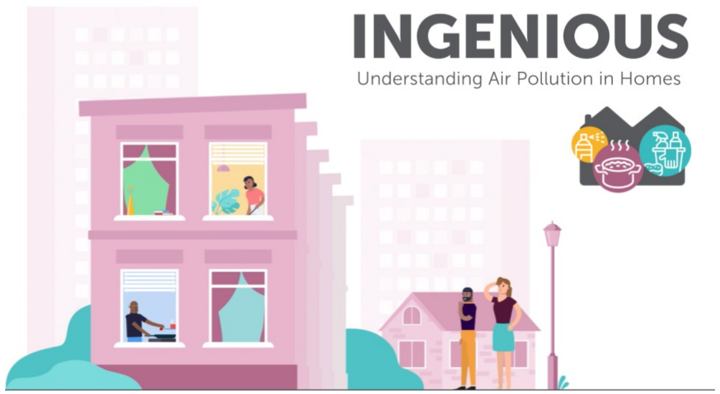
UNIVERSITY of York

Natural Environment Research Council




# Towards understanding air pollution in homes: the INGENIOUS project

**Nic Carslaw (and the INGENIOUS Team)**

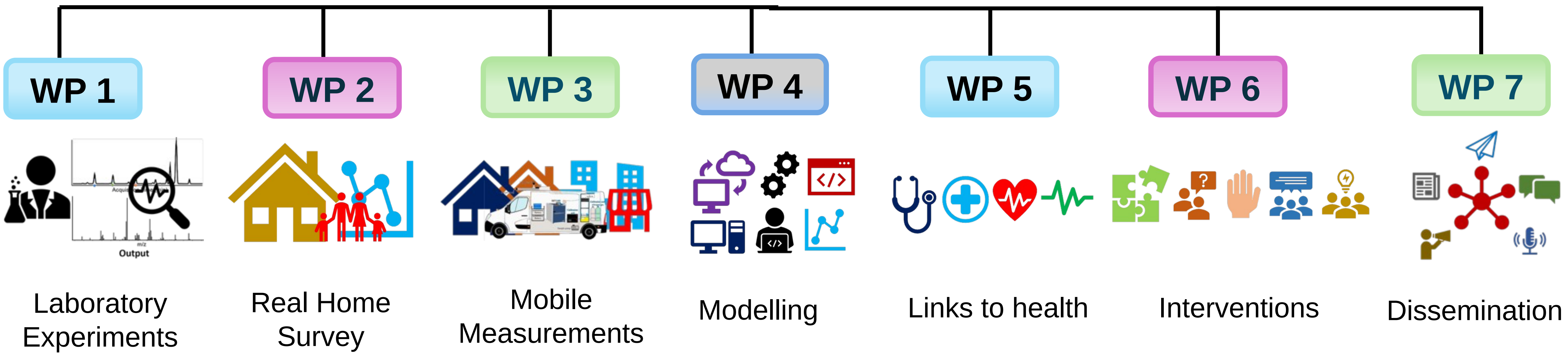
- Introduction: summary of indoor pollutant concentrations (Nic)
- Focus on under heating and mould (Lia)
- Focus on health inequalities (Tiffany)

The University Of Sheffield. | MANCHESTER 1824 The University of Manchester | bib We are family | UNIVERSITY OF CAMBRIDGE | SEI Stockholm Environment Institute | TINCTURE NATURALS · LONDON | reckitt | RICARDO | WSP | immaterial | HomeLINK | National Centre for Atmospheric Science

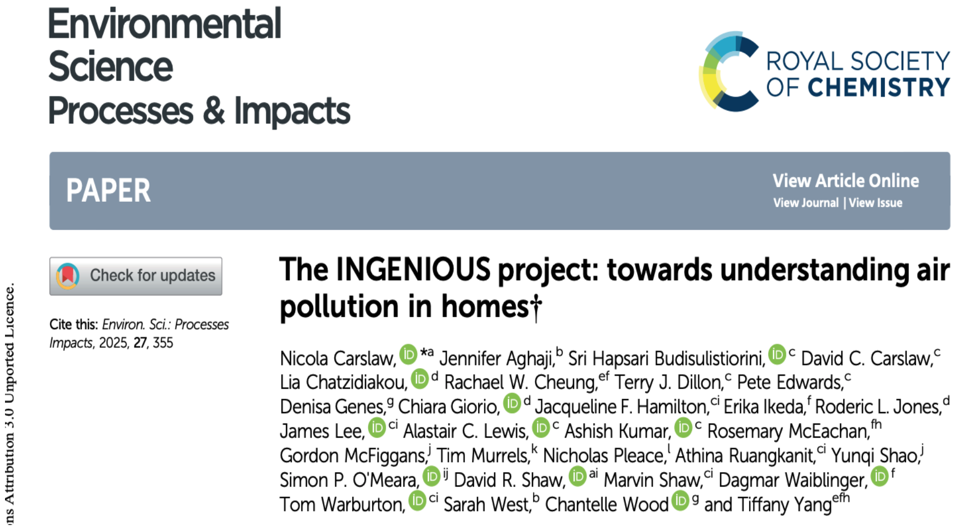
# Aims

The overarching aims of INGENIOUS are to:

- Undertake **first** comprehensive mapping of main sources, transformations and fate of air pollutants in UK homes
- Identify inequalities in exposure and the consequent impacts on health amongst diverse populations
- Identify the physical, social and behavioural factors that control pollutant distribution
- Co-design novel, scalable interventions to improve air quality and health.



# Highlights so far…



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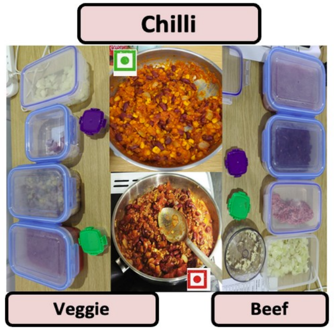
## The INGENIOUS project: towards understanding air pollution in homes†

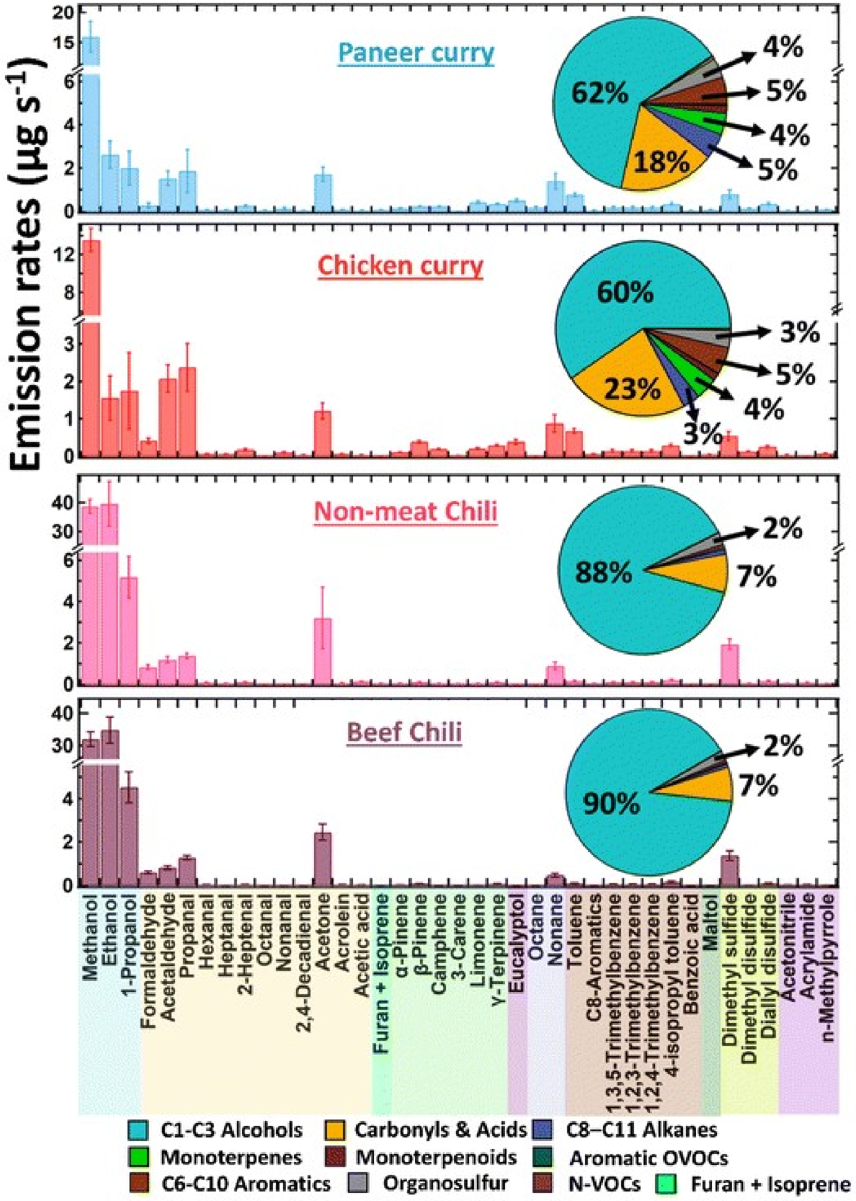
Nicola Carslaw,[*a] Jennifer Aghaji,[b] Sri Hapsari Budisulistiorini,[c] David C. Carslaw,[c] Lia Chatzidiakou,[d] Rachael W. Cheung,[ef] Terry J. Dillon,[c] Pete Edwards,[c] Denisa Genes,[g] Chiara Giorio,[d] Jacqueline F. Hamilton,[ci] Erika Ikeda,[f] Roderic L. Jones,[d] James Lee,[ci] Alastair C. Lewis,[c] Ashish Kumar,[c] Rosemary McEachan,[fh] Gordon McFiggans,[j] Tim Murrels,[k] Nicholas Pleace,[l] Athina Ruangkanit,[ci] Yunqi Shao,[j] Simon P. O'Meara,[ij] David R. Shaw,[ai] Marvin Shaw,[ci] Dagmar Waiblinger,[f] Tom Warburton,[ci] Sarah West,[b] Chantelle Wood[g] and Tiffany Yang[efh]

- Providing a significant body of data towards an indoor emissions inventory
- To successfully complete IAQ measurements in more than 300 homes in Bradford which showed:
  - Wide variability in indoor concentrations between houses: behaviour is key
  - High $PM_{2.5}$ concentrations in kitchens, >>WHO guidelines
  - High $CO_2$ in bedrooms at nighttime
  - Evidence of under heating below WHO guidelines for health indicating fuel poverty
- Providing evidence that most deprived families are subject to much higher $PM_{2.5}$ than least deprived

www.ingenious.york.ac.uk

# Cooking emissions



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Cite this: DOI: 10.1039/d5em00385g

**Chemical fingerprints of cooking emissions and their impact on indoor air quality**

Ashish Kumar,[*a] Catherine O'Leary,[a] Ruth Winkless,[a] Wael Dighriri,[a] Marvin Shaw,[ac] David Shaw,[bc] Nicola Carslaw[b] and Terry Dillon[*a]

Average air change rate: 0.73 $h^{-1}$


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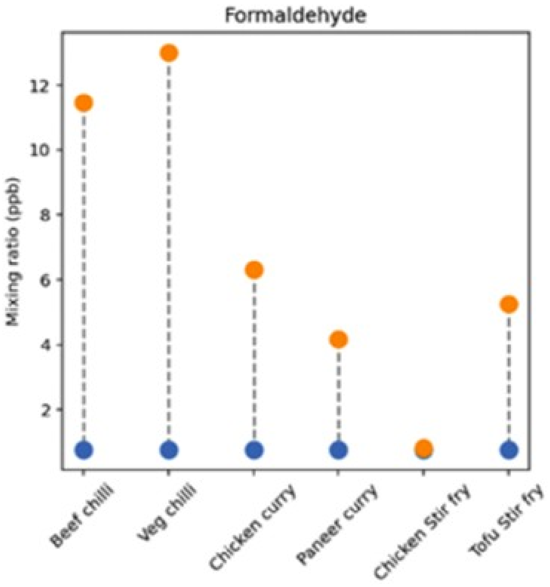
Chemical fingerprints of cooking emissions and their impact on indoor air quality

Ashish Kumar,*[a] Catherine O'Leary,[a] Ruth Winkless,[a] Wael Dighriri,[a] Marvin Shaw,[ac] David Shaw,[bc] Nicola Carslaw[b] and Terry Dillon*[a]

