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Research Article

Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment

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Abstract

Background: Tackling climate change, together with improving indoor air quality, offers a significant opportunity to improve residents' health and well-being. This requires the evidence base to inform an energy-efficient retrofit design.
Objectives: (i) To develop a protocol that could be implemented by local authorities across a range of housing typologies and (ii) to deploy this protocol to establish baseline conditions in $n = 30$ homes ahead of energy-efficient retrofitting.
Methods: Working with the local council and the community, this baseline study (In2Air) developed and deployed a protocol across 30 single-storey one- and two-bedroom properties owned by Newcastle City Council, United Kingdom, and occupied by tenants (> 55 years). The following data were collected before homes underwent a fabric-first intervention: indoor and outdoor air quality (for ~3 weeks); energy consumption (for ~12 months); occupant behaviour and home-specific details; self-reported general health and well-being.
Results: The collected baseline data indicated that the mean $PM_{2.5}$ (particulate matter < 2.5 µm in diameter) concentrations ranged from 3 to 24 µg/m^3 (excluding three homes where smoking occurred indoors). No homes had monitoring period means above the current United Kingdom (2019) outdoor annual mean limit (25 µg/m^3); however, 21 homes had monitoring period means above the current World Health Organization (2021) annual mean guidance value (5 µg/m^3).

Strong correlations were observed between indoor $PM_{2.5}$ and indoor PM_{10} (particulate matter < 10 µm in diameter) , suggesting similar sources, while no-to-weak correlations were observed between indoor carbon dioxide and indoor $PM_{2.5}$. Moderate-to-good ventilation was suggested by indoor concentrations of carbon dioxide across all the study homes. The lack of correlation between carbon dioxide and particulate matter highlights the need for housing professionals to add particulate matter to their usual indoor air quality assessment suite of carbon dioxide, temperature and humidity.

Most homes had mean humidity levels within the range considered healthy (i.e. between 40% and 60%), with only three homes above this range. With respect to the baseline health and well-being scores, compared to the comparison population, data for this initial time point indicated most participants (83%) had a physical health score below the norm, which likely reflects the age (> 55 years) of the cohort. In comparison, the mental health score for

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most participants (74%) was at or above average. Here, the physical layout of the estate with communal amenities may well be engendering a positive sense of belonging. The mean/median ICEpop CAPability score suggests a high level of capability across the cohort.

Limitations: Our study focused on changes to the building envelope across a limited number of building types and parameters and utilised fixed, low-cost sensors at indoor and outdoor monitoring locations rather than personal air quality monitors.

Conclusions and future work: The baseline conditions reported in this article provide the basis on which to inform and evaluate the effects of energy-efficient refurbishment across this social housing stock as part of future research. The developed protocol and the study findings offer the potential to support and inform decision-making of council retrofit teams across the United Kingdom with their ongoing decarbonisation plans.

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Introduction

Air pollution is a leading cause of mortality and morbidity worldwide and is a major driver in health inequality. It disproportionately affects the young (it can damage growing lungs and stunt growth), older people, those with compromised immune systems or with relevant pre-existing medical conditions [e.g. chronic obstructive pulmonary disease (COPD) and asthma] and those who live in deprived areas, typically with higher levels of air pollution and poor quality housing.[1] Given we spend a great deal of our time indoors, indoor air quality (IAQ) is central to our health and well-being, and improvements to the indoor environment can be an important mechanism for addressing health disparities among low-income and vulnerable populations.[2]

To meet international climate targets we need to cut carbon dioxide emissions to 'net zero' by 2050. To support this ambition, homes will need to significantly reduce energy demand, necessitating highly insulated buildings, increased air tightness and the adoption of new ventilation strategies. It is anticipated that a minimum Energy Performance Certificate (EPC) band C will be introduced in the UK for both private rented and social housing.[3] This will result in a substantial increase in the number of homes requiring energy upgrades. A fabric-first approach is a common low-tech intervention method aimed at reducing energy demand and providing more comfortable environments for occupants.[4] Fabric-first energy retrofit schemes are designed to decrease the air permeability of the building envelope, making homes relatively airtight. In the absence of adequate ventilation, concentrations of moisture, carbon dioxide (CO_2), particulate matter (PM) and other pollutants can accumulate within homes, compromising health and well-being.[5]

While improving household energy efficiency has the potential to improve thermal comfort and alleviate fuel poverty, the air sealing of homes can result in compromised IAQ, increasing the subsequent risk of allergic and respiratory diseases, along with promoting mould growth. Indeed, National Institute for Health and Care Excellence (and predecessor organisations) guidelines[1] and systematic reviews of household air pollution[6–8] highlight the health risks of poor IAQ. A recent study of household energy efficiency interventions across social housing in southwest England concluded that residing in energy-efficient homes could increase the risk of adult asthma. Specifically, for every unit increase in household energy efficiency, there was a 2–3% higher risk of adults consulting a doctor for asthma.[9] Over the past decade, researchers have investigated a wide range of green retrofit building practices and policies.[10] Much of this research has focused on exploring the advantages associated with improved energy efficiency from environmental sustainability and carbon emission reduction perspectives. A noticeable gap emerges in the literature, with a scarcity of studies that incorporate IAQ (beyond CO_2, humidity and temperature) along with health and well-being to enhance the efficient design of retrofit interventions.[11] The monitoring of a broad spectrum of air quality (AQ) parameters is beyond the scope of most 'real-world' studies because of the need to monitor a statistically significant number of homes. However, by selectively monitoring the changing concentrations of the key AQ parameters (PM, temperature, relative humidity and CO_2) in homes, we can assess whether the buildings are adequately ventilated and provide a comfortable environment when occupied, both before and after the retrofit. Elevated concentrations of indoor CO_2 often indicate inadequate ventilation and are typically used as a surrogate measure of the amount of outdoor air introduced into the home.[12,13] PM is a major contributor to air pollution,[14] and both short- and long-term exposures to PM are associated with increased mortality from all causes, cardiovascular disease, respiratory disease and lung cancer.[15–17] Furthermore, robust evidence supports a causal relationship between short-term PM exposure and adverse effects on conditions such as asthma, COPD exacerbations and combined respiratory-related diseases,[18] and studies show that exposure to $PM_{2.5}$ can contribute to or exacerbate hypertension, diabetes and elevate the risk of Alzheimer's.[19–22] While there are no legal limits in the UK for indoor PM concentrations, the recent lowering of World Health Organization (WHO) guideline values for annual mean $PM_{2.5}$ exposure (from 10 to 5 µg/m^3, 2021)[14] is indicative of health effects observed at much lower concentrations than previously suggested. A greater understanding of the range of PM concentrations observed in 'real' homes, at scale, both before and after household energy efficiency interventions is therefore both timely and increasingly relevant if we are to use social housing decarbonisation funding levers to tackle both climate change and to improve indoor environmental quality.

The overarching aim of this collaborative study (In2Air) is to evaluate the changes in IAQ (as characterised by the changes in CO_2, PM_{10}, $PM_{2.5}$, temperature and relative humidity), energy consumption, health and well-being resulting from 'fabric-first' household energy efficiency interventions. The objectives of phase 1, reported herein, were (1) to work with the local authority and community participants to develop a monitoring and survey protocol that is practical to deploy and which could be implemented by local authorities across a range of housing typologies, at scale, both before and after energy-efficient refurbishment and (2) to deploy the protocol to collect sufficient baseline data across a pilot cohort of homes to enable post-retrofit evaluation of the impacts of the building works on key IAQ metrics, health and well-being of occupants. A follow-on study, now under way (NIHR160372; www.in2air.org.uk), is re-monitoring these same homes/households post retrofit, extending the building typologies studied and conducting a health economic evaluation.

Study site, building typology and retrofit design

Researchers from Northumbria and Newcastle Universities, working in partnership with Newcastle City Council (NCC) Fairer Housing Unit, selected a terraced bungalow archetype (single-storey building) with homes located in Walker, in the east end of Newcastle upon Tyne. The bungalows consist of 89 terraced homes, set out in three-square courtyard greens. The properties were built in the 1930s and fall into one of five subarchetypes (*Table 1*). All have traditional cavity wall construction with tiled pitched roofs. All homes were equipped with both gas and electricity connections. Each block of homes, typically consisting of 30–40 residences, shares a single communal boiler. This communal gas-fired boiler supplies central heating through wall-mounted radiators. Each individual home has an individual gas-fired boiler for providing hot water for the kitchen and bathroom sinks. All homes have electric cookers and electric showers (no baths except for one property). Communal laundry facilities are available, with running costs included in the rent. All properties have some loft insulation and double glazing, with a current energy performance rating of EPC D.[23]

Funding, as part of the UK Government's Social Housing Decarbonisation Fund, was secured by NCC to improve

TABLE 1 Housing archetype information[a]

Subarchetype description	Small, end-terrace, single bedroom	Larger, end-terrace, single bedroom	Small, mid-terrace, single bedroom	Larger, end-terrace, two bedrooms	Larger, mid-terrace, two bedrooms
Number of this subarchetype in the study	6	0	17	5	2
Gross internal area (m^2)	34	46	34	49	49
Number of bedrooms	1	1	1	2	2
Current annual heating demand[a] (kWh/m^2. year)	135	116	116	112	96
Existing airtightness test result[a] (Q50 m^3/hour.m^2 @ 50 Pa)	14.07	8.02	12.66	10.18	7.76
Required whole dwelling[a] ventilation rate (l/s)	19	19	19	25	25

[a] Data derived from the retrofit report for each property. Airtightness test results were determined by Apex Acoustics (www.apexacoustics.co.uk) as part of the programme of pre-retrofit air tests. The required whole dwelling ventilation rates were determined following guidance in table 1.3.[24] Further details can be obtained from the coauthor and Retrofit Coordinator, Adam Vaughan.

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the energy performance of these bungalows with a target to bring all the properties up to energy performance rating of EPC C. A full retrofit survey was undertaken under PAS2035 standards,[25] and the following package of works were identified: new windows and doors (A+ rating with argon-filled double glazing and trickle vents); top-up loft insulation to 400 mm, new insulated loft hatch; continuous mechanical extraction fans to bathroom and kitchen areas, with automatic boost with light in the bathroom and solar photovoltaic (PV) panels fitted to the roofs. The distributed (continuous) mechanical extract ventilation consisted of two fans extracting moist 'stale' air from the kitchen and the bathroom (the 'wet' spaces), combined with the passive window vents (background ventilators tested in accordance with BS EN 13141-1[26]) in the living room and bedrooms to admit a balancing supply of 'fresh' external air. The retrofit works were designed to reduce energy demand by improving the thermal performance and air tightness of the properties, with the solar PV providing no-cost electricity to the tenants. As part of the retrofit works, heat meters are being installed to enable individual charging for central heating. Additionally, all homes featured porch areas that were not deemed as internal spaces for the purpose of the retrofitting project. Consequently, the external doors of these areas were not included in the retrofit.

Materials and methods

Protocol development

Informed by the literature, guidance on conducting building performance evaluation of occupied buildings[25] and through consultation with our local authority partner and members of the External Steering Committee [which included AQ specialists at the Building Research Establishment (BRE) and the UK Health Protection Agency], the In2Air protocol was developed. The protocol, including participant materials and monitoring equipment choice, were additionally informed by several rounds of interaction with consumer panels and community groups [supported through a Public Involvement Fund (award rds3897) from the Research Design Service North-East and Cumbria], and through interactions with our study cohort. As a result of this wider engagement activity, we adapted the protocol to reduce reporting bias and further support engagement. These included:

- Completing the survey questionnaires as a face-to-face conversation with a researcher, rather than directly by the participant online. This allows questions to be further explained to the participant where needed, reducing misinterpretation of questions.
- Replacement of noisy monitors and reduction in the parameters monitored to PM, CO_2 (indoor only), temperature and relative humidity, with indoor monitoring only in living rooms, to minimise the number of units required per household.
- Enabling remote researcher access to the AQ monitor data to allow for the checking and collection of data with minimum disturbance to participants.
- Better encouraging participation by reducing the burden of participation (e.g. removal of a sleep diary and making the activity diary optional) and agreeing with each household the type of compensation voucher preferred, from a set of options.
- Modifying the IAQ feedback report provided to each household; we remain mindful of the need to further modify the household feedback report with input from members of each study cohort.
- Modifying our inclusion criteria due to the high number of households that were not eligible to participate due to age and smoking. For example, we removed the barrier to smokers and instead requested they refrain from smoking indoors, or near the outdoor AQ monitor during the monitoring period.

The resultant protocol (version 1.1; available at www.in2air.org.uk) was then deployed across 30 single-storey, terraced properties owned by NCC and occupied by senior tenants (> 55 years). We collected the following data sets before homes underwent a fabric-first intervention:

- paired indoor and outdoor concentrations of $PM_{2.5}$ and PM_{10} (*Air quality monitoring*)
- indoor CO_2 concentrations (*Air quality monitoring*)
- paired indoor and outdoor temperatures and relative humidity (*Air quality monitoring*)
- energy consumption data and associated home energy survey (*Domestic energy audit and monitoring*)
- a home/occupier survey and self-reported general health (GH) and well-being [using standard validated survey tools: Short-Form Health Survey (SF-36v2, of which there are 36 questions), ICEpop CAPability measure for Adults (ICECAP-A), Use of Health and Care Services (UoHCS)] (*Questionnaire Surveys*).

Participant engagement activities and recruitment

Establishing trust through community-based partnerships is essential. In this respect, the In2Air research team worked in collaboration with the delivery specialist team at Your Homes Newcastle (YHN) and the wardens of the two estate community centres. In late August 2022, the occupants of the 89 bungalows received details of the planned retrofit works and information on voluntary participation in the In2Air study, sent out by YHN.

Informed by engagement with our community partners, a range of activities and resources were developed to drive interest and recruitment. Resources/activities included door-to-door leafleting (a publicity flyer), use of local community information boards, a project website and community engagement events (e.g. coffee mornings and 'show and tell' lunches). The role of Community Research Champions, early adopters/participants who were willing to be the first in their area/block to host monitors, also played a key role in building trust between the residents and the research team and encouraging others to participate.

Informed consent was obtained prior to the participants taking part in the study. Written materials provided to potential participants [e.g. participant information leaflet (PIL) and consent form; included in *Appendix 1*] were approved by Northumbria University Research Ethics Committee (No. 51426/ ID3115) in compliance with the local regulatory and legal requirements.

Air quality monitoring

Previous research, including our own in the North-East conducted as part of the Home Biome project (NERC NE/T004401/1), commonly indicates similar patterns of PM concentration variation in kitchens and living rooms, with evidence of peak PM concentrations occurring at similar times in both rooms.[27] Therefore, and to reduce the burden on participants and manage study costs, it was agreed that each home would host a single indoor monitor in the living room, paired with a nearby outdoor monitor, to provide an indicative measure of IAQ over the monitoring period. Guidance on the positioning of sensors was informed by BS 40101.[25]

Based on our main environmental parameters of interest (i.e. PM_{10}, $PM_{2.5}$ and CO_2 concentrations, as well as indoor humidity and temperature due to their impact on mould growth and thermal comfort[1]), candidate low-cost AQ sensors were identified through internet search, researcher recommendations and recent review/performance-assessment research papers.[28,29] Our chosen monitors needed to fulfil the following criteria: (1) compact, combined sensors ($PM_{2.5}$, CO_2, temperature and relative humidity) minimising space requirements; (2) quiet operation, thus reducing disruption to participants; (3) reporting in standard units (e.g. particle mass concentrations), not just as AQ indices; (4) logging at 5-minute or better resolution; (5) ability for remote data access, but with sufficient internal storage so data are not lost if data transmission is intermittent and (6) available for retail purchase in the UK at a cost of < £350 per unit (2022 prices), with rapid order-to-receipt of goods.

Our selected low-cost monitors [AirVisual - IQAir® Pro (AVPro, Steinach, Switzerland) and AirVisual Outdoor (AVO) by IQAir] were deployed to measure paired indoor and outdoor air conditions for approximately 3-week duration before homes were retrofitted (technical data on these sensors are available[30]). All sensors were combined within a single indoor or outdoor unit. $PM_{2.5}$ monitoring was via a particle count approach, making the unit quieter than is typical for gravimetric methods. Measurements of CO_2 (indoor only), temperature and humidity were also recorded by the same unit.

Existing literature on the duration of monitoring required to establish an IAQ baseline varies widely, ranging from a few days, including weekend/weekdays and seasonal sampling, up to 12 months.[2,25,31] Informed by the literature, and our community engagement activities, monitoring was conducted for 3–4 weeks, with a monitoring period to capture conditions before retrofitting, which will be repeated after retrofitting. Our monitoring targeted a worst-case scenario as we focused on monitoring the autumn/winter period (September–February) when IAQ in the UK can be expected to be at its worst[32] due to prevailing meteorological conditions and more limited indoor ventilation because windows and doors are more likely to be closed. Furthermore, in autumn/winter, it is relatively common for the elderly population to spend more time indoors, which increases indoor exposures. For our approach to monitoring domestic AQ, see *Appendix 2*.

Domestic energy audit and monitoring

An energy assessment was conducted on each of the homes. This assessment encompassed a level 1 walk-through energy audit aimed at discerning energy consumption patterns, behavioural tendencies and peak usage periods. Energy audits can identify the approaches for improving energy efficiency.[33]

Due to the absence of individual gas meters for central heating at household level, it was not feasible to obtain precise data on energy usage for each specific home. However, as part of the retrofitting process, heat meters are being installed to measure the thermal energy consumption of each individual dwelling. Heat meters calculate energy transfer based on the flow rate of the heating medium water and the temperature difference between the supply and return pipes, providing accurate data for billing and energy management in residential heating systems.[34] At the time of the data collection phase, the heat meters had been installed but not yet commissioned. To gather information on individual

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electricity and gas use (for heating kitchen and bathroom sink tap water), meter readings were recorded at the start and end of the monitoring period. Additionally, the occupants' utility bills covering a period of 12 months were collected and analysed to gain an understanding of energy usage patterns. For our approach to monitoring domestic energy consumption, see *Appendix 3*.

Questionnaire surveys

Standard questionnaire instruments were used to collect baseline data on (1) home characteristics (e.g. Likert scale questions on thermal comfort within the building, prevalence of condensation, damp and mould) and activities/behaviours that influence IAQ; (2) occupier characteristics (e.g. age and gender) and (3) self-reported health and well-being, collected for all adults in each household using Short-Form Health Survey (SF-36v2, which consists of 36 questions), ICECAP-A and UoHCS surveys. All homes with dual occupancy were input as two responses and the mean, median, maximum and minimum scores were used as part of sensitivity analyses.

The home characteristics, activities and behaviours survey was adapted from one previously used by BRE (Upton, personal communication). Topics include information about residents and time spent in the home, seasonal thermal comfort, supplementary heating devices, energy use behaviours and attitudes, ventilation behaviours, perception of AQ, condensation, damp and mould, use of air fresheners, laundry habits, smoking, vaping and cooking habits.

The SF-36v2 is an established and widely used health-related quality of life measure that considers five domains: mobility, self-care, usual activities, pain/discomfort and anxiety/depression.[35] The collected responses were converted using the licensed scoring algorithms available within the Quality Metric® software (IQVIA Quality Metric Inc., Durham, NC, USA). The license and analysis package generates eight functioning types' scores, as well as physical component and emotional component scores.

