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The INGENIOUS project: towards understanding air pollution in homes†

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This paper provides an overview of the INGENIOUS (UnderstandING the sourcEs, traNsformations and fates of IndOor air pollUtantS) project, aiming to better understand air pollution in homes. Although our homes are the microenvironment in which we spend most of our time, we know relatively little about the sources, transformation processes and fates of indoor air pollutants, or our exposure to them. INGENIOUS aims to address this knowledge gap by delivering: an indoor emissions inventory for UK homes; comprehensive air pollutant measurements in 310 homes in Bradford using a combination of low cost-sensors and more advanced air quality instrumentation; an analysis of the impact of indoor air pollution on outdoor air quality and *vice versa* using mobile measurements; insight into future indoor air quality using detailed air pollution models; identification of indoor air pollutants that warrant further toxicological study; and better understanding of the barriers and facilitators for behaviour that drives improved indoor air quality. Median daily $PM_{2.5}$ and CO_2 concentrations varied from 7.8 μg m^{-3} and 666 ppm in the summer, to 16.4 μg m^{-3} and 857 ppm in the winter respectively in our sampled homes. Peak daily $PM_{2.5}$ concentrations above 150 μg m^{-3} were frequently observed across all seasons, and were driven by cooking. Cooking activities also generated high concentrations of volatile organic compounds during emissions measurements, such as harmful aldehydes (up to ~50 ppb), and alcohols (up to ~600 ppb) from a chicken stir-fry. Our sampled homes displayed a wide variation in indoor pollutant concentrations, with a strong link to behaviour, including frequency and type of cooking activities, and use of ventilation.

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Environmental significance

Net zero ambitions are leading to measures to reduce greenhouse gas emissions, including through reducing energy loss from buildings by making them more airtight. However, if the main sources of air pollution in a building are indoors, such measures increase the air pollutant exposure of the building occupants. The INGENIOUS project has investigated air pollution in 310 occupied homes in the UK, exploring links between air pollutant concentrations, occupant behaviour, and health. Our findings show that cooking leads to the highest particulate matter concentrations and that carbon dioxide concentrations are often elevated in bedrooms at nighttime, owing to poor ventilation. Indoor air quality is complex, and air pollutant sources and fates need to be better understood to design appropriate mitigation.

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Introduction

In developed countries such as the UK, we spend 90% of our time indoors,[1] with our homes being the individual microenvironments where we spend the most time (about two thirds). Most of our exposure to air pollutants happens indoors, even if these pollutants are generated outdoors. Outdoor air pollutants can enter buildings through doors, windows and cracks in the building fabric. Such pollutants depend on the building location and typically comprise ozone (O_3), volatile organic compounds (VOCs), nitrogen oxides (NO_x) and particulate matter (PM). The latter two pollutants can be a particular issue for buildings adjacent to busy roads, and hence subject to ingress from transport emissions.

However, there are also numerous sources of air pollutants indoors, including emissions from building materials, furnishing and decorative materials, and occupant activities. Emissions from building, decorative and furnishing materials are highest when they are new and are dominated by VOCs.[2–5] Occupant emissions can be further divided into passive and active emissions. Passive emissions derive from skin and breath and include squalene, fatty acids, carbon dioxide (CO_2), acetone, nitric oxide, ammonia (NH_3) and isoprene.[6–8] Active emissions follow activities such as cooking, cleaning, and air freshener use, and include VOCs, nitrous acid, NO_x, NH_3, chlorinated compounds and PM.[7,9] Pollutants from both indoor and outdoor sources combine in buildings to form a complex chemical mixture, about which relatively little is known.[10] In fact, a recent review identified ~900 unique chemical species measured in indoor air, from these combined sources.[11]

Regardless of whether air pollutants are formed indoors or outdoors, there are numerous large-scale epidemiological studies that provide evidence for a causal relationship between exposure to air pollution and increased rates of mortality and morbidity.[12] The World Health Organisation (WHO) recently stated that improving air quality would reduce the global incidence and impact of diseases such as lung cancer, stroke and asthma, with indoor and outdoor air pollution identified as one of the greatest risks to global human health.[13] Most of this evidence is derived from studies that have primarily used data from fixed outdoor air pollution monitoring networks. However, this oversimplification ignores indoor air exposure, resulting in inadequate exposure metrics, and introducing errors in health models and consequently large uncertainties surrounding human exposure to indoor air pollution.

There are currently few data with which to quantify indoor air pollutant emissions, building-to-building variability, chemical speciation of indoor air pollutants, ingress of outdoor air pollution indoors, or of indoor-generated air pollutants outdoors. There is even less data exploring the social, economic or lifestyle factors that can lead to elevated indoor air pollutant exposures. Less affluent homes likely experience worse indoor air quality (IAQ) than more affluent households, with exposure to tobacco smoke and higher outdoor air pollutant concentrations also more common for lower socio-economic groups.[14] However, the reality is likely to be more nuanced than a simple divide by social class. Lower quality housing may be less airtight than newer, more expensive homes allowing indoor emissions to escape more easily, whilst large, expensive town houses converted to flats can be badly ventilated and suffer from higher air pollutant concentrations indoors following poor retrofitting practices.[15]

Perhaps more importantly, differences in cooking practices, ventilation behaviour, internal building materials and the use of solvent containing products indoors will also be subject to wide variations across populations and hence have differential effects on IAQ and subsequent air pollutant exposure. Differences in individual behaviour have been shown to lead to large variations in IAQ, even for identical houses (with identical building materials, design and outdoor air quality), often driven by the frequency and diversity of household product use.[16] In fact, one generalisation that can be made about the status of IAQ in homes is that it is hard to generalise.

Consequently, a fundamental understanding of how air pollution is caused, transformed and distributed in homes is required, otherwise behavioural, technical or policy interventions to reduce future air pollution exposure, or to improve energy efficiency may have little impact, or even be counterproductive. A good example is energy efficiency measures that aim to make buildings more airtight and reduce energy usage. However, where sources of air pollutants are predominantly indoors, reducing ventilation rates may increase overall exposure to air pollution, and to any potentially harmful effects of the resulting pollutant mixture. Interventions also need to be based on a thorough understanding of behaviour in buildings. For instance, extractor fans in kitchens and bathrooms are often under-used,[17] because they are noisy, inefficient, or residents forget to use them. Whilst an intervention introduced purely on scientific terms may be easy to understand, it is unlikely to be successful unless it also considers human behaviour.

These factors combine to create a complex multidimensional problem, where indoor and outdoor air pollution sources, pollutant transformation processes, and building design, management and use, are the driving physical and chemical factors for IAQ, but modified by human behaviour. The INGENIOUS (UnderstandING the sourcEs, traNsformations and fates of IndOor air pollUtantS) project is investigating these controlling factors and their interdependencies, through undertaking the first comprehensive mapping exercise of the main sources, transformations and fate of air pollutants in typical, occupied, UK residences. It is also aiming to identify inequalities in exposure and the consequent impacts on health amongst diverse populations, as well as to identify the physical, social and behavioural factors that control pollutant distribution in people's homes. To achieve these aims, we have assembled a multi-disciplinary team combining expertise in air pollution monitoring and modelling, health science, behavioural science, citizen science, and social policy.

The INGENIOUS project is addressing these issues through seven specific objectives, each of which are addressed through a work package (WP). These objectives are to:

• Characterise indoor emission sources (*e.g.* cooking, cleaning, air freshener use) in UK homes and to construct a consumption and activity-based bottom-up UK emissions inventory for indoor air (WP1).

• Investigate behavioural factors and building characteristics affecting IAQ in UK homes representative of a range of socio-economic classes, and to explore inequalities in exposure to air pollution and their immediate effects on respiratory and mental health (WP2).

• Undertake localised mobile emissions measurements in and around study homes and buildings with distinct emission profile sources (*e.g.* catering venues, beauty salons), to understand the impact of indoor sources on outdoor air quality and *vice versa* (WP3).

• Use detailed indoor chemical and aerosol microphysical models to provide insight into IAQ in support of the measurements in homes and to predict how these may change into the future (WP4).

• Identify potential health impacts arising from the different pollutant sources in homes (WP5).

• Identify the perceived physical, psychological and social barriers to behaviours that reduce production of and/or exposure to indoor air pollutants, and co-design (with beneficiaries and stakeholders) and evaluate behaviour change interventions to reduce pollutant exposure indoors (WP6).

• To provide evidence-based recommendations that are designed to reduce exposure to indoor air pollution, reduce inequalities in exposure and to translate into policy, practice, and clear and accessible guidance (WP7).

