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InAPI (v1.0): an Excel-based Indoor Air Pollution Inventory tool to visualise activity-based indoor concentrations of pollutants and their emission rates for the UK.

Andrea Mazzeo[1,3], Christian Pfrang[1], Zaheer Ahmad Nasir[2*]

1. University of Birmingham - School of Geography, Earth and Environmental Sciences, Edgbaston, B15 2TT, UK

2. Cranfield University, - Faculty of Engineering and Applied Sciences, Cranfield Environment Centre, College Road, Cranfield MK43 0AL, UK

3. (now at) Lancaster University - Lancaster Environmental Centre, LA14YQ, UK

*Corresponding author

Zaheer Ahmad Nasir

z.a.nasar@cranfield.ac.uk

Abstract: Indoor air quality (IAQ) has become a critical focus of research due to the substantial amount of time people spend indoors (approximately 80–90% of their lives), where a significant proportion of air pollution exposure occurs. However, understanding how time and activity dependent sources, as well as built environment characteristics, influence pollutant emissions and distributions remains very limited. Addressing these challenges, *InAPI* — an Excel-based *I*ndoor *A*ir *P*ollution *I*nventory tool — has been developed using data synthesised from a comprehensive review of UK indoor air pollution research. For the development of the InAPI tool, we have categorised existing literature by pollutant types, indoor environments, and activities, identifying significant knowledge gaps and offering an open-access database of typical pollutant concentrations and emission rates. InAPI leverages this database, which includes estimates of emissions from multiple sources based on chemical mass balance methods, to enable users to visualise indoor pollutant levels and emission characteristics across the varied UK indoor settings. Despite the fragmented methodologies in historical IAQ research and the underrepresentation of key sources, pollutants, and environment-specific characteristics (in particular ventilation and occupant behaviour), InAPI consolidates this evidence into a practical and easy-to-use tool. This tool facilitates standardisation of IAQ measurement protocols and the creation of activity-based indoor emission inventories, bridging critical research gaps. By providing a robust platform for understanding indoor air pollutant dynamics, InAPI represents a significant step forward in advancing IAQ research in the UK and beyond given the transferability of the approach, supporting efforts to mitigate indoor air pollution and inform policy initiatives nationally and globally.

1. Introduction

Indoor air quality (IAQ) is a critical determinant of public health and well-being, as individuals spend approximately 80–90% of their lives indoors and responsible for around 3.2 million deaths globally in 2020 (Klepeis et al., 2001; Lewis et al., 2023; WHO, 2019). Indoor environments, including homes, schools, offices, and public spaces, harbour a diverse mix of pollutants from sources such as building materials, furniture, consumer products, heating systems, and occupant's activities (Hulin et al., 2012; Weschler & Carslaw, 2018). These pollutants include volatile organic compounds (VOCs), particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2), and biological agents, which can accumulate indoors, often exceeding outdoor concentrations (Harrison, 2020; Harrison & Hester, 2019). As a result, IAQ is a significant contributor to overall air pollution exposure, particularly for vulnerable populations such as children, the elderly, and those with pre-existing health conditions (Maung et al., 2022; WHO, 2010).

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Understanding the dynamics of indoor air pollution is essential to elucidate their impact on health and develop effective mitigation strategies. However, the field faces several challenges, including the lack of comprehensive emissions inventories, inconsistent measurement methodologies, and insufficient consideration of time- and activity-dependent variations in pollutant levels (Shrubsole et al., 2012). The exchange of pollutants between indoor and outdoor environments—the indoor–outdoor continuum—further complicates the picture, particularly as ventilation strategies evolve in response to climate change and energy efficiency goals (Dimitroulopoulou et al., 2017). Despite decades of research, these gaps highlight the urgent need for tools that can synthesise data on broad range of indoor air pollutants, the contribution of multiple and time-dependent sources and activities to air pollutant emissions, model pollutant behaviour, and inform evidence-based IAQ management.

