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Ventilation provision and use in homes in Great Britain: A national survey

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ABSTRACT

People in Britain spend most of their time indoors within their homes. Whilst indoors, occupants are exposed to the indoor environment, which can affect comfort and health. Ventilation is the exchange of air between indoors and outdoors, which can alter the indoor environment and modify occupant exposures. However, ventilation can also contribute to heat loss, energy use and carbon emissions.

Despite the importance of ventilation, there is no large-scale data on ventilation provision and use in British homes. To address this gap, this study undertook a questionnaire survey using an established survey organisation to identify installed ventilation provision and use in 1861 British homes. A key focus was on relating the installed provision with long established building standards. These standards require mechanical ventilation in kitchens and bathrooms to extract moisture and pollutants at source, as well as trickle vents to provide background ventilation.

The key findings are that 71 % of homes did not have ventilation provision that met these standards. Homes built after the introduction of these mandatory building standards had a higher proportion of compliant provision, but 41 % of these did not. Provision was poorer in older homes, with only 22 % of homes built before 1991 having this ventilation provision. Only 11 % of all respondents had mechanical ventilation, trickle vents and had also received information or advice on how to use their ventilation system. 22 % of the respondents reported that they had mould or damp on walls or surfaces in their homes.

1. Introduction

1.1. Indoor environmental quality, ventilation and health

On average, people in Britain spend 95 % of their time indoors and 66 % in their own homes [1]. Whilst indoors, occupants are exposed to the indoor environment (thermal, indoor air quality, visual and noise) and this exposure impacts comfort, well-being and physical health [2]. The World Health Organization [3] estimates that 3.2 million people die prematurely every year due to illnesses arising from exposure to household air pollution. Ventilation is the supply and extract of air to and from a space or spaces in a building [4]. Ventilation modifies the indoor environment, which in turn modifies occupants' exposure to the indoor environment, which can then impact occupants' health [5]. Associations between ventilation and health in housing are well-established [5–8], and standards for ventilation are referenced in both guidance [9,10] and regulations [4,11].

Despite the strong associations, demonstration of causality between poor ventilation and health has remained elusive [5,12,13]. However, in 2022 the coroner's report into the death of a young child in England concluded that this was due to a lack of ventilation [14]. The media coverage of this case has raised the public profile of ventilation and led to new Government guidance for landlords, which includes specific recommendations for ventilation [15]. This case and the development of the subsequent guidance raised the question of what ventilation provision exists in British homes.

In addition to its importance for health, ventilation can cause heat loss, which can account for up to 50 % of the heat loss from a well-insulated building [9,16]. Thus, there is a conflict between the need to ventilate to create a comfortable, safe and healthy indoor environment and the need to minimise heat loss, energy consumption, carbon emissions and its impact on the climate. Consequently, ventilation lies at the intersection of health, energy and the climate [17].

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1.2. Types of ventilation provision and associated standards

Ventilation in homes arises from a combination of controlled and uncontrolled air exchanges between indoors and outdoors. Uncontrolled natural ventilation (infiltration and exfiltration) occurs through adventitious or unintentional gaps and cracks in buildings, driven by temperature and pressure differences [18]. Controlled ventilation occurs through purpose provided devices [4]. Building Regulations were first introduced in 1985 [19] and since then, there have typically been four main types of 'approved system' for providing controlled ventilation in homes. These are: background ventilation with (1) intermittent extract ventilation, (2) passive stack ventilation, (3) continuous (centralised or decentralised) extract ventilation and (4) continuous mechanical ventilation with heat recovery [4,11]. The first system type is the most common in British homes, which includes (1) extract ventilation in rooms where water vapour or pollutants are likely to be released (kitchens and bathrooms), (2) background ventilation to provide fresh air, dilute, disperse and remove water vapour and pollutants not removed by extract ventilation and finally (3) intermittent purge ventilation (by windows) to remove high concentrations of moisture or pollutants that have been released from occasional activities [4,12, 20–22]. However, with increasing airtightness and higher energy standards, continuous mechanical ventilation systems and balanced systems with heat recovery are becoming more common. These systems have long been adopted in new Scandinavian and Canadian dwellings, and there is an increasing prevalence of these systems around the world [19, 21].

Dimitroulopoulou [12] presented a detailed review of ventilation standards/regulations in European countries, showing the wide range of natural and mechanical ventilation strategies, which are discussed below. Most standards use a performance-based air exchange rate of 0.5 air changes per hour [12].