In short, INGENIOUS will provide comprehensive measurements of IAQ in real, occupied homes, coupled with information on building characteristics and occupant health (WP2), occupancy behaviour (WP2, WP6), alongside quantification of emission rates of indoor pollutants from a range of sources (WP1, WP3). Current and future IAQ will be probed (WP4), potentially harmful occupant activities identified (WP1, WP2, WP4, WP5), potential behavioural interventions tested (WP6) and policy recommendations identified (WP7). This paper provides an overview of the INGENIOUS project. It describes the methodology we have adopted and then provides some initial findings from the study.

Experimental

The 4 year INGENIOUS programme (2021–2025) builds on the extensive, long-standing longitudinal birth cohort study, 'Born in Bradford (BiB)',[18,19] which follows the health and wellbeing of over 12 500 families in Bradford, covering a range of social groups. BiB is a representative research-active cohort of families with children born in the city of Bradford, UK, between 2007 and 2011 (~60% of the eligible population at time of original recruitment). Fifty percent of mothers in the cohort are of South Asian origin and half of all BiB families are living within the fifth most deprived areas of England and Wales. At the time of original recruitment, all BiB parents were of working age, one-third of families lived in rented accommodation, one-third of mothers rated their financial situation as insecure, and one-third of households had more than 5 occupants. Routine primary health care records can be retrieved monthly for 99% of parents and children based on geocoded residential address, and education data (*e.g.* academic performance, free school meals) are available for 85% of the children enrolled in the BiB birth cohort study. By using the BiB cohort, we have been able to include multi-ethnic and deprived groups that are 'seldom heard' and under-researched in this area.

The work packages are now described in more detail in the following sections.

WP1

WP1 aims to provide the first UK indoor air pollutant emissions inventory, through a series of controlled laboratory experiments that quantify chemically-speciated indoor emission rates from key activities in the home (*e.g.* cooking, cleaning and use of homecare products such as air-fresheners). Although there are detailed inventories for outdoor sources such as the National Atmospheric Emissions Inventory, NAEI,[20] there is no equivalent for the indoor environment. At present, emissions from some indoor sources are included as a subset of the NAEI, *e.g.* solvent use, gas used for cooking, wood stove emissions *etc.*, but not all sources, and not in a comprehensive manner. For instance, although gas used for cooking is included, emissions from cooking food are not. This absence of understanding around indoor pollution sources makes it difficult to construct models of indoor exposure, to simulate the impact of policy inventions, or to explore the benefits, for example, of product reformulation. The activity- and consumption-based estimates of emissions from different occupant activities have been carried out based on well-controlled experiments in the laboratory through methodologies developed at the University of York (UoY) over recent years.[21,22] In short, carefully scripted and reproducible experiments focusing on different activities such as cooking, cleaning and air freshener use, were carried out in a range of controlled indoor chambers, whilst a suite of continuous, *in situ*, measurements were made.

The facilities comprise an emission chamber (Fig. 1a) stationed at the Wolfson Atmospheric Chemistry Laboratories (WACL), and a semi-realistic kitchen facility, DOMESTIC (Fig. 1b), both at the UoY. The DOMESTIC kitchen facility has been previously described in detail by Davies *et al.*[22] The emission chamber is a 2 m^3 (1 m × 1 m × 2 m) glovebox cubicle made of tempered glass (4 mm thickness) and anodized aluminium. The glass and edges of the chamber are sealed using an inert thermoplastic elastomer sealing pane that is suitable for testing VOC emissions at room temperature (Bosch Rexroth, Germany). A constant flow of ~50 L min^{-1} of ambient air enters the chamber using two high-capacity membrane pumps (Model 2563C-24 and Model 412722, Welch Ilmvac GmbH), ensuring a small positive pressure inside the chamber for a dynamic and turbulent flow of air and enhancing air mixing. The chamber temperature and relative humidity were maintained at 19.0 (±0.5) °C and 25 (±5)% respectively. Measured air change rates were 0.41 (±0.12) h^{-1} for the emission chamber and 0.73 (±0.30) h^{-1} for the kitchen facility.

Fig. 1 (a) The emission testing chamber (b) interior view of the DOMESTIC kitchen facility and cooking station.

Simulated cooking and cleaning experiments were conducted following in-house developed protocols based on the recommended manufacturer guidelines for product use and for general cooking recipes used commonly in UK households.[22–24] Realtime measurements of VOCs were conducted using a Selected Ion Flow Tube-Mass Spectrometer (SIFT-MS; Voice200 Ultra; Syft Technologies, New Zealand).[21,22,25,26] Offline samples of post-activity indoor air were also collected in 3 L SilcoCan air sampling steel canisters (Restek, USA) and analysed using a TD-GC-MS (TD: TT24-7 Series 2, Markes International; GC-MS: 6850/5975C Quadrupole, Agilent Technologies), for speciated information on VOCs such as monoterpenes. More details on the instrumentation (and their acronyms) can be found in Table S1 in the ESI.† Initial screening of the cleaning and home-scented products was performed using equilibrium headspace GC-ToF-MS, following the protocols described in Harding-Smith *et al.*[27] The GC-ToF-MS experiments informed the targeted analysis of selected masses on SIFT-MS in the ion-selective mode, during the scripted cleaning and home-scented product use in the emission testing chamber. The targeted analysis of VOCs during the cooking experiments was based on the initial screening of emissions in the full mass scans (m/z 17–400) and known VOC emissions from cooking reported previously.[22,28] A total of 41 speciated VOCs were measured in the cooking experiments, 34 VOCs in cleaning experiments, and 45 VOCs from other scented products used in homes.

WP2

WP2 aims to understand patterns of indoor air pollutant exposure, how these patterns are influenced by the physical characteristics of buildings and by occupant behaviours, how indoor AQ affects health, and to identify inequalities in exposure across the BiB cohort. To achieve this aim, we implemented the most comprehensive study of IAQ and its major controlling factors and impacts to date. We recruited families living in households from the Born in Bradford cohort. The selected households were stratified by ethnicity, housing tenure (private/mortgaged *vs.* rented), and the presence (or not) of an asthmatic child (see Table 1).

Whilst the ethnicity and housing tenure were broadly representative of the overall BiB cohort, we deliberately recruited families with asthmatic children to be half of the total sampled. Actual rates of asthma in the BiB cohort are closer to

Table 1 Characteristics of the 321 recruited homes from the BiB cohort

		Ethnicity		
		South Asian (49%)	White (British) (41%)	Other (10%)
Housing tenure	Private/mortgaged property (76%)	$n = 126$	$n = 94$	$n = 25$
	Rented property[a] (24%)	$n = 30$	$n = 38$	$n = 8$

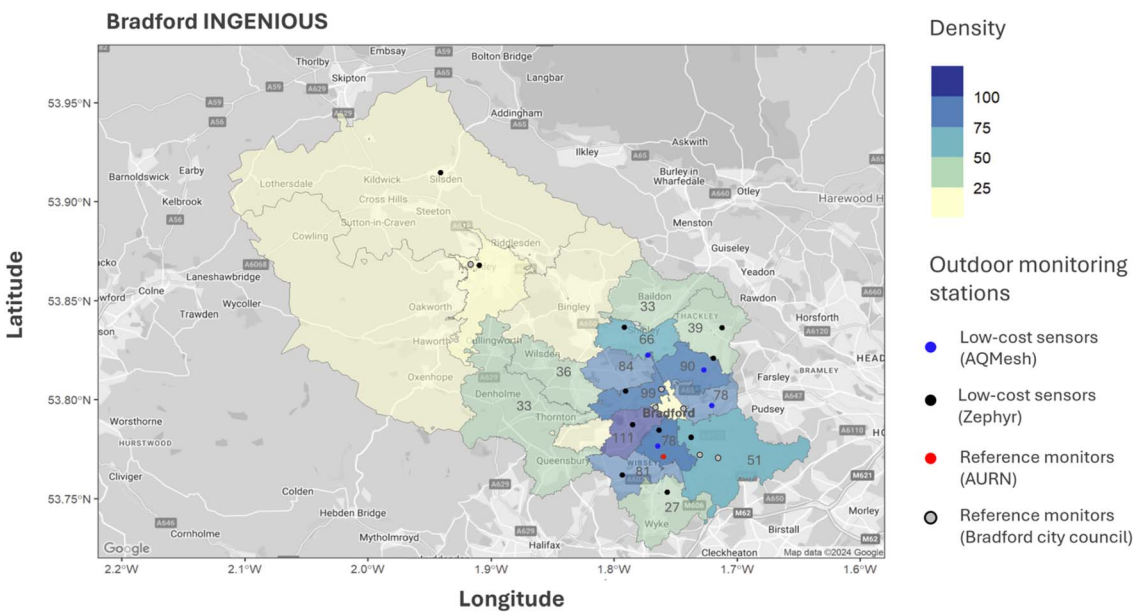
[a] Includes private rental and social housing.

