the attention on secondary aerosol formation,[48] and reactive gaseous species related to particular activities and their impact on health.[49–51] Other models have been used to compute probabilistic sensitivity analyses using the replicated Latin Hypercube method to understand which parameters have the highest impacts on final concentrations.[102]

The impact of the indoor emissions of CO_2 and $PM_{2.5}$ has been investigated in different parts of the UK. Measurements were analysed in comparison to buildings' efficiency, evaluating the impact on occupants' health.[103,104] Exposure levels have also been analysed in relation to public spaces such as hospitals or offices during particular cleaning activities,[105,106] highlighting how modification of cleaning product formulations could reduce occupants' exposure to indoor air pollution.[107] Physical properties of buildings, ventilation rates, energy efficiency and overheating have also been analysed as potential parameters influencing the levels of indoor air pollution in the UK.[98,108–110] This aspect is particularly relevant to the current drive towards net zero in the building sector. Finally, the representability of all these parameters has been compared with different conditions in intercomparing research projects including the UK, and EU in the case of the emissions, exposure patterns and health effects of consumer products in the EU (EU EPHECT project[88]).

Despite the vast amount of literature published on indoor air pollution modelling, the task of representing a sufficient number of chemical mechanisms acting simultaneously or competing with each other is very complex. Indoor environments are highly variable in area, volume, and ventilation parameters, only to cite a few variables that can be drastically different when applied to commonly encountered types of dwellings: private houses (*e.g.*, mid-, or end-terrace, semi- and detached houses, flats, bungalows), public offices (both open and enclosed spaces), occupational buildings (*e.g.*, hospitals, classrooms) and recreational places (*e.g.*, restaurants, pubs, gyms). Moreover, a large number of activities can take place in these environments, consecutively or in parallel, strongly influencing the chemical transformations of reactive species, even before those physical processes such as deposition or resuspension are taken into account.

3 Research gaps and challenges

The science of indoor air pollution took up progressively more and more space in the clean air and public health research landscape. Whilst research on indoor air pollution in the UK has covered a wide range of activities, environments and air pollutant species, much of the research is focused on concentration-based measurements with diverse sampling designs. An additional gap is in the complementary information relating to the environments where the measurements took place, as this is often missing or partially reported, while crucial to accurate interpretation and model description of the indoor space. In particular, dwelling/room volumes, occupants' number and activities and ventilation type/performance are often only partially reported or absent. This limits the estimation of activity-based emission rates for different indoor air pollutants. Whilst the design of indoor air quality measurements depends on the objectives and goals of monitoring (*e.g.* exploratory, source identification, indoor air quality interventions efficacy, exposure assessment) in a specific environment, a set of good practices can be followed for measuring indoor air quality. These include: (a) conducting simultaneous indoor and outdoor measurements for various pollutants; (b) ensuring representative sampling durations and appropriate temporal resolution; (c) selecting suitable instruments and measurement locations; (d) collecting information on indoor sources, occupant density, activities and their duration, building materials and ventilation design; and (e) measuring environmental characteristics (hygrothermal conditions and lighting) as well as building characteristics, such as volume and ventilation rate.

A significant step forward would be the standardisation of indoor air monitoring including sampling design and a series of environmental and temporal parameters to be adhered to. Furthermore, methods of sampling and subsequent measurement of indoor contaminant concentrations should be evaluated in terms of precision and reproducibility with standards being established. An important gap to fill in order to produce self-consistent databases is to cover all the main variables of this complex system of emissions, environmental and physical environments. For instance, it is key to fill the gap of information relating to missing, but important pollutants (such as NH_3 and SO_2) for which no representative measurements are available at the national level to date.

Finally, despite the progress made in the field of numerical modelling for indoor air pollution, there is still a clear lack of knowledge of the characteristic emission rates by activity and pollutant. Filling this gap with measurement campaigns to derive precise and detailed emission factors based on all key individual activities would represent important, but currently missing tiles in the mosaic of the indoor emissions in the UK.

4 Conclusion and future directions

Despite the challenges that indoor air science is facing and the gaps identified, the advances made in the UK regarding indoor air pollution research landscape can be translated to create the first self-consistent database of indoor air pollutant concentrations along with characteristic emission rates for specific activities, pollutants, and environments. The available literature and reports published in the UK on indoor air pollution can be categorised in an easy-to-use database that will provide all the mandatory and complementary information about IAQ in the UK. The proposed approach is to categorize the available

data into a range of concentrations of indoor air pollutants according to macro- and micro-environments, emission sources and activities. This approach would lead to the development of an inventory of indoor air pollutants along with the necessary tools to cater the needs of various stakeholders such as policy-makers, architects, developers and a cross-disciplinary community of IAQ researchers. These tools will help tackling indoor air pollution with holistic and transdisciplinary approaches in the future, which is crucial for achieving net-zero goals in indoor spaces.

Existing gaps in the measurements can be filled initially by using measurements from other countries such as the US and the EU and can be updated with new measurements from the UK as they become available. The concentrations can be converted to emission rates using chemical mass balance methods based on available ancillary data of dwelling size and ventilation rates. Emission rates of indoor air pollutants calculated based on activity-related measurements in the UK will represent an important input for the numerical modelling of indoor air simulations and determining the effectiveness of interventions. The development of an inventory of indoor air pollutants represents a step-change in the field of indoor air pollution research in the UK. In the long run, such an inventory can be combined with user-friendly visualization tools to provide a representation of indoor emissions and their sources for academic and non-academic audiences.

Data availability

No new data were generated during this study.

Author contributions

AM, ZN: investigation, formal analysis, methodology, visualization, and writing—original draft. AM, ZN, CP: investigation, methodology, and writing—review and editing. ZN, CP: review and editing. CP, ZN: funding acquisition, supervision, and writing—review and editing. ZN, CP: conceptualization, supervision, methodology, administration, resources, and writing—review and editing. All authors contributed to the article and approved the submitted version.

Conflicts of interest

There are no conflicts of interest to declare.

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