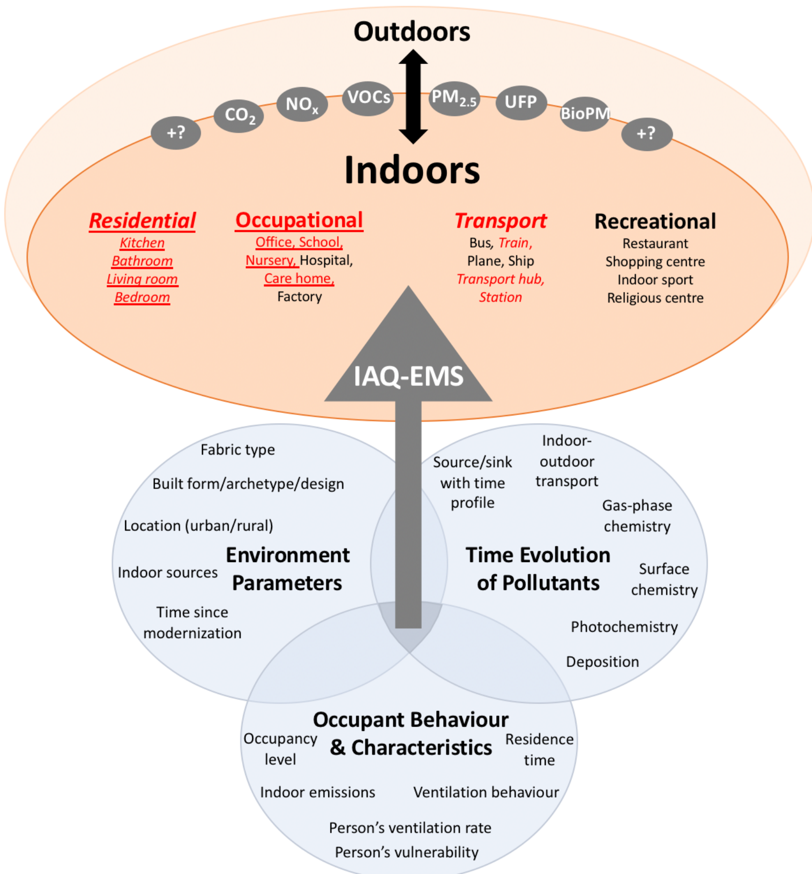

Figure 1: Conceptual framework for the "Indoor Air Quality Emissions & Modelling System (IAQ-EMS)" project. Indoor spaces in red font are the focus of this project with the underlined spaces identified as measurement locations.

The project "Indoor Air Quality Emissions and Modelling System (IAQ-EMS)", funded by the Met Office and the UK Research & Innovation (UKRI) Strategic Priorities Fund (SPF)'s Clean Air programme, addresses these challenges by integrating advanced modelling and measurement approaches (see the conceptual framework of IAQ-EMS in Figure 1). This project is organised into five interconnected work packages (WPs), including the development of a pollutant inventory tool,

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a combined chemistry and large-eddy simulation model for high temporal and spatial resolution indoor air dispersion, and a flexible multi-box model for broader applicability at modest computational cost. These tools focus on key issues such as intra-room mixing, room-to-room pollutant exchange, and interactions with outdoor air, enabling a more nuanced understanding of indoor air pollution dynamics. The tool and model developments are underpinned by targeted measurement campaigns designed to collect high-quality pollutant data by deploying reference instruments across representative UK indoor environments.

A key part of the IAQ-EMS framework is the development of a comprehensive inventory database of indoor air pollutants based on field measurements and literature review. This work categorises pollutants, environments, and activities into a structured database, forming the foundation for the InAPI tool. InAPI consolidates data on pollutant concentrations, emission sources, occupant behaviours, and environmental parameters, enabling users to explore indoor pollution levels across diverse settings. By leveraging chemical mass balance methods (see Section 2.2), the tool quantifies key emission sources using measurement-based evidence. Furthermore, InAPI connects these findings to relevant literature, making it an accessible resource for researchers, policymakers, and model developers.

The overarching goal of InAPI is to provide a comprehensive and user-friendly platform for understanding the state of indoor air pollution in the UK. It highlights average pollutant concentrations in both private and public spaces, identifies critical emission sources, and supports the development of standardised approaches for IAQ measurement and modelling. By addressing knowledge gaps and synthesising existing evidence, InAPI advances IAQ research, paving the way for improved indoor air pollution management and policy. This innovative tool offers valuable insights for addressing IAQ challenges in the UK and beyond.

2. Methodological approach

2.1 Indoor measurements in the UK

InAPI is excel based tool based on the first indoor air pollution (concentrations and emissions) inventory created for the UK (Mazzeo et al., 2023) . InAPI utilizes data from the indoor air pollution database to illustrate activity-specific concentrations and emission rates of indoor air pollutants. The database has been selectively organized to reflect pollution levels across four primary built environment types: residential, occupational, recreational, and transportation settings. Within each of these categories, the data is further broken down by micro-environments, specific activities, and, where applicable, types of fuel used (refer to Figure 2).