The ICECAP-A is a measure of capability validated with the UK adult population (18+ years) for use in economic evaluation (ICECAP, Bristol Medical School, Population Health Sciences, University of Bristol). The measure of capability in the adult population was chosen, rather than the one specifically for older people (> 65 years), given plans to expand the study to a wider range of building typologies which will encompass a broader age range of adults than the current study. The measures are linked to a capability approach which defines well-being in terms of an individual's ability to 'do' and 'be' the things that are considered important in terms of general well-being across five attributes: feeling settled and secure; love, friendship and support; independence; achievement and progress; enjoyment and pleasure.[36] Each attribute has a four-point score ranging from no capability (0.00) to full capability (1.00). The data collected were converted using the licensed scoring algorithm and a score for each of the five attributes, as well as an overall summary score, was obtained for each participant.

The UoHCS is a standard tool to support quantification of economic costs and frequency of use of services. The questionnaire captures the use of primary care services, including the number of contacts with general practitioner, nurses and other health professionals as well as relevant social services (e.g. meals on wheels) used by the participant in the 3 months prior to the interview. It attempts to capture all potential forms of primary care. For example, primary care consultations may be face-to-face at the practice, at the participant's home, or by telephone. Capturing this differentiation is important as the cost of each of these varies. The collated data were coded (e.g. score of 0 where no service has been used), with numbers representing an intensity of need for individuals. A table of service unit costs was generated (e.g. price per general practitioner visit at the surgery, or at the home) using information available in costs of health and social care and NHS tariffs.[37,38] Statistical Product and Service Solutions (SPSS) (IBM SPSS Statistics version 2.8.0.1.1; SPSS Inc., Chicago, IL, USA) was used to combine the codes with the costs to provide a cost per participant.

Data analyses

Co-location study

As part of the quality control procedure, all IQAir AVPro (indoor) and IQAir AVO monitors were colocated in a living room for 8 days, along with a Particles Plus® (PP) 7301-AQM2 (Stoughton, MA, USA) reference monitor for comparison. The PP monitor is compliant with ISO 21501-4[39] for PM, which relates to the calibration and verification of light scattering airborne particulate counters. Monitoring data (for $PM_{2.5,10}$ CO_2 concentration, temperature and relative humidity) from both types of IQAir monitors were compared with that measured by the PP monitor, thus ensuring a common reference for instrument performance. Comparison of monitors' performance against each other and against the PP monitor was carried out using the Pearson's correlation analysis statistic of Minitab version 19 (Minitab, Llc, State College, Pennsylvania, performance characteristics provided in *Appendix 4*, *Tables 6* and *7*). For PM_{10}, the slopes from the calibration plots were significantly higher than 1.0, indicating that the IQAir monitors substantially under-read compared to the PP (see *Appendix 4*, *Table 8*, *Figures 6* and *7*). Therefore, to ensure that the research monitor concentrations aligned with those of the reference monitor, a correction was carried out to generate $PM_{10(adj)}$ concentrations. For $PM_{2.5,}$ temperature, humidity and CO_2 concentrations of the indoor and outdoor monitors both have average slopes close to 1 and high R^2 values and as such no data corrections were applied (see *Appendix 4*, *Tables 9–12*, *Figures 8–14*). Full details of the co-location study are included in *Appendix 4*.

Characterising baseline air quality, health and well-being

For each AQ parameter monitored, normality testing was undertaken using the Kolmogorov–Smirnov test, with the median, arithmetic mean, minimum and maximum measurements determined based on hourly measurements for the monitoring period and for three different time periods: 24 hours; daytime (07.00–23.00 hours), considered to be the most 'active' time of the daily 24-hour period, when members of the study households were most likely to be awake and carrying our household activities; and night-time time (23.00–07.00 hours), considered to be 'non-active/less-active' time. We might, for example, expect indoor $PM_{2.5}$ concentrations to be higher during the daytime, as this was when the study participants did most of their cooking, cleaning and other activities that could generate spikes in PM concentrations. Higher concentrations of PM during the daytime, when compared to the night-time, may result in the daytime hours having a greater impact on health and/or well-being. In addition, increased levels of physical activity can also lead to changes in breathing patterns and an increased inhaled dose of air pollution.[40] As such, we wanted to explore if the daytime 'active' period had a greater influence on health and well-being than during the non-active/less-active phase.

As part of a data cleaning exercise, indoor PM data for three homes where smoking occurred indoors were excluded from the final data set to remove this confounding variable (i.e. homes IA15, IA18 and IA21) and from home IA28 after the point at which the PM sensor developed a fault. In addition, all indoor measurements (PM, CO_2, temperature and humidity) were removed from the data set for the period when occupants were away from the home for more than 24 hours (IA18, 23 December–9 January; IA19, 24–27 December and IA29, 12–19 February). The arithmetic average number of full days monitored per home was 28 (range 13–41 days).

Pearson's correlations were explored between the indoor environmental variables. To explore associations between the indoor and outdoor measurements, univariable analyses were conducted using simple linear regression on hourly arithmetic mean data. Associations between an outcome and more than one explanatory variable were done using multiple regression with backwards elimination. This method for multiple regression is an iterative process, and at each stage, the least significant variable is eliminated. We used a threshold of $p < 0.1$, so when all variables were significant at $p < 0.1$, we had our final model. It should be noted that for some analyses that all variables were eliminated.

Results and discussion

In *Cohort and home characteristics*; *Indoor baseline air quality/environmental data*; *Indoor–outdoor and indoor–indoor air quality comparisons*; *Outdoor $PM_{2.5}$ and roadside versus inner estate comparisons*; *Energy use and occupants' behaviour*; and *Multivariate analysis of the indoor air quality and health/well-being data*, we describe and discuss key findings of the baseline data collected for this initial time point, before retrofitting (i.e. In2Air Objective 2). In *Protocol refinement*, we consider refinements to the protocol (In2Air Objective 1) to inform future work.

Cohort and home characteristics

Across the 30 homes recruited into the baseline study, 25 homes had single occupancy and 5 homes had double occupancy. Most respondents were ≥ 65 years (80%) and identified as female (69%) (*Table 2*).

Participants spent a median of 1.57 hours per day out of the home (mean 2.7, minimum 0 and maximum 11.1 hours). All homes, except one, had electric cookers and hobs, with an extractor fan fitted in their kitchen in the corner of the room in the ceiling. When asked how often they

TABLE 2 Age and sex of study participants

Age category	Female	%	Male	%	Total
55–64 years	4	11.4	3.0	8.6	7
≥ 65 years	20	57.1	8.0	22.9	28
Total	24	68.6	11.0	31.4	35

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used the kitchen extractor fan, 37% of participants replied often, 30% never, 17% sometimes and 17% rarely; one participant noted that their kitchen extractor fan was not working. Participants were more likely to open a window or door when cooking, 47% often, 27% sometimes, 17% never and 10% rarely. 53% never closed the kitchen door when cooking, 27% often closed it, 13% sometimes and 7% rarely.

All homes had extractor fans in the bathrooms, some on the wall and some within the shower cubicle. In 33% of participants' homes, the fan came on automatically with the bathroom light; 33% of participants reported switching on their bathroom extractor fan regularly, 17% never, 13% rarely and 3% sometimes.

When asked how often they opened windows in the winter to let fresh air in or for any reason other than cooling down the room, 33% of the participants answered occasionally, 30% answered never, 27% answered every day and 10% said most days. When describing their indoor air on a scale from odourless to smelly, 41% of participants said odourless, 28% said neutral, 24% said occasional odours and 7% said smelly; 67% of participants regularly (once a week or more) used air freshener sprays, 23% used scent diffusers, 13% used candles and 23% did not use any. When describing their home air on a scale from still to draughty, 33% said very draughty, 30% reported some draughts, 30% said neutral, while 7% were described as always or usually still.

For the SF-36v2 health-related quality of life measure, when the baseline health and well-being scores for the study cohort for this first baseline time point were compared to the general population data (QualityMetric 2009 US General Population sample), most participants (83%) had a physical component summary (PCS) scores very much below the norm, even taking into account the margin of error (*Figure 1a*). This baseline is not surprising, given the age of the cohort. Data for the four categories which underpin the PCS are presented in *Figure 1c*. *Figure 1c* indicates the lowest scoring category is physical functioning (PF), followed by bodily pain (BP), with GH and role physical (RP) performing slightly better, albeit still below the norm. In comparison, the mental component summary (MCS) scores for most participants (74%) is at or above average, taking into account the margin of error (*Figure 1a*). For the four categories which underpin the MCS (*Figure 1b*), vitality (VT) is the lowest performing category role, closely followed by role emotional (RE); however, social functioning (SF) and mental health (MH) lie very close or slightly above the norm. The physical layout (three-square courtyards around communal grassed area with parking) and communal amenities (community centres and laundry facilities) of these small housing estates for people > 55 years of age may well be engendering a sense of belonging, leading to a more positive MCS when compared to (age-related) physical health impacts.

Overall summary scores for ICECAP-A ranged from 0.55 to the maximum possible score of 1.0 (mean = 0.81; median = 0.85; *Table 3*); validated with the UK adult population (18+ years), scores can range from 0, which represents 'no capability', to 1.0, which represents 'full capability'. While the mean/median score suggests a high level of capability across the cohort, 5/35 participants had ICECAP-A scores at the lower end between 0.55 and 0.60.

The average estimated cost of health and care services accessed over 3 months prior to the UoHCS survey was £245 (median £179) and ranged from £0, where four participants had accessed no health or social care, to £784.

Indoor baseline air quality/environmental data

For each of the environmental parameters monitored, summary data are reported below, except for PM_{10}. Only $PM_{2.5}$ data are reported, as $PM_{2.5}$ is the particulate fraction most strongly associated with adverse health effects because of the ability of these particles to penetrate more deeply into the respiratory system and the calibration data were more statistically robust.

As the distribution of the environmental measurements were found to be non-normal, we present summary data

TABLE 3 The ICECAP-A attribute scores and overall summary score for all participants (*n* = 35) in the baseline study

	Settled and secure	Love, friendship	Independent	Achievement	Enjoyment and pleasure	Summary score
Minimum	2	2	1	1	2	0.55
Maximum	4	4	4	4	4	1.00
Mean	3.3	3.5	3.2	2.7	2.9	0.81
Median	3	4	3	3	3	0.85

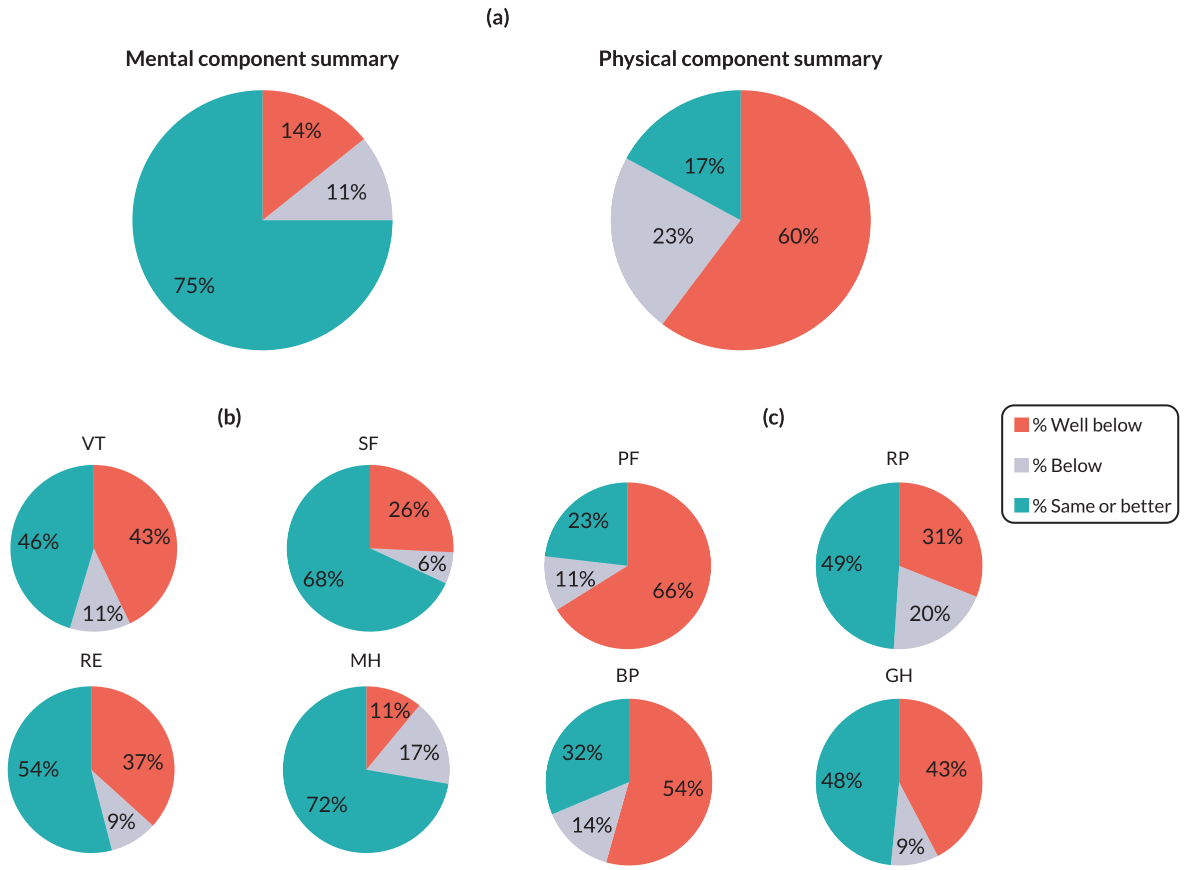

FIGURE 1 Baseline health and well-being scores from the SF-36v2 survey. (a) % sample whose MCS scores and PCS scores are the same or better, below or well below the general population norm normative data from the Quality Metric 2009 General Population Sample; (b) MCS Scale scores: VT, SF, RE and MH; (c) PCS Scale scores: PF, RP, BP and GH.

for both arithmetic mean and median values. While the median better reflects an 'average' central tendency when data are non-normally distributed, it should be noted that both national[41] and WHO[14] PM guideline values refer to annual or daily average/mean data.

Indoor particulate matter$_{2.5}$

The mean $PM_{2.5}$ concentrations over the monitoring periods (3–4 weeks during November 2022–March 2023) were compared to both the current UK (25 μg/m^3; 2019)[41] and WHO (5 μg/m^3; 2021)[14] annual average guidance values. While these current guidelines are for outdoor air, an increasing body of opinion suggests that we should also consider them to be appropriate for indoor environments.[42] Three households reported indoor smoking, and these homes had mean $PM_{2.5}$ concentrations of 71, 88 and 189 μg/m^3, respectively, for the monitoring period. If we exclude these three homes, then $PM_{2.5}$ means ranged from 3 to 24 μg/m^3; no homes had a 3- to 4-week monitoring period mean above the UK (2019)[41] outdoor annual mean limit (25 μg/m^3), while 21 homes had monitoring period means above the WHO (2021)[14] annual mean guidance value (5 μg/m^3) (*Figure 2*). With the UK Government positioned to set a target of 10 μg/m^3 for the annual mean concentration limit to be met by 2040,[43] we additionally considered this target. Ten homes reported monitoring period means above this target, although we acknowledge that our monitoring period was targeted to provide a worst-case scenario during the UK autumn/winter period. Clearly, retrofitting presents an opportunity to improve IAQ and 'future-proof' these homes ahead of more stringent AQ guidelines in the future.

There is currently no 24-hour mean $PM_{2.5}$ guideline in the UK, and so to monitor daily exceedances, the 24-hour mean $PM_{2.5}$ concentration for each home was compared to the current WHO (2021)[14] 24-hour $PM_{2.5}$ guideline (15 μg/m^3). Excluding 3 homes where smoking occurred indoors during the monitoring period, 18 of the 27 homes had at least three or more exceedances of this guideline during the monitoring period, with 24-hour means ranging from 3 to 24 μg/m^3 (see *Appendix 4*, *Table 6*). In total, 20% of the days monitored during this baseline study exceeded the current WHO (2021)[14] $PM_{2.5}$ 24-hour guideline (15 μg/m^3).

To better understand what might be driving the diurnal $PM_{2.5}$ concentration changes, we investigated the hourly mean $PM_{2.5}$ concentration for each home. The mean

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diurnal pattern, combining all homes (except for homes where smoking occurred indoors), is presented in *Figure 3*. As might be expected, the timing of homes' peak $PM_{2.5}$ concentration generally varied with cooking times, typically morning breakfast and evening meal. This is further highlighted by the diurnal pattern for each individual home (see *Appendix 5*, *Figure 15*).

In addition, we split the 24-hour day into daytime 'active' (07.00–23.00 hours) and night-time 'non-active/less-active' (23.00–07.00 hours) time periods. As might be expected, the active daytime part of the diurnal cycle was when the mean (and median) indoor $PM_{2.5}$ concentrations were typically at their highest (*Table 4*).

Indoor carbon dioxide, temperature and humidity

Guideline concentrations [typically for schools and offices, rather than residential contexts, and reported for daily mean (during the occupied period only)] suggest that CO_2 concentrations ≤ 1000 ppm, 1000–1500 ppm and > 1500 ppm represent good, moderate and poor IAQ, respectively.[44] On the basis of the 24-hour mean indoor CO_2 concentrations, our baseline monitoring indicated that 84% of study homes had good ventilation, 16% moderate ventilation, with none in need of additional ventilation (*Figure 4*). Mean indoor CO_2 concentrations for the baseline monitoring period and maximum mean/median CO_2 concentrations were all below 1500 ppm

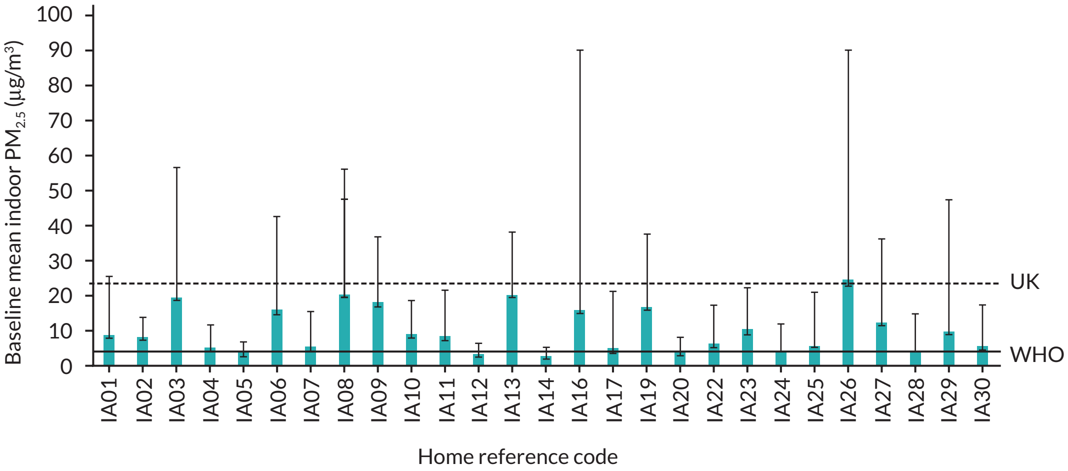

FIGURE 2 Mean hourly indoor $PM_{2.5}$ concentrations for the baseline 3- to 4-week monitoring period (November 2022–March 2023). The error bar indicates the positive standard deviation. The dashed line represents the current (2019) outdoor annual mean guideline for the UK,[41] and the lower solid line the current (2021) annual mean WHO[14] guideline. Note: the three homes where cigarettes were smoked indoors have been removed from the data set.