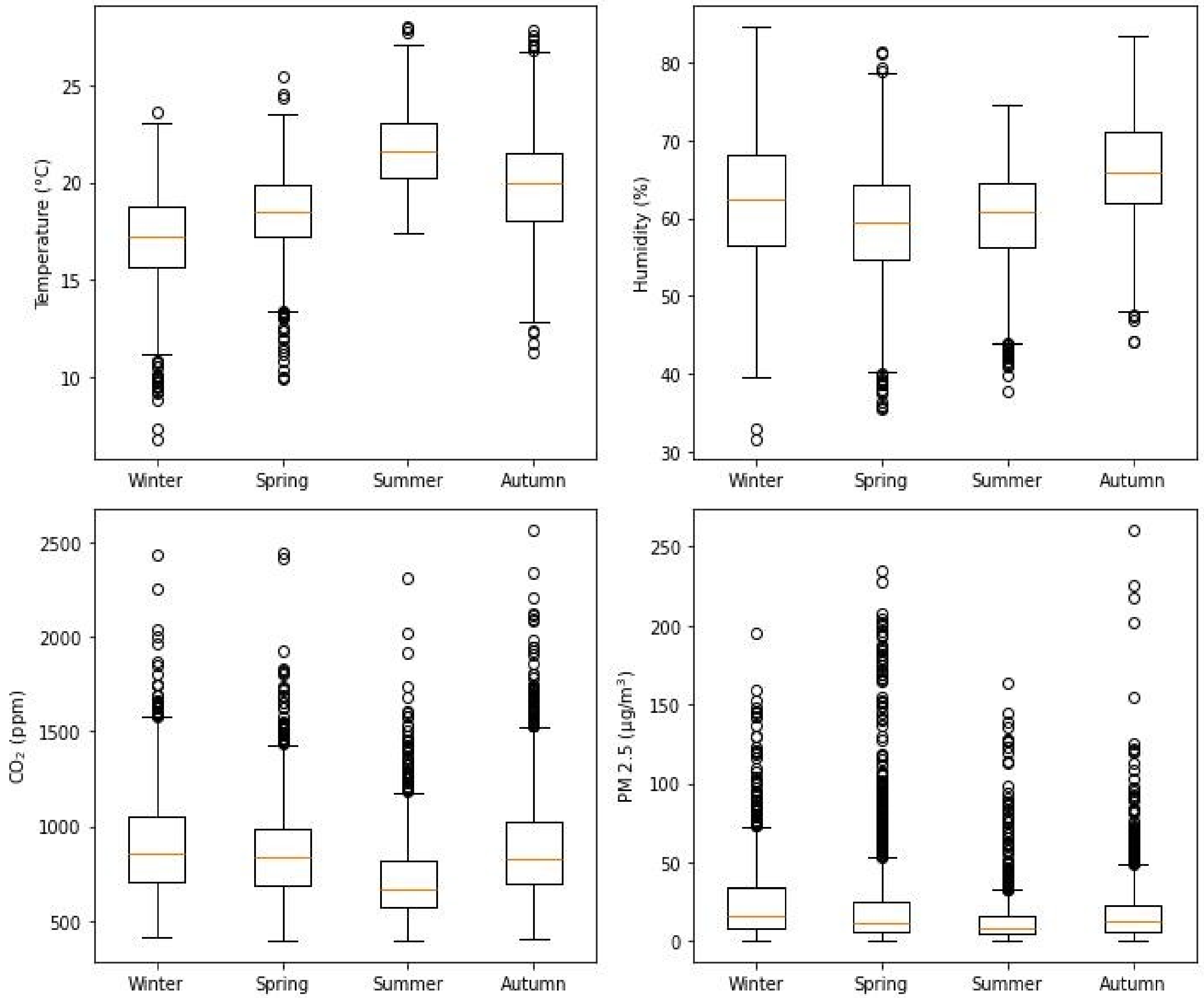
# Cooking emissions: health effects?

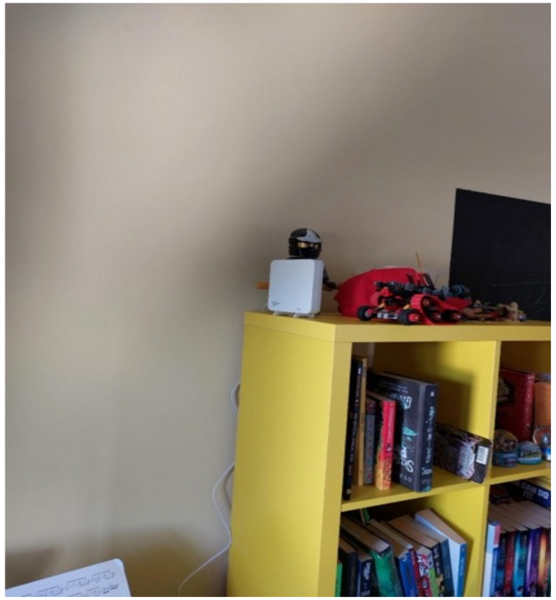



Cooking
Not cooking

- Cooking formaldehyde up to 12 ppb > background:
  - higher than reference concentration (7 µg $m^{-3}$/5.7 ppb) for sensory irritation from US EPA
  - higher than 8 hour reference exposure levels (9 µg $m^{-3}$/7.3 ppb) for non-cancerous impacts from the California OEHHA
- Average cooking acetaldehyde 0.028–0.090 mg $m^{-3}$, exceeding the IARC prescribed limit by a factor of 9–30.
- **Exceedances are for a short duration**: reference values are established for a constant exposure over a prolonged period of time.
- Implications for those who work in professional kitchens
- Many other species emitted for which we have no health data at present

# Low Cost Sensor data summary from 310 homes in Bradford



- Variability between houses > seasons
- Internal T often low
- Indoor $PM_{2.5}$, $CO_2$ can be high

Lia Chatzidiakou, Dave Shaw, University of York

# Distribution of bedroom night-time $CO_2$ concentrations


- > 1000 ppm 60 % of the time
- > 2000 ppm 20% of the time

Lia Chatzidiakou, University of York

# Impact on cognitive performance

Environmental Health Perspectives

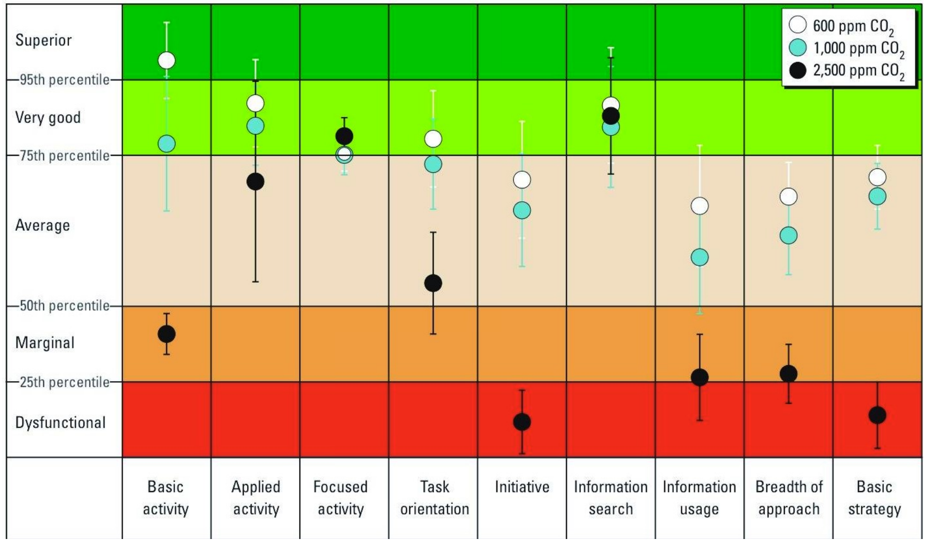
Environ Health Perspect. 2012 Sep 20;120(12):1671–1677. doi: 10.1289/ehp.1104789

## Is $CO_2$ an Indoor Pollutant? Direct Effects of Low-to-Moderate $CO_2$ Concentrations on Human Decision-Making Performance

Usha Satish [1], Mark J Mendell [2,✉], Krishnamurthy Shekhar [1], Toshifumi Hotchi [2], Douglas Sullivan [2], Siegfried Streufert [1], William J Fisk [2]

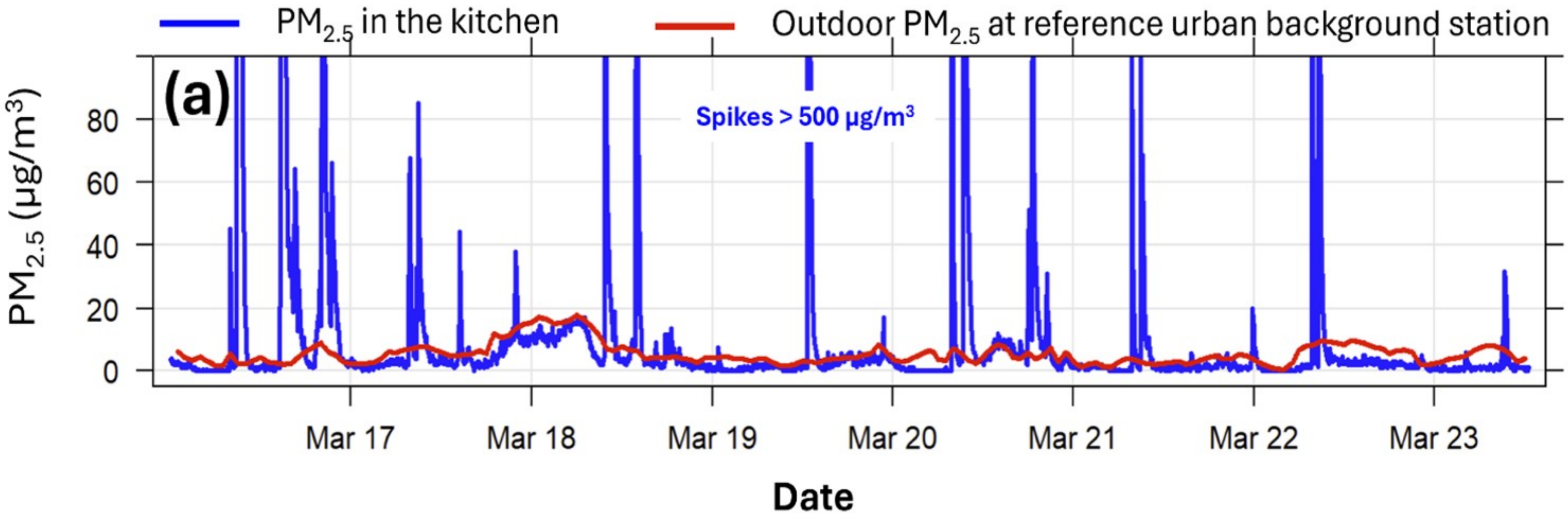
Author information Article notes Copyright and License information

PMCID: PMC3548274 PMID: 23008272



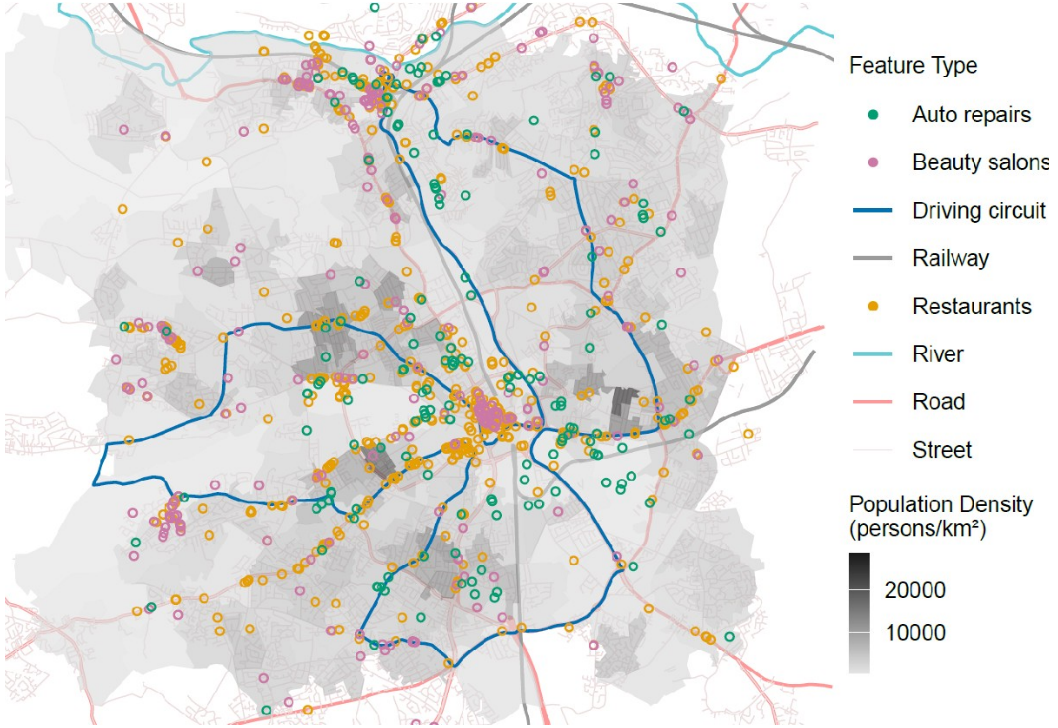

- Concentrations in bedrooms often exceed those known to affect cognitive performance
- $CO_2$ is likely an indicator for high concentrations of other pollutants, so for inadequate ventilation in general
- Given many children spend significant time in their rooms, could be having an impact