UK indoor air pollutants measurements cover a vast range of contaminants. Gaseous pollutants (NO, NO_2, CO, CO_2, O_3), aerosols (particulate matter of different sizes: PM_{10}, $PM_{2.5}$, $PM_{1.0}$ and ultrafine particles, UFPs), biological aerosols (bacteria and fungi) and around 40 different individual volatile organic compounds (VOCs). Scientific literature focused on UK focused on indoor measurements covers a long time range but provides highly sparse and broadly variable data amount and quality.

Information relating to the best available UK indoor air pollution research start in 1996 and the most recent literature included was from 2022. The period between the 1996 and 2000 has been characterised by a small number of research articles published for the UK (7 in total) divided between the different categories, while the period between 2000 and 2010 has seen a first rapid growth in indoor air investigations with a higher number of papers regarding field measurements in indoor domestic environments and a smaller increase in modelling research articles. Finally, the

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last decade between 2010 and 2022 has seen an additional increase in number of papers across all the fields. The volume of publications has grown more than threefold in relationship to modelling work, around threefold in domestic and non-domestic environments and less than doubled in multi-environments.

UK domestic environments have been monitored in 52% of the studies, reporting averaged concentrations distributed over monthly, seasonal, and even annual periods. The remaining 48% of the papers report data accounting for the time duration of particular activities and/or the distribution of the concentrations on a total time of 24 hours, often with 10-minute time steps. In UK non-domestic environments, the reported field measurements are distributed over long time periods for 72% of the studies vs. 28% of the works that relate to measurements of specific activities or on short time frames (within 24 hours). The reason for this difference compared to the previous category can be related to the different time periods spent in these two types of environments and to the quantity and quality of emission sources acting in the two environments. In the first case, few emission sources, and different environments can contribute to the average measured concentrations of a particular air pollutant. In the second case, the office/school hours are shorter and the variety and quantity of emission sources are lower. Finally, the multi-environments time frame is always related to activity time or short averages (within 24 hours). The reason for this is that these papers are focused on the comparative behaviours of similar chemical species in different conditions.

2.1.1 Sampling methods

Various measurement techniques described in field sampling research articles have been categorized according to the type of pollutant. For this analysis, the techniques have been broadly classified into four macro-categories: active sampling (e.g., air pumps, canisters, impactors), passive sampling (e.g., sorbent tubes, diffusive filters), gravimetric methods (e.g., particle filters), and optical methods (e.g., optical counters, sensors, chemiluminescence, UV, and infrared instruments).

Different pollutants and analysis techniques require the use of distinct sampling devices.. We highlight that the highest percentage of passive sampling methods is related to research that aimed to monitor a large number of dwellings and multiple pollutants simultaneously. The purpose of these works was essentially the analysis of average concentrations of particular pollutants focused on quantification of exposure levels for which the low temporal resolution of passive samplers was sufficient.

Other articles that have reported the monitoring of few air pollutants simultaneously, but in a single environment, have often used optical methods both for gaseous pollutants and for aerosols. These samplers are easy to use and often active in sampling air, collecting data at high time frequencies with relatively low associated errors. Aerosols have been monitored principally using these devices even if in some cases gravimetric samplers were used to collect particles on filters. Some of these works have also used the filters for microscopy analysis. Finally, papers that used active sampling and in particular air pumps for VOC analysis and/or canister/impactors for aerosols are more oriented to specific analysis of source apportionment relating to a particular activity, or, in the case of aerosols, particle size distribution.

2.1.2 Representative environments

The observations of indoor species and related activities were divided into four main groups: Residential, Occupational, Recreational and Transport. Residential provides the most detailed

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information relating to the type of activity and the type of pollutant. Activities associated with cooking are divided according to the type of fuel used for cooking (e.g., electric cooking or gas cooking) and in some case the specific cooking methods (e.g., boiling, frying potatoes, baking etc.). The second most thoroughly documented activity within Residential pertains to heating, involving central heating systems, and different independent heating fuels such as wood, coal, peat, and portable electric heaters. Finally, other activities sampled for the residential environment are relating to smoking and use of cleaning products and extractor fans in kitchens.

Sampling relating to transport environments covers different types of transport vehicles, accounting for private cars and taxis, trains, buses and the London Underground. Measurements were taken during sample journeys and were limited to the study of aerosols (PM_{10}, $PM_{2.5}$) and in the case of trains also included $PM_{1.0}$.

A wider class of pollutants has been monitored in the occupational environments including observations in private and public offices, hospitals, and different schools in the UK.

Information relating to volumes/areas of the sampling sites is provided in the InAPI tool together with the ventilation rates when the information is provided in the articles referenced.