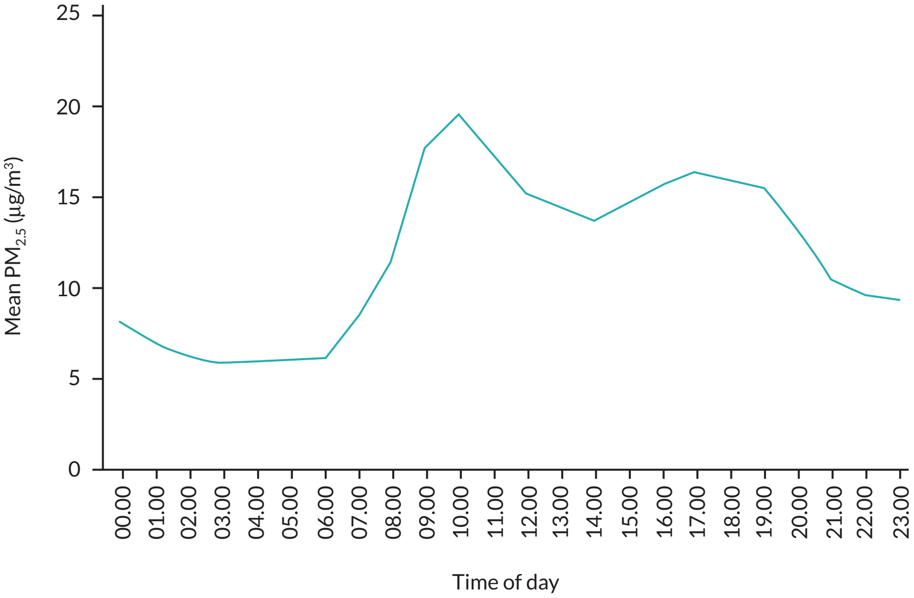

FIGURE 3 Mean diurnal $PM_{2.5}$ concentrations for all homes, except those where indoor smoking occurred during the study period.

TABLE 4 Indoor $PM_{2.5}$, CO_2, humidity and temperature for the baseline monitoring period

Measurement	Mean	Median	Minimum	Maximum
Individual home indoor $PM_{2.5}$ (μg/m^3)				
24-hour mean	10	8	3	24
24-hour median	5	4	2	14
Daily mean (07.00–23.00)	13	10	3	34
Daily median (07.00–23.00)	7	2	2	18
Nightly mean (23.00–07.00)	7	2	2	18
Nightly median (23.00–07.00)	4	3	2	13
Individual home indoor CO_2 (ppm)				
24-hour mean	838	770	559	1379
24-hour median	802	732	526	1418
Daily mean (07.00–23.00)	879	810	570	1400
Daily median (07.00–23.00)	847	805	570	1421
Nightly mean (23.00–07.00)	762	718	519	1359
Nightly median (23.00–07.00)	734	672	476	1399
Individual home indoor humidity (%)				
24-hour mean	52	51	39	72
24-hour median	52	51	39	73
Daily mean (07.00–23.00)	52	51	39	72
Daily median (07.00–23.00)	52	51	39	73
Nightly mean (23.00–07.00)	51	51	38	72
Nightly median (23.00–07.00)	52	51	38	73
Individual home indoor temperature (°C)				
24-hour mean	20	20	14	26
24-hour median	20	20	15	26
Daily mean (07.00–23.00)	20	21	14	26
Daily median (07.00–23.00)	20	21	15	26
Nightly mean (23.00–07.00)	20	20	14	26
Nightly median (23.00–07.00)	20	20	14	26

(*Table 4*). We asked participants to rate the air in their homes on a scale of 1–5, where 1 was stale and 5 was very fresh; 96% of participants rated their home ≥ 3 (3 at 43%, 4 at 30% and 5 at 23%). None rated it at 1 (stale).

Our baseline monitoring indicated the maximums of both the mean and median temperatures were 26 °C, while the minimum mean and median temperatures were 14 °C and 15 °C, respectively (see *Table 4* and *Appendix 6*, *Figure 16*). In the winter (when using heating), the temperature in homes was described as comfortable (53%), comfortably cool (10%) and uncomfortably cold (30%). Single respondents (3%) reported homes to be comfortably warm or uncomfortably hot, respectively. When asked if their heating kept them warm enough in the winter months, 40% answered yes/always, 38% answered most of the time and 20% only some of the time. A single respondent answered that their heating never kept them warm enough. When asked how often they opened windows in the winter to let in cooler air because the home was too hot, 60% of the

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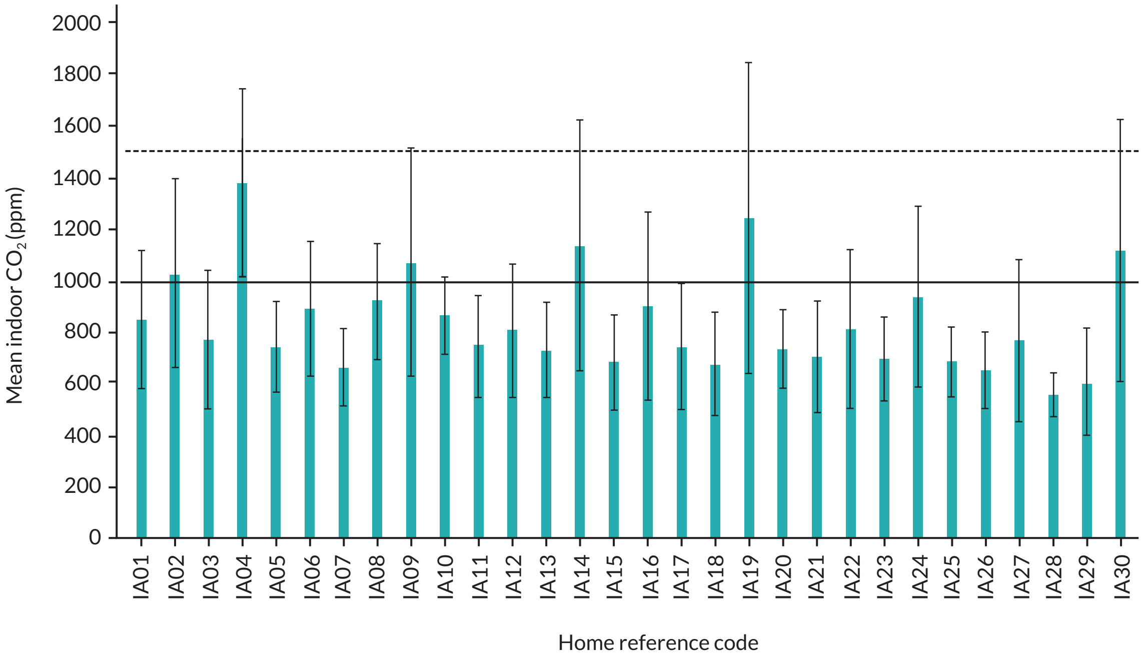

FIGURE 4 Mean indoor CO$_2$ concentrations for the baseline monitoring period. The error bar indicates the standard deviation. Values ≤ 1000 ppm (below the solid line), 1000–1500 ppm (between the solid and dashed lines) and > 1500 ppm (above the dashed line) represent good, moderate and poor IAQ, respectively.[44]

participants answered never, 30% answered occasionally, two participants (7%) answered every day and one answered most days; 20% of participants reported being very happy with the temperature in their home, 17% were happy, 33% satisfied and 30% unhappy.

Our baseline monitoring indicated a maximum mean and median humidity of 72% and 73% and a minimum of 38% and 39%, respectively (see *Table 4*). The majority of homes indicated mean humidity levels within the range considered healthy (i.e. between 40% and 60%),[42] with only three homes falling above this range. These three homes reported > 60% humidity for > 85% of the baseline study period (IA04, IA10, IA14; *Figure 17* and *Appendix 6*, *Table 13*).

Indoor–outdoor and indoor–indoor air quality comparisons

Univariate relationships between the indoor and outdoor environmental variables (hourly arithmetic mean data) were as follows: 20/30 homes showed a statistically significant ($p < 0.05$) association between the indoor and outdoor levels of humidity; 28/30 homes showed a statistically significant ($p < 0.05$) association between indoor and outdoor temperatures; 22/27 homes showed a statistically significant association between indoor and outdoor PM$_{2.5}$ concentrations. While indoor activities (such as cooking, smoking and cleaning) can produce large amounts of PM, it is well documented that outdoor PM is a significant contributor to indoor PM levels. Indeed, an association between indoor and outdoor PM has been reported by numerous studies highlighting the ingress of fine PM from outdoors through air exchange.[45–47] Outdoor PM can ingress indoors via mechanisms such as natural ventilation and infiltration through cracks and leaks in the building envelope and via active mechanical ventilation, given filters do not remove all outdoor PM. The indoor PM$_{2.5}$ concentration/outdoor PM$_{2.5}$ concentration (I/O ratio) represents the relationship between indoor and outdoor particle concentrations. We observed a high variability of I/O ratios (based on hourly mean indoor PM$_{2.5}$ concentration/hourly mean outdoor PM$_{2.5}$ concentration) across 27 homes: mean I/O PM$_{2.5}$ ratios ranged from 0.3 to 5.0 (see *Appendix 7*, *Table 14*). A systematic review of 77 studies reporting I/O ratios across various locations for a range of PM particle sizes highlighted mean ratios ranging from < 0.5 up to > 3.[47] This range is perhaps not surprising, given the variety of influencing factors and studies which suggest that I/O ratios can also vary seasonally as a result of changing human activities across the seasons (i.e. generally higher correlations of indoor and outdoor concentrations and I/O ratios closer to unity during summer in climates where occupants open windows during the warmer season).[47] Indeed, as noted by Chen and Zhao,[47] it is difficult to make generalisations about the indoor/outdoor relationship from I/O ratios without more detailed information on home characteristics and occupant behaviours.

Pearson's correlations between the indoor environmental variables (hourly arithmetic mean data): strong correlations were observed between indoor $PM_{2.5}$ and indoor $PM_{10(adj)}$ (with r ranging from 0.860 to > 0.990), suggesting similar sources, while no-to-weak correlations were observed between indoor CO_2 and indoor $PM_{2.5}$ and indoor CO_2 and indoor $PM_{10(adj)}$ (with r ranging from 0.017 to 0.303). While moderate-to-good ventilation was suggested by indoor concentrations of CO_2 across the study homes (*Figure 4*), the lack of correlation to PM has important implications for retrofit teams undertaking post-work IAQ monitoring. This observation provides an important message to the architectural profession, where IAQ often remains synonymous with monitoring CO_2, temperature and humidity despite recommendations to monitor PM in BS 40101.[25] Decarbonisation funding for retrofitting provides a timely opportunity for environmental health education and interventions to improve IAQ. If we are to leverage this opportunity to tackle poor IAQ, then we need to monitor IAQ across a broad range of parameters, making the most of the increasing availability of low-cost sensors and 'smart technologies' to generate the evidence base for green retrofit approaches.

Outdoor particulate matter$_{2.5}$ and roadside versus inner estate comparisons

Outdoor $PM_{2.5}$ concentrations at the study location had P10–P90 (10th to 90th percentile values) ranging from 1 to 48 µg/m^3, with a mean of 11 µg/m^3. Summary of the outdoor $PM_{2.5}$ concentrations at each of the 27 homes are provided in *Appendix 8*, *Table 15*.

As an aside, and to address concerns raised by the study participants who were interested to know if differences could be observed between PM measurements recorded by the outdoor monitors at homes along the main road compared to outdoor monitors at the inner estate homes, we investigated these comparisons. Data were tested using a paired t-test, with the results and discussion included in *Appendix 8*. Outdoor $PM_{2.5}$ was significantly higher ($p < 0.0001$) at the roadside homes compared with the homes in the inner estate.

Energy use and occupants' behaviour

We used various approaches to quantify mean daily energy consumption based on the best available data for that home. Due to difficulties in obtaining these data, we only have information for 19 of the 30 homes. We used smart meter readings where available, together with utility bills for the previous 12-month period. Daily electricity consumption varied from 2.1 to 28.4 kWh per day, with gas consumption ranging from 0.3 to 2.3 kWh per day (*Figure 5*).

The onsite energy audit and conversations conducted with the occupants of the homes revealed a wide range of behaviours and corresponding energy use patterns. While all participants used the communal gas central heating to heat their homes in winter, 25% of residents used an additional heating device to supplement their central heating. These devices included electric blankets ($n = 2$), hot water bottles ($n = 2$) and electric heaters ($n = 4$).

Nearly all occupants expressed an increased awareness of escalating energy prices, energy poverty and the necessity to limit heater usage during colder months to avoid unaffordable utility bills; 11% reported a change in their energy use because of the recent energy crisis and increase in energy prices; 38% reported having reduced their use of fuel for heating as much as possible, 50% said they had not tried to reduce it at all and others said they found it hard to reduce, could reduce it further or did not know.

Multivariate analysis of the indoor air quality and health/well-being data

To explore which of the monitored indoor environmental variables influence or predict health and well-being measures at this baseline time point, we used multivariable analysis in SPSS (see *Characterising baseline air quality, health and well-being*).

Table 5 summarises the findings of the multivariable regression analysis and highlights which of the five environmental variables (i.e. the explanatory variables: CO_2, $PM_{2.5}$, $PM_{10(adj)}$, temperature and humidity) influence or predict the health and well-being measures (i.e. the response variable). We tested four sets of data for the environmental variables, by using four separate regression models: two data sets included all the measurements over the 24 hours of daily measurement, but used either mean (model 1) or median (model 3) as the measure of central tendency, and the other two data sets used measurements collected in the most active period only (07.00–23.00 hours), again split into either mean (model 2) or median (model 4) as the measure of central tendency. We considered that the environmental variables measured during the active period were likely to have a greater influence on health and well-being. Indeed, the mean and median environmental measurement values using data from the active period (models 2 and 4) predict more of the variability in that health and well-being score than their 24-hour data equivalent (see *Table 5*). While we comment on each of the four data sets/models, given the median is a better measure of central tendency with non-normally distributed data, and the active period is when most residents are likely to have maximum exposure, on balance, model 4 is our preferred model and we cover this in greater depth.

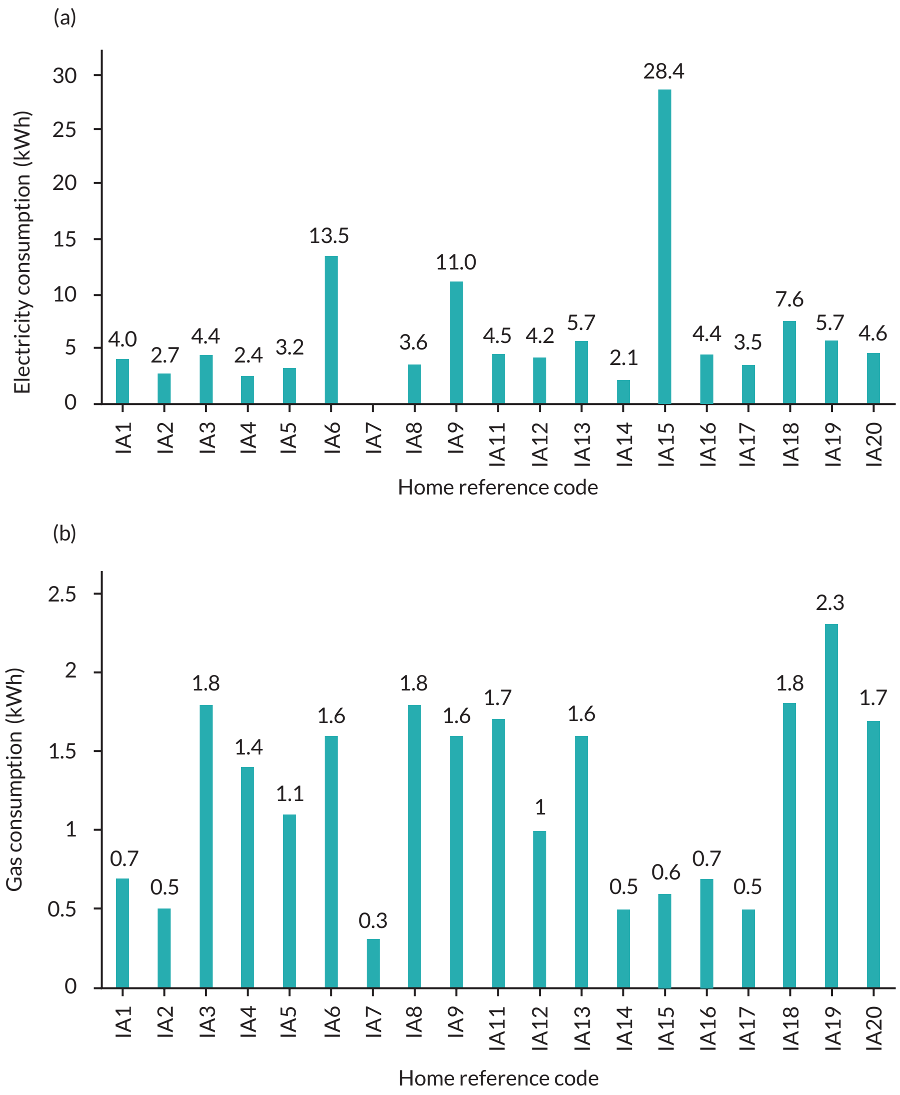

FIGURE 5 Daily mean electricity (a) and gas (b) energy consumption (kWh).

The model R^2 value (indicated by the % in brackets in *Table 5*) indicates how much of the variability of the health and well-being score can be predicted by that environmental variable or combination of variables. We have included all environmental variable contributions with p-values < 0.1 in *Table 8*; greater statistical significance is indicated with asterisks * for $p < 0.05$ and ** for $p < 0.01$. Some of the response variables were not affected by any of the explanatory variables, indicating only random variation (e.g. SF36v2 Mental Component Summary), while other response variables indicated statistically significant influence, albeit usually very low explanation of the response variable by the explanatory variables (see *Table 5*). For example, in model 4, 34% of the variability in the physical function score can be predicted by the active hours' median CO_2 and $PM_{10(adj)}$ concentrations and temperature, so 66% of that variability is down to other unexplained factors. As only 11% of the variability in UoHCS costs in the last 3 months (also model 4) can be predicted by CO_2 concentration, so 89% of the variability is due to other unexplained factors.