10%.[29] Air quality was assessed in three rooms (kitchen, living space, bedroom) within each home for a two week period, with around 6 new homes recruited each week over the period from March 2023 to April 2024. We used a child's bedroom in our houses where possible, unless the occupants declined. More details around the recruitment process can be found in Ikeda *et al.*[23] To achieve a target sample size of 300, we initially recruited 321 households. Of those, 310 met our sensor analysis criteria, which were that each sampled home had a collection rate of over 50% per day, in each of the three rooms per household, and had at least 7 days' worth of data that could be used for analysis. The 310 homes were distributed in and around Bradford as shown in Fig. 2, which also shows reference monitors from Bradford City Council and the AURN.[30]

At the start of each sampling period, a researcher obtained informed consent from the householder, conducted a standardised semi-structured questionnaire on key housing features, and installed air quality monitoring equipment as described below. The information collected covered outdoor building characterisation (*i.e.* nearby noise and pollution sources), building age and construction type and quality, ventilation type and frequency of use, and characterisation of indoor emission sources.[23] Over the two week monitoring period, the participants were asked to fill in daily diaries to record health indicators focusing on respiratory and atopic symptoms and mood. They were also asked to record key behavioural patterns (*e.g.* the frequency and timing of cooking, cleaning, using personal care products and ventilation) on one weekday and one weekend day during the 2 week monitoring period. After two weeks, the researcher collected the air quality equipment and participants completed a survey based on standardised questionnaires to identify self-reported health for mothers,[31,32] frequency of behavioural patterns, and parent-reported health questionnaires for children[33,34] (in line with WP6).

Commercial low-cost sensors (LCS) (AirGradient) were used to measure carbon dioxide (CO_2) and PM mass concentrations, relative humidity (RH) and temperature (T) in the kitchen, living room, and a bedroom in all sampled households for a 2 week period. The performance of similar sensors has been characterised comprehensively in several studies across diverse geographical settings/seasons,[35–37] in outdoor, indoor and commuting microenvironments. These devices are compact, almost silent, have low power demands and transmit data through Wi-Fi provided by the deployment team to a secure server for post-processing. Bespoke software automated the management and post-processing of the large volume of raw data collected with the sensors.[35,36,38] More information on the AirGradient sensors can be found in the ESI.† Note that long-term measurements were also collected in 10 of the homes, with a LCS installed in the living room for a year.

Indoor exposure to VOCs was assessed in a subsample of 124 households using a unique methodology, whereby air was sampled over 72 hours into a passivated, evacuated 6 L canister, then analysed at the UoY using GC-FID-QMS[39] (see Table S1 in ESI†). The sampling is effectively continuous, but biased towards the first 48 hours at an approximate linear rate, followed by a decreasing rate over the final 24 hours. This methodology provided an unprecedented level of VOC speciation, from simple chemicals such as ethane from natural gas, to monoterpenes from fragrance and cooking, ethanol mainly



Spatial distribution of INGENIOUS households by postcode district and locations of the outdoor monitoring stations of the outdoor sensor network

Fig. 2 The spatial distribution of the 310 INGENIOUS households by postcode district and locations of the outdoor monitoring stations. The density of household locations within each postcode district is indicated by the shading of that area (see legend on figure). Numbers are also included where there are more than 25 homes within a district. The outdoor monitoring stations consisted of a variety of low-cost sensors, as well as reference monitoring equipment used both as part of the Automatic Urban and Rural Network[30] and by Bradford City Council.

from solvent use, and chlorinated hydrocarbons likely arising from painting, decorating and bleach use. Typically, more than 100 VOCs were quantified over a very wide dynamic range, from sub-part per trillion to over two parts per million.

We also aimed to perform detailed $PM_{2.5}$ composition measurements in ~150 households, using MiniVol Portable Air Sampler (Airmetrics, USA), which have low power consumption, quiet operation and are usually suitable for indoor sampling. The sample flow rate (3 L min^{-1}) is low compared to typical outdoor PM samplers and so longer sampling times (typically 72 hours) were required to collect sufficient samples for analysis. Unfortunately, the microsamplers require continuous use of a pump, which was too big and/or noisy for some households. Consequently, we were only able to collect 112 samples.

Thirty-four of these samples were then analysed in WACL at the UoY. The measured composition was compared to both the emission profile fingerprints generated in WP1 and a library of secondary organic aerosol (SOA) tracer compounds to aid identification of species. GC × GC × ToFMS was used to analyse collected samples (see Table S1†). Calibration curves were created for 127 compounds based on their prevalence in indoor environments and their potential for toxicity. These calibration curves were used to quantify target compounds; data from the quantitative analysis was then used to predict health outcomes.

A FIGAERO-I^--CIMS and HR-AMS (see Table S1†) were used in WP2 to analyse filter samples collected in the other 78 households off-line at the University of Manchester. This filter sample analysis aimed to provide a better understanding of indoor $PM_{2.5}$ exposure patterns in the Bradford homes, both through providing chemical composition data, but also through investigating potential sources by retrieving discrete factors contributing to the composition profile, constrained to characteristic mass spectral fingerprints from sources characterised in the HIP-Tox (Hazard Identification Platform to Assess the Health Impacts from Indoor and Outdoor Air Pollutant Exposures, through Mechanistic Toxicology) consortium project.[40] For the households who hosted the additional VOC and PM sampling equipment, the equipment was delivered on day 10/11 of the 2 week sampling period and removed with the LCS on day 14. These households were also asked to complete one additional behavioural pattern diary over the period between days 10/11 and 14 and to also document the main meals cooked at home for those days.

Finally, to support the indoor measurements, outdoor measurements from meteorological stations and reference and LCS air pollution networks deployed around Bradford (see Fig. 2) were employed. These reference instruments and sensors reported *T*, RH, $PM_{2.5}$, PM_{10}, NO_2 (nitrogen dioxide), O_3 (ozone), wind speed and direction. Measurements of other gases, such as CO (carbon monoxide), NO (nitric oxide) and CO_2, were also available from some of these instruments.

WP3

WP3 aims to combine mobile and static VOC (and other pollutant) measurements with new approaches to data analysis, to identify and quantify the impact of different indoor air sources on outdoor air quality. Quantifying the impact that indoor emissions have on outdoor air quality is a challenge given the wide variety of pollutants involved, the complex processes responsible for dispersion of these emissions to the outdoor environment, and the potential for chemical processing. There are few outdoor measurements related to these often diffuse indoor sources, which makes it difficult to evaluate their significance, although recent work in the US has shown them to be potentially of major significance.[41]

Several types of outdoor measurement campaigns have been undertaken as part of INGENIOUS: (i) targeted measurements in proximity to known source types (ii) static measurements in suburban areas, and (iii) mobile measurements for source emission mapping. For (i), VOCs, NO_x, NO_2, O_3 and CO_2 measurements were made near distinct source types where volatile consumer product emissions are likely to be important, such as nail salons, hairdressers and dry cleaners. These measurements helped to establish the feasibility of detecting known VOC species at potential 'hotspot' locations. For (ii), measurements focused on emissions from domestic dwellings with minimal contribution from other sources (based on source information and local meteorology during sampling). The mobile measurements (iii) aimed to evaluate the spatial and temporal nature of indoor emissions sources over a wider urban area, to better understand the contribution from buildings relative to sources such as road traffic.

The mobile measurements were made over summer and winter to understand differences in emission sources and their chemical processing for different meteorological conditions and focused on two contrasting urban areas: York and Bradford. York was chosen for its convenience, to maximise the range of experiments and field campaigns that could be performed whilst reducing logistical issues. Mobile measurements in Bradford established baseline outdoor conditions to aid the interpretation of measurements made in WP2 and inform the modelling studies as part of WP4. Measurements were collected using the WACL Air Sampling Platform (WASP), an advanced mobile laboratory equipped with a SIFT-MS for the real-time detection of 32 VOCs every six seconds. The compounds were selected based upon their known abundance in ambient and indoor air as reported in previous studies.[25,42] Additional instruments measured NO_x, CO, O_3, methane, PM_1, $PM_{2.5}$, and PM_{10}. The campaign spanned February–March and June–September of 2023 and included sampling during different times of day: morning (10:00–12:00 h), afternoon (13:00–15:00 h), and evening (16:00–18:00 h), and both weekdays and weekends.