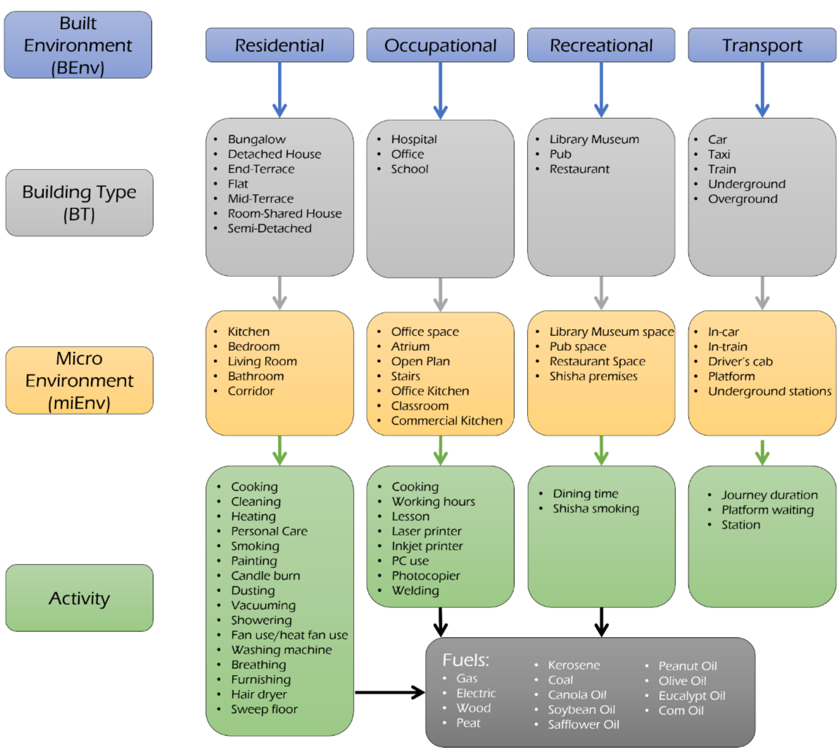

Figure 2: Macro and micro categories of division of data in the UK indoor pollution database reflected in the presented tool. Highlighted in blue are the four largest areas of division of the data (namely Built Environment, BEnv). In grey and yellow, the first (Building Type, BT) and second (Micro Environment, miEnv) levels of subdivision of the environments across the four Built Environments. In green we highlight the individual activity types for which

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UK measurements are available and which are visualisable in InAPI tool. For some of these activities information about the fuel type is also provided (see dark grey box).

2.2 Indoor emission rates by activity

Estimating the concentration of a pollutant in an indoor environment is influenced by various factors. It requires information about the location, the temporal variations of the pollutant's sources and sinks, and the different factors that affect airflow and turbulence, which in turn impact how the pollutant disperses within the indoor space. Complex mathematical equations can be used to analyse dispersion characteristics and chemical reactions occurring indoors. However, such analyses often have limitations due to their complexities and high computational demands. This makes it challenging to explore sensitivities to a wide range of input parameters, and the results can be difficult to interpret. A simplified method that is widely used and easy to apply in different scenarios is the box or zonal model (Arata et al., 2021; Morawska et al., 2001; Plaisance et al., 2017; Watson et al., 2001). This model is based on the principle of mass conservation and assumes that the pollutant is well mixed within each room. This assumption is valid if the time required for mixing in the room is relatively short compared to the timescales of fluctuations in indoor source emission rates, sinks, and air exchange. The formula for the calculation of the indoor concentration levels can be written as (Chen et al., 2000; Koutrakis et al., 1992):

$$\frac{dC_i}{dt} = P\alpha C_{out} + \frac{Q_s}{V} - (\alpha + k)C_{in} \qquad \text{Eq.1}$$

where C_{in} and C_{out} are the indoor and outdoor concentrations, respectively, P is the penetration coefficient, α is the air exchange rate, k is the deposition rate, t is the time and V is the efficient volume of the sampling environment.

We employed this equation as basis to derive the average emission rate ($\overline{Q_s}$) with a simplified equation (Eq.3) by using average values instead of functions and also introducing some assumption: the penetration coefficient (P) is commonly assumed to be close to 1 (Wallace, 1996) and the air exchange rate (α) has been taken from the individual original research articles (when provided by the authors) or calculated from the following equation (Eq. 2) in absence of data:

$$\alpha = \frac{1}{t}\ln\frac{C_t}{C_0} \qquad \text{Eq.2}$$

where C_t and C_0 are the indoor concentrations at time t and 0, respectively (Nantka, 1990).