The sign of the unstandardised linear regression coefficient from the fitted models indicates whether the health and well-being score increased or decreased as the environmental variable increased (see *Table 5*). In model 2, an increase in the mean concentration of $PM_{10(adj)}$ during active hours was associated with an increase in UoHCS costs in the previous 3 months (although the $PM_{10(adj)}$ only predicts 14% of the variability). Several SF36v2 physical components (PF, role limitations due to physical health problems and the summary score for the physical components and GH) all decrease with an increase in temperature. Indeed, lower SF36v2 PF scores are associated with higher indoor temperatures across all four data sets/all four models. With an elderly cohort,

TABLE 5 Summary of best fit models by backwards elimination multivariant regression models with $PM_{2.5}$, CO_2, $PM_{10\ (adj)}$, temperature and humidity as predictors of measures of health and well-being

Health and well-being variable		Mean 24 hours	Mean active hours	Median 24 hours	Median active hours
ICECAP-A score					
UoHCS (cost)		$-PM_{2.5}$ (11%) UoHCS = 393.11–11.78 $PM_{2.5}$	+ PM_{10} (14%) UoHCS = −3.33 + 1.64 PM_{10}		+ CO_2 (11%) UoHCS = −48.25 + 0.37 CO_2
SF36v2 overarching summary scores (average)	SF36v2 mental component summary (MCS)				
	SF36v2 physical component summary (PCS)			− Temp*, − Hum, + PM_{10} (24%) $SF36_{PCS}$= 159.12–1.022 Hum + 0.36 PM_{10}–3.89 Temp	− Temp (13%) $SF36_{PCS}$= 64.69–1.43 Temp
SF36v2 subset scores	SF36v2 BP		+ $PM_{2.5}$ (12%) $SF36_{BP}$= 25.77 + 1.13 $PM_{2.5}$		
	SF36v2 GH				−Temp (12%) $SF36_{GH}$= 113.01–3.15 Temp
	SF36v2 MH	+ PM_{10} (12%) $SF36_{MH}$= 67.10 + 0.18 PM_{10}			
	SF36v2 PF	−Temp (14%) $SF36_{PF}$= 115.98–3.87 Temp	−Temp (14%) $SF36_{PF}$= 118.08–3.92 Temp	−Temp (11%) $SF36_{PF}$= 107.20–3.42 Temp	$-CO_2$, −Temp**, + PM_{10} (34%) $SF36_{PF}$ = 191.19–0.05 CO_2 + 1.04 PM_{10}–6.16 Temp
	SF36v2 role limitations due to personal or emotional problems (RE)				
	SF36v2 role limitations due to physical health problems (RP)				−Hum*, −Temp**, + CO_2 (26%) $SF36_{RP}$= 450.53 + 0.06 CO_2 −4.10 Hum −11.39 Temp
	SF36v2 SF		−Hum*, −Temp*, + PM10 (24%) $SF36_{SF}$= 404.21–2.78 Hum + 0.467 PM_{10}–9.689 Temp		−Hum, −Temp (14%) $SF36_{SF}$= 385.94–2.63 Hum–8.52 Temp
	SF36v2 VT				

Note
The fitted models are included and the model R^2 value is indicated by the % in brackets. All contributions with p-values < 0.1 are included with greater statistical significance indicated with asterisks (* for $p < 0.05$ and ** for $p < 0.01$).

also comes a demand for higher indoor air temperatures due to age-dependent changes in thermoregulation, exacerbated by longer periods of time spent at home.[26] As such, this may reflect our elderly cohort and, additionally, participants with restricted movement requiring higher home temperatures for comfort.

Not all model findings, however, are readily interpretable, due to possible collinearity between explanatory variables. In model 4, using median active hours' data, SF36v2 PCS and SF36v2 GH is negatively associated with temperature (as noted above, likely reflects our elderly cohort), UoHSC cost is positively associated with levels of CO_2, while SF36v2 PF is negatively associated with levels of CO_2 and temperature and is positively associated with in levels of $PM_{10(adj)}$. SF36v2 role limitations due to physical problems is negatively associated with humidity and temperature and is positively associated with levels of CO_2, and SF36v2 SF is negatively associated with humidity and temperature. In model 2, using mean active hours data, while UoHCS cost is positively associated with levels of $PM_{10(adj)}$ and SF36v2 BP is positively associated with levels of $PM_{2.5}$, which might be understood in a context of reduced IAQ driving reduce health outcomes, SF36v2 SF is positively associated with levels of $PM_{10(adj)}$ and is negatively associated with humidity and temperature. However, collinearity between explanatory variables may also have a role to play.

In summary, in terms of our baseline (pre-retrofit) findings for each health and well-being variable, we found that the ICECAP-A score could not be predicted by any of the environmental measurements, with somewhat contradictory significant environmental predictors for UoHSC, all predicting < 15% variability. Prediction increased with median active hours' CO_2 and mean active hours' $PM_{10(adj)}$. Of the SF36v2 summary scores, none of the environmental variables we measured were significant predictors for the MCS; 24% of the SF36v2 PCS was predicted by a combination of median 24 hours temperature, humidity and $PM_{10(adj)}$. Lower physical component summary scores had higher temperature and humidity and lower $PM_{10(adj)}$ concentrations (possibly less likely to be active and cooking). Similarly, a higher median active hours' temperature (13%) predicted a lower SF36v2 PCS.

For the SF36v2 subsets: poorer GH was predicted by higher median active hours' indoor temperature. Poorer MH was predicted by higher mean 24 hours' indoor $PM_{10(adj)}$ concentrations. More body pain was predicted by higher mean active hours' $PM_{2.5}$ concentration. Poorer PF was predicted by higher mean 24-hour temperature, higher mean active hours' temperature, higher median 24-hour temperature and (the strongest prediction we found at 34%) a combination of higher median active hours' CO_2 and temperature and lower median active hours' $PM_{10(adj)}$.

Role limitations due to physical health problems were predicted by the median active hours' data set only by a combination of increased humidity and temperature and lower CO_2. While higher indoor temperatures may be preferred by those with greater physical health problems, how we might interpret the humidity and CO_2 data are less clear. Lower SF scores were predicted by a combination of lower mean active humidity and temperature and higher $PM_{10(adj)}$ concentrations and also by a combination of lower median active humidity and temperature. Variability in role limitations due to personal or emotional problems and VT score were not predicted by any of the measured environmental variables.

Protocol refinement

A detailed critique on the robustness and usefulness of each element of the protocol for the purposes of pre- to post-retrofit change identification can only be undertaken after the post-retrofit data collection phase; however, our experiences of deploying the In2Air protocol (version 1.1) highlight areas for change, as outlined below.

Survey modifications

We recommend the inclusion of an open question to capture any respiratory health issues (e.g. asthma and COPD) experienced by the home occupants as well as any out-of-pocket costs related to health-seeking activities, such as the purchase of products from a pharmacist for self-medicating. While the health and well-being surveys we used are established, validated tools, the home characteristics, activities and behaviours survey is an unpublished survey adapted from one supplied by BRE. We were guided by BRE's experiences of its deployment and robustness across a broader range of building types but remain open to further modifications, especially in the context of our usage investigating pre- to post-retrofit change. The addition of a question as to the presence of pets at the property would seem prudent; pets, particularly cats and dogs, may require internal and external doors and/windows to be opened for access and the increased potential to bring in outdoor soil on paws and create additional dust in a home.

As local authorities are particularly well positioned to disseminate climate action cobenefit-related messaging to their communities, an opportunity exists to incorporate such messaging as part of the post-retrofit survey. Here, we recommend the use of a recently developed survey to explore the perceptions of UK citizens of the co-benefits of climate action.[48] Such a survey has the potential to engage a broader public audience to contribute to a cleaner, greener future.

Addition of a control group

While the health benefits of housing interventions are notoriously difficult to isolate because of the many confounding variables,[49] longitudinal cohort studies, covering a period before and after an intervention, have been deployed as a suitable approach.[50–52] However, our somewhat mixed findings from the regression analysis on health outcomes and exposures (see *Multivariate analysis of the indoor air quality and health/well-being data*) led us to explore how best to include a control group as part of any follow-on activity. The control cohort needed to be of sufficient size to fulfil statistical power requirements while maintaining study costs and overall feasibility. To achieve this, we recommend including a control group of participants who receive the home/occupier survey as well as the health and well-being surveys (ICECAP-A, SF36v2 and UoHCS), as these can be administered using an online delivery approach. This approach focuses on the key health/well-being attributes being monitored, enabling identification of changes occurring in the control group during the study period independent of the retrofit intervention. A propensity score method is proposed to minimise the sample size for a control group[53–55] by enabling the research team to understand how closely participants in homes undergoing retrofit and controls match. Comparison of control group data with the retrofit cohort will allow us to identify changes specific to the retrofit group.

Consideration of a ‘rebound effect’

It is also important to consider the potential for any rebound effects. For example, in certain cases, the anticipated energy savings post retrofit may be partially offset by increased energy use, often attributed to this so-called rebound effect.[56,57] Going forwards, we recommend the need to proactively address this concern by incorporating an awareness-raising component targeted at occupants during energy audits, site visits and interviews. By enhancing occupants’ awareness about energy efficiency practices, our aim is to encourage responsible and mindful energy consumption behaviour. Fostering a culture of energy awareness may contribute to mitigating the rebound effect and ensuring that the benefits of the energy efficiency retrofits are maximised.

Additional in-study sensor quality control

We recommend periodic instrument quality assurance checks to understand any instrument drift during the period of usage. We also recommend particular attention be paid to ensuring, where feasible, that the same individual monitors are deployed during both the pre- and post-intervention monitoring of each home.

Limitations

Monitoring AQ and energy use in residential housing presents several well-documented limitations, which can significantly affect the generalisability of findings and their applicability to diverse contexts. Many studies focus on specific building typologies, such as detached houses or urban apartment complexes, limiting the applicability of findings to other contexts. Indeed, this pilot study focused on a social housing community that was strategically chosen to provide a narrow range of confounding variables. Given the nature of these properties (all single-storey, relatively small, one- and two-bedroomed properties, occupied by one to two tenants, all older than > 55 years), broader generalisations may be limited, and both the developed protocol and the baseline findings need to be validated against a more diverse range of communities and building typologies.

Air quality monitoring often relies on low-cost sensors due to budget constraints, but these devices face accuracy challenges and typically require calibration to account for local environmental conditions, such as temperature and humidity fluctuations. These limitations can lead to discrepancies in measurements as sensor performance can vary significantly across different climates,[58] reducing the reliability of comparative studies. Furthermore, gaps in data collection can arise from spatial and temporal inconsistencies in sensor placement in multiroom housing, leaving critical zones under-monitored.[59] Our study focused on changes to the building envelope and utilised fixed indoor and outdoor monitoring locations. Monitoring in one room only (i.e. the main living room) potentially misses important exposure information such as conditions in the bedroom where participants are likely to spend significant time. We designed and implemented a pragmatic protocol using currently available low-cost, low-impact (e.g. small and quiet) sensors suitable for large-scale home deployment. Portable monitors, however, are considered the ‘gold standard’ for individual exposure assessment as fixed location monitors can underestimate the true level of personal PM exposure.[60,61]

In addition, the study relied upon the efficacy of newly purchased ‘factory-calibrated’ sensors. While a co-location study and cross-comparison to a PP sensor were undertaken, there is a measurement uncertainty with all sensors, but particularly low-cost sensors and

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validation against reference monitors (such as tapered element oscillating microbalance for PM or indeed or any instrument that meets the BS EN 16450[62] criteria) are needed to independently confirm the accuracy of the data. Uncertainty varies significantly dependent on the averaging time frames and establishing uncertainty of data across both short term (up to 1 day) and longer term (the 3- to 4-week monitoring period) is recommended.

Indoor and outdoor exposure can vary seasonally, and it is important to note that our study took place only in the UK autumn/winter when IAQ can be expected to be at its worst[32] and there remains a need to establish baseline IAQ in both heating and non-heating seasons.

It remains challenging to comprehensively assess the indoor domestic AQ, at scale, given the multitude of sources of indoor air pollution. Our study focused on a narrow range of AQ variables, and limitations of our study include not monitoring other key pollutants in air, particularly those that can accumulate much higher concentrations indoors than out due to their release from a range of indoors sources, such as carbon monoxide (CO), from the incomplete combustion of fuels in heating and cooking appliances, as well as emissions arising from soft furnishings, painting and decorating, and the use of construction, cleaning and personal care products (e.g. volatile organic carbons, semi-volatiles and flame retardants).[32] For NO_2, the concentrations are generally higher outdoors, except when there is poorly extracted gas cooking.[32]

Energy-use monitoring in housing studies encounters similarly significant limitations. Occupant behaviour is a major source of variability, as cultural practices and individual preferences for heating and cooling can create discrepancies in energy consumption patterns even within identical housing typologies.[63] In addition, energy efficiency conclusions drawn from studies of single-family homes often fail to translate to high-rise residential buildings, where architectural designs, occupancy densities and ventilation systems vary widely.[64] Technical and logistical barriers also compound these challenges. Retrofitting older housing stock with advanced energy monitoring systems is not only costly but also technically challenging, as buildings constructed before the 1970s often lack the infrastructure to support such technologies.[65] Privacy concerns further hinder the adoption of detailed monitoring systems, as residents may resist installations that could inadvertently reveal personal habits.[66] Together, these limitations indicate that, while findings from individual studies are valuable, their broader applicability is often constrained. Addressing these gaps requires incorporating diverse housing typologies, integrating advanced, context-aware monitoring systems and exploring multisite studies to better generalise results across different socio-environmental contexts.

Equality, diversity and inclusion

Participant recruitment specifically targeted under-represented groups in health-related research, which is the elderly and communities living in social housing. To remove financial barriers to study participation, we provided financial incentives/compensation which covered costs incurred related to the time spent with a researcher and energy use of the sensors. To remove mobility barriers, participants were able to undertake all elements of the study from their home.

Conclusions and future work

The UK Social Housing Decarbonisation fund is providing an opportunity to use architecture and design to improve both the energy efficiency, as well as the IAQ, in social housing. A significant outcome of this pilot project was the development and deployment of a protocol (version 1.1; available at www.in2air.org.uk). The baseline conditions captured in this study provide the basis on which to inform and evaluate the effects of energy-efficient retrofit across this social housing stock as part of ongoing research (NIHR160372; www.in2air.org.uk). This is particularly relevant for affordable housing organisations which operate on very limited budgets, and additional costs of mechanical ventilation above those required for minimum regulatory compliance can be prohibitive. With the exclusion of three homes where smoking occurred indoors, no homes had monitoring period mean $PM_{2.5}$ concentrations above the current UK (2019)[41] outdoor annual mean limit (25 $\mu g/m^3$); however, 21 homes had monitoring period means above the stricter WHO (2021)[14] annual mean guidance value (5 $\mu g/m^3$). Retrofitting presents an opportunity to improve IAQ and ‘future-proof’ these homes ahead of more stringent AQ guidelines in the future.

Individual exposures are influenced by a range of indoor and outdoor sources as well as behavioural activities, and our results show that a detailed evaluation of home characteristics and occupant behaviours is needed when estimating indoor exposure to pollutants. Here, smoking is a key example as indoor smoking in three of our monitored homes led to elevated $PM_{2.5}$ concentrations, well above current UK guidelines. Cooking also has a direct impact on residential indoor PM concentrations, as suggested with peaks often occurring around mealtimes.

Electricity and gas energy consumption were established, based on data gathered from utility bills and meter readings. Unfortunately, the energy monitoring and assessment revealed various issues of energy data absence, data that we deemed necessary to collect to help inform how we achieve net zero energy targets. However, most of the occupants exhibited a high level of awareness of the energy dilemma and the need to control their energy use.

Tackling both climate change (via reduced household energy use) while at the same time improving IAQ has significant potential to improve residents' health and well-being. If we are to improve IAQ, then we need to see greater routine monitoring of PM concentrations in addition to the more commonly monitored environmental metrics of temperature, humidity and CO_2. Moderate-to-good ventilation, determined by the indoor concentrations of CO_2, was observed across all of the study homes at this baseline monitoring time point. Importantly, the lack of correlation between CO_2 and PM concentrations has implications for retrofit teams undertaking post-retrofit IAQ monitoring and serves to galvanise the architectural profession, where IAQ often remains synonymous with CO_2 monitoring only.

The delivery of 'net-zero' changes across all social housing stock will take time; however, the protocols developed in this study, and the baseline findings, have the potential to directly inform decision-making of council retrofit teams across the UK with their ongoing decarbonisation plans.

Additional information

CRediT contribution statement

Jane Entwistle (https://orcid.org/0000-0002-4375-4502): Conceptualisation (equal), Data curation (lead), Formal analysis (lead), Funding acquisition (lead), Investigation (lead), Methodology (equal), Project administration (lead), Resources (supporting), Software (equal), Visualisation (lead), Writing – original draft (lead), Writing – reviewing and editing (lead).

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Data-sharing statement

The In2Air study investigators are committed to furthering research by sharing, where possible, de-identified individual home and participant data. Data are shared in accordance with the project data management plan at https://doi.org/10.25398/rd.northumbria.24786027.v1. For any other data requests or queries, please contact the corresponding author.

Ethics statement

Ethical approval for the study was granted (30 August 2022) from Northumbria University Research Ethics Committee (submission reference 51426) based on draft protocol v0.2. Following finalisation of protocols, a re-submission to Northumbria University Research Ethics Committee (submission reference ID3115) was made and subsequently granted (29 March 2023).

Information governance statement

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List of abbreviations

AQ	air quality
AVO	AirVisual Outdoor
AVPro	AirVisual Pro
BP	bodily pain
BRE	Building Research Establishment
COPD	chronic obstructive pulmonary disease
EPC	Energy Performance Certificate
GH	general health
IAQ	indoor air quality
ICECAP-A	ICEpop CAPability measure for Adults
I/O	indoor $PM_{2.5}$ concentration/outdoor $PM_{2.5}$ concentration
MCS	mental component summary
MH	mental health
NCC	Newcastle City Council
PCS	physical component summary
PF	physical functioning
PIL	participant information leaflet
PMxx	particulate matter (size fraction)
PP	Particles Plus
PV	photovoltaic
RE	role emotional
RP	role physical
SF	social functioning
SPSS	Statistical Product and Service Solutions
UoHCS	Use of Health and Care Services survey
VT	vitality
WHO	World Health Organization
YHN	Your Homes Newcastle

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Appendix 1 Participant information leaflet and participant consent form

Participant information leaflet

We are inviting you to take part in a study to help explore how home energy efficiency modifications affect IAQ and energy use. Before deciding whether to participate, here is some information about the project and what you would be asked to do if you take part.

Why are we doing this study?

The UK Government has set challenging targets to reduce our production of greenhouse gases (the ‘net-zero’ challenge), as these gases cause the planet to warm and drive climate change. Homes play a large part in greenhouse gas emissions and, in response, housing providers are making changes to homes to reduce household energy use. Local authorities and private homeowners around the UK are adding extra insulation, reducing draughts and adding solar panels to make homes more energy efficient. We want to find out if these changes alter the amount of fresh air in the home or the health and well-being of residents.

We want to measure energy use, small inhalable particles, temperature, humidity and fresh air in ___________ before the energy efficiency building works are carried out. Technology is now available that can do this with small, quiet monitors.

What will you be asked to do?

If you decide to take part in the study, your participation will involve the following:

1. Placing a small, quiet, air quality monitor in your living room and another outside your home. The monitors will record the very small (inhalable) particles in air, ventilation, temperature and humidity in the room. You will be able to view the measurements on its screen. The sensors will be left in place for at least 4 weeks, ideally longer, or until your retrofit works begin, whichever is sooner.
2. Allow the researcher to see your energy bills for the previous 12 months.
3. Allow the researcher to read your gas and electricity meters at the start and end of your monitoring period.
4. Help us complete a survey about your health and well-being and about your home and things that affect what we are monitoring, like the number of people, their activities and ventilation, if you have damp problems and items in your home that may use a lot of energy.