WP4

WP4 aims to explore the relative importance of indoor and outdoor environments for different indoor air pollutants and how this will change in the future, through the use of state-of-the-art models. INCHEM-Py[43,44] is an open-source detailed chemical box model based on the Master Chemical Mechanism (MCM).[45] The MCM considers the degradation of >140

atmospheric VOCs and has been modified in INCHEM-Py to include additional reactions that consider emissions from and deposition to indoor surfaces, indoor photolysis *via* attenuated outdoor light and artificial lighting indoors, exchange with outdoors, and gas-to-particle partitioning reactions for the oxidation of limonene, alpha- and beta-pinene.[46,47] The model (including previous versions) has been used to gain insight into indoor activities, such as cleaning using surface cleaners and air cleaning devices[48] and the impact of ozone and hydrogen peroxide interactions on indoor surfaces.[49,50]

The PyCHAM (CHemistry with Aerosol Microphysics in Python) model couples gas-phase chemistry with aerosol microphysics.[51,52] This open-source model was developed to simulate chamber experiments and is generally applicable to indoor and outdoor applications. Aerosol particles evolve in the model by multicomponent condensation and evaporation and by coagulation and losses to surfaces. Vapours interact with all particle size fractions and with indoor surfaces. A primary focus of recent work has been the inclusion of autoxidation mechanisms leading to the formation of Highly Oxygenated organic Molecules (HOM), necessary for the prediction of observed SOA mass from mixed VOCs.[53]

The two models have been primed with source emission profiles based on the measurements in WP1 and evaluated using the sensor data, household parameters and behavioural diaries collected in WP2. The models will analyse the complex chemical interactions between indoor air pollutants, as well as explore the transformation of emissions from activities in typical residences under a broader set of conditions. By varying the model parameters (*e.g.* ventilation rates, low emission materials/products), simulations can be used to demonstrate the efficacy of interventions, as well as to estimate the impact of potential future climates on our exposure to pollutants within our own homes. The models can also be used to probe how ventilation might impact on the balance of exposure to air pollution between indoors and outdoors for a range of conditions.

WP5

WP5 aims to quantify the health impacts of indoor air pollutant mixtures linked to different sources, both now and in the future. Robust toxicological data only exists for a relatively small subset of the components found indoors (such as formaldehyde and PM), which makes it challenging to fully understand the health impacts associated with complex mixtures of chemicals (*e.g.* from different sources). Building on the concentrations and emission rates measured and modelled as part of WPs1–4, the potential health impacts from indoor air mixtures associated with different activities (considering current and future indoor and outdoor AQ scenarios) will be assessed. We will focus on sources that make high contributions indoors and provide a ranking of air pollution hazard from these sources across the sampled houses, using the mechanistic toxicological approach developed within our sister consortium project, HIP-Tox.

The HIP-Tox project has developed a platform to rank the toxicological hazard associated with real pollutants from a range of sources. Using *in vitro*, animal *in vivo* and controlled human exposures to repeatable and well-defined pollutant challenges from woodsmoke, diesel exhaust, cooking emissions and secondary organic aerosol from ingredients of cleaning products, the study has enabled the ranking of these pollutant sources with respect to their impact on neurodegenerative disease. Biomarker analyses and epigenetic fingerprinting of human body fluids and transgenic murine tissue samples, along with measurements of appropriate endpoints from *in vitro* cellular models have been used alongside a full chemical characterisation of the pollutants to investigate the mechanistic pathways for the disease outcomes. A library of the mass spectrometric signatures of these sources has been expanded to include further source samples (for example from additional cooking recipes) and these are being used to constrain a factor analysis of the entire set of filter samples from the 78 BiB homes for which the same CIMS and HR-AMS instruments have been used. This will provide an estimate of the fractional contribution of the PM mass from each of the broad source categories, enabling the pollutants to be ranked in terms of their risk as determined in the HIP-Tox studies. Whilst this will not give a definitive and quantitative hazard estimate, it will provide the first attempt to evaluate and rank pollutant risk to health in real homes.

WP6

WP6 aims to examine the physical, psychological and social drivers, and barriers to behaviours that impact on exposure to air pollutants indoors and to design and evaluate interventions to improve IAQ through changes in behaviour. WP6 focused on ventilation as a key mitigating behaviour of indoor air pollution. We used a multi-faceted, mixed-methods approach to examine physical, psychological and social barriers to ventilation behaviours and to co-design and evaluate a behaviour change intervention to improve ventilation in domestic kitchens. WP6 comprised 4 individual studies, as summarised in Fig. 3.

In study 1, semi-structured interviews were conducted with 30 BiB families that participated in WP2 to examine current ventilation behaviours in homes, investigate people's understanding of indoor air pollution and its effect on health, and the barriers and drivers of ventilation behaviours. In study 2, the findings of study 1 were used to design and conduct a larger online survey on a representative sample of 310 British adults (representative for age, gender, ethnicity, region, social grade, educational level), recruited *via* an online participant recruitment platform Prolific,[54] to extend our understanding of the barriers and drivers of ventilation behaviours across the wider population. Both studies used the COM-B (Capability, Opportunity, Motivation – Behaviour) Model[55] as a framework for understanding what individual, social or environmental changes are needed to enable ventilation behaviour. In both studies, barriers to improving IAQ identified as most relevant to future policy development (*e.g.*, structural and financial barriers that cannot be addressed through individual behavioural change) were identified for WP7, and those that could be addressed through individual behavioural change informed studies 3 and 4.

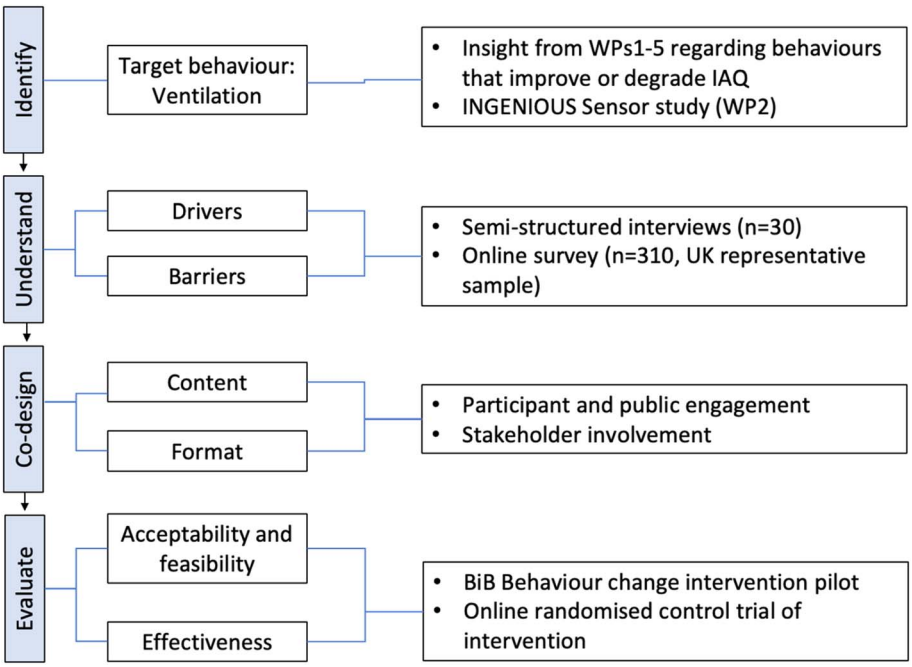


Fig. 3 Flowchart of the intervention development process used in WP6.

Studies 3 and 4 use the behaviour change technique taxonomy[56] and behaviour change wheel framework[55] to design and evaluate a behavioural intervention to encourage people to ventilate their kitchens while cooking, cleaning and using consumer products. We worked with members of the community and the extended research team to co-design the behavioural intervention, an animated video that includes information about the health impacts of indoor air pollution, key pollution sources in the kitchen and how to reduce these pollutants by ventilating effectively.

Study 3 is currently piloting the behaviour change intervention in 90 BiB households over a period of 4 weeks. Participants are randomly allocated to an intervention group (shown the animated video on day 14) or a waitlist control group (shown the animated video on day 28). The same AirGradient sensors are deployed in participants' kitchens to monitor IAQ over a period of four weeks. Sensors on external windows and doors in the kitchen are being used to record opening and closing behaviours, and online survey measurements assess occupant health (as for WP2) and cooking, cleaning and ventilation behaviours

Table 2 A detailed breakdown of the emissions measurements carried out as part of WP1 and classified into cooking, cleaning or home scented product use

Cooking		Cleaning		Home scented products	
Frying in oils	***Number of experiments***	***Product class***[a]	***Number of experiments***	***Product class***	***Number of experiments***
Rapeseed oil	1	Surface cleaners	10	Electrical plug-in diffusers	8
Sunflower oil	1	Bathroom cleaners	5	Essential oil mist diffusers	7
Olive oil	1	Floor cleaners	3	Reed diffuser	1
Groundnut oil	1	Bleach	7	Bathroom freshener (gel)	1
Coconut oil	1	Window cleaner	1	Bathroom freshener (liquid)	1
Ghee	1	**Total**	**26**	Room spray (aerosol)	4
Total	**6**			Wax melts	8
				Scented candle	1
Full recipes	***Number of experiments***			Bakhoor	3
Beef chilli	6			Frankincense	2
Non-meat chilli	7			Incense stick	3
Chicken stir-fry	6			**Total**	**39**
Tofu stir-fry	7				
Chicken curry	7				
Paneer curry	6				
Total	**39**				

[a] All the cleaning products tested in this study were considered to be fragrant based on the manufacturer's label information indicating the presence of "parfume/perfume" in the formulation.