Additional assumptions made in the calculations consider that when no indoor source is present, the indoor concentrations can be approximated by the outdoor concentrations (Morawska et al., 2001) and that therefore the initial indoor concentration ($C_{\mathrm{in(0)}}$) can be used to replace missing outdoor concentrations. In the light of this, the determination of the average emission rates follows Eq. 3:

$$\overline{Q_s} = V \times \left[\frac{C_{in(t)} - C_{in(0)}}{\Delta T} + \left(\overline{\alpha + k}\right) \times \overline{C_{in}} - \alpha \times C_{in(0)}\right] \qquad \text{Eq. 3}$$

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where $C_{in(t)}$ and $C_{in(0)}$ are the peak and initial concentrations during an activity, α is the air exchange rate, $\left(\overline{\alpha + k}\right)$ is the average removal rate and ΔT the time between the initial and the peak concentrations (He, 2004).

Information about the volume of the sampling environment was taken from the original information provided in each article. When this information was missing, average sampling volumes were taken from the English Housing Survey 2019 – 20 (Ministry of housing, 2018). When the original articles did not specify the volume of the environment where measurements were conducted, the InAPI tool expresses emission rates using three reference values—minimum, mean, and maximum volume. In such cases, emissions are estimated based on a volume range associated with various dwelling types. The reference volume ranges (min, mean, max) used include: end-terrace houses (64 - 172 - 1038 m^3), mid-terrace houses (53 - 162 - 703 m^3), semi-detached homes (68 - 185 - 1019 m^3), detached houses (84 - 305 - 2033 m^3), flats (29 - 130 - 606 m^3), and bungalows (43 - 154 - 618 m^3).

Finally, emissions estimated through chemical mass balance (hereafter referred to as CMB) calculations were compared with emission rates reported in UK-based literature, relevant subsectors of the National Atmospheric Emissions Inventory(NAEI, 2021) and supplemented with data from countries with similar profiles to the UK—specifically the United States and Australia (hereafter referred to as "Lit").

2.3 Strength and limitations of the InAPI tool

The information collected in the inventory for indoor air pollution has been chosen according to a literature review of all the research published on the topic of indoor air pollution in the UK. In the first instance, the objective of the work was to give a wide insight into the current level of indoor air pollution research conducted in the UK and representative of human activities. In light of this, all experimental measurements taken place in the UK were collected. These papers covered a long time interval (between 1996 and 2022) and accounted for different methodologies of sampling, instrumentation, time/duration of sampling and experimental conditions. All the studies selected were peer-reviewed journal articles.

The first group of data was filtered to take into account only measurement that took place during particular activities connected with the four Built Environments. This sub-group of literature was catalogued reporting all the mandatory information necessary for the conversion of activity-based concentrations into emissions.

The methodology applied and the use of the chemical mass balance has both strengths and weaknesses. While its simplicity and ease of use make it an effective tool for estimating emission rates of aerosol and gas species across various activities, it does have limitations. The method assumes uniform pollutant concentrations within the space and a constant air exchange rate throughout the activity. Additionally, it neglects processes such as condensation and coagulation and does not account for competing processes that can affect reactive species.

Furthermore, calculating emissions involves uncertainties linked to several parameters that are not always reported during indoor measurements. These parameters include indoor environmental conditions (such as temperature and relative humidity), a lack of information on outdoor concentrations, the exact positioning of the sampler within the building, and human activities and behaviours. Despite these challenges, the emission rates calculated using the InAPI tool provide average emissions related to selected sources, often utilizing air exchange rates and volumes derived directly from measurement sites.

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3. Case Studies

To demonstrate the potential use of the InAPI tool, two case studies will be presented. The first focuses on the visualisation of NO_2 from heating activity in residential environments, while the second compares HCHO emissions across different environments.

3.1 NO_2 from heating activities in residential environments

In the visualization section for indoor measurements, all filters were reset to allow for the selection of all possible variables. In the pollutants section, NO_2 is selected and filtered by Built Environment "RESIDENTIAL". The resultant selection allows the user to visualize the bar chart showcasing NO_2 indoor measurements from heating activities using various fuels and from all available residential micro-environments (e.g., living room, bedroom, kitchen) (Figure 3). The concentrations are reported in the original units at this stage to reflect the original conditions of sampling.