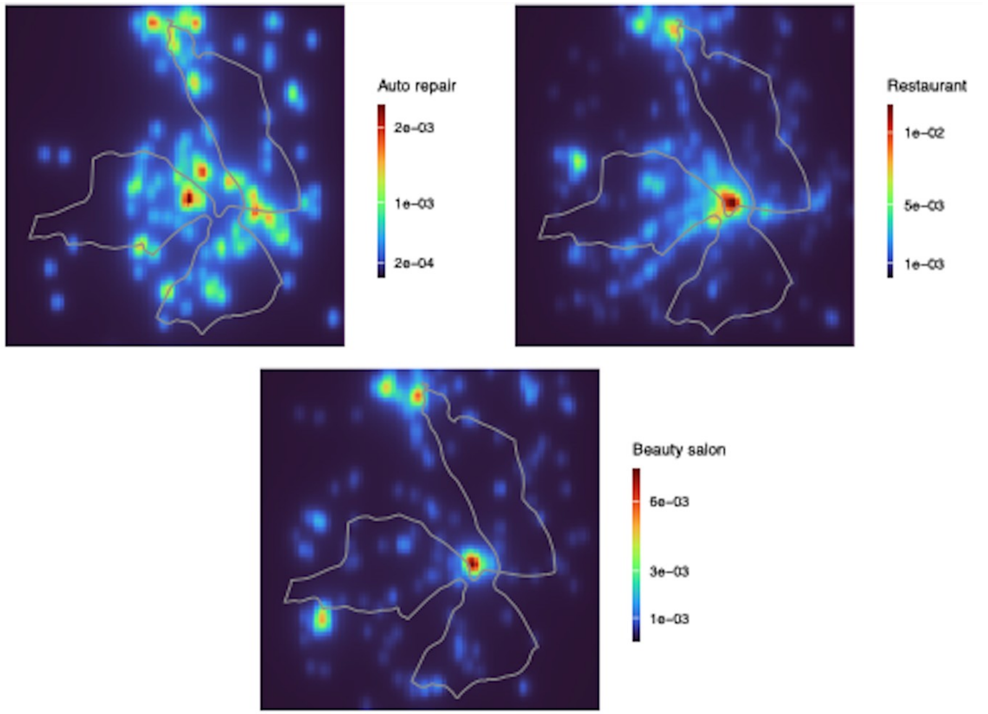
# Indoor and outdoor $PM_{2.5}$




- Indoor $PM_{2.5}$ follows outdoor concentrations in the absence of occupant activities
- High concentrations driven by occupants, mainly cooking
- Drive to reducing indoor PM (mean~20 µg/$m^{3}$) might be a more economic means to reduce exposure than efforts to lower outdoor concentrations (mean~10 µg/$m^3$)

# Detecting indoor emissions outdoors?




Budisulistiorini, S.H., Moore, T.C., Shaw, M.D., Drysdale, W.S., Lee, J.D.and D.C. Carslaw (2025). Linking Indoor Commercial Source Emissions to Outdoor Volatile Organic Compounds Using Mobile Measurements, ES&T Air, submitted.

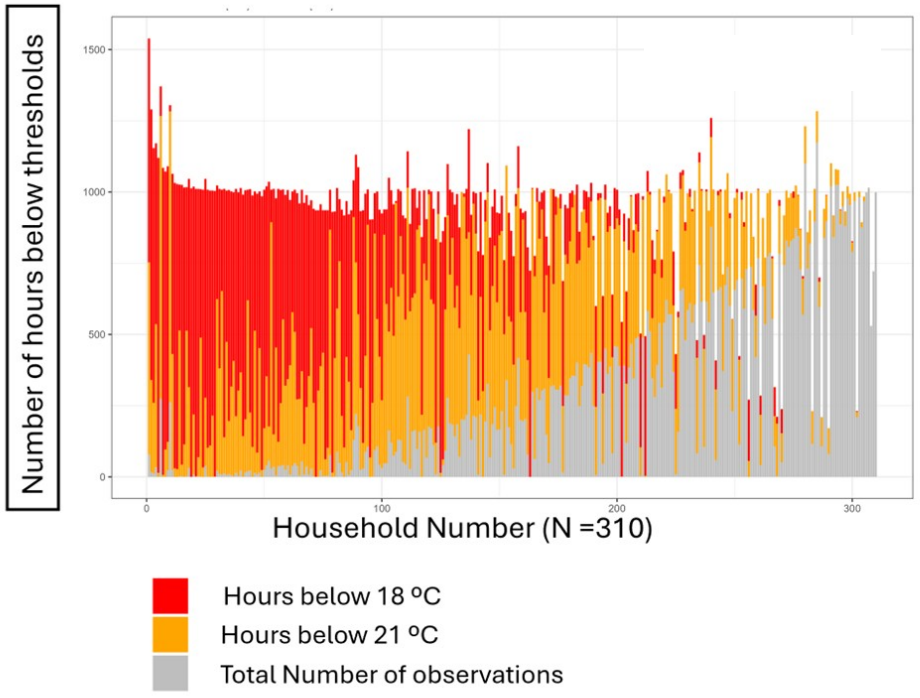
- New approach developed to highlight influence of sources taking account of their density and dispersion
- The source factor used to test the strength of the relationship between a measured VOC concentration with a factor representing approximate source influence
- Species such as acetone are most strongly related to sources such as beauty salons

# Underheating, a serious harm to health

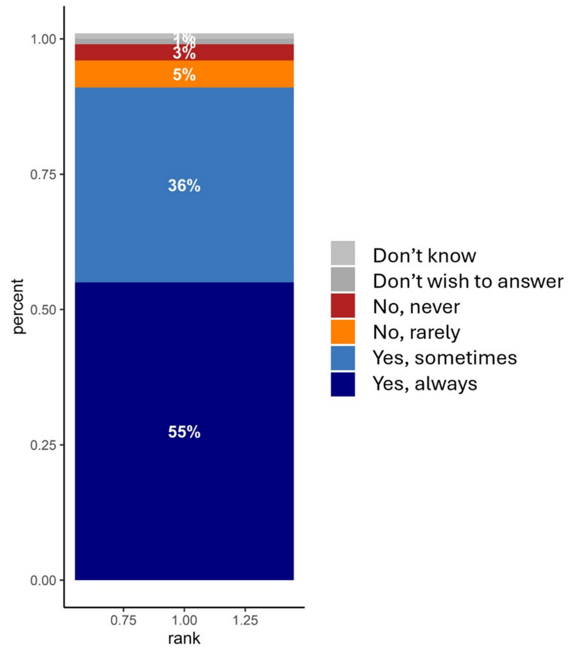
~ 30 % of households below recommended temperatures

~ 10 % of households reported fuel poverty

**Thermal comfort – thresholds**




**When you are at home on a typical day in winter, are you (and everyone in your household) warm enough?**



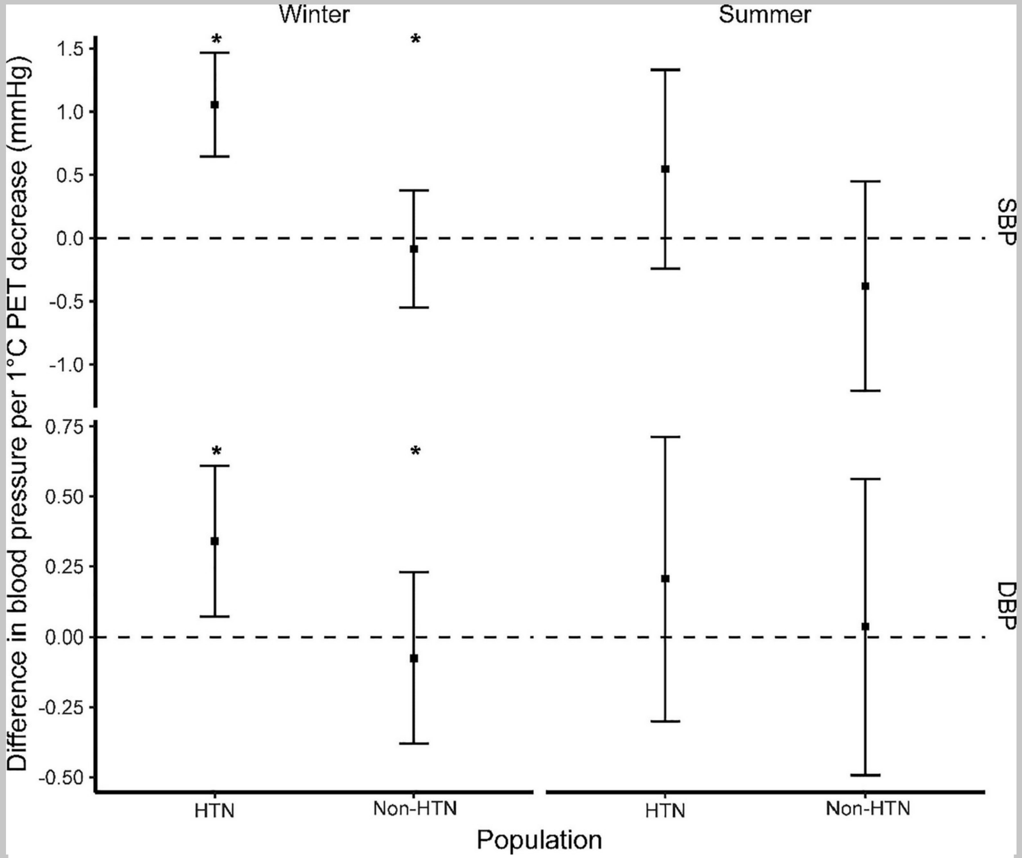

**With these thresholds underheating is quite common and may have significant health implications**

**It is currently estimated that cold and damp homes cost the NHS £1.4 billion annually**

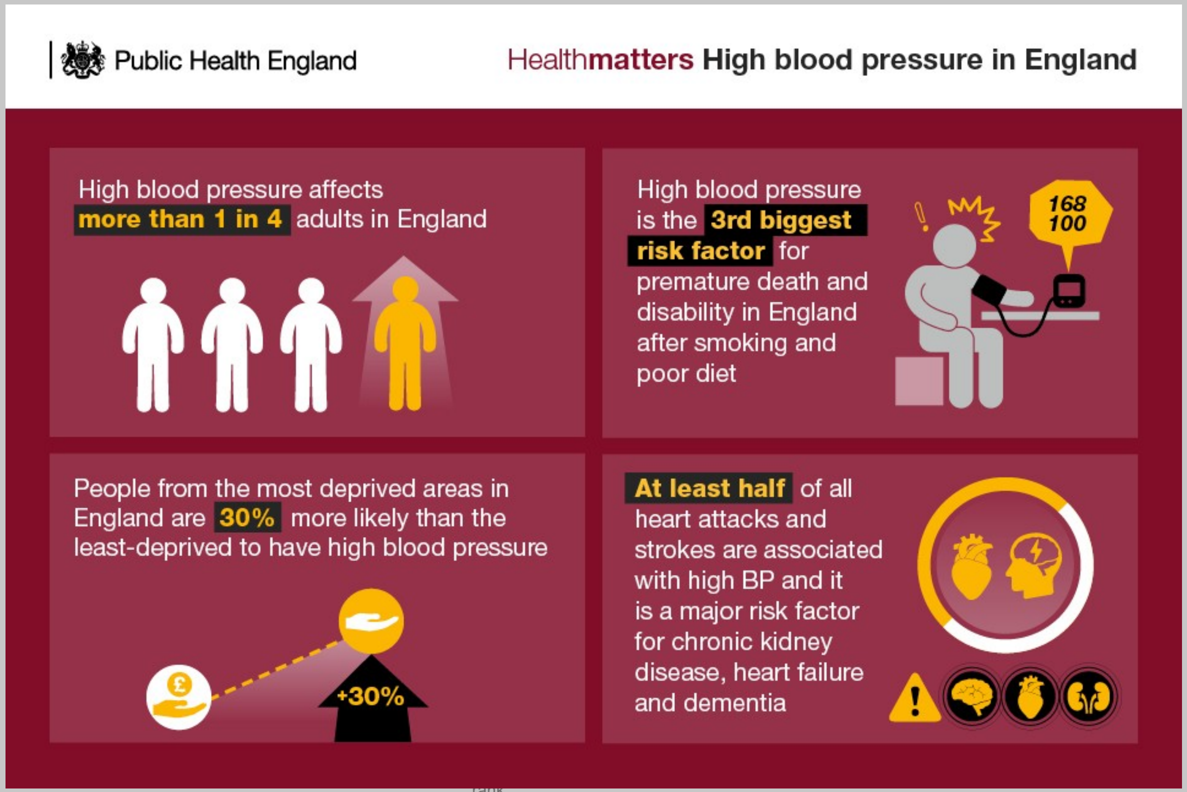
# Underheating, a serious harm to health