(adapted from WP2). Study 4 will evaluate the effectiveness of the ventilation intervention on changing behaviour and improving health and wellbeing in a larger representative (see above) sample of British adults in Great Britain, recruited *via* the Prolific platform (Prolific website, nd).

WP7

WP7 aims to synthesise the information from WPs1–6 and translate findings to policy-makers and other decision-takers. At project inception we held a stakeholder mapping exercise and created an 'Impact Panel', with membership drawn from parliamentary groups, civil servants, industrial partners and academic and non-academic experts in IAQ. This panel has met twice a year and has enabled co-production of an engagement strategy for INGENIOUS, and provided a platform to test ideas about how to convey key findings to policymakers in central, national and local government across the UK. The impact panel has also been used to explore how best to convey realistic and practical risk management of IAQ to the members of the public, and to housing developers and landlords. Through this early

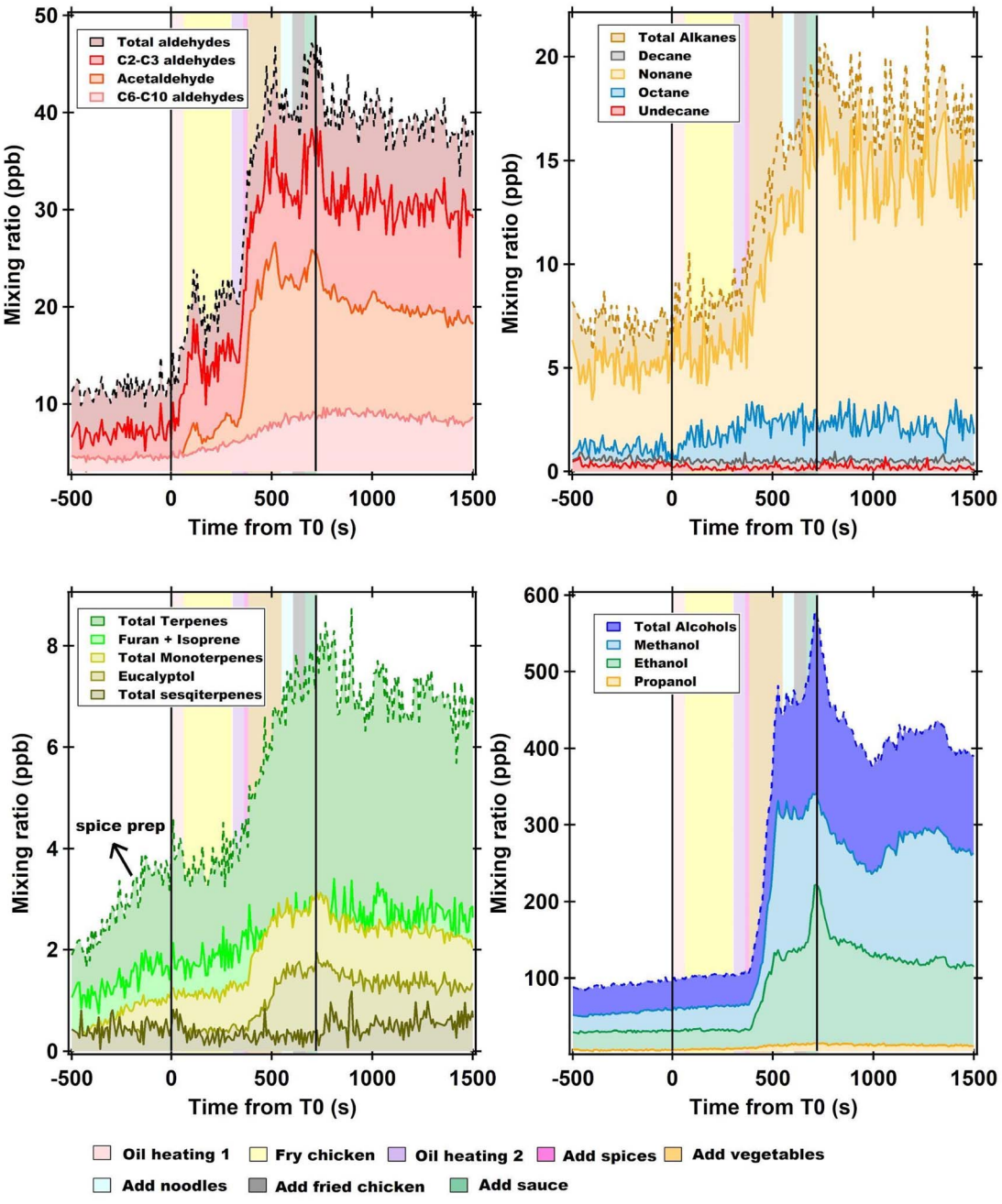


Fig. 4 Mixing ratios of aldehydes (top left panel), alkanes (top right panel), terpenes (bottom left panel), and alcohols (bottom right panel) measured using the SIFT-MS during the cooking of chicken stir-fry. The grey-shaded region shows the cooking duration and time T_0 represents the start of the cooking (when the oil is first added to the heated pan). The data shown is the averaged data of six cooking experiments.

engagement we have gained vital insight into key policies, allied projects and other activities, and ensured buy-in for our interventions, which will help with roll-out and scale-up if they are effective at improving IAQ and health.

Results and discussion

In this section, some example results are described from work packages 1–4. More detailed findings will form the focus of a number of publications in the coming months.

For WP1, we have carried out 110 separate experiments where emissions were measured, as detailed in Table 2. There were 45 experiments dedicated to various cooking activities, 26 to cleaning, with the remaining 39 experiments investigating the use of various scented products used in the home such as diffusers and air fresheners.

Fig. 4 shows a representative time series of the selected VOCs as their homologous groups, *i.e.*, aldehydes, alkanes, terpenes, and alcohols, measured during the cooking of chicken stir fry. At the different stages of the cooking, different VOCs are emitted. Monoterpene concentrations began increasing during the spice preparation phase before cooking, when fresh ginger, garlic, and chilies were chopped. When these spices were added to the pan at 360 seconds, another increase in the concentrations of monoterpenes and monoterpenoids like eucalyptol was observed. Aldehyde concentrations began to increase when the oil was heated in the pan at the initial stages of cooking and again when oil was added to the pan for the second time.