Who can take part?

Anyone living in a bungalow in _________, who will be having energy efficiency retrofit works on their home can participate. For households where someone smokes indoors, if the smoker agrees to smoke outside during the study, then the household can take part.

How will we process the data obtained from you?

Your questionnaire answers, activity records and air data will be stored in anonymised form on the password-protected secure private network of Northumbria University. It will only be accessed by researchers working directly on this project.

If you do not want to continue participating in this research, what should you do?

You can change your mind and exit the study at any time without giving a reason. If you withdraw from the study, we will process the data according to your wishes, either retain or delete it from our records. However, please note it is not possible to delete anonymised data once published (see below for further details).

What will happen to the results of the research and how will my confidentiality be protected?

Your personal information will be stored on a password-protected secure private network at Northumbria University and will only be accessed by researchers working directly on this project. We will write up the findings of this study to share with all interested parties; however, your information will not be identifiable (you will remain anonymous). If you would like, we will also provide you with a summary of the findings and your air quality data.

What are the possible benefits and disadvantages to taking part?

There are no expected disadvantages from taking part in this study. You will be reimbursed up to £80 for running the air quality monitor and for your time answering the questionnaires and completing the diary. We provide you with updates and you will gain understanding of activities that impact your home's IAQ.

Who is organising this research and what if there is a problem?

The research is being undertaken by Northumbria University, Newcastle University and Newcastle City Council. The work is led by Professor Jane Entwistle and Dr Richard McNally. If you have any questions, you can contact us on NUMBER or ee.in2air@northumbria.ac.uk and we will do our best to answer your questions.

You might also like to …

Know more about how much different appliances in your house cost to run. We are looking for two homes that would like to know more about their day-to-day energy use. We have equipment that can measure detailed energy use. The kit is small and would not be intrusive. If you would like to find out more about this, please contact us on NUMBER or E-MAIL.

Help us to design the study

We are looking for two _________ residents to join the Community Steering Committee to help us plan community activities and to make sure we target any of the community's worries and interests around air quality and fuel efficiency. If you would like to find out more about this role, please contact us on NUMBER or E-MAIL.

Participant consent form

I have read and understood the information for participants in the In2Air research project of Northumbria University, a project in collaboration with Newcastle City Council and Newcastle University. I understand that this research will explore how home energy efficiency modifications affect IAQ, energy use and the GH and well-being of the study participants.

The study has been explained to me by Name: ______________

I understand that taking part is voluntary and that I can change my mind at any time without giving any reason, without penalty. If consent is withdrawn, any personal data collected up to that point will be destroyed unless consent is given to keep it.

I understand that the information I provide will be treated with the strictest confidence and stored securely.

I am aware I will be asked to provide the following:

- survey responses (including questions on my GH and wellbeing)
- gas and electricity bills
- access to gas and electricity meters.

I consent to the collection of IAQ data in my home.

I agree to E-meter energy usage research equipment being installed and operated in my home for 12 months.

Yes	No	N/A

N/A, not applicable.

I agree that all these data will be stored in an anonymised form at Northumbria University and may be used for further related research.

The Data Protection Officer for Northumbria University is NAME.

If you have any questions which you feel have not been covered by the PIL, or if you have concerns or a complaint in relation to the University processing your personal data, please do not hesitate to e-mail us at: dp.officer@northumbria.ac.uk. If your request is urgent, please call NUMBER.

I have also received a copy of the In2Air Research Participant Privacy Notice.

I would like to be informed of the research findings for my home.

Please provide the e-mail or postal address where you would like the results sent to

……

I agree to take part in the study.

Signed:
Name:
Date:

I confirm that the above person has received the PIL about the In2Air study. I have explained the nature of the study and allowed an opportunity to ask questions about the study.

Signed:
Name:
Date:

Appendix 2 Detailed approach undertaken for monitoring domestic air quality

The In2Air Study will measure $PM_{2.5'10}$, CO_2 temperature and humidity indoors, paired with $PM_{2.5,10}$, temperature and humidity outdoors. PMs are a measure of inhalable smoke and fine dust particles such as those from cooking, smoking or outdoor traffic. Exposures to PM are associated with an increased risk of allergic and respiratory diseases. CO_2 is a good indicator of the level of air exchange between indoor and outdoor environments. Raised levels of CO_2 are regarded as sign of inadequate ventilation and often used as a surrogate measure of the amount of outdoor air introduced into the home. Humidity is linked to the occurrence of black mould in homes. The more frequently AQ measurements are recorded by the AQ monitors, the more precisely the impacts of activities in or outside the home on indoor AQ can be identified.

Sampling period

We will measure matched indoor and outdoor air conditions for a minimum of 4-week duration before the homes are retrofitted with the energy efficiency measures. Current literature on the length of monitoring required to establish an indoor AQ baseline varies widely from a few days (e.g. 4 days) with weekend/weekday and seasonal sampling, up to 12 months.

Equipment

Air quality measurements

One combined indoor monitor will be placed in the living room of each home, and one outside the property (so we can correct for relevant external factors). To contain study costs, In2Air will deploy low-cost monitors. Another consideration has been to minimise the burden on participants. AirVisual Pro (indoor) and AVO have been selected for the In2Air study, as they each combine $PM_{2.5,10}$, CO_2, temperature and relative humidity into a compact, quiet unit, minimising space required and disruption in participants' homes. Both indoor and outdoor AQs are displayed on the indoor AVPro screen. Power and internet access (Wi-Fi connection) for the AVO are provided by a flat PoE Ethernet cable (power and data) through a window, wall or door feed through.

Comms and data access

The AVPro and AVO monitors are linked together by Wi-Fi. We will provide a Wi-Fi hotspot (e.g. me-fi or pebble) to each home in order that researchers can connect to and manage the monitors remotely as well as download the data without the need to visit the residence. The AVPro screen should be disabled so as not to provide information on the quality of air to study participants, which could alter behaviour. Measurements will continue to be taken and stored with the screen off.

Researchers contact details to be left with participants and also with the Community Centre warden in case of any issues with the monitors.

Placement of equipment

Indoor

Ideally, the indoor monitor should be placed in a room most commonly used by occupants. For the In2Air study, we have selected the living room. The monitor should be away from doors, openable windows, air supply vents and grilles (minimum 1 m > 2 m if possible) and specific sources of pollutants (e.g. fireplace or place where candles or incense are burned). If there are incoming ventilation supply points, the monitor should be placed between these. The monitor should not be placed somewhere that would be a nuisance to the study participants, or use a socket that they regularly need, or have a trailing power cable that could be a trip hazard. Head height (where participants are breathing when seated) is desirable if possible. An adapter plug can be used in order that the Wi-Fi hotspot and AQ monitors use only one socket. See BS 40101: 2022.[25]

Outdoor

Placement near to any ventilation inlets (or frequently opened doors or windows) will give the quality of air that will be ventilating into the building. Shelter from direct sunshine and prevailing rain is desirable. When using paired indoor–outdoor units connected by cable, secure placement with no trailing cables should be ensured. Recommendations and consideration for installation of the IQAir Visual Outdoor in the IQAir Visual Outdoor User and Installation Manual should be adhered to, where possible. See table 13 in BS 40101:2022.[25] Where BS 40101: 2022 guidance for placement cannot be followed, a note to reflect this will be reported in the meta data.

Technical information (extracted from AirVisual Outdoor and AirVisual Pro user manuals)

Sensor specifications

AirVisual Outdoor and AirVisual Pro

Nephelometer: Laser light scattering technology with remote calibration. This technology is quieter than the typical gravimetric technology equipment. This particle count approach provides a calculated mass concentration based on the assumed density and shape of the particles.

Measurement frequency

AVPro**:** In standard mode, the AVPro records time, $PM_{2.5,10}$, CO_2, temperature, humidity, AQI and AQI data every 10 seconds.

AVO**:** The AVO collects data every minute in standard mode. A uniform sampling frequency of 1 minute will be selected for all outdoor monitors.

Default sensor mode takes measurements approximately 12× less frequently than continuous sensor mode – so, continuous mode should expose the sensor to 12× more pollution over time, which may impact the rate of drift. Without recalibration, the $PM_{2.5,10}$ sensor will continue to depict valid trends of higher and lower pollution levels, although it may lose a degree of precision over time. Users concerned with maintaining topmost accuracy in the long term can recalibrate their $PM_{2.5,10}$ sensor every so often using the IQAir recalibration service offered by their service centres.

Air quality reading metadata to be documented

Property data:

- site/project
- address
- postcode

(Anonymisation may be required.)

Location of data point:

- floor/level
- room/zone

Device:

- manufacturer of device
- model
- serial number
- accuracy of data captured provided by the device (from technical data sheet or calibration record)
- calibration date (most recent)

Appendix 3 Approach undertaken for auditing and monitoring domestic energy consumption

Acquisition of accurate energy data underpins all carbon reporting and will be used to support NCC establish a protocol for energy monitoring to create evidence-based net zero strategies.

Level 1 energy audit

Before embarking on implementing building energy efficiency measures, it is important to establish a baseline of the current building performance, and where it stands with respect to current standards, so that measurement and verification of proposed interventions are attainable. The American Society of Heating, Refrigeration and Air-Conditioning Engineers has developed guidelines for energy audits and categorised them into levels 1, 2 and 3.

The In2Air baseline data collection study will conduct a level 1 energy audit on all homes in the study that involves a basic walk-through assessment, analysis and review of utility bills over the preceding 12-month period and other operating data, as well as a short survey with occupants (hours of occupation, times and periods of use of heating, lighting, domestic hot water, etc.; for survey questions see Supplementary Information 3 in the protocol (version 1.1; available at www.in2air.org.uk). Monthly utility bills (electricity and gas), collected from the surveyed homes for up to the previous 12-month period, will enable us to understand the energy use patterns, tariff structure, etc., before any interventions. This basic evaluation is designed to identify energy efficiency problems and understand the current building performance. Data collected will be analysed to create a profile for the selected architypes and establish baseline energy consumption pre intervention.

Building general data

Building architype	
Address	
Date of energy audit	
UPRN (unique property reference number)	
Gross floor area	
Number of stories	N/A
Building age	
Energy consumption per m^2	(to be calculated as part of the data analysis)
Number of occupants	(obtained from survey data)
Typical hours of occupation per week	(to be calculated as part of the data analysis)
Start of baseline monitoring date	
Gas MPAN	Include digital photography of the meter and the reading
Gas meter reading at start of monitoring (to the block of four)	
Property heat meter reading at start of monitoring	Include digital photography of the meter and the reading
Electric MPAN	Include digital photography of the meter and the reading
Electricity meter reading at start of monitoring	
End of baseline monitoring date	
Gas meter reading at end of monitoring (to the block of four)	Include digital photography of the meter and the reading
Property heat meter reading at end of monitoring	Include digital photography of the meter and the reading
Electricity meter reading at end of monitoring	Include digital photography of the meter and the reading

MPAN, Meter Point Administration Number.

Building characteristics

Building structure	
External wall cladding	
Roof cladding	
Wall insulation	
Roof/loft insulation [type(s)]	
Roof/loft insulation [type(s)]	Very minimal; minimal; acceptable (recommended amount); good (above recommended amount); very good
Floor insulation	
Externals windows (No.)	
Externals windows (type)	
External doors (No.)	
External doors (type)	
EPC	
Details of ventilation	
Details of any passive (trickle) ventilation (and their status – in use/covered, etc.)	e.g. window trickle vents, air bricks, roof vents
Details of any continuous ventilation (and their status – in use/covered, etc.)	
Extractor fan(s) in kitchen (if present): detail location(s) (above hob, etc.), extraction to outside or recirculation, maintenance status	
Extractor fan in bathroom (if present): detail location(s) (in ceiling, etc.), extraction to outside or recirculation, maintenance status	
Tumble drier (if present): detail location (in kitchen, etc.), extraction (none, to outside, condensing type)	

Large equipment and appliances inventory

Area no.	Description	Item	Type	Total power	Typical daily operating hours	Any additional comments
Example:	Lounge room	LED TV	Samsung			
Example:	Kitchen	Stove				
Example:	Kitchen	Fan				

Heating, air conditioning and any additional ventilation

Area no.	Description	Item	Type	Total power	Temperature set	Typical daily operating hours
Example:	Kitchen	Boiler				
Example:	Kitchen	Radiator				
Example:	Bathroom	Electric shower				

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al*. Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

Supplementary information

Area no.	Description	Notes and observation
		e.g. Is water heated by gas but with an electric shower? Note: we are not capturing detailed info on individual light fittings and type, but if significant lighting is there in property, then this should be captured here (e.g. may be useful to consider over the December monitoring period if the property is exceptionally well illuminated!)

Appendix 4 Co-location procedures and data

Data for the calibration exercise were conducted using AVPro indoor and AVO monitors and a colocated reference PP 7301-AQ M2 monitor. The calibration was carried out for PM_{10}, $PM_{2.5}$, CO_2, temperature and humidity. Co-location data were plotted with the PP data on the *y*-axis and AirVisual data on the *x*-axis, thus yielding the equation of a straight line

$$PP = slope \times AirVisual + \text{intercept} \tag{1}$$

where PP and AirVisual are data for the parameter under consideration. Performance data for the indoor and outdoor monitors are shown in *Appendix 4*, *Tables 6* and *7*, respectively. For PM data, the co-location data from one of the indoor monitors (Unit 8) were excluded because of a malfunction in the instrument.

TABLE 6 Performance characteristics for AVPro (indoor) compared to PP 7301

Measurement parameter	Mean slope (with range)	Mean intercept (with range)	Mean R^2 (with range)
$PM_{2.5}$ conc.	1.076 (0.779–1.39)	1.167 (0.82–1.40) μg/m^3	83.9% (73–89.9%)
PM_{10} conc.	2.746 (1.458–4.757)	2.042 (0.797–3.407) μg/m^3	85.2% (58.3–96.0%)
CO_2 conc.	0.918 (0.827–0.992)	420 (398–466) ppm	67.2% (57.2–79.5%)
Temperature	1.200 (1.173–1.249)	−1.02 (−2.02 to −0.14) °C	92.3% (89.1–94.7%)
Relative humidity	0.967 (0.915–1.052)	−4.98 (−8.42 to −3.16) %	80.3% (72.0–85.8%)

TABLE 7 Performance characteristics for AVO compared to PP 7301

Measurement parameter	Mean slope (with range)	Mean intercept (with range)	Mean R^2 (with range)
$PM_{2.5}$ conc.	0.905 (0.848–0.955)	1.215 (1.07–1.42) μg/m^3	79.1% (76.6–85.2%)
CO_2 conc.	N/A	N/A	N/A
PM_{10} conc.	2.877 (2.553–3.099)	1.551 (0.833–2.811) μg/m^3	62.2 (56.4–69.3%)
Temperature	1.027 (0.942–1.100)	1.59 (0.18–3.57) °C	93.1% (89.2–96.1%)
Relative humidity	0.924 (0.870–0.998)	1.67 (−1.37 to 7.33) %	84.9% (71.0–93.6%)

For PM_{10}, the slopes from the calibration plots listed in *Table 8* were significantly higher than 1.0, indicating that the AirVisual monitors substantially under-read compared to the PP. Therefore, to ensure that the AirVisual (indoor and outdoor) PM_{10} concentrations aligned with those of the reference monitor, a correction was carried out using *Eqn 1* to generate $PM_{10(adj)}$ concentrations, and the specific slopes and intercepts for each unit that were applied are detailed in *Appendix 4*, *Table 8*.

For $PM_{2.5}$, the indoor and outdoor monitors both have average slopes close to 1 (see *Appendix 4*, *Table 9*), relatively small intercepts and high R^2 values, and as such, no data corrections were applied. For the AVPro, the average slope of 1.076 indicates that the monitors under-read compared to the PP monitor by about 7%. The AVO over-reads by approximately 10%.

TABLE 8 The PM_{10} calibration data for AVPro indoor (P01–P11) and outdoor monitors (O01–O11) compared to a colocated reference PP 7301-AQ M2 monitor

PP vs. indoor PM_{10}		PP vs. outdoor PM_{10}	
Monitor ID	**Parameters (and R^2)**	**Monitor ID**	**Parameters (and R^2)**
P01	PP = 4.757*P01 + 2.364 (65.7%)	O01	PP = 2.974*O01 + 1.663 (57.5%)
P02	PP = 3.094*P02 + 0.797 (88.5%)	O02	PP = 2.992*O02 + 2.811 (56.4%)
P03	PP = 1.108*P03 + 2.937 (48.9%)	O03	PP = 2.816*O03 + 1.245 (66.1%)
P04	PP = 2.502*P04 + 1.745 (87.1%)	O04	PP = 2.877*O04 + 0.908 (69.3%)
P05	PP = 2.303*P05 + 2.145 (90.7%)	O05	PP = 2.731*O05 + 1.418 (63.3%)
P06	PP = 2.216*P06 + 2.646 (94.7%)	O06	PP = 3.099*O06 + 2.455 (57.9%)
P07	PP = 1.458*P07 + 0.929 (96.0%)	O07	PP = 2.783*O07 + 1.632 (60.9%)
P08	PP = 0.376*P08 + 8.647 (3.6%)	O08	PP = 2.877*O08 + 1.053 (62.6%)
P09	PP = 1.528*P09 + 1.597 (93.3%)	O09	PP = 2.553*O09 + 1.214 (67.2%)
P10	PP = 4.197*P10 + 3.407 (58.3%)	O10	PP = 2.921*O10 + 1.827 (60.3%)
P11	PP = 2.659*P11 + 2.751 (92.7%)	O11	PP = 3.032*O11 + 0.833 (62.6%)

Note

The data are shown as parameters of the equation for the linear line of best fit, where the PP data were plotted on the *y*-axis and the AirVisual data on the *x*-axis, as shown in *Appendix 4*, *Figures 6* and *7*. The figure in parentheses is the R^2 value for the calibration, expressed as a percentage.