In Scandinavian countries, Stymne et al. [23] found that 59 % of 3696 Swedish homes were naturally ventilated, 30 % had mechanical extract ventilation, and 10 % had mechanical supply and extract ventilation. Similarly, 67 % of 344 Oslo homes were naturally ventilated, 32 % had mechanical extract ventilation, and much less had supply and extract ventilation (1 %) [24]. However, both surveys are old, and the percentages are likely to have changed. A recent survey of bedroom ventilation in Danish housing (n = 497) reported 40 % with natural ventilation, 25 % with mechanical extract, and 35 % with balanced mechanical ventilation [25].

In England, a 2001 survey of air pollutants in 1216 homes reported that 43 % of homes had extract fans, but this study did not collect information on other ventilation devices (e.g., trickle vents) to provide a comprehensive characterisation of ventilation provision, thereby limiting comparison with other research [26]. This same study reported that 3 % of respondents had mould on kitchen walls, 9 % on bathroom walls, 2 % on living room walls, and 6 % on bedroom walls; however, it is not clear what percentage of all dwellings were affected [26]. A recent study of 80 English homes reported that 25 % of homes had mould [27]. Given the gaps in knowledge and changes in housing stock over the last 20 years, these data need to be updated.

There is a requirement to reduce energy consumption and carbon emissions from both new and existing dwellings to abate climate change. Progressive revisions to building regulations have raised standards of thermal performance in new dwellings throughout Britain to conserve fuel and power [4], but the biggest challenge lies with reducing energy consumption and carbon emissions from existing homes, where the British housing stock is the oldest in Europe and possibly the world [28].

Energy efficiency measures for both new buildings and retrofit have typically improved thermal standards but have also increased airtightness, making the provision and use of effective ventilation more critical for occupants' health [29–31]. Modelling by Hamilton et al. [32] highlighted the potential negative consequences for occupants' health when not fully considering ventilation as part of home energy efficiency interventions/energy retrofits. There is growing evidence that both recently constructed homes and homes which have undergone energy efficiency retrofits are airtight, have poor levels of ventilation and experience poor indoor environmental quality (IEQ) [12,27,33–35].

In recent years, the increasing assessment of buildings in use has identified performance gaps between intended/modelled and actual performance in use [27,34,36–38]. Whilst initially focusing on energy performance, it is now apparent that gaps also apply to ventilation and IEQ [27,39,40], which could have implications for occupants' health. These studies tend to identify two principal and interlinked causes of poor ventilation – a lack of ventilation provision and a lack of knowledge of ventilation.

1.3. Lacking ventilation provision and poor knowledge of ventilation

Dimitroulopoulou [12] concluded that poor use and the lack of knowledge of ventilation systems are the main reasons for poor levels of ventilation in dwellings. An example of this is illustrated with trickle vents, which are intended to provide constant background ventilation and should normally be left open [4], but Dimitroulopoulou et al. [33] found them open in only 4 of 17 homes. Furthermore, the authors reported that their operation had a significant positive impact on ventilation rates. Similarly, a recent survey of 80 homes in England found only 29 % of trickle vents open; despite most (86 %) occupants reporting that they understood the purpose of the trickle vents in their homes [27]. The same study found only 2 of 55 homes to have trickle vents and intermittent extract air flow rates that met the requirements of Approved Document F, and only 1 of 25 homes with continuous extract ventilation air flow rates and trickle vent (TV) provision that met the regulations. This lack of provision and its poor performance are implicated in elevated concentrations of humidity, CO_2 and VOCs [27]. A range of other studies in Europe have also reported poor ventilation provision and poor performance of ventilation [41–43].

The literature on ventilation describes a vast range of drivers and barriers for window, trickle vent and mechanical ventilation use [44–47]. Furthermore, the literature describes a broad range of internal and external behavioural factors that interact in complex ways and are highly variable across different households, the extent of which is not likely to be adequately captured in small samples [48].

1.4. Knowledge gap and aims of this research

Studies on ventilation in British homes have typically used a case study approach, and there is a lack of evidence at scale. As a result, ventilation provision and use have not been adequately characterised for the British housing stock. This indicates a significant gap in our understanding of ventilation provision, occupants' knowledge, and ventilation behaviour in British homes at scale. This data is important, as the evidence may be used to inform energy modelling, estimate the burden of disease caused by poor ventilation, inform health-related messaging and importantly, advise and shape policies and strategies for the improvement of existing homes in Britain.