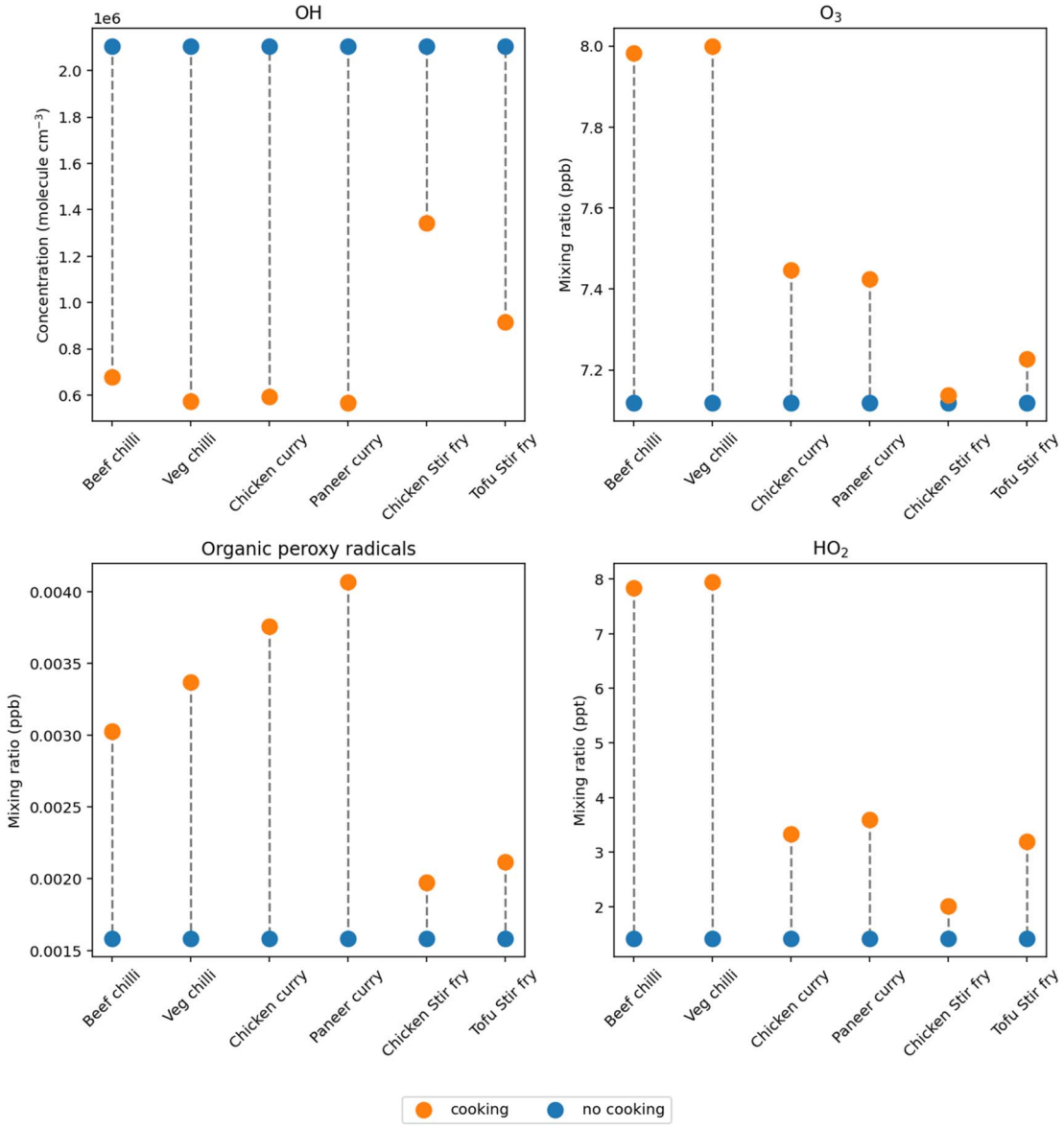


Fig. 5 The change in average simulated mixing ratios/concentrations of radical species and ozone during cooking of the six different meals measured in WP1, as simulated by INCHEM-Py. Cooking time was 12 min for the stir fries, 18 min for the paneer curry, 21 min for the chicken curry and 26 min for the chillies. The background concentration for each species was simulated with no cooking activity (blue), compared to the simulated concentration during the cooking activity (orange).

Heating of the oil also led to emissions of long-chain alkanes such as nonane, as observed in previous studies.[22,28,57]

Alcohols like methanol and ethanol were emitted when the vegetables were added to the pan and were the dominant species, also consistent with previous studies.[22,28] Another major emission of alcohols occurred during the addition of the stir-fry sauce suggesting that the sauce contents (there were no alcoholic ingredients listed) resulted in alcohol emissions. The emission rates will be quantified for each of these cooking and cleaning experiments to form the basis of a comprehensive indoor emissions inventory, as well as to constrain the INCHEM-Py and Py-CHAM models to further explore the impact of these emissions on IAQ as part of WP4.

For instance, Fig. 5 shows the predicted radical species, and ozone concentrations (or mixing ratios) during simulated cooking experiments for the different meals, compared to a no cooking scenario using the INCHEM-Py model. The simulations were based on the characteristics of the DOMESTIC facility in which the experiments took place, as defined in Table S2.† A total of 39 VOC species were quantified through the emissions measurements for each meal, 33 of which are present in the chemical mechanism used by INCHEM-Py. The emission rates of these 33 VOC species were used to constrain the model for the cooking simulations, to predict radical concentrations which were not measured.

Fig. 5 shows that hydroxyl radicals (OH) are consumed by the cooking activities, more or less equally for chilli and curry, less so for the stir fry meals. The hydroperoxy (HO_2) and organic peroxy radicals (RO_2) are formed during all the cooking activities. For HO_2, formation is most pronounced when cooking chilli, whereas for RO_2, curry is the most important meal type. Ozone is formed through all the cooking activities, more so for the chilli and curry meals. These differences arise because of the type and concentrations of VOCs emitted from each meal type, and the ongoing chemistry (see Fig. 6). Ozone only reacts with double-bonded species such as monoterpenes and alkenes through ozonolysis reactions, which form OH (and peroxy) radicals at various yields. The OH radical reacts with all VOCs, predominantly forming the peroxy radicals, RO_2 and HO_2. In the presence of NO, peroxy radicals can react to form NO_2, with HO_2 converted to OH and RO_2 converted to HO_2 in the process (Fig. 6). In the presence of attenuated sunlight or overhead lighting, NO_2 can then be photolysed to form ozone. The chemistry is clearly complex, but it is possible for ozone reactions to produce OH radicals and *vice versa*, increasing the oxidative capacity of the indoor environment. Depending on the VOC mix and the $NO : NO_2$ ratio during the cooking activities, different radical concentrations will be observed, as well as differing concentrations of other secondary pollutants that might result from the ongoing chemistry.

As part of WP2, 3.5 million IAQ measurements were collected, with a mean collection rate of 93%, and a median of 98%. Lower collection rates were noted in some households with lower cellular connectivity (for more details, see Fig. S1, ESI†). Fig. 7 shows the average *T*, RH, CO_2 and $PM_{2.5}$ measurements split by season.

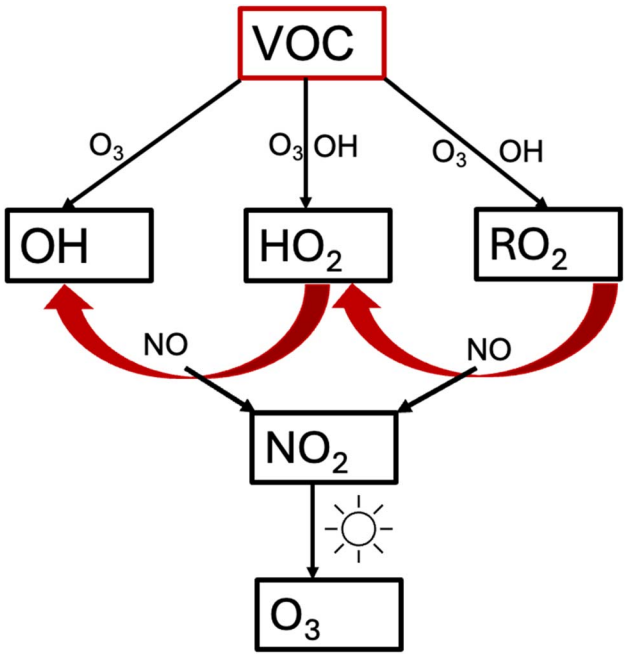


Fig. 6 Reactions following oxidation of VOCs indoors: HO_2: hydroperoxy radical; RO_2: generic term for organic peroxy radicals; NO: nitric oxide; NO_2: nitrogen dioxide; O_3: ozone; OH: hydroxyl radical; VOC: volatile organic compounds.

Fig. 7 shows a significant amount of variability between the homes across all the measured values. Peak internal temperatures were observed in summer, with the opposite pattern observed for relative humidity as expected. Note that some of the internal temperatures were very low in the winter, averaging well below 10 °C for a 24 hour period, and for a not inconsiderable fraction of the households. In fact, Fig. 7 shows strong evidence for fuel poverty amongst some of our households. Indoor CO_2 concentrations also demonstrate a high degree of variability. The median CO_2 concentration was lowest in the summer (666 ppm), presumably owing to more window opening and better ventilation, and highest in the winter at 857 ppm. However, concentrations exceeding 2500 ppm were also observed, mainly in bedrooms at nighttime, indicating that many of them are poorly ventilated. Although there is little evidence to link health effects to exposures below 5000 ppm of CO_2, concentrations below 1000 ppm are often recommended for satisfactory IAQ.[58]

For PM, the high measured concentrations are linked mainly to days with sustained cooking activities. Median $PM_{2.5}$ concentrations varied between 16.4 μg m^{-3} in the winter and 7.8 μg m^{-3} in the summer. For context, the WHO guideline value for a 24 hour average exposure is 15 μg m^{-3},[13] a value that was exceeded for 40% of the time in the homes in which we measured. Fig. 8 shows the indoor and outdoor $PM_{2.5}$ concentrations from one of our sampled households during March 2023. By using information from the occupant's diary, we were able to identify that indoor $PM_{2.5}$ matched outdoor concentrations closely in the absence of cooking activities. However,