TABLE 9 The $PM_{2.5}$ Calibration data for AVPro indoor (P01–P11) and AVO monitors (O01–O11) compared to a colocated reference PP 7301-AQ M2 monitor

PP vs. indoor $PM_{2.5}$		PP vs. outdoor $PM_{2.5}$	
Monitor ID	**Parameters (and R^2)**	**Monitor ID**	**Parameters (and R^2)**
P01	PP = 1.183*P01 + 1.037 (84.1%)	O01	PP = 0.940*O01 + 1.195 (78.0%)
P02	PP = 1.120*P02 + 1.332 (80.9%)	O02	PP = 0.925*O02 + 1.420 (76.7%)
P03	PP = 0.573*P03 + 0.967 (50.1%)	O03	PP = 0.893*O03 + 1.247 (78.4%)
P04	PP = 1.160*P04 + 1.284 (78.6%)	O04	PP = 0.902*O04 + 1.169 (81.2%)
P05	PP = 0.988*P05 + 1.292 (84.0%)	O05	PP = 0.883*O05 + 1.103 (82.1%)
P06	PP = 1.111*P06 + 1.131 (87.6%)	O06	PP = 0.955*O06 + 1.352 (76.7%)
P07	PP = 0.779*P07 + 0.828 (89.9%)	O07	PP = 0.848*O07 + 1.309 (76.6%)
P08	PP = 0.090*P08 + 2.179 (7.6%)	O08	PP = 0.883*O08 + 1.102 (79.0%)
P09	PP = 0.969*P09 + 0.903 (88.1%)	O09	PP = 0.875*O09 + 1.121 (85.2%)
P10	PP = 0.987*P10 + 1.399 (73.0%)	O10	PP = 0.913*O10 + 1.275 (77.2%)
P11	PP = 1.390*P11 + 1.295 (85.8%)	O11	PP = 0.940*O11 + 1.078 (79.7%)

Note

The data are shown as parameters of the equation for the linear line of best fit, where the PP data were plotted on the *y*-axis and the AirVisual data on the *x*-axis, as shown in *Appendix 4*, *Figures 8* and *9*. The figure in parentheses is the R2 value for the calibration, expressed as a percentage.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al*. Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

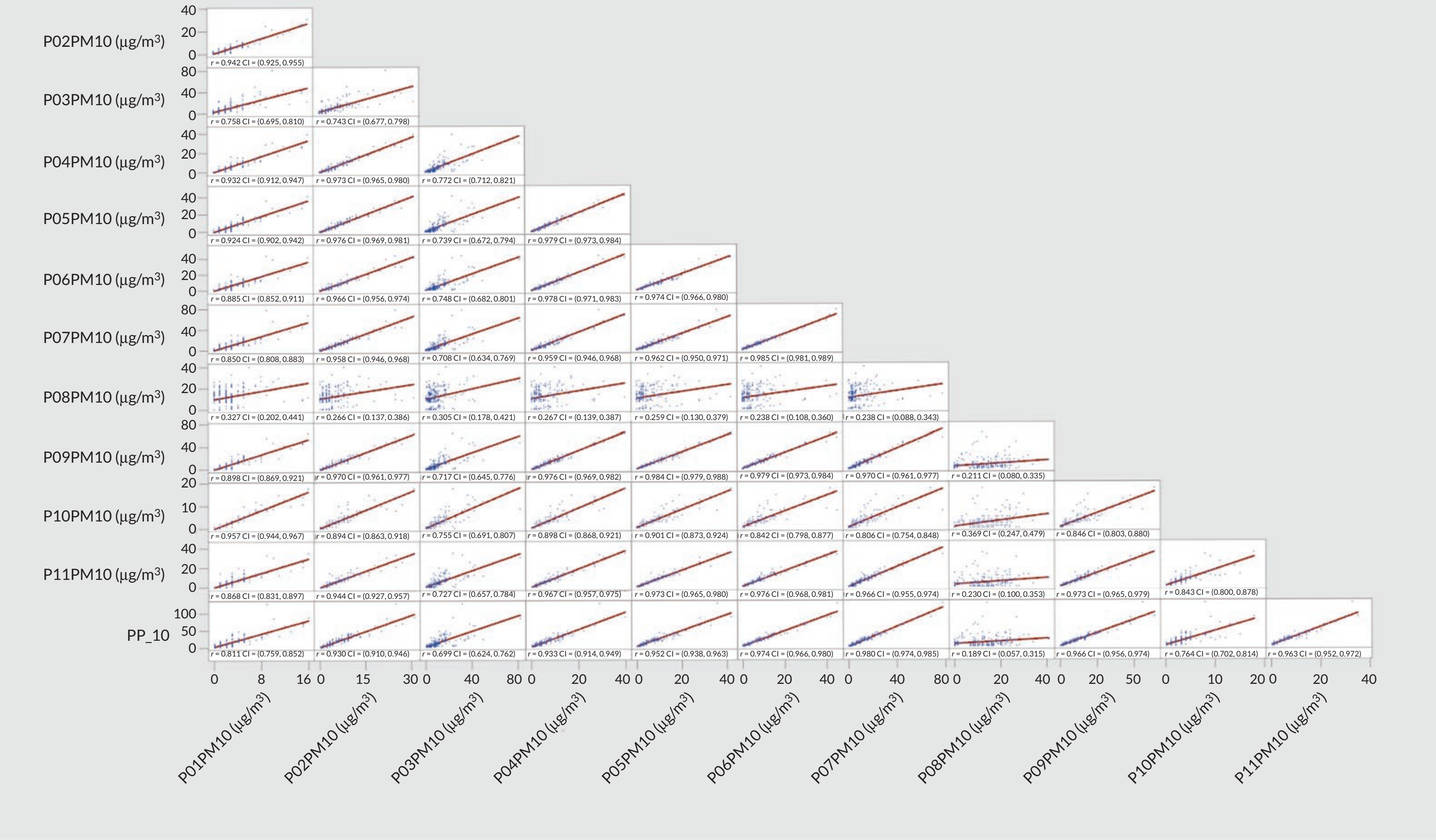

FIGURE 6 The PM_{10} calibration data for the AVPro indoor (P01–P11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 8*. CI, confidence interval.

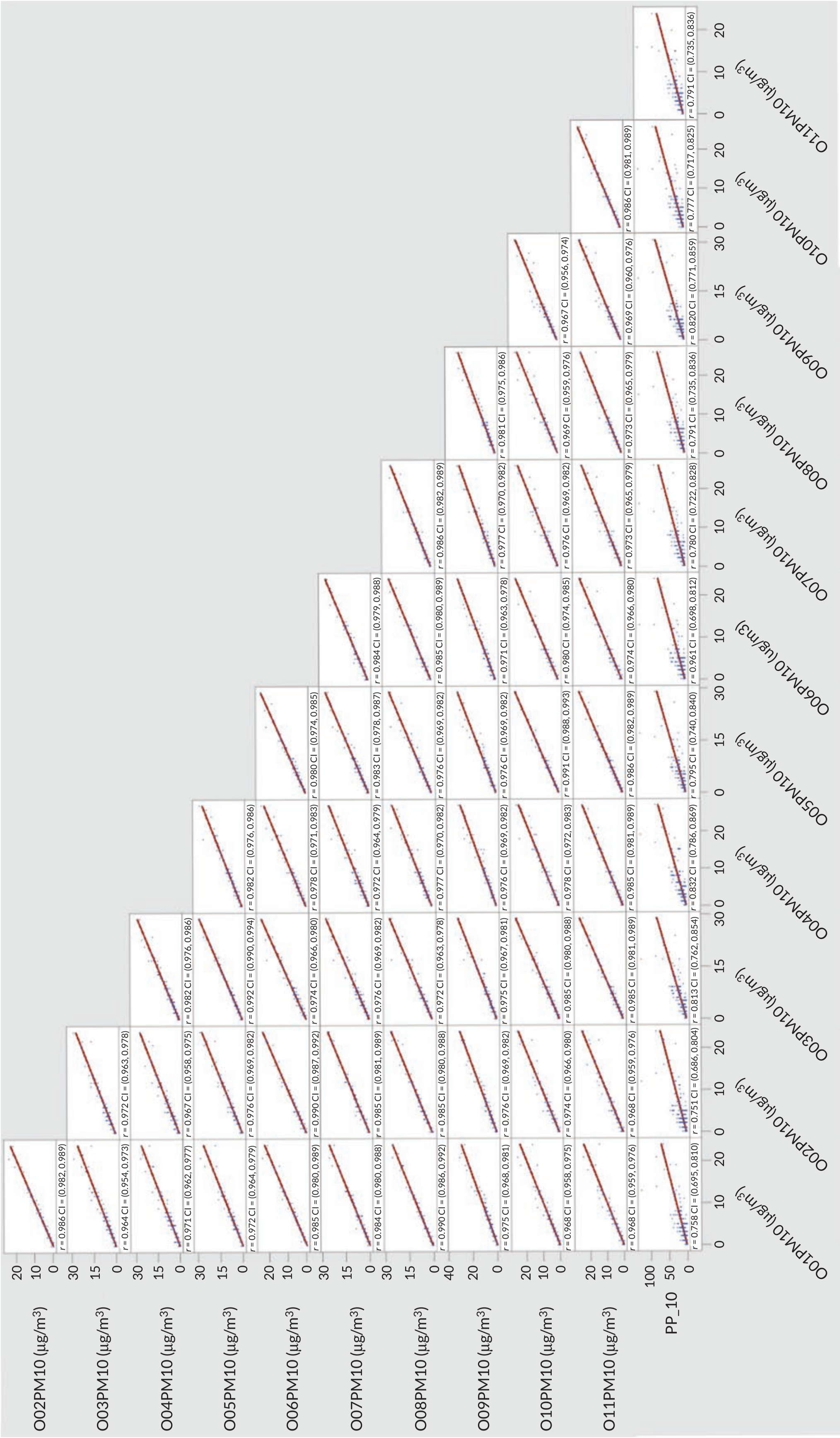

FIGURE 7 The PM10 calibration data for the AVO (O01–O11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 8*.

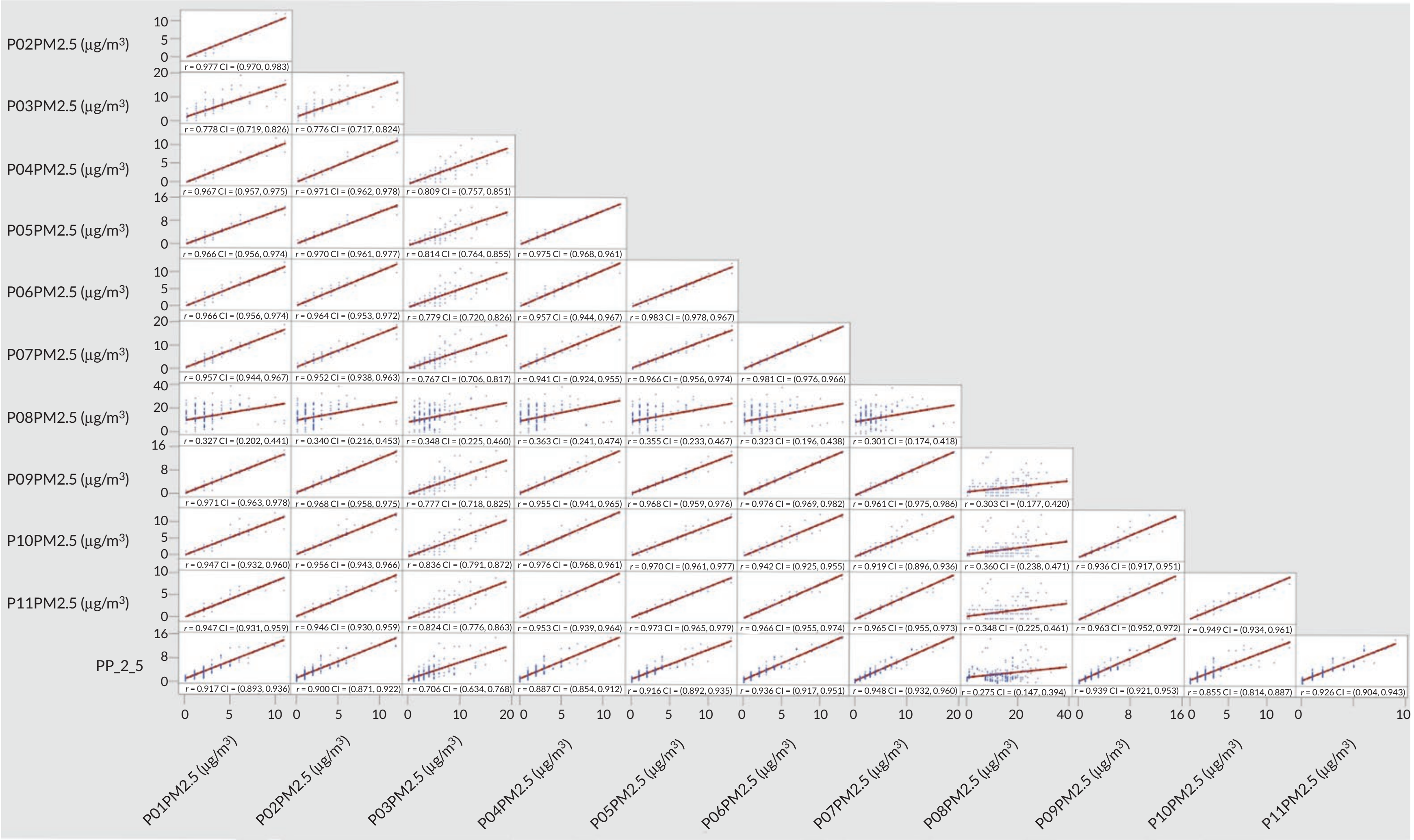

FIGURE 8 The $PM_{2.5}$ calibration data for the AVPro indoor (P01–P11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 9*.

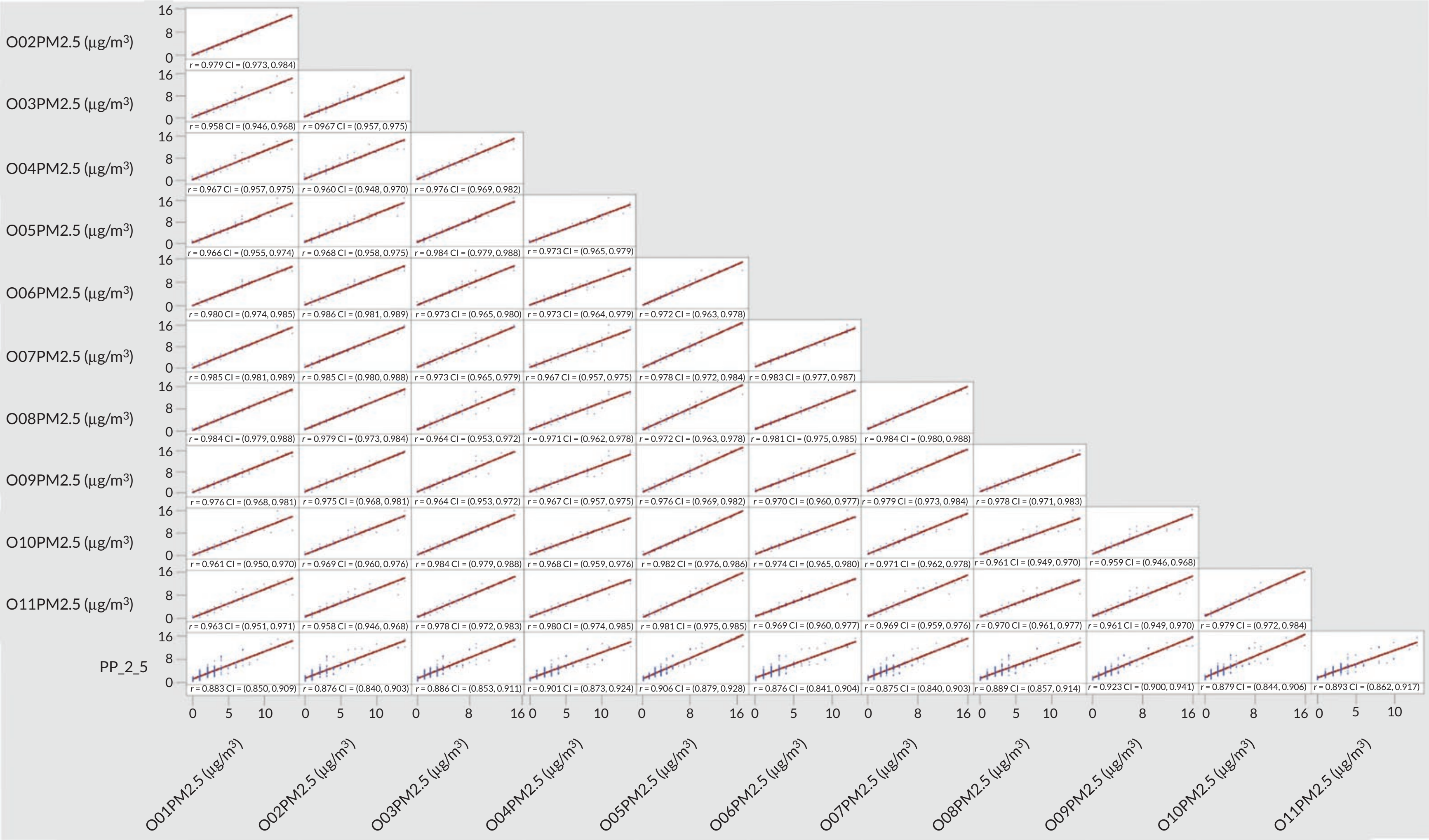

FIGURE 9 The PM$_{2.5}$ calibration data for the AVO (O01– O11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 9*.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al.* Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

For CO_2 concentrations (AVPro indoor monitor only), temperature and humidity, the slope is close to 1 (see *Appendix 4*, *Tables 10–12*). For CO_2, there is a large intercept (mean of 420 ppm) compared to the PP monitor; however, based on the intermonitor comparisons (see *Appendix 4*, *Figure 10*), we were satisfied that the relative differences between time periods and homes could be reproducibly determined using the AVPro by using the factory-certified CO_2 calibrations.

TABLE 10 The CO_2 calibration data for AVPro indoor (P01–P11) monitors compared to a colocated reference PP 7301-AQ M2 monitor

PP vs. indoor CO_2	
Monitor ID	**Parameters (and R^2)**
P01	PP = 0.9414*P01 + 413.9 (66.7%)
P02	PP = 0.992*P02 + 398.7 (74.0%)
P03	PP = 0.827*P03 + 466.1 (57.2%)
P04	PP = 0.948*P04 + 406.9 (79.5%)
P05	PP = 0.892*P05 + 427.5 (64.1%)
P06	PP = 0.876*P06 + 430.5 (64.3%)
P07	PP = 0.934*P07 + 414.8 (68.2%)
P08	PP = 0.949*P08 + 399.4 (69.0%)
P09	PP = 0.925*P09 + 412.2 (66.6%)
P10	PP = 0.9166*P10 + 427.3 (65.2%)
P11	PP = 0.899*P11 + 426.6 (64.6%)

Note
The data are shown as parameters of the equation for the linear line of best fit, where the PP data were plotted on the y-axis and the AirVisual data on the x-axis, as shown in *Appendix 4*, *Figure 10*. The figure in parentheses is the R^2 value for the calibration, expressed as a percentage.