~ 30 % of households below recommended temperatures

~ 10 % of households reported fuel poverty



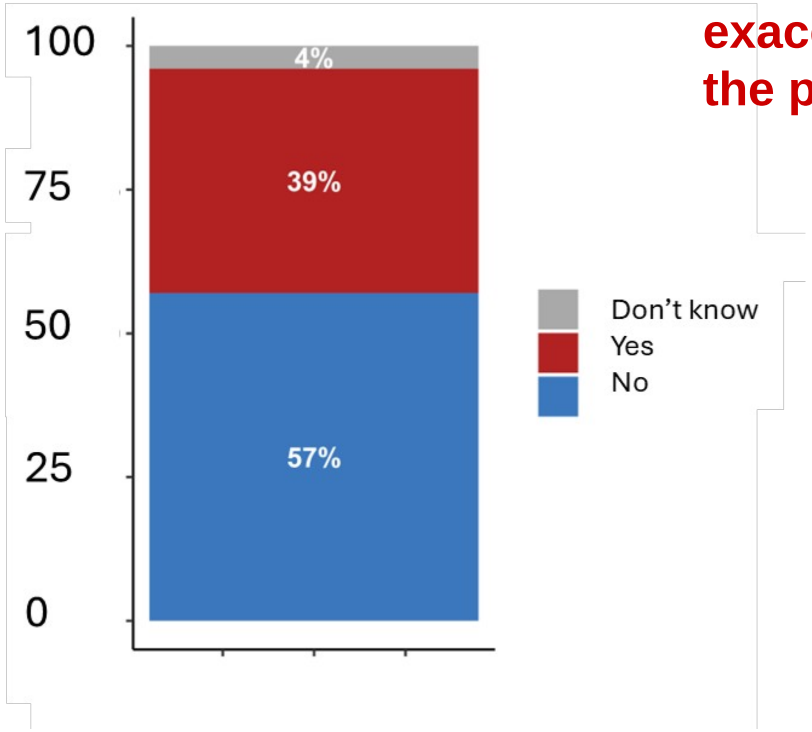

**Undeheating particularly harmful on cardiovascular function of hypertensive individuals (results from AIRLESS study)**




**It is currently estimated that cold and damp homes cost the NHS £1.4 billion annually**

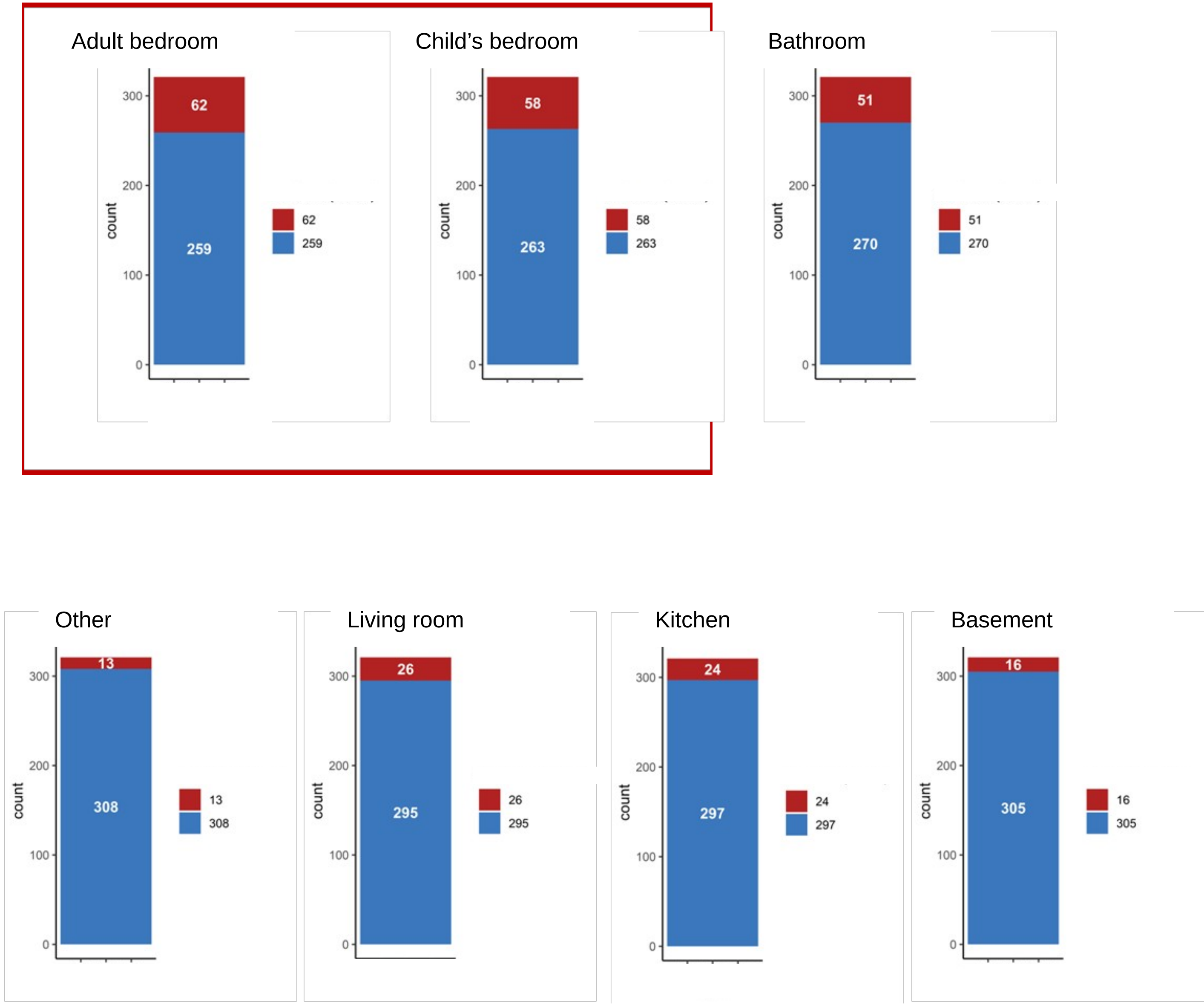
# Mould growth (self-reported)

**Reduced ventilation exacerbates the problem**

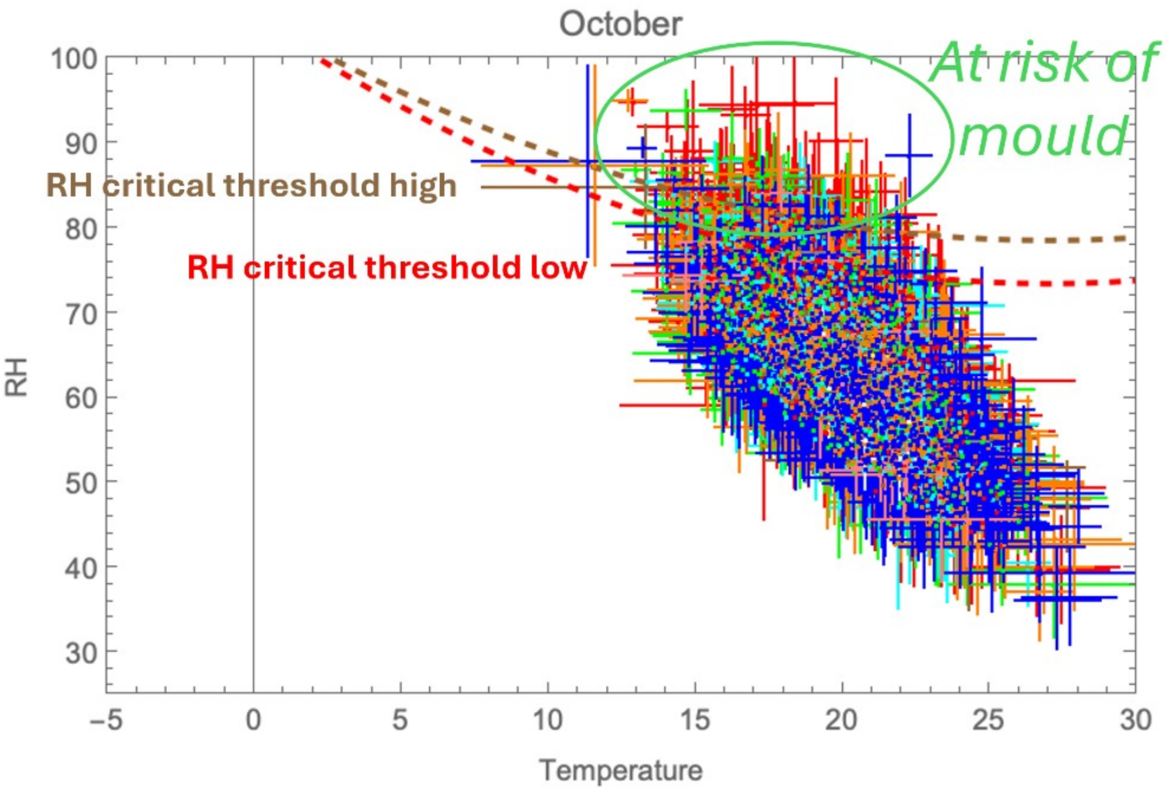


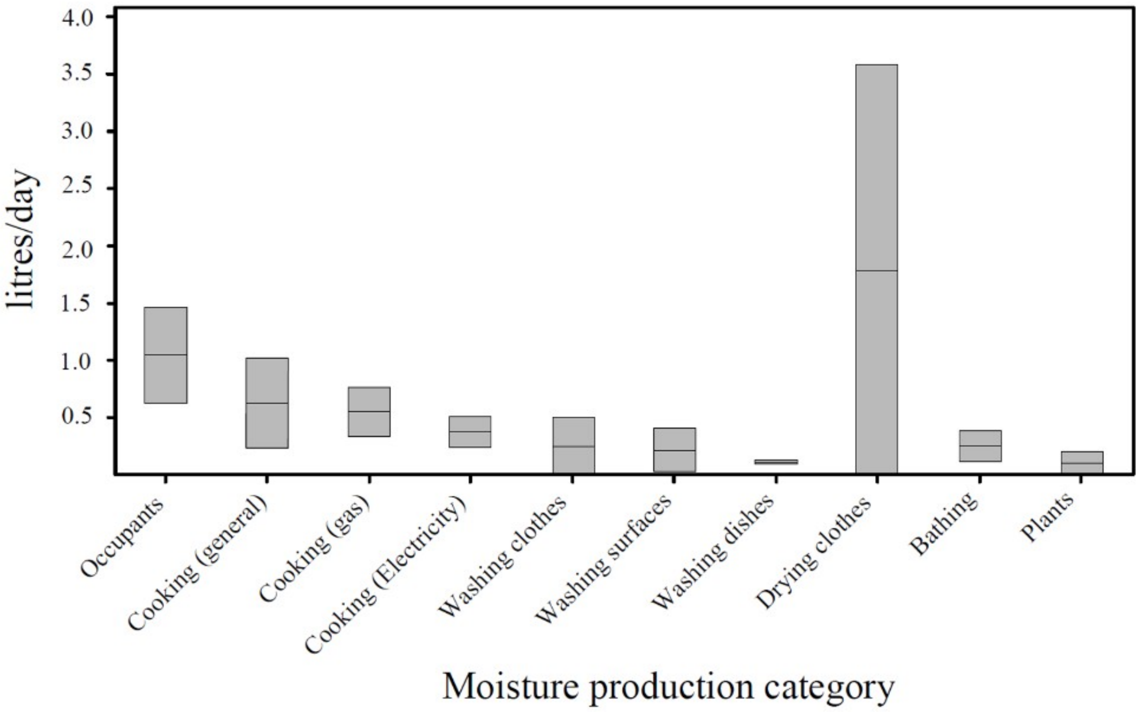

**Mould growth is primarily driven by water activity (RH on surfaces) and has significant health impacts**

In which rooms are there signs or smells of mould or damp? (Tick all that apply)