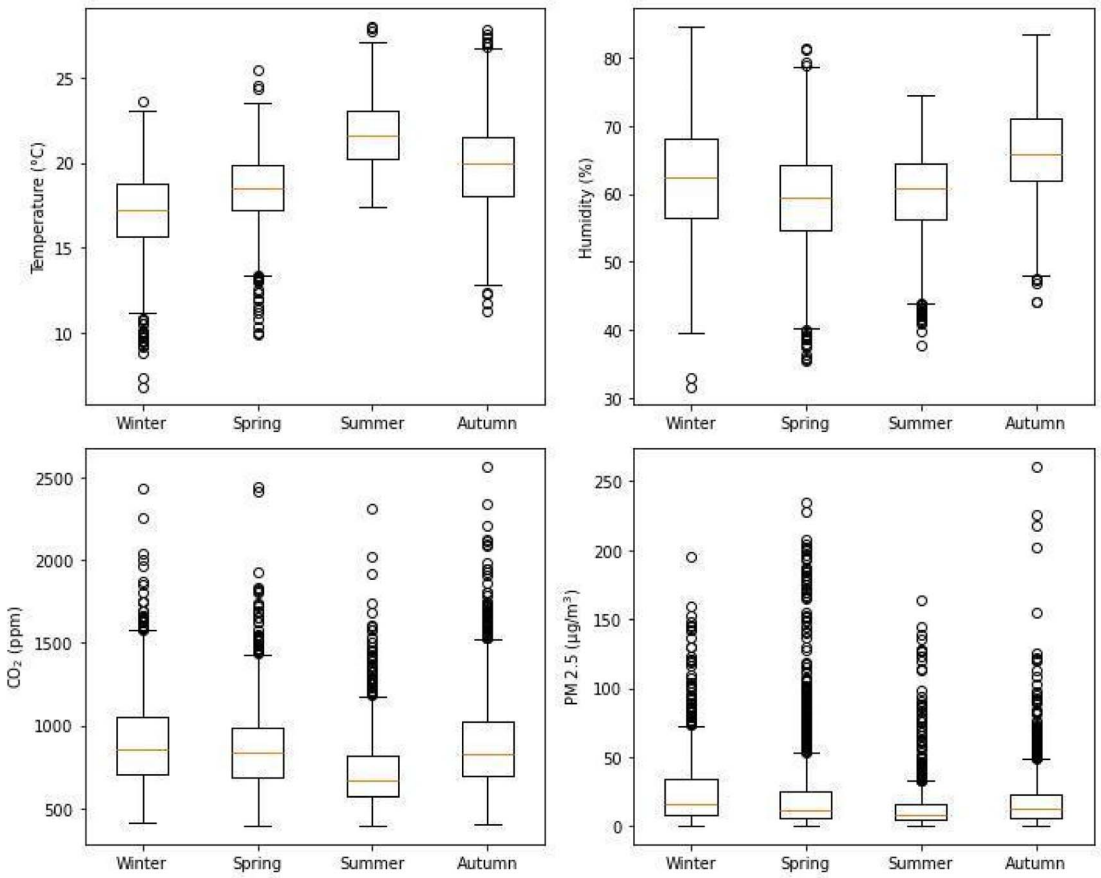


Fig. 7 Distribution of internal temperature, relative humidity, $PM_{2.5}$ and CO_2 for measurements taken across all of the households using the AirGradient sensors. Each datapoint used to construct these plots is a household average across all 3 rooms for a single measured day. The gold lines show the median values, with boxes spanning the interquartile range (IQR) of the 25th and 75th percentile values. The whiskers extend 1.5 times the IQR plus the 75th percentile above and minus the 25th percentile below. Fliers, beyond the whiskers, are shown as black circles. There are between 989 and 1489 household days per boxplot.

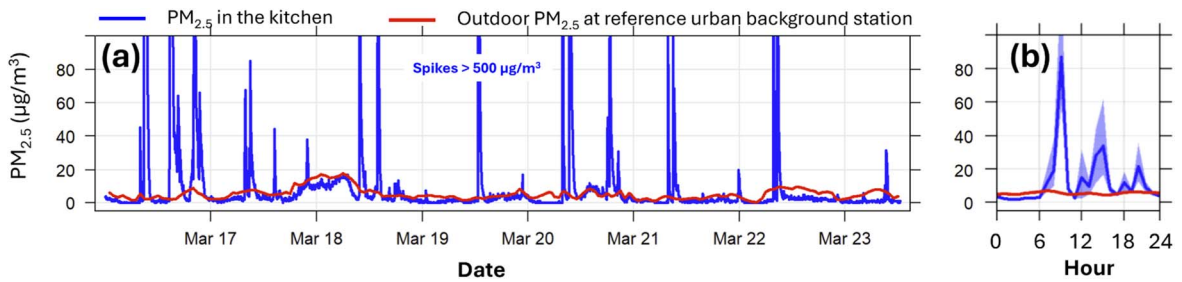


Fig. 8 Indoor and outdoor $PM_{2.5}$ concentrations in one of the sampled kitchens during March 2024 over a week in µg m^{-3}. (a) Indoor PM levels closely follow outdoor levels indicating the contribution of outdoor generated pollution indoors with clear events (*i.e.* cooking) elevating indoor levels above outdoor background. (b) A clear diurnal profile can be noticed for indoor sources driven by behavioural patterns of the occupants (active emissions). Calculated mean with 95% confidence interval in the mean.

during cooking events, peak concentrations exceeding 500 µg m^{-3} were observed.

We were able to explore the $PM_{2.5}$ peaks in more detail, using the PyCHAM model as part of the WP4 activities. Fig. 9 shows the contributions from different sources to predicted indoor $PM_{2.5}$ concentrations on a simulated day, assuming that there was a frying event and a mopping event (using a limonene-based cleaning product) at 06:00 h and a shower (using limonene-emitting shower gel) an hour later at 07:00 h. The simulations use two contrasting air change rates (ACRs) based on those typically observed in the sampled homes and assume there are no extractor fans operating in the household. The dominant contribution to indoor $PM_{2.5}$ mass for both ACRs is from indoor-generated primary organics, specifically from

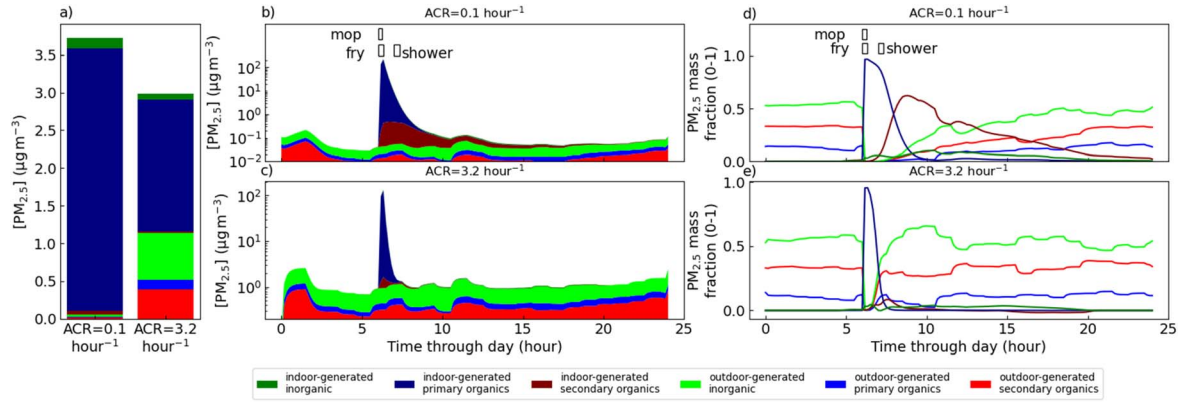


Fig. 9 Simulated indoor $PM_{2.5}$ concentrations for a day where there is 1 frying event, 1 fragranced (limonene-based) mop and 1 limonene-emitting shower activity. Different colours show the contributions to indoor $PM_{2.5}$ from different sources. The results show (a) the arithmetic mean of that simulated day for 0.1 h^{-1} (left stack) and 3.2 h^{-1} (right stack); the absolute mass concentration profiles over time for 0.1 h^{-1} (b) and 3.2 h^{-1} (c); and the relative mass concentration profiles over time for 0.1 h^{-1} (d) and 3.2 h^{-1} (e).

frying. Despite the large difference in ACR between the two simulations, the total $PM_{2.5}$ concentrations are similar. Although increasing ACR allows more outdoor-generated particles to come indoors (40% of $PM_{2.5}$ mass is of outdoor origin in the simulated high ACR case), it also expels indoor-generated particles to the outdoors. Note that the outdoor concentrations were assumed to be 8 μg m^{-3} for both scenarios. Peak indoor $PM_{2.5}$ concentrations are 230 and 130 μg m^{-3} for the 0.1 and 3.2 h^{-1} ventilation rates respectively, in accordance with the range of our measured values, as are the daily average $PM_{2.5}$ mass concentrations (Fig. 7 for comparison).