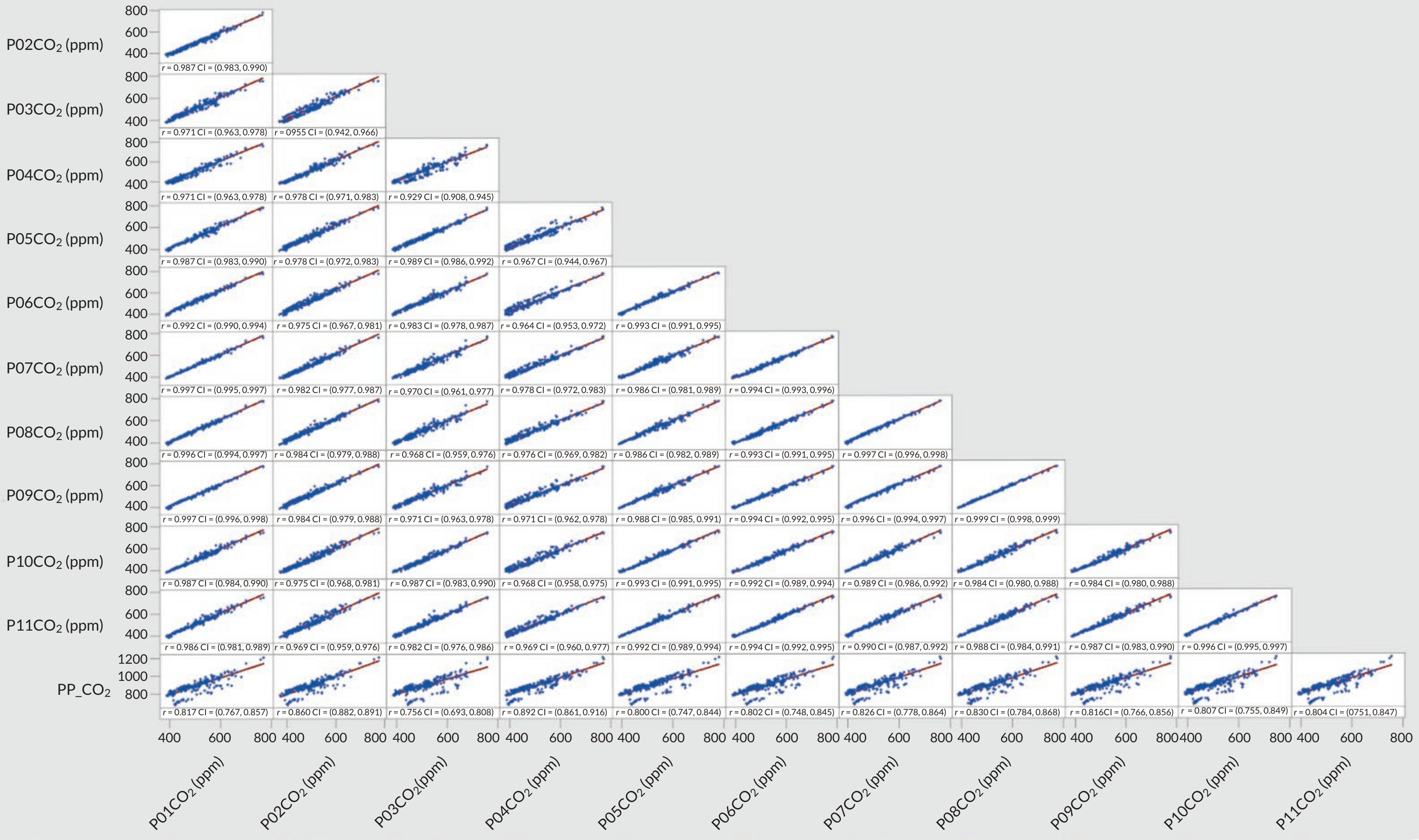

FIGURE 10 The CO_2 calibration data for the AVPro indoor (P01–P11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 10*.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al.* Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

TABLE 11 Temperature (°C) calibration data for AVPro indoor (P01–P11) and outdoor (O01–O11) monitors compared to a colocated reference PP 7301-AQ M2 monitor

PP vs. indoor temp (°C)		PP vs. outdoor temp (°C)	
Monitor ID	**Parameters (and R^2)**	**Monitor ID**	**Parameters (and R^2)**
P01	PP = 1.216*P01 – 0.942 (91.3%)	O01	PP = 1.100*O01 + 1.554 (93.5%)
P02	PP = 1.222*P02 – 1.473 (92.2%)	O02	PP = 1.050*O02 + 0.3927 (93.2%)
P03	PP = 1.204*P03 – 0.1432 (93.7%)	O03	PP = 0.9864*O03 + 2.085 (89.2%)
P04	PP = 1.193*P04 – 1.392 (92.1%)	O04	PP = 0.9421*O04 + 3.566 (94.0%)
P05	PP = 1.179*P05 – 1.337 (89.1%)	O05	PP = 1.025*O05 + 1.049 (93.6%)
P06	PP = 1.176*P06 – 1.046 (91.3%)	O06	PP = 1.010*O06 + 1.077 (92.6%)
P07	PP = 1.202*P07 – 1.149 (93.2%)	O07	PP = 1.003*O07 + 3.291 (96.1%)
P08	PP = 1.173*P08 – 0.3142 (92.4%)	O08	PP = 1.029*O08 + 2.268 (95.6%)
P09	PP = 1.249*P09 – 2.023 (91.5%)	O09	PP = 1.083*O09 + 1.851 (94.1%)
P10	PP = 1.195*P10 – 0.9713 (94.7%)	O10	PP = 1.046*O10 + 0.2048 (92.1%)
P11	PP = 1.196*P11 – 0.5332 (93.7%)	O11	PP = 1.019*O11 + 0.1807 (90.8%)

Note

The data are shown as parameters of the equation for the linear line of best fit, where the PP data were plotted on the *y*-axis and the AirVisual data on the *x*-axis, as shown in *Appendix 4*, *Figures 11* and *12*. The figure in parentheses is the R^2 value for the calibration, expressed as a percentage.

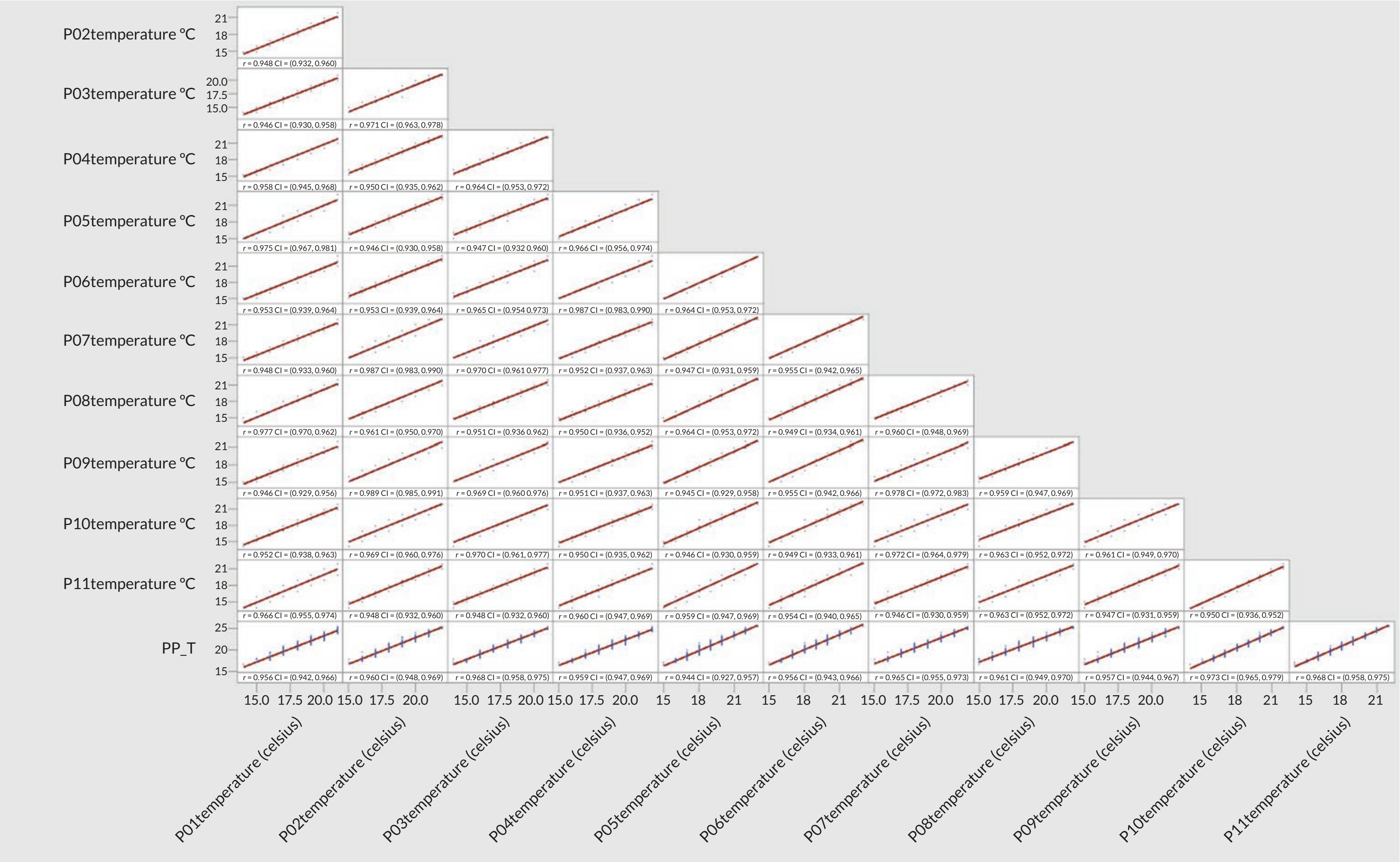

FIGURE 11 Temperature (°C) calibration data for the AVPro indoor (P01–P11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 11*.

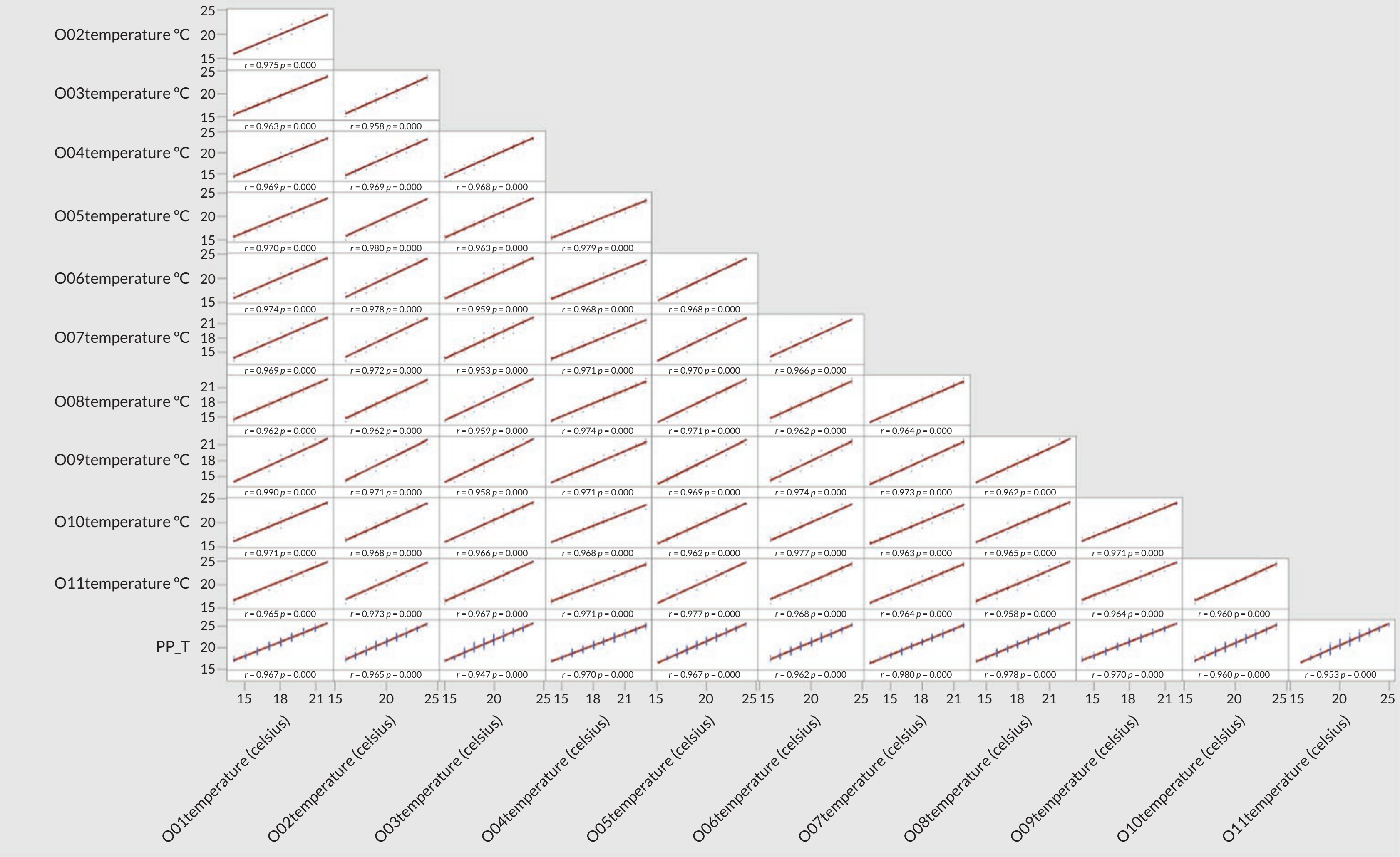

FIGURE 12 Temperature (°C) calibration data for the AVO (O01–O11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 11*.

TABLE 12 Relative humidity (%) calibration data for AVPro indoor (P01–P11) and outdoor (O01–O08) monitors compared to a colocated reference PP 7301-AQ M2 monitor

PP vs. indoor relative humidity (%)		PP vs. outdoor relative humidity (%)	
Monitor ID	**Parameters (and R^2)**	**Monitor ID**	**Parameters (and R^2)**
P01	PP = 0.9951*P01 − 7.178 (81.7%)	O01	PP = 0.8701*O01 + 2.615 (87.6%)
P02	PP = 1.052*P02 − 8.417 (85.6%)	O02	PP = 0.9984*O02 + 0.327 (84.6%)
P03	PP = 0.9422*P03 − 5.987 (80.7%)	O03	PP = 0.9269*O03 + 2.877 (71.0%)
P04	PP = 0.9703*P04 − 3.962(75.1%)	O04	PP = 0.9540*O04 − 1.387 (83.6%)
P05	PP = 0.9568*P05 − 3.258 (72.0%)	O05	PP = 0.9663*O05 + 3.016 (82.3%)
P06	PP = 0.9813*P06 − 4.462 (78.8%)	O06	PP = 0.8836*O06 + 7.328 (86.0%)
P07	PP = 0.9665*P07 − 4.942 (81.2%)	O07	PP = 0.8804*O07 − 0.7664 (93.6%)
P08	PP = 0.9353*P08 − 4.4274 (80.7%)	O08	PP = 0.9179*O08 − 595 (90.5%)
P09	PP = 0.9915*P09 − 5.630 (79.8%)	O09	No data
P10	PP = 0.9316*P10 − 3.375 (85.8%)	O10	No data
P11	PP = 0.9150*P11 − 3.164 (82.6%)	O11	No data

Note

The data are shown as parameters of the equation for the linear line of best fit, where the PP data were plotted on the *y*-axis and the AirVisual data on the *x*-axis, as shown in *Appendix 4*, *Figures 13* and *14*. The figure in parentheses is the R^2 value for the calibration, expressed as a percentage.

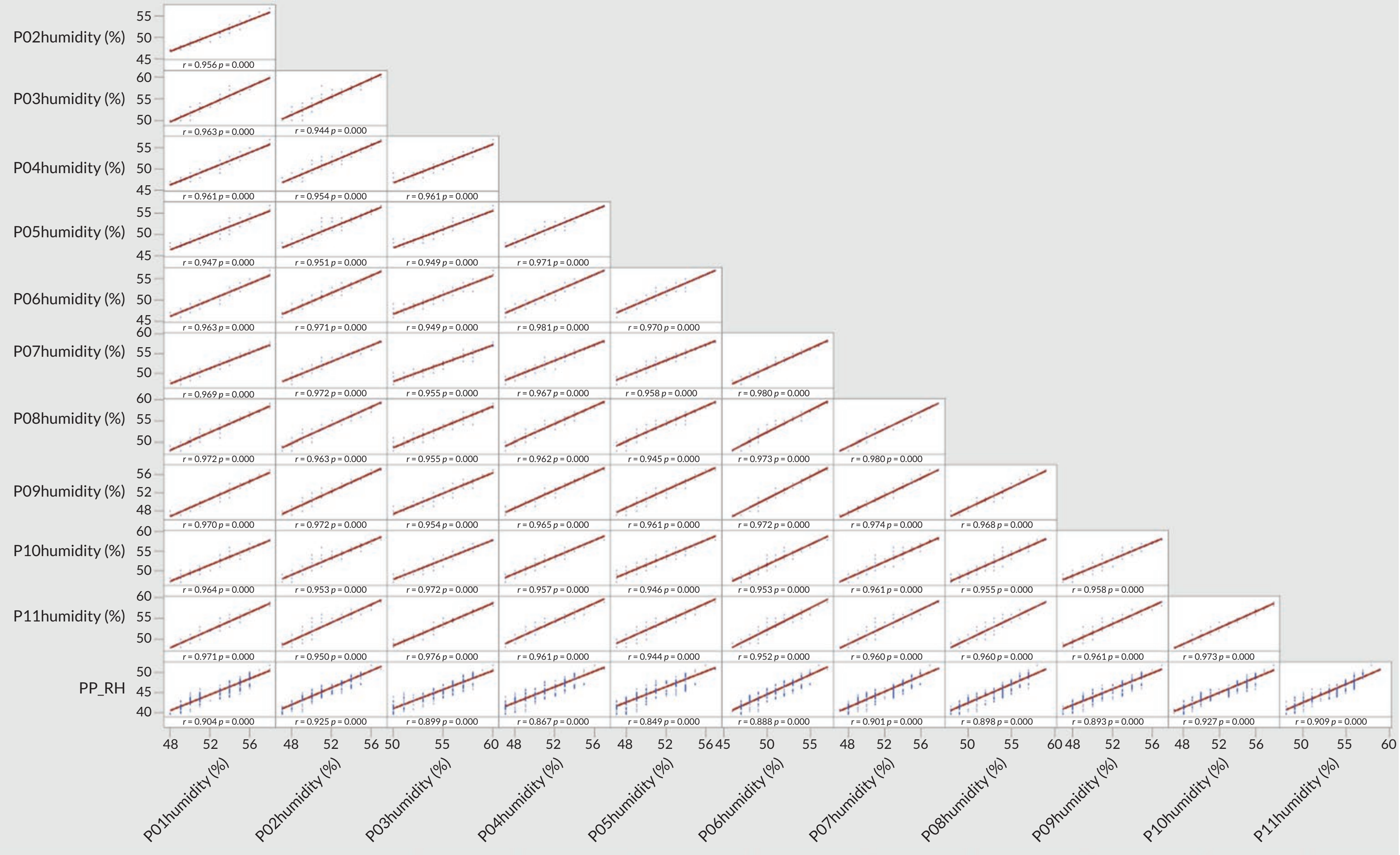

FIGURE 13 Relative humidity (%) calibration data for the AVPro indoor (P01–P11) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 12*.