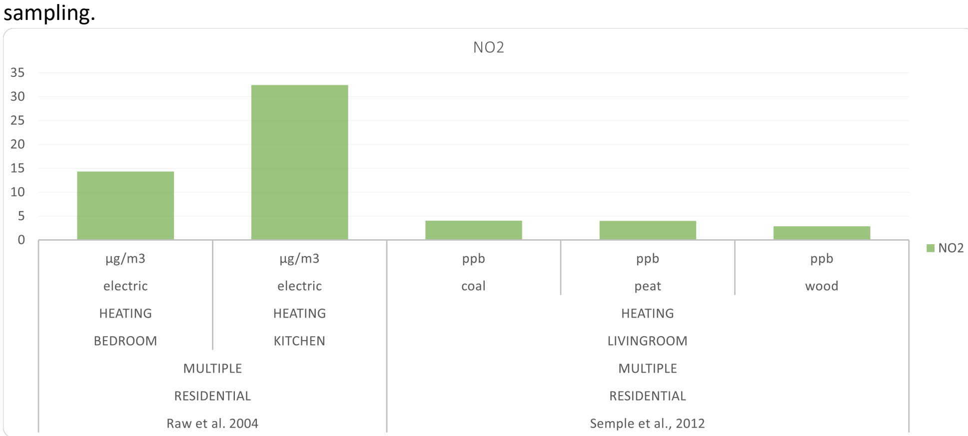

Figure 3: Bar chart showing the indoor measurements of NO_2 from heating activities in residential environments in the UK according to literature.

By making the same filtered selection in the visualization area of the emissions section, emission rates calculated using the chemical mass balance can be visualized in terms of emission rates in mg/h (Figure 4).

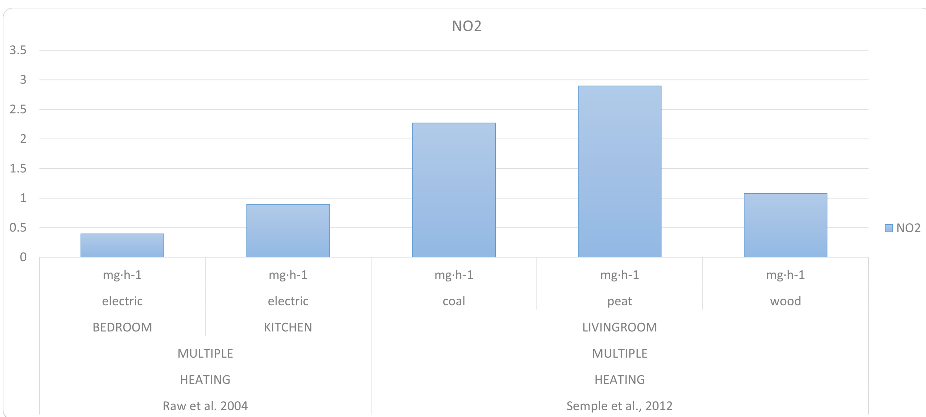

Figure 4: Bar chart showing the indoor emissions of NO2 from heating activities in residential environments in the UK according to calculations made using the chemical mass balance method.

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The values of NO_2 emissions visualized in this manner are limited to what is available from literature for the UK at the time of creating the Indoor Air Pollution Inventory. This information can be compared with emission rates obtained from other literature sources outside the UK. Section B of the emissions visualization allows for a similar selection of filters to visualize emissions of NO_2 from heating activities (Figure 5).

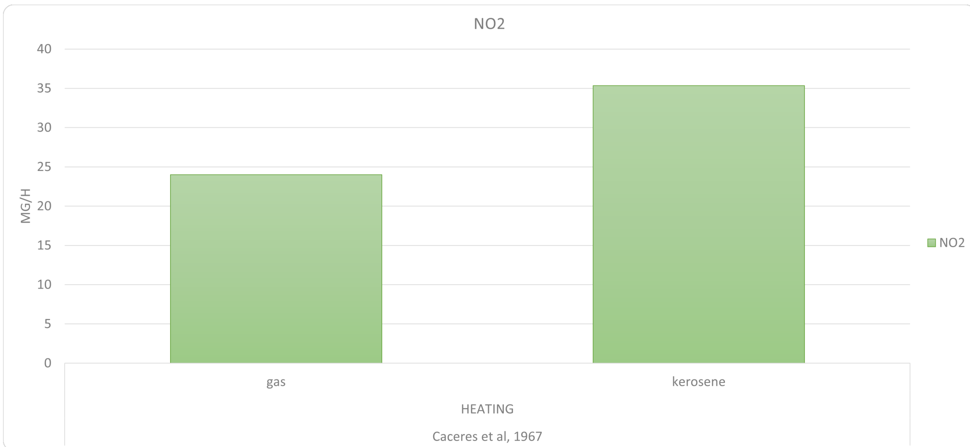

Figure 5: Bar chart showing the available information on emissions of NO_2 from heating activities in residential environments found through literary review outside the UK.