# Mould prediction (microbial model)



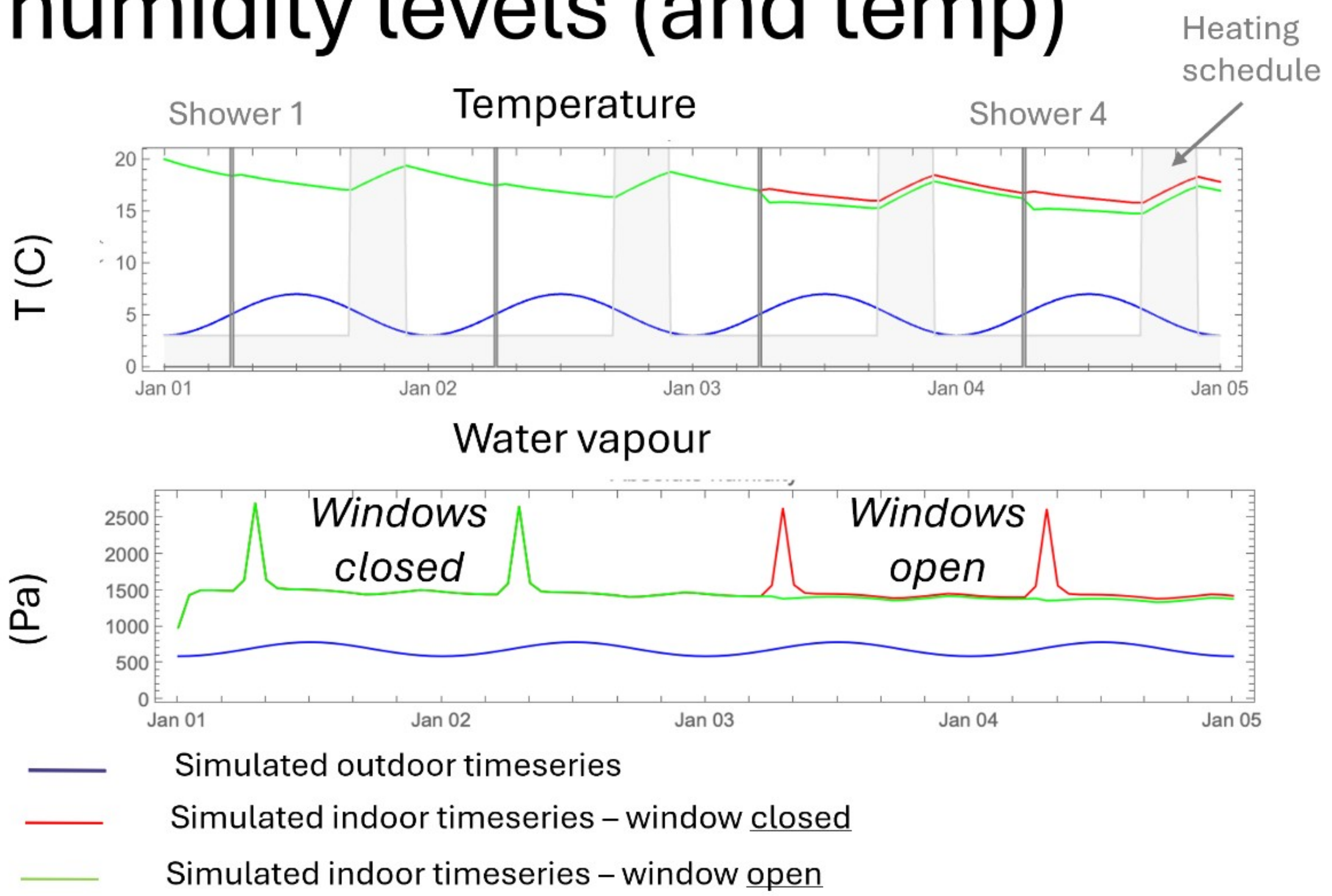

*Assessing monthly mould risk in all rooms of all households with a validated microbiological model [1]*

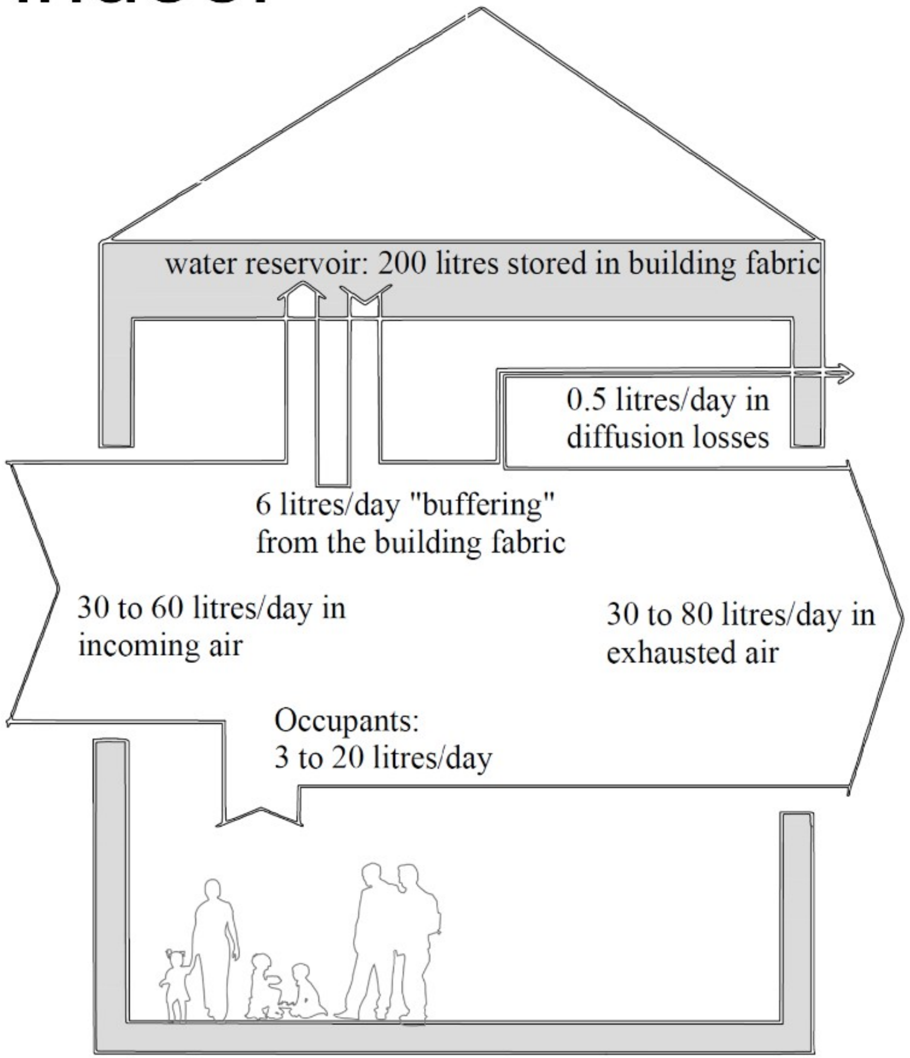
**Extensive dataset - Subset above mould threshold**

**The most critical period for mould growth appears to be the Autumn**

[1] Johansson et al., 2021, https://doi.org/10.1016/j.jobe.2021.102301

# A conceptual model to understand indoor humidity levels (and temp)

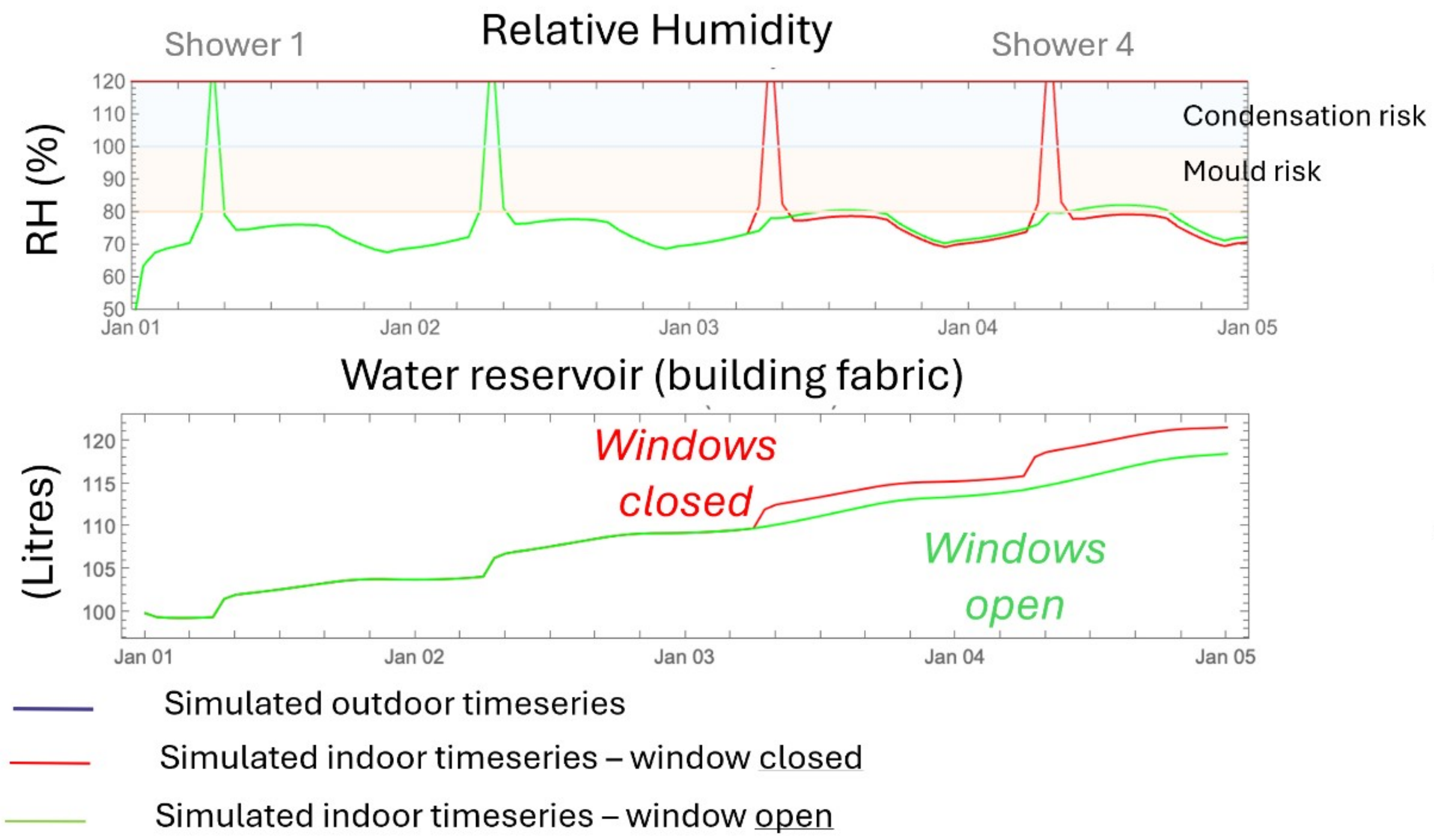


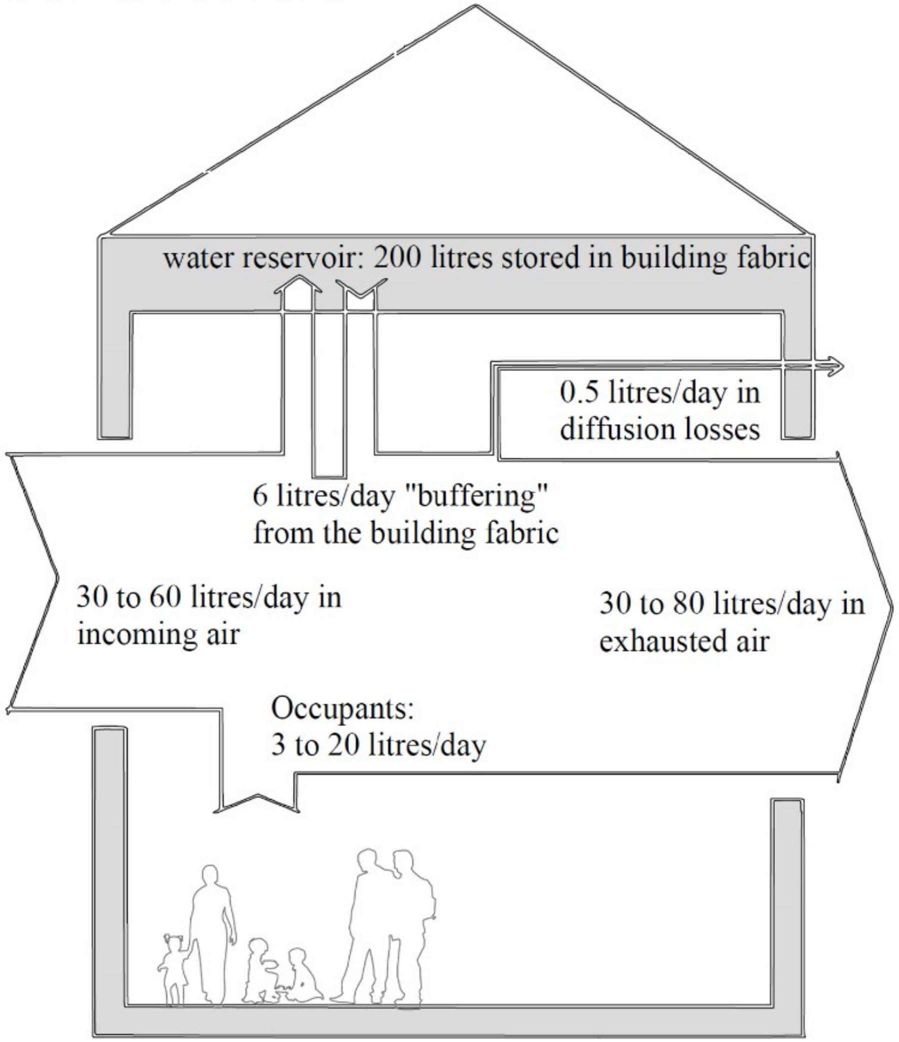




*Typical daily moisture flows in a house –*
*Adapted from* Oreszczyn and Pretlove 1999