Comparing Fig. 9d and e shows how outdoor $PM_{2.5}$ relatively quickly (within 1 hour) returns to being the main mass contributor following indoor activities with an ACR of 3.2 h^{-1}, which is due to the relatively quick expulsion of primary particulates and semi-volatile vapours from indoor activity. In contrast, it takes at least 6 hours for the same to happen with an ACR of 0.1 h^{-1}. Indoor-generated secondary organics spend 2.5 hours as the main mass contributor under the low ACR, because semi-volatile vapours generated from the indoor activities can condense onto indoor surfaces when they are at relatively high gas-phase concentration (during and soon after precursor VOC emission) and then evaporate off as the gas-phase concentration decreases. This process makes these vapours available for condensation to the particle-phase, as observed in Lunderberg *et al.*[59]

Increasing the ventilation rate increases the amount of outdoor $PM_{2.5}$ that an occupant is exposed to indoors. It is also possible to be exposed to more outdoor $PM_{2.5}$ when indoors than when outdoors, due to infiltration of outdoor air from

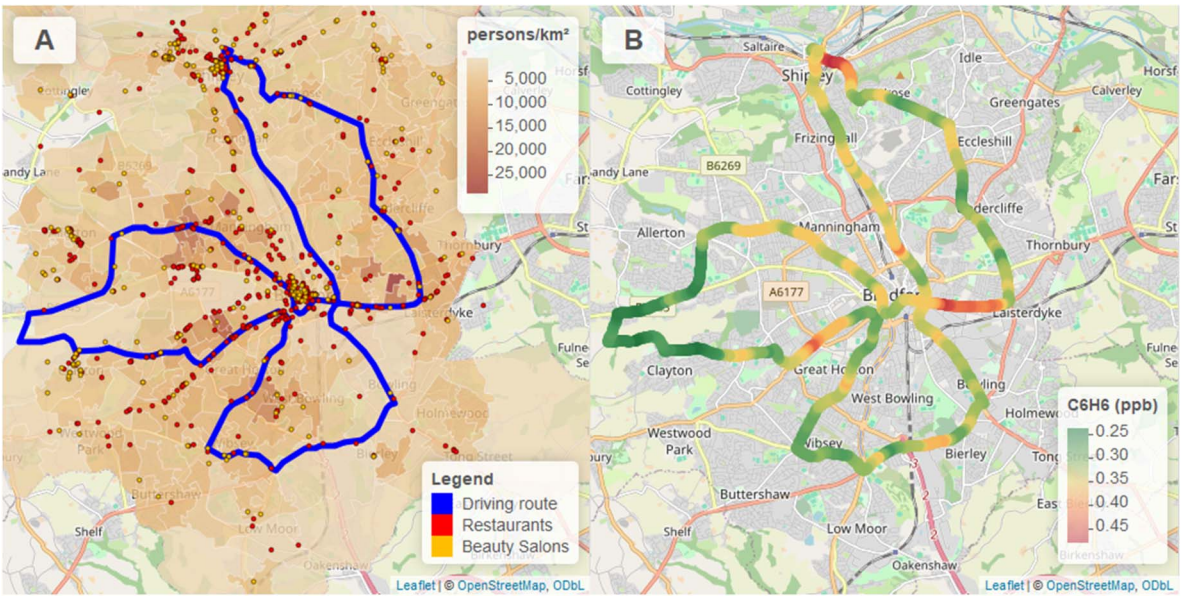


Fig. 10 (A) The mobile measurement route in Bradford is overlaid on an OpenStreetMap base layer, generated using the Leaflet R package. The map also displays population density derived from Lower-layer Super Output Area (LSOA) estimates (Office of National Statistics) and selected commercial establishments (Google Maps). (B) Median spatial concentrations of benzene (C_6H_6) from 22 mobile measurement loops are shown.

increased ventilation rates. If it is assumed that 90% of the time is spent indoors[1] and the remaining 10% outdoors, under these conditions, the time-integrated outdoor $PM_{2.5}$ exposure indoors: outdoors is 0.064 : 1 for 0.1 h^{-1} and 1.28 : 1 at 3.2 h^{-1}.

The mobile measurements made as part of WP3 revealed spatial variations in air pollutant concentrations across Bradford and York. As an example, Fig. 10 shows the driving route and the resulting benzene concentrations across Bradford based on repeat measurements of a route designed to capture different source influences *e.g.* restaurant-dominated and areas of high housing density. Benzene is a known tracer for exhaust emissions and is also released from wood and biomass burning. Moreover, WP1 laboratory experiments have shown that cooking activities are another source of benzene emissions. The numerous sources of benzene (and other VOCs) make it challenging to robustly disentangle the different source contributions spatially. New analysis approaches are being developed to establish stronger links between source types and their contributions to urban VOC and other pollutant measurements. One promising approach is to consider the density of source types (such as restaurants) as a metric that can be related to VOC composition.

Conclusions

One of the most striking features of our results to date has been the wide variability in the measured temperatures and indoor air pollutant concentrations within the sampled houses in Bradford. This variation was observed both within and between households, indicating that the behaviour of the occupants is key for the observed IAQ. High $PM_{2.5}$ concentrations were frequently noted in kitchens during cooking activities, with concentrations well above those recommended by the WHO.[13] We also noted that measured CO_2 concentrations were often high in bedrooms at nighttime. Although outdoor air pollutant concentrations influenced those measured indoors in the absence of occupant activities, it was the indoor activities that led to the highest indoor concentrations for the pollutants we studied. At the current time, it is unclear whether repeated acute elevated exposures are more or less hazardous than continuous lower-level exposures to different sources. Moreover, it is unclear whether indoor or outdoor generated particles are more harmful, either at the same concentrations, or at the likely received ambient doses.

There is also strong evidence from our results that a number of our sampled households were living in fuel poverty. Our sampling period coincided with some of the highest fuel prices on record for UK householders, and 7% of sampled households reported that they were never, or rarely, able to keep the house warm in winter. Low internal temperatures are a concern, as they can lead to health effects directly,[60] and indirectly through condensation on internal surfaces and hence the formation of mould, which has also been shown to be detrimental to health.[61]

Finally, our results have shown that a significant proportion of air pollution measured indoors derives from indoor activities, particularly the peak concentrations. This observation has implications for net zero policies that are aiming to reduce energy/carbon emissions from buildings through making them more airtight. Doing so without a detrimental impact on IAQ represents a huge challenge and requires a paradigm shift in building standards, design and architecture for both newbuild and retrofit. As such measures build in momentum over the next decade or so, it is critical that we also consider the resultant impact on IAQ. However, outdoor air pollutants also have an impact, particularly for background concentrations indoors in the absence of occupant activities. The continued reduction of traffic-derived outdoor air pollutant concentrations will benefit many homes, and enable them to use natural ventilation to remove pollutants generated indoors, without worrying about what they are letting in.

Data availability

Data supporting this article have been included as part of the ESI.† Both of the models described are available as open-source models. Data for Fig. 4, 5 and 7–10 are available at **https://doi.org/10.15124/98e5ba8a-0568-476b-b388-e1f245110523**.

Author contributions

N. C.: conceptualisation, methodology, investigation, visualisation, writing – original draft, writing – review & editing, supervision, funding acquisition. J. A.: writing – review & editing. S. H. B.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. D. C. C.: conceptualisation, methodology, investigation, writing – review & editing, funding acquisition. L. C.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. R. W. C.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. T. J. D.: conceptualisation, investigation, methodology, writing – review & editing, supervision, funding acquisition. P. E.: conceptualisation, writing – review & editing. D. G.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. C. G.: conceptualisation, methodology, writing – review & editing. J. F. H.: conceptualisation, methodology, writing – review & editing, funding acquisition. E. I.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. R. L. J.: conceptualisation, methodology, writing – review & editing, funding acquisition. J. L.: conceptualisation, methodology, writing – review & editing, funding acquisition. A. C. L.: conceptualisation, methodology, writing – review & editing, funding acquisition. A. K.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. R. M.: conceptualisation, methodology, investigation, writing – review & editing, funding acquisition. G. M.: conceptualisation, methodology, investigation, writing – review & editing, funding acquisition. T. M.: investigation, writing – review & editing. N. P.: conceptualisation, methodology, investigation, writing – review & editing, funding acquisition. A. R.: methodology, investigation, data curation, formal analysis, validation, writing – review & editing. Y. S.: methodology, investigation, data curation, formal

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Conflicts of interest

There are no conflicts to declare.

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