The totals obtained from the UK and from outside the UK differ. The former ranges from 0.4 to 3.0 mg/h, while the latter ranges from 24 to 35 mg/h. The discrepancy in the emissions can be attributed to the different types of fuel used and the different publication dates of the literature articles employed for the calculations, with the literature for the UK being more recent.

The information can be presented in more detail using the area BEnv. Comparisons. Here, selecting the visualization of NO_2 from cooking in multiple building types and kitchen micro-environments allows for the visualization of different cooking micro-activities and their individual contributions to the total (Figure 6). To gain a more detailed view of the high levels of emissions from literature outside the UK, the BEnv. Comparison area of the tool can be utilized.

In the Residential section, filtering the data to visualize heating activities for NO_2 enables more detailed information about the individual micro-activities contributing to the elevated levels of NO_2. The comparison reveals that the highest levels of NO_2 are attributed to town gas stove emissions, which are around 70 mg/h (Cáceres et al., 1967).

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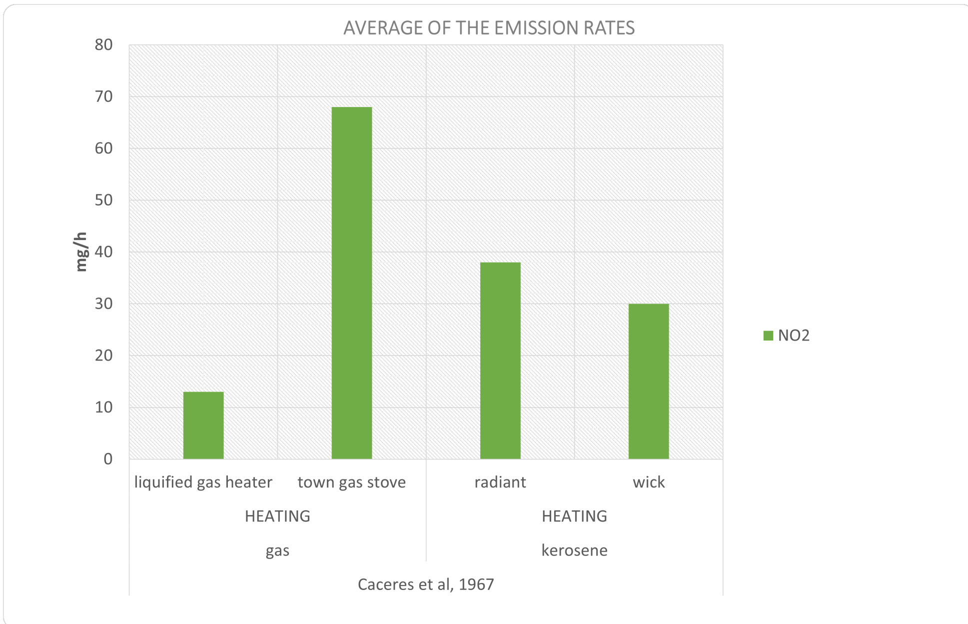

Figure 6: Bar chart showing the micro-activities of heating in residential environments and the relative emissions of NO2 calculated from indoor measurements conducted outside the UK and reported in literature.

Finally, a comparison of the magnitude of the emissions of NO2 from heating activities with other activities is made using the Residential Focus area of the InAPI tool. Here, in section A., selecting NO2 allows for calculating the percentage of emissions of this species among all available activities. The magnitude of NO2 is almost evenly divided between cooking (40.1%) and heating (59.9%) activities. .

3.2 HCHO from emissions from different environments

In this second case study, the emissions of formaldehyde (HCHO) from cleaning activities are visualized for different types of built environments: residential and occupational. The "Benv. Comparison" area of the tool can be used for this purpose. In the Residential and Occupational sections, filters for HCHO and cleaning are applied. The tool will generate two bar charts with the available information from measurements from the UK converted into emissions rates using the chemical mass balance for Residential environments (Figure 7, a) and for Occupational environments (Figure 7, b), namely classrooms of schools.

The emissions calculated for HCHO are 9 mg/h for residential environments and between 3.7 and 3.9 mg/h for classrooms. The difference in emissions can be attributed to the varying sizes of the environments where cleaning activities occur, the different compositions of cleaning products used, and the distinct cleaning procedures employed in each environment.