**Water vapour can be removed with timely ventilation**

# A conceptual model to understand the effect of timely ventilation on mould risk



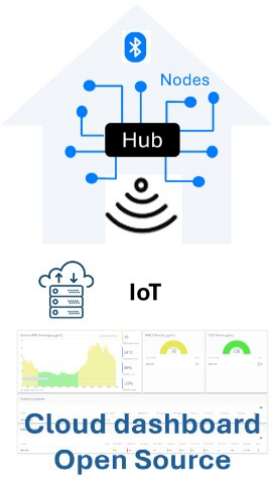




*Typical daily moisture flows in a house –*
*Adapted from* Oreszczyn and Pretlove 1999

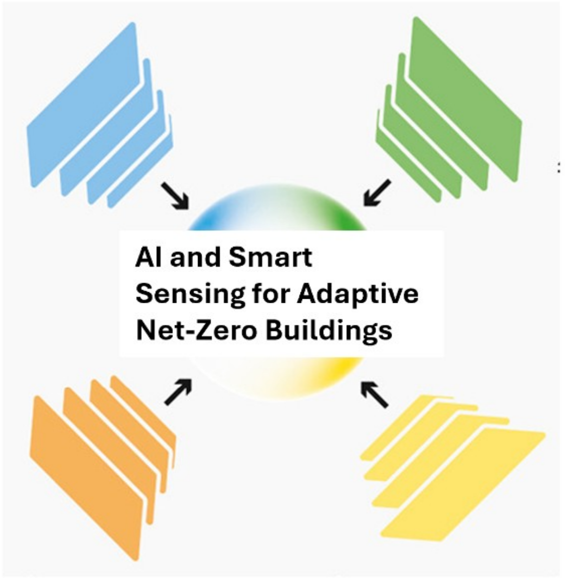
**Opening windows (at the right time) reduces water condensing on surfaces and mould risk !**

# Watch this space…

## Hardware Innovation

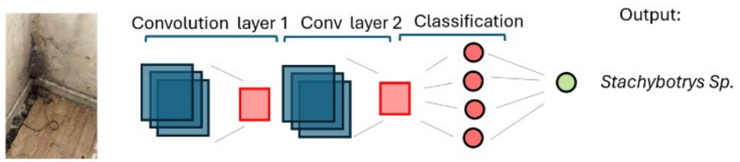



Smart participatory sensing with AI-Driven insights

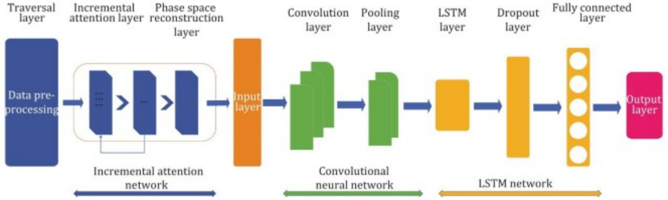



## Novel AI and data science layering

### Image recognition

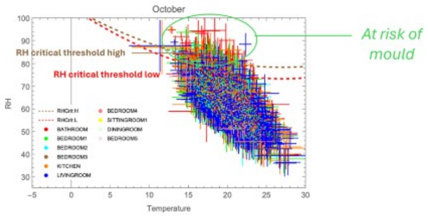


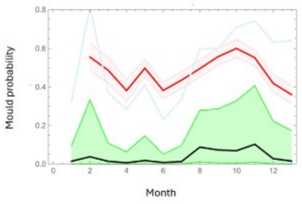

### Extend physical models




### Interpretability

### Improved risk prediction



# Inequalities in indoor air pollution: Particulate matter ($PM_{2.5}$) in 309 homes from Born in Bradford

UK Indoor Air: research at the science-policy interface

November 5, 2025

Tiffany Yang – Born in Bradford, BTHFT

Rachael Cheung
Born in Bradford

# Research questions

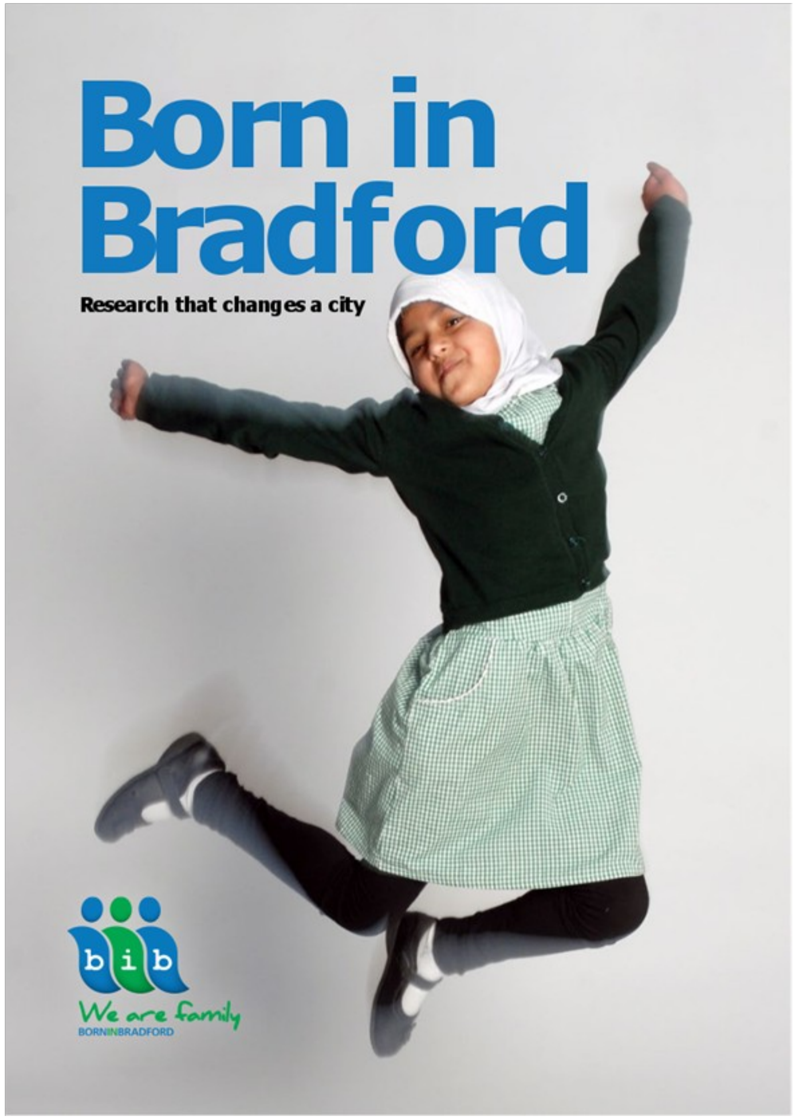
1. What levels of indoor $PM_{2.5}$ are observed in homes?

2. How does this relate to known social determinants of health (housing tenure, ethnicity, deprivation)?

# Research setting

- Born in Bradford families

- 5th largest local authority in England
- 57% White British, 25% of Pakistani origin
- 13th most deprived local authority in England
- 20% of residents living in fuel poverty
- Annual outdoor $PM_{2.5}$ 2021-2023: 7.1-8.4 μg/$m^3$



# Methods: Data collection

Aim: 300 Born in Bradford households recruited for ~ 2 weeks

Per home:

Figure 3 Image of the AirGradient sensor.

Sensor 1: Child's bedroom

Sensor 2: Kitchen

Sensor 3: Living room

→ Averaged per home

- Home characteristics, e.g. tenure, occupancy, household size, pet ownership (Day 1)
- Building characteristics, e.g. type, age (Day 1)
- Health and behaviour characteristics, e.g. smoking, perceptions of air quality (Day 14)

# Methods: Analysis

Per home, $PM_{2.5}$ metrics:

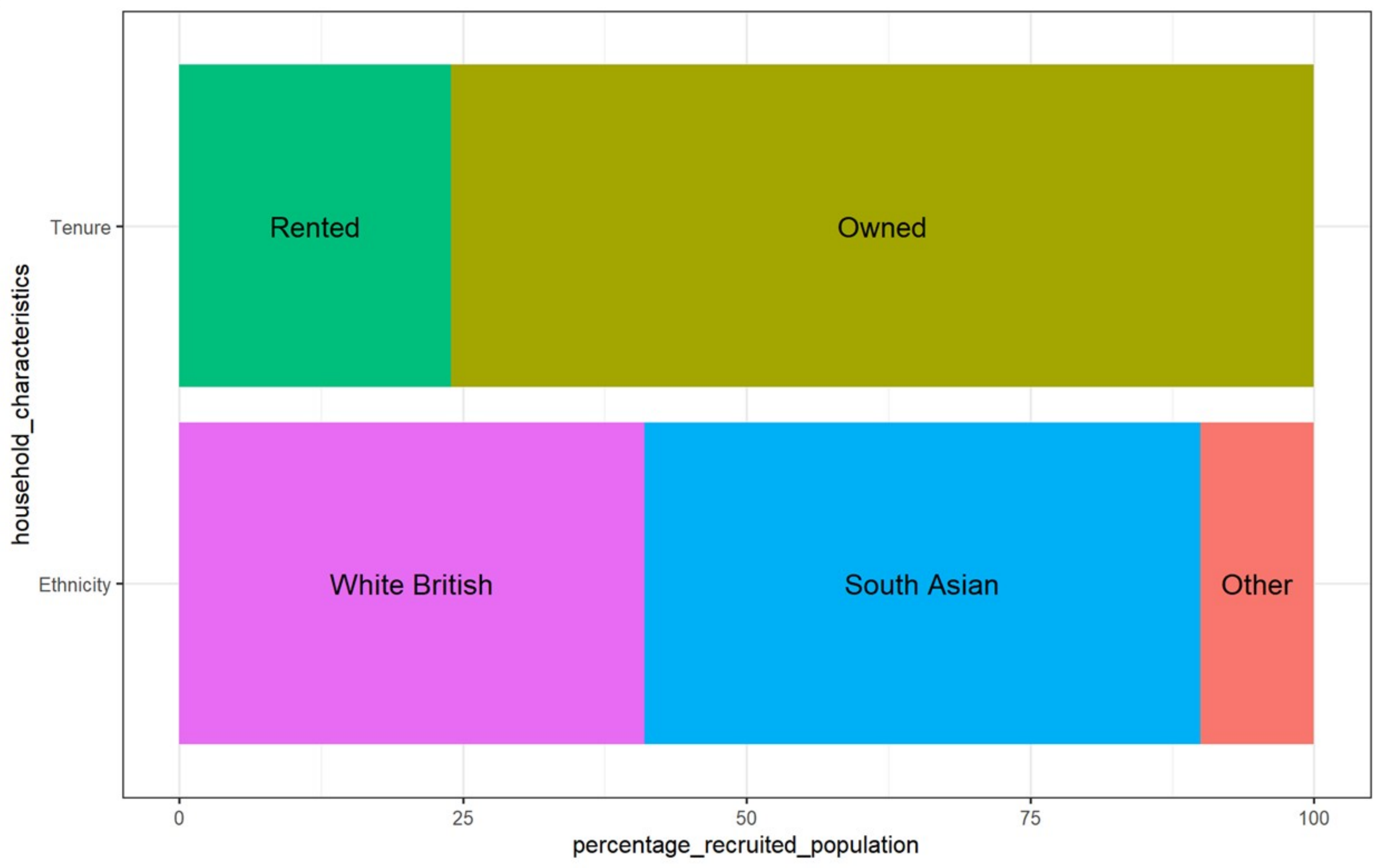
1. Mean daily average concentration (μg/m$^3$)
2. % daily average concentration > 15 μg/m$^3$
3. % hourly average indoor > 100 μg/m$^3$

Descriptive, group-based, mean comparisons to look at $PM_{2.5}$ by three key social determinants of health:

- Housing tenure
- Ethnicity
- Deprivation
- Two-sample unpaired Wilcoxon tests/Kruskal-Wallis + pairwise Wilcoxon with false discovery rate corrections for p-values