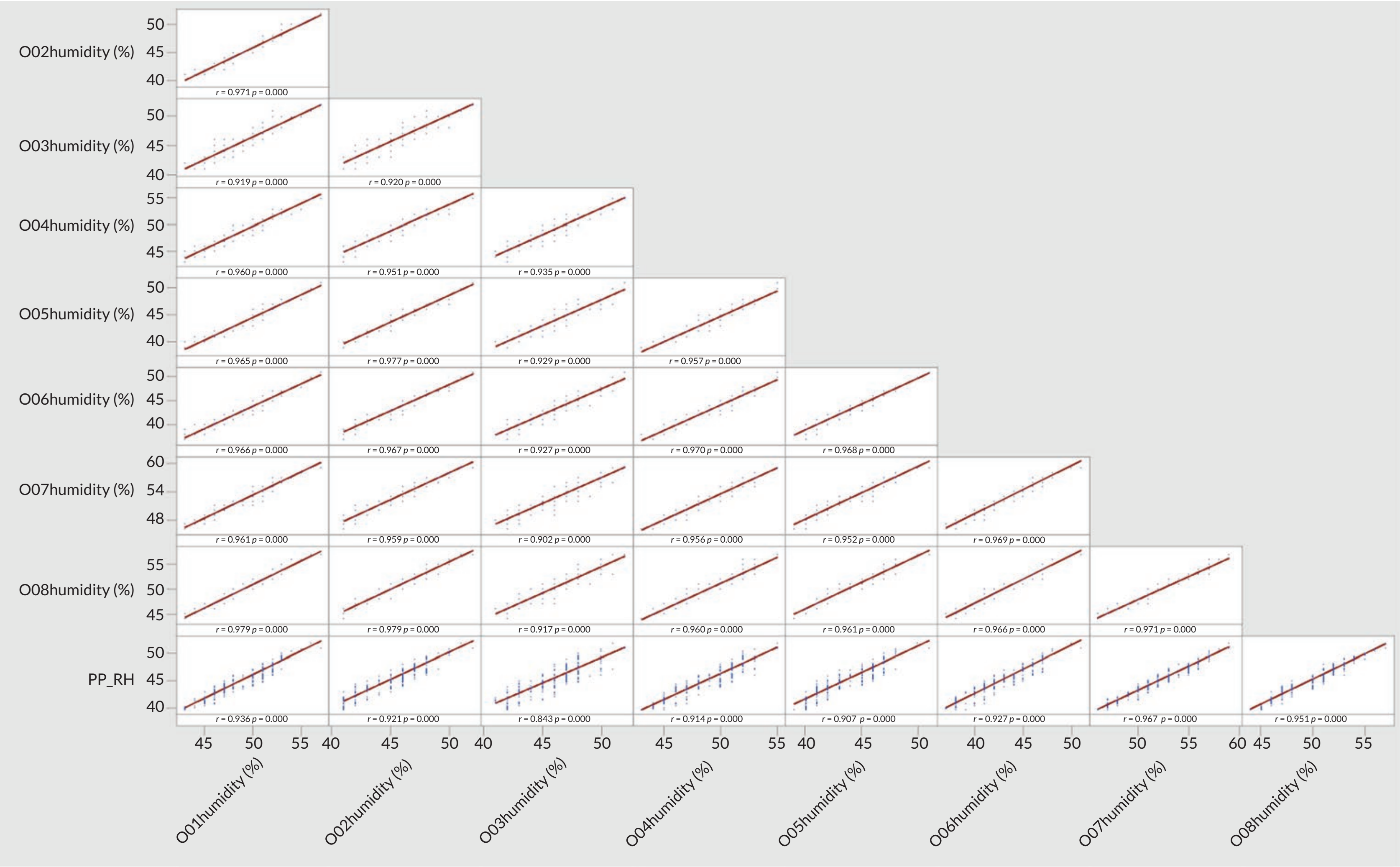

FIGURE 14 Relative humidity (%) calibration data for the AVPro indoor (O01–P08) monitor compared to a colocated reference PP 7301-AQ M2 monitor. The line is the best fit to the data points using linear least squares and the parameters listed in *Appendix 4*, *Table 12*. No data were obtained for units O09–O11.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al.* Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

Appendix 5 Diurnal patterns of mean indoor $PM_{2.5}$ concentrations

$PM_{2.5}$ concentrations throughout the day for all participants' study periods, except those where indoor smoking, are shown in *Appendix 5*, *Figure 15*. The timing of homes' peak $PM_{2.5}$ concentration generally varied with cooking times. For example, homes IA3 and IA28 have the highest peaks at breakfast time, homes IA8 and IA9 have the highest peaks associated with evening meal, while homes IA16 and IA26 have peaks at both these times.

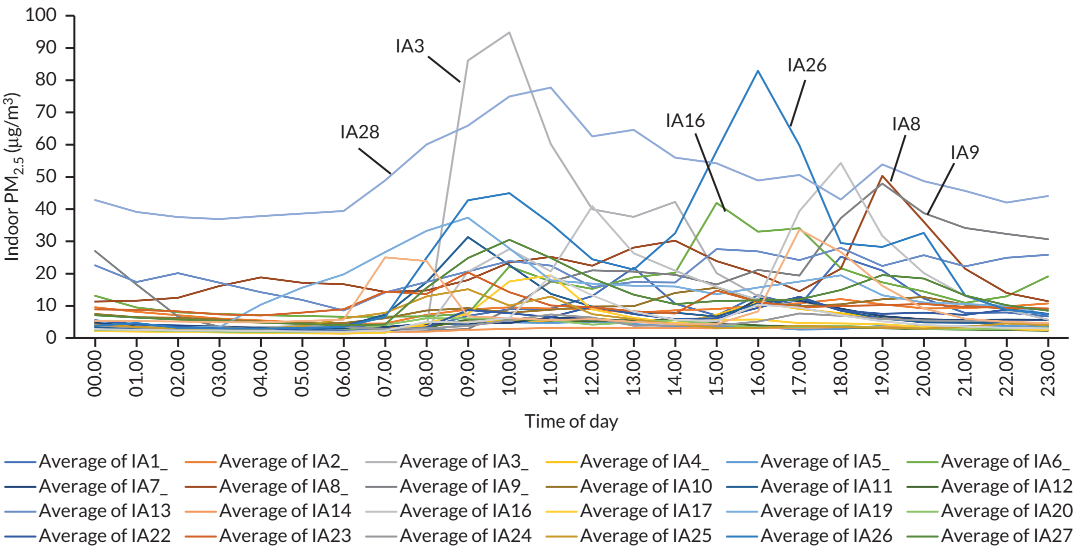

FIGURE 15 Diurnal patterns of mean indoor $PM_{2.5}$ concentrations.

Appendix 6 Temperature and humidity

Temperature

Our baseline monitoring indicated a mean temperature that ranged from 14 °C to 26 °C (*Appendix 6*, *Figure 16*). When asked if there were any rooms in the home that were significantly warmer than others, 20% of participants reported that their bedroom was warmer. Single respondents reported their living room, second bedroom or bathroom to be warmer. When asked if there were any rooms in the home that were significantly cooler than others (except for unheated porches, which almost all reported to be cold), 33% of participants reported a cooler bedroom, 20% reported a cooler bathroom, 10% reported a cooler passage (these all had the passage leading off their porch with the wet rooms, i.e. the kitchen and bathroom, on either side). A single participant reported a cooler living room.

Humidity

Our baseline monitoring indicated the majority of homes had mean humidity levels within the range considered healthy (i.e. between 40% and 60%; *Appendix 6*, *Figure 17*). Concerning the three homes that had > 60% humidity for > 85% of the baseline study period, all recorded the lowest average temperatures in the study of 14–16°C (IA04, IA10, IA14; *Appendix 6*, *Table 13*). A further home (IA06) recorded > 60% humidity for over 54% of the time and a mean temperature of 19 °C; this home also reported pets coming in and out of the house. In these four homes with significant humidity for > 50% of the time, only one household reported the air as humid, two as neutral and one as very dry. All other homes had mean temperatures ≥ 19 °C and humidity > 60% for ≤ 4% of the study period.

When describing their indoor air on a scale from dry to humid, 10% of participants described it as very dry, 17% as dry, 63% as neutral, 7% as humid and a single respondent as very humid. It is interesting to note that in the three homes reporting high indoor humidity, measured humidity > 60% was recorded in only one of these three homes. When asked if they used humidifiers, 7% of participants said often, and 93% said never. When asked if they used de-humidifiers, 17% of participants said often, and 83% said never. When asked about the frequency of having condensation on their windows, 47% of participants said often, 17% sometimes, 10% rarely and 10% never. Window condensation was frequently reported in porches, also bedrooms (10%), kitchens (7%), bathrooms (3%) and living rooms (3%); 7% of window condensation was described as seasonal. We also asked about the frequency of condensation on any walls or ceilings; 62% said never, 21% said often or sometimes (17% in the porch, 7% associated with damp on gable end walls) and 17% did not know. We followed this up by asking about damp patches on internal walls; 17% of participants reported the gable end or outer to be wall damp, and other participants reported there was no dampness in their house. When asked if they noticed areas of mould on their walls or ceilings, 72% of participants replied never, 21% often and 7% sometimes. Mould was almost always reported in the porches, and it was reported in the bedroom and bathroom of one home; 47% of participants washed most of their laundry at home, 43% used the communal laundry facilities and 10% had laundry taken care of by a family members or friend. In winter, 70% of participants dried their laundry in the communal tumble driers, 41% on airers or radiators in the home.

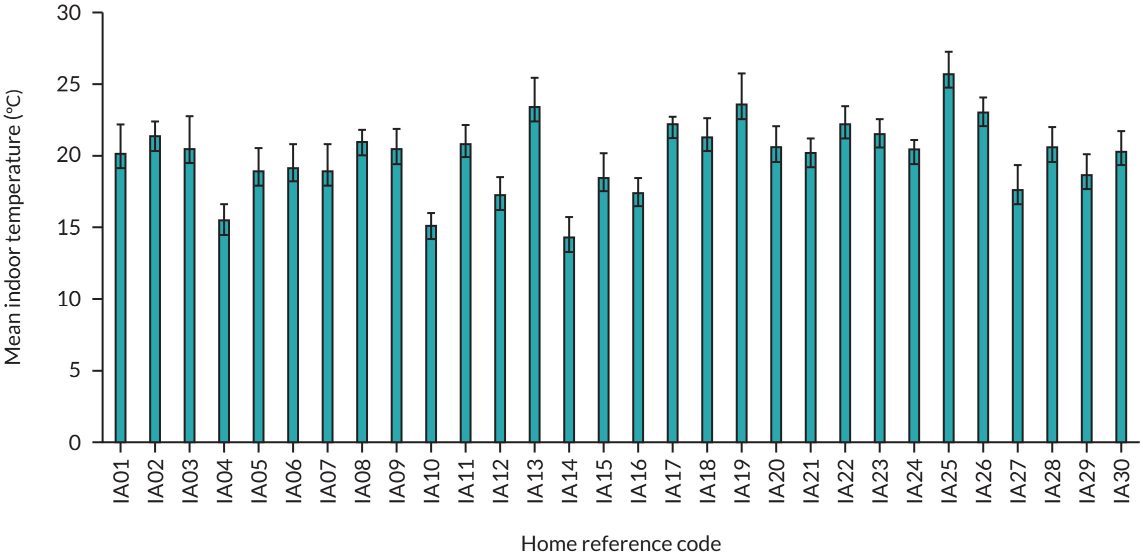

FIGURE 16 Mean indoor air temperature for the baseline monitoring period.

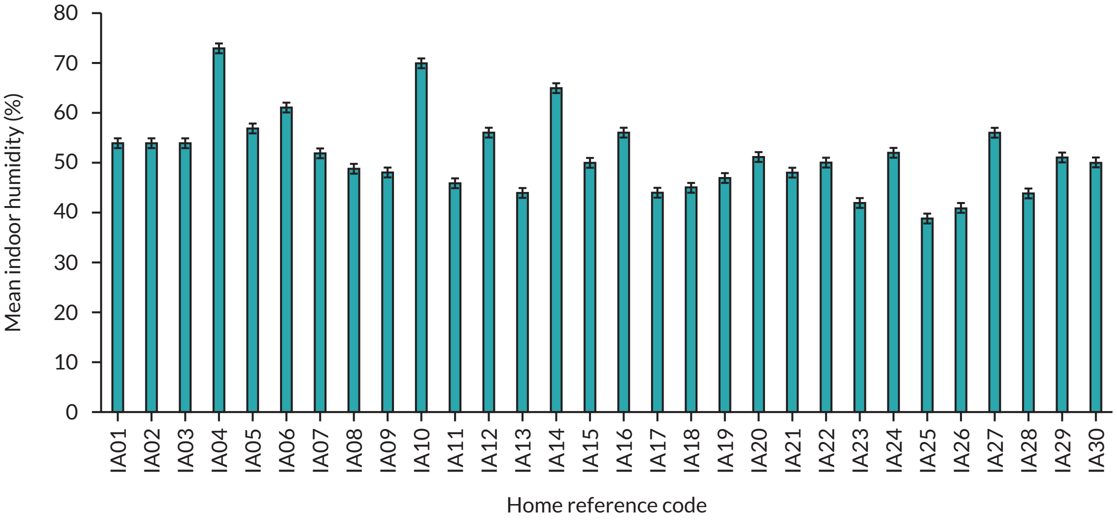

FIGURE 17 Mean indoor humidity for the baseline monitoring period. The error bar indicates the standard deviation.

TABLE 13 Individual home mean indoor temperature and humidity the baseline monitoring period

Home reference code	% time over 60% humidity	Mean temperature (°C)	Median temperature (°C)
IA01	4	20	20
IA02	0	21	21
IA03	1	20	20
IA04	100	16	16
IA05	3	19	19
IA06	54	19	19
IA07	1	19	20
IA08	0	21	21
IA09	0	20	20
IA10	99	15	15
IA11	0	21	21
IA12	0	17	17
IA13	0	23	24
IA14	87	14	15
IA15	0	18	19
IA16	4	17	17
IA17	0	22	22
IA18	0	21	21
IA19	1	24	24
IA20	3	21	21
IA21	1	20	20
IA22	0	22	22
IA23	0	22	22
IA24	0	20	20
IA25	0	26	26
IA26	0	23	23
IA27	9	18	18
IA28	0	21	20
IA29	4	19	19
IA30	0	20	20

Appendix 7 Indoor/outdoor particulate matter$_{2.5}$ ratios

Appendix 7, *Table 14* reports the mean hourly average indoor PM$_{2.5}$ concentration divided by outdoor PM$_{2.5}$ concentrations for each home in the study.

TABLE 14 Indoor/outdoor ratio (mean, median, 10th and 90th percentiles) for mean hourly PM$_{2.5}$

	I/O ratio			
Home reference code	**Mean**	**Median**	**P10**	**P90**
IA01	1.4	0.5	0.2	2.2
IA02	1.7	0.9	0.2	4.0
IA03	2.8	0.6	0.2	7.6
IA04	0.6	0.3	0.2	1.0
IA05	0.4	0.3	0.1	0.7
IA06	2.5	1.3	0.0	5.0
IA07	0.7	0.5	0.2	1.0
IA08	3.2	1.4	0.4	6.7
IA09	1.3	0.3	0.0	4.0
IA10	0.8	0.5	0.3	1.0
IA11	1.6	0.7	0.2	3.8
IA12	0.7	0.3	0.1	1.5
IA13	5.0	2.3	0.6	11.5
IA14	0.4	0.3	0.1	0.7
IA16	4.6	0.7	0.2	5.0
IA17	1.0	0.5	0.1	2.0
IA19	3.2	1.2	0.1	7.3
IA20	0.9	0.5	0.2	2.0
IA22	1.5	0.6	0.2	3.0
IA23	2.4	1.1	0.3	5.0
IA24	0.8	0.3	0.1	1.0
IA25	0.7	0.3	< 0.1	1.0
IA26	4.2	0.5	< 0.1	9.6
IA27	3.2	1.0	0.3	4.8
IA28	0.3	< 0.1	< 0.1	0.5
IA29	1.3	0.3	< 0.1	1.3
IA30	1.1	0.3	0.1	2.0

Note
The data presented below do not include homes where indoor smoking occurred.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al*. Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851

Appendix 8 Outdoor particulate matter$_{2.5}$ concentrations and roadside versus inner estate comparisons

Descriptive statistics for the outdoor PM$_{2.5}$ concentrations at each of the 27 homes are provided in *Appendix 8*, *Table 15*.

TABLE 15 Descriptive statistics for outdoor PM$_{2.5}$ concentrations (µg/m^3) for the baseline monitoring period

	Mean	Median	P10	P90
IA01	11.5	7.0	3.0	28.0
IA02	11.2	6.5	3.0	24.0
IA03	12.7	7.5	3.0	32.0
IA04	13.2	7.0	3.0	30.0
IA05	14.5	7.0	3.0	37.0
IA06	10.0	5.0	2.0	27.0
IA07	12.9	7.0	3.0	31.0
IA08	14.4	8.0	3.0	36.9
IA09	18.6	11.0	4.0	48.0
IA10	14.8	8.0	4.0	35.0
IA11	8.7	6.0	2.0	21.7
IA12	8.5	6.0	1.0	21.7
IA13	8.9	6.0	2.0	22.0
IA14	9.2	6.0	2.0	20.0
IA15	8.2	5.0	2.0	17.0
IA16	6.3	4.0	1.0	14.0
IA17	7.1	5.0	2.0	16.0
IA18	6.7	4.0	1.0	15.0
IA19	9.0	6.0	2.0	18.0
IA20	6.6	5.0	1.0	14.0
IA21	11.1	5.0	1.0	35.1
IA22	10.1	4.0	1.0	34.0
IA23	12.6	5.0	1.0	41.0
IA24	11.0	5.0	1.0	35.9
IA25	10.3	5.0	1.0	29.8
IA26	11.3	5.0	1.0	37.4
IA27	10.8	5.0	1.0	36.0
IA28	12.0	5.0	1.0	39.0
IA29	13.9	7.0	2.0	45.0
IA30	13.9	7.0	2.0	45.0

Some of the study participants were particularly interested to know if differences could be observed between PM measurements recorded by the outdoor monitors at homes along the main road and those placed around the inner estate. The data were tested using a paired *t*-test, and results indicated that outdoor $PM_{2.5}$ were significantly higher (both $p < 0.0001$) at the roadside homes compared with the homes in the inner estate. In addition, indoor $PM_{2.5}$ was statistically significantly higher ($p = 0.0199$) in roadside homes (see *Appendix 8*, *Table 16*). The difference in the outdoor PMs between busy roadside and less-trafficked inner estate areas could be expected; PM from road traffic comes from a range of sources such as road abrasion, exhaust pipe emissions, tyre wear, brake-wear and vehicle-induced resuspension of road dust (WHO, 2013). $PM_{2.5}$ are emitted from the exhaust pipe with road abrasion, giving rise to larger particles ($PM_{2.5–10}$).[67] That said, no outdoor monitors had monitoring period (3–4 weeks during November 2022 to March 2023) means above the current UK[41] (2019) outdoor annual mean limit (25 µg/m^3); however, both the inner estate as well as the roadside homes outdoor monitors had monitoring period means above the current WHO[15] (2021) annual mean guidance value (5 µg/m^3).

TABLE 16 Mean $PM_{2.5}$ concentrations recorded by the indoor and outdoor monitors at homes along the main road (roadside homes) and those of the inner estate homes

Measurement	Inner estate homes mean (µg/m^3) (*n* = 21)	Roadside homes mean (µg/m^3) (*n* = 7)	*p*-value
Indoor $PM_{2.5}$	8.7	10.5	0.0199
Outdoor $PM_{2.5}$	10	12.08	*< 0.0001*

Note
Statistically significant *p*-values in italics.

This article should be referenced as follows:
Entwistle J, Ahmed T, Bramwell L, Coulby G, Deary M, Mansell O, *et al*. Gathering baseline data to assess household energy interventions' impact on indoor air quality, occupant health, and wellbeing: In2Air a non-randomized experiment. [published online ahead of print September 3 2025]. *Public Health Res* 2025. https://doi.org/10.3310/SOSO8851