Finally, Section B of the Residential Focus can help illustrate the contribution of HCHO to the total volatile organic compounds (VOCs) emissions from cleaning activities. By selecting "CLEANING" in Section B1, it is possible to quantify the impact of HCHO at 1.5% of the total VOC emissions from these activities. The majority of these emissions are attributed to chlorine-based compounds

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(26%), which are typical of bleaching processes, followed by monoterpenes (21%) and limonene (15%), commonly found in scented cleaning products.

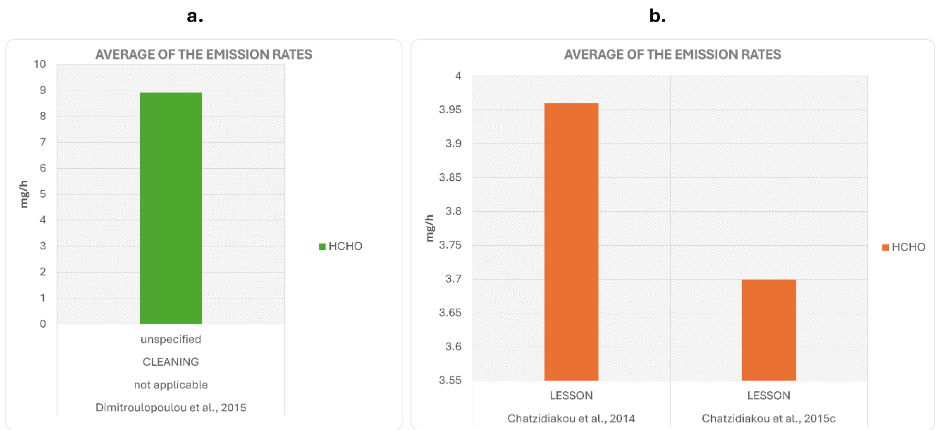

Figure 7: Bar chart from the Benv Comparison section of the InAPI tool showing the emissions of HCHO from cleaning activities in (a) residential and (b) occupational environments. Emissions are calculated using measurements from the UK converted using the chemical mass balance.

4. Conclusions and future developments

The InAPI tool represents a significant advancement in indoor air quality (IAQ) research by consolidating UK-specific data on pollutant concentrations, emissions, and related activities. Developed as part of the IAQ-EMS project, it integrates field measurements and literature to create a flexible database, categorising pollutants, environments, and activities. By applying chemical mass balance methods, the InAPI tool provides the measurement-based quantification of emission sources, offering valuable insights for academics, policymakers, and model developers. This tool facilitates evidence-based strategies for IAQ management and research, helping to highlight existing research and knowledge gaps.

Future work will focus on refining the InAPI tool by developing detailed emission factors for indoor air pollutants, categorised by the specific activity and environment. These emission factors will be critical for advancing numerical models that simulate pollutant behaviour in indoor settings. Accurate emission factors, derived from real-world data, will enable these models to predict the dispersion of pollutants, intra-room mixing, and room-to-room exchange under various conditions, such as changes in ventilation, occupant behaviour, and pollutant sources (Dimitroulopoulou et al., 2017). Additionally, the development of activity-specific and environment-specific emission factors will support the design of more personalised IAQ management strategies, helping to identify critical sources of pollution in different settings, across residential spaces, offices and schools.

To enhance the predictive capabilities of the InAPI tool, future efforts would focus on validating emission factors and modeling predictions through targeted measurement campaigns in various indoor environments. This approach will help capture a wider range of indoor air quality (IAQ)

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scenarios and refine emission source data, thereby improving the tool's applicability across a diverse array of indoor settings. Additionally, field studies are urgently needed to examine how strategies aimed at maximizing energy efficiency in built environments impact indoor pollution levels and their variability over time.

Future integration of the InAPI tool with global IAQ initiatives and datasets would ensure alignment with international best practices and contribute to the development of standardised indoor air quality models. Collaboration with international experts and researchers would support the validation and refinement of emission factors, while cross-border efforts will enable broader application of the tool, providing insights into IAQ challenges across different regions. These advancements will offer researchers, policymakers, and model developers an essential resource for tackling indoor air pollution, ultimately leading to healthier indoor environments and more effective policy interventions (Shrubsole et al., 2012; Weschler, 2009).

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: conceptualisation, supervision, methodology, administration, resources, and writing—review and editing. All authors contributed to the article and approved the submitted version.

Data availability statement

The InAPI tool version 1.0 is available on Zenodo Repository (Mazzeo et al., 2025) together with the underlying indoor emissions inventory database (Mazzeo et al., 2023)).

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Conflicts of interest

There are no conflicts of interest to declare.

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