# Results: Sample

- 321 households
- 309 homes with sensor data > 7 days and at least 50% collection rate per hour and per day
- From March 2023 – April 2024



# Results: AirGradient sensors

- 3.5 million observations ~ 13,850 home-room-days and ~300,000 home-room-hours
  - $M$ = 13.6 days and $M$ = 924.2 hours per home
  - Participants at home $M$ = 76% of day (VERY rough estimate)

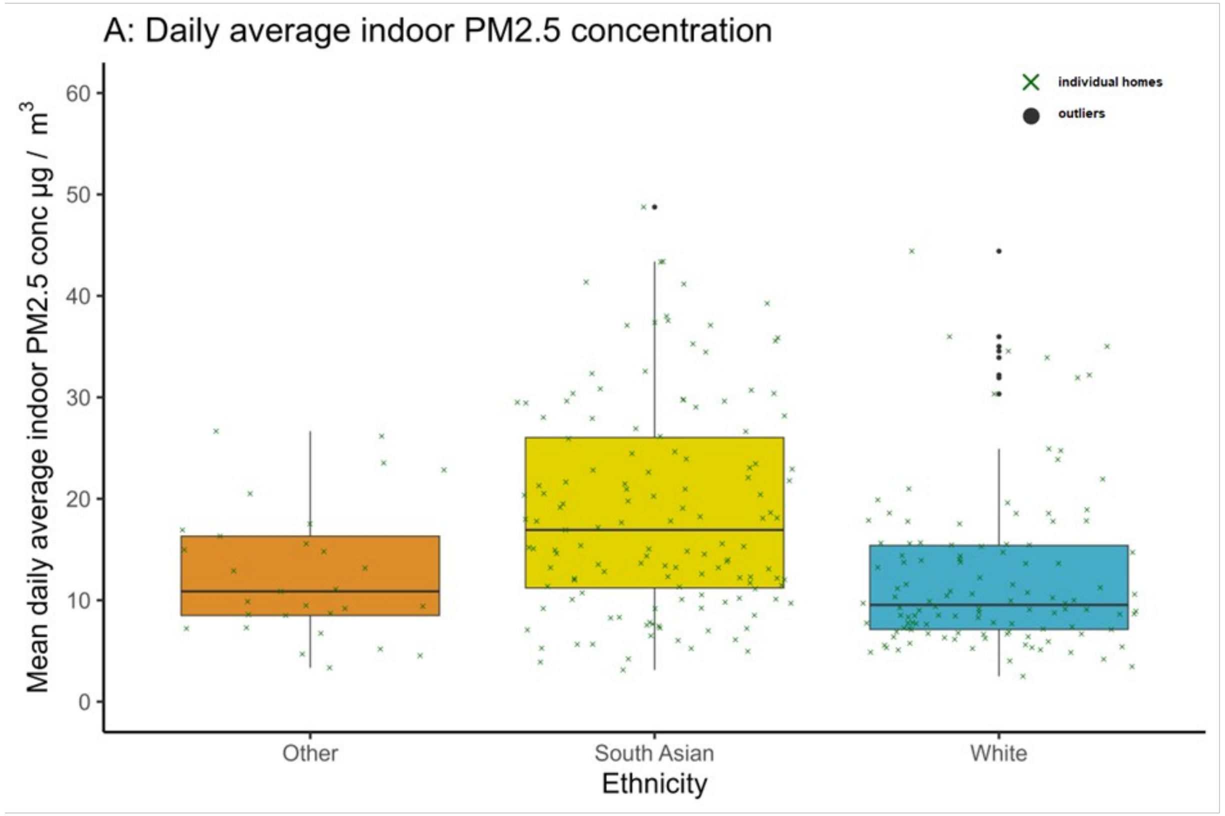
Overall, in the two-week observation period per home:

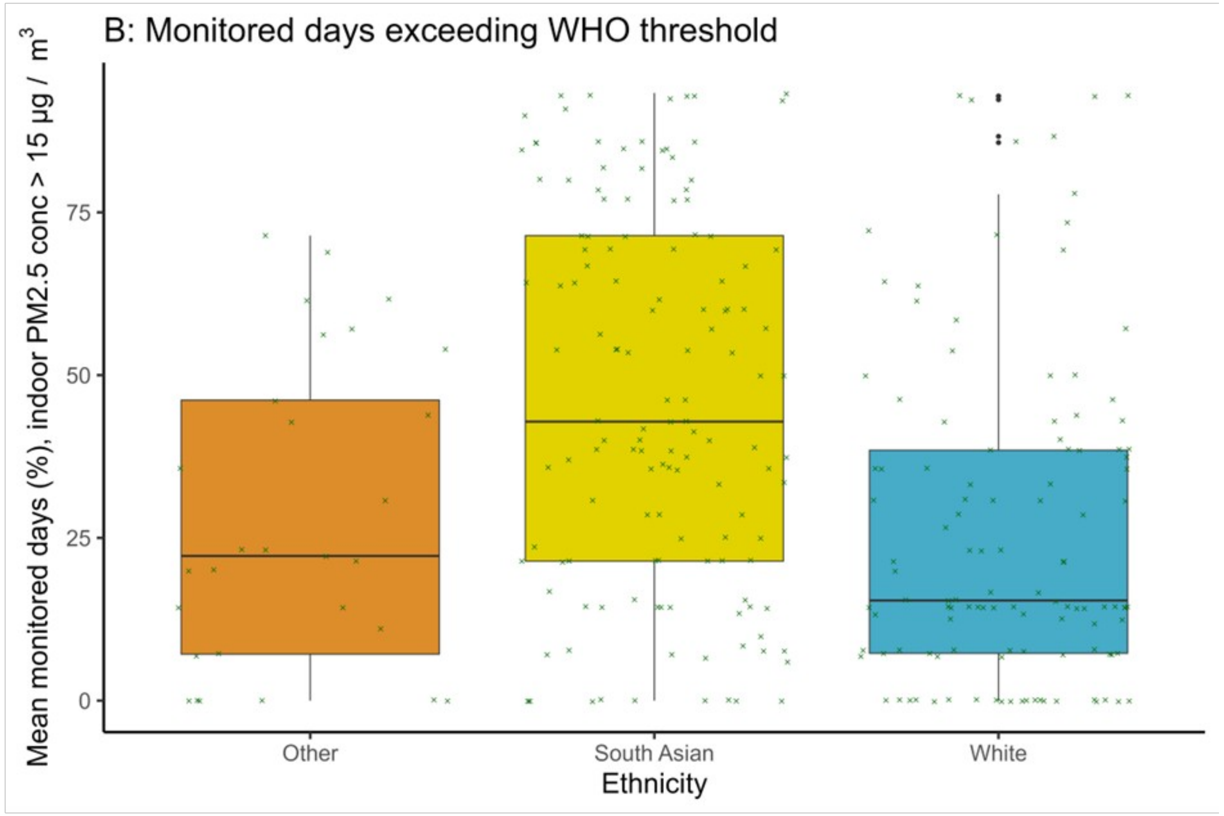
1. Mean daily indoor $PM_{2.5}$ concentration = 20.2 $\mu g/m^3$ (SD = 25.7)

2. Exceeded WHO daily threshold an average of 41% monitored days:
   Range 0% (37 homes) to 100% (20 homes)

3. Exceeded 100 $\mu g/m^3$ an average of 4% monitored hours
   Range 0% (21 homes) to 68% (1 home)

# Results: Ethnicity




Mean = 16.6 µg/m³

Mean = 17.2 µg/m³

Mean = 23.5 µg/m³

$p = .004$

$p < .001$

Mean = 33%

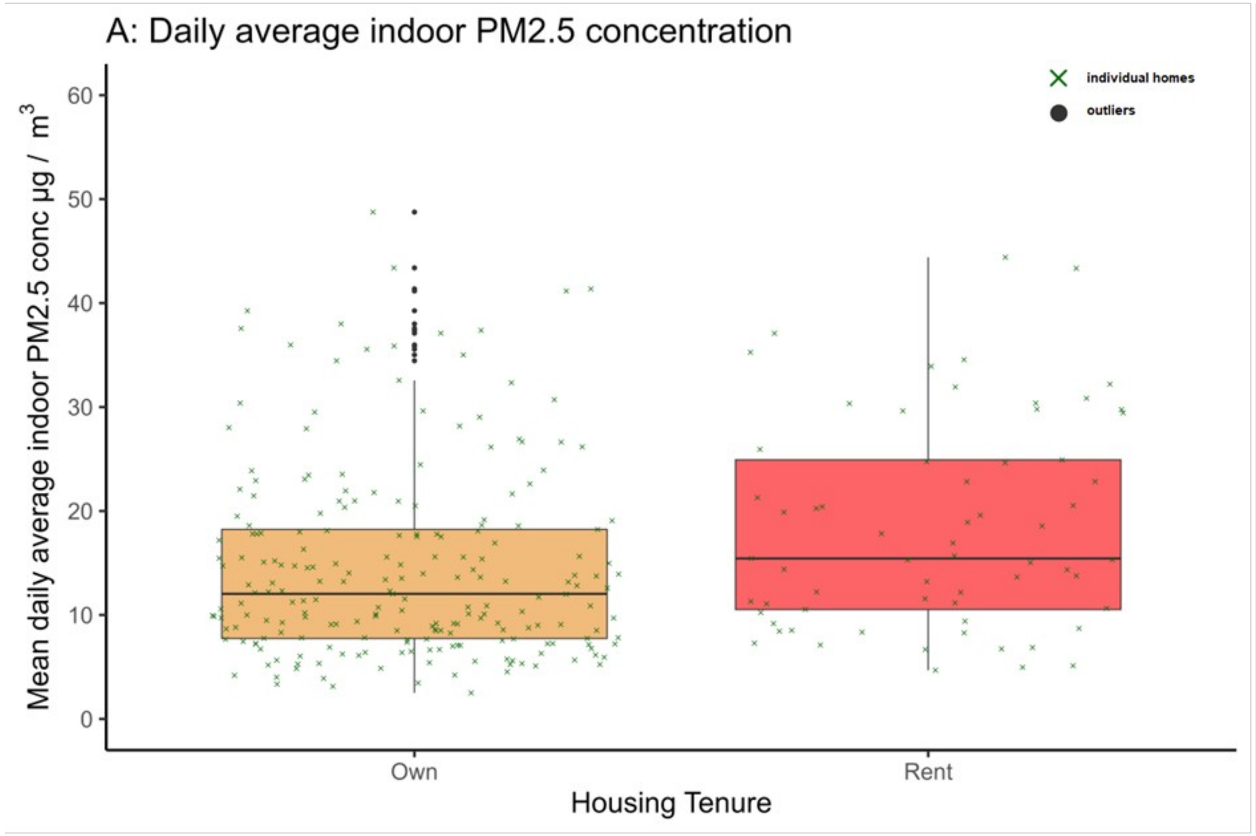
Mean = 31%

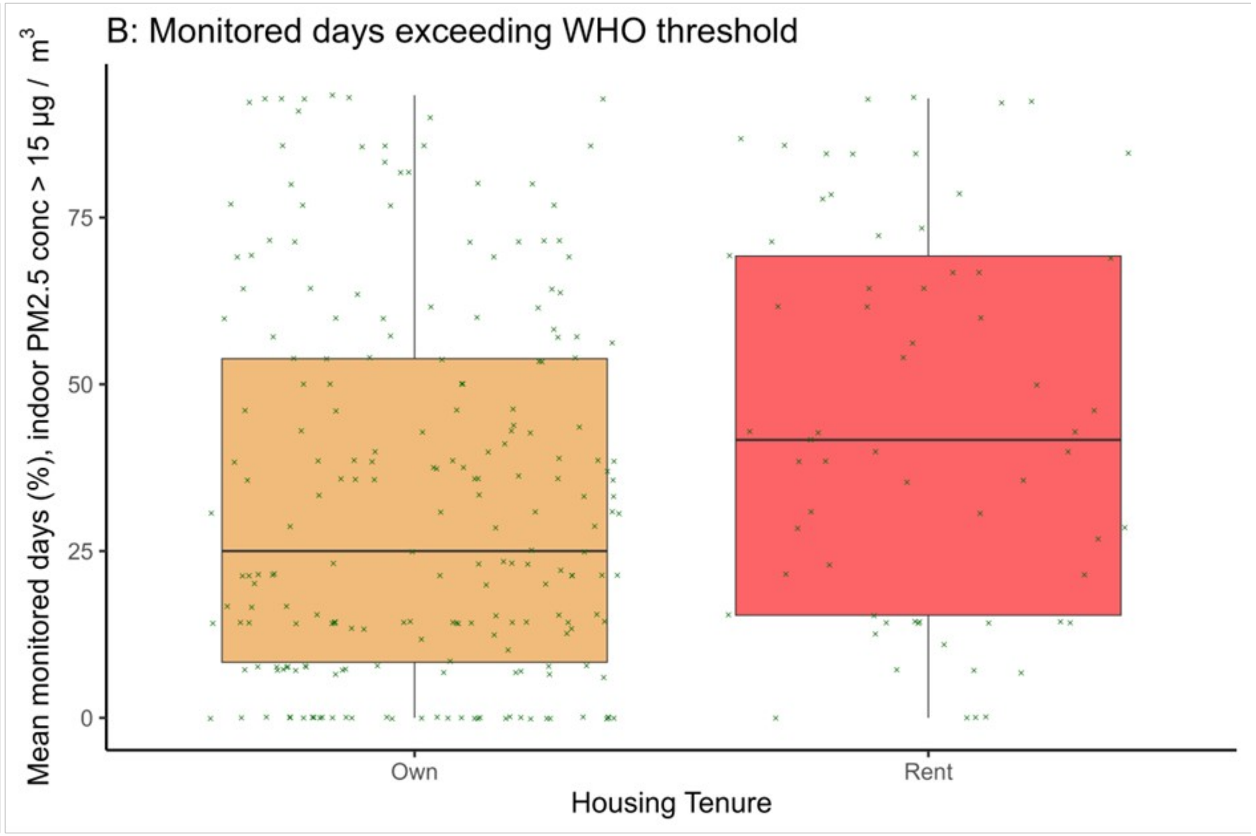
Mean = 51%

$p = .005$

$p < .001$

# Results: Housing tenure



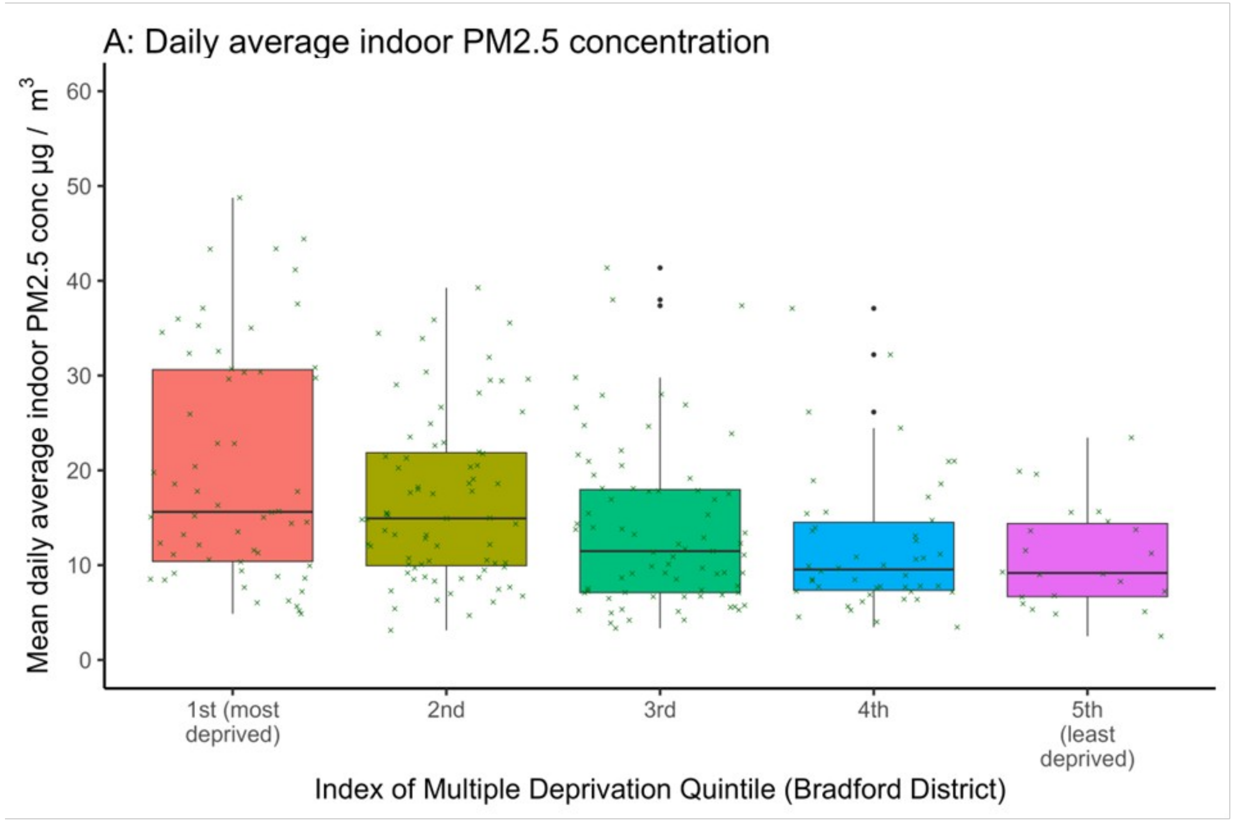

Mean = 19.0 µg/m$^3$ Mean = 23.9 µg/m$^3$

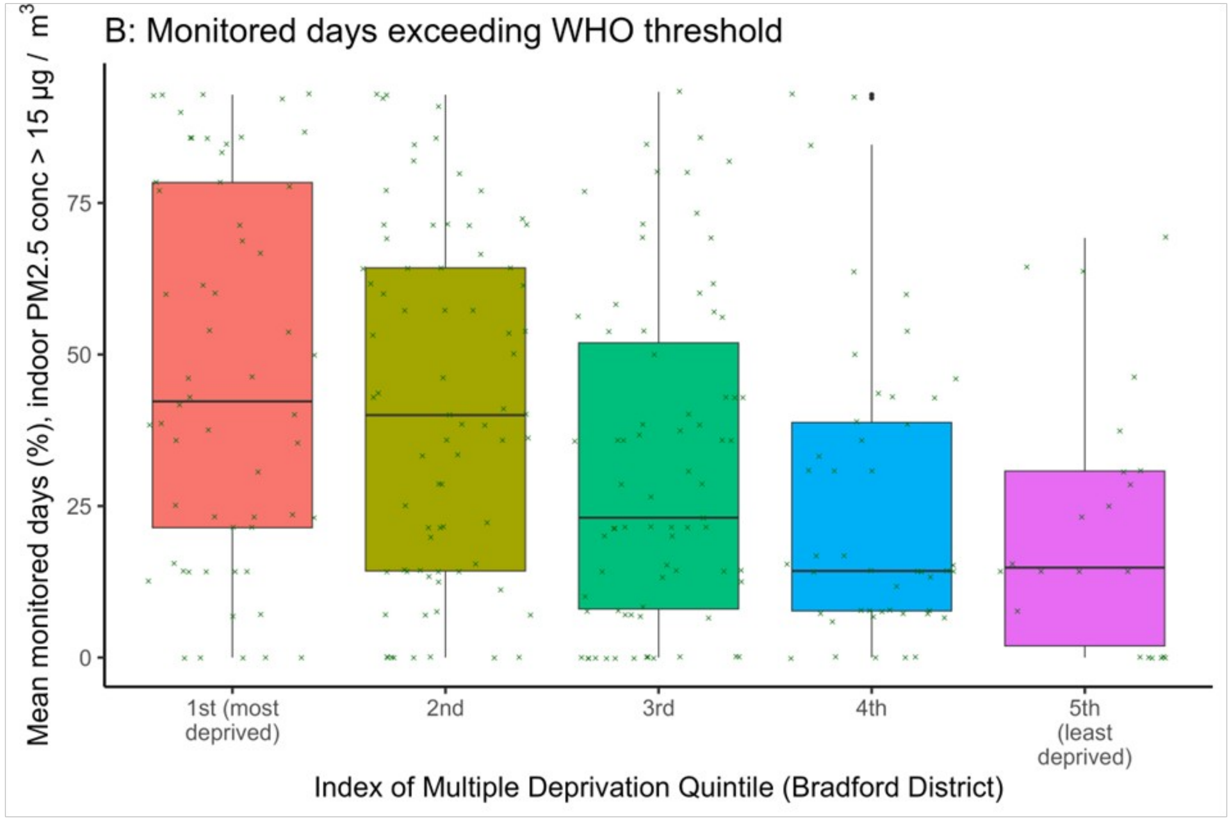
*p* = .003

Mean = 38% Mean = 51%

*p* = .003

# Results: Deprivation



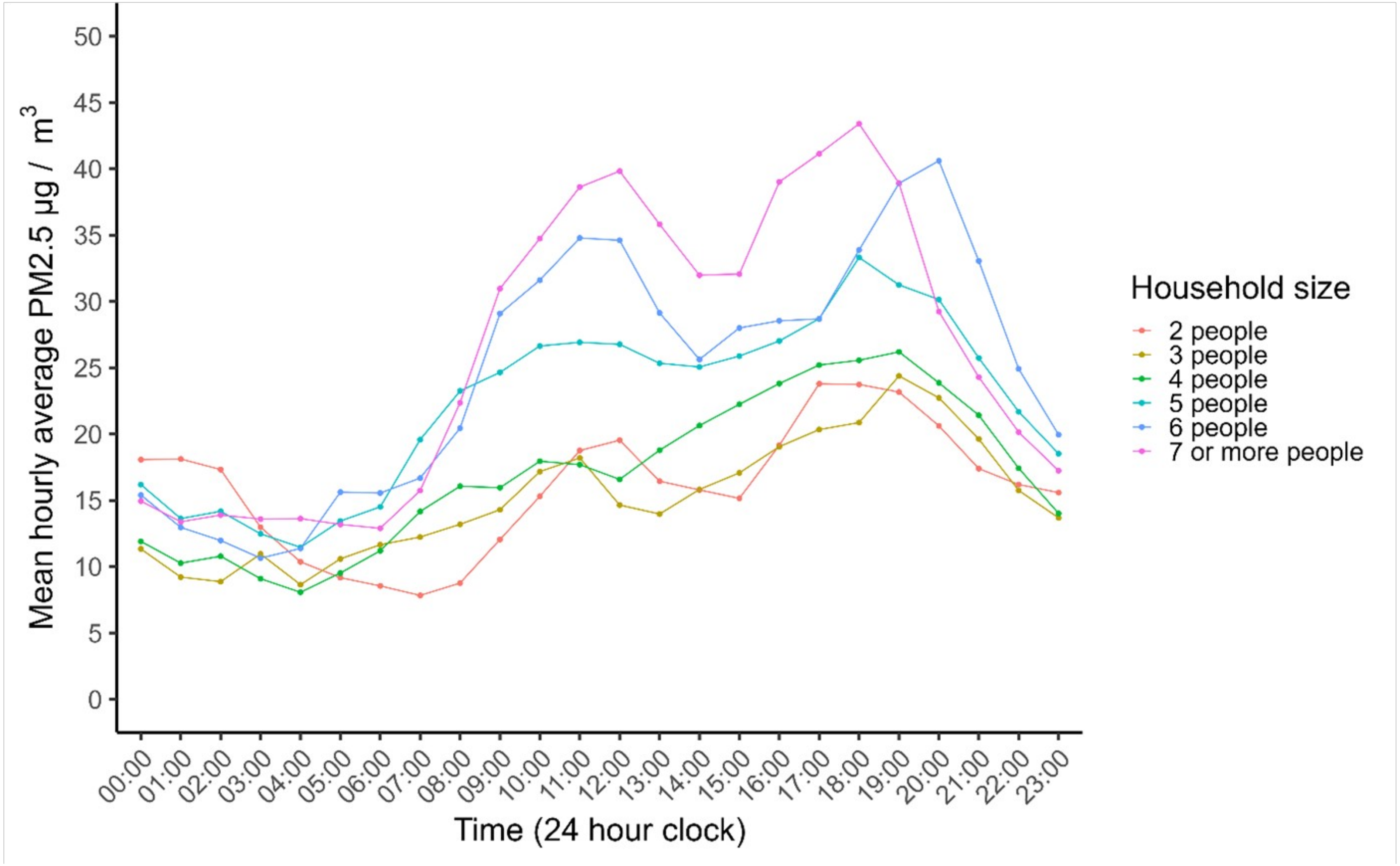

Mean = 23.8 µg/m³ Mean = 12.8 µg/m³

*p* = .003

Mean = 52% Mean = 26%

*p* = .005

# Results: Household size



# Conclusions

- High indoor $PM_{2.5}$ levels recorded in homes:
    - Exceeding WHO 24-hour thresholds 41% of days
    - Highest $PM_{2.5}$ concentrations in areas of deprivation, South Asian homes, rented accommodation

- Need
    - Urgent need to tackle indoor air pollution as a health risk factor, esp. in deprived areas and minority ethnic households, and for more research
    - Longer duration of monitoring
    - Understanding interplay between buildings and occupant behaviours
    - National public awareness campaigns, policy action on buildings