The primary research question for this research is: What ventilation provision exists in British homes? Secondary research questions include: What systems are provided and where are they located? Have occupants received information on how to use their ventilation systems? What are the barriers and drivers for the operation of ventilation systems in British homes?

2. Methods

2.1. Survey development and deployment

A questionnaire survey was developed by the authors using a range of sources including methodology and questions based on previous and current studies being undertaken by Sharpe [49–51], which evaluated not only the ventilation provision in homes but also the nature of occupants' interaction. Related questions were drawn from similar research on ventilation to compare, contrast and develop insights [26, 52–54]. Finally, subject matter experts from the Future Urban Ventilation Network (FUVN) were consulted on the questionnaire design.

The questionnaire (see Appendix A) collected 4 categories of data:

1. (Social) household and demographic (age, gender, ethnicity, employment status, marital status, number of people and children in household, parental status, use of social media, number of smokers, tenure type, duration living in home, number of people in each bedroom).
2. (Physical) dwelling characteristics and services (archetypes, construction date, heating systems, number of bedrooms, postcode, trickle vents, mechanical ventilation and controls, presence of IAQ sensor).
3. (Behavioural) ventilation use (trickle vent use and operation in all rooms, window opening behaviours, impact of COVID on ventilation behaviours, impact of IAQ sensor on ventilation behaviours and awareness of IAQ, drivers and barriers for trickle vents, mechanical ventilation, and windows).
4. (Contextual) other contextual information, including health conditions affecting ventilation, type and source of ventilation advice received, perceptions of indoor air quality, pollution and thermal comfort, presence of mould and damp and bedroom door use.

An established survey organisation (YouGov) was commissioned to administer the questionnaire. YouGov initially drew a representative (gender, age, employment status and social grade) sub-sample from their panel (2.6 million adults) and invited them to respond to the survey. Before taking part in the survey, participants were screened again based on the current responses to ensure the overall sample was representative and, if suitable, they were informed of the estimated survey duration and their reward for taking part. Participants were then free to opt in or out of the survey. YouGov held much of the household and demographic data on the participants, reducing the time to complete the survey and associated fatigue.

The survey was deployed on the 17th of June 2022 to the YouGov sub-sample of 2039 adults in England, Wales and Scotland (Great Britain). The survey was completed by all participants using the YouGov online platform. The median time to complete the questionnaire was 12 minutes.

The authors compared the final sample with population level data for dwelling age, dwelling type, tenure, heating type, respondent age, respondent gender, respondent employment status and household social grade – this analysis is presented in Appendix B. This analysis shows that whilst the sample in this research is not strictly representative of the British stock, given the large sample size, the results are relevant to the British housing stock.

2.2. Quality assurance, quality control and data clean-up

Data was imported into Python, checked for completeness. Dichotomous and categorical variables were defined, and where questions had multiple responses, these were combined to form complex categorical variables. All open responses were cleaned, corrected and classified into discrete categories. The survey design and deployment method resulted in complete responses from all participants. Participants living in static caravans, mobile homes/trailers, did not know, other, or prefer not to say were removed from the data ($n = 58$). Responses were also excluded where response time indicated a lack of engagement ($n = 103$) and where mutually exclusive answers were provided ($n = 17$), leaving a total of 1861 responses for analysis.

2.3. Analysis

Frequencies and percentages are used to describe most of the variables in this paper. Bivariate associations between categorical variables were assessed using the Chi-square test of independence with a standard alpha threshold of 0.05 for statistical significance. This paper only presents the statistical calculations for dwelling age and tenure. There are other statistically significant associations in the data, but these are not presented in this paper and will form part of future papers.

2.4. Definitions and derived variables

Several variables were derived from the base data for further analysis, a key question associated with this was: What is the installed ventilation provision in British homes, and how does this compare with minimum standards?

National standards for ventilation were first introduced in the 1985 Building Regulations, which contained requirements for ventilation in all new dwellings, stating that ventilation must be provided in habitable rooms, kitchens and bathrooms to ensure a healthy and comfortable living environment [19]. The requirements for ventilation in housing were subsequently updated with the publication of the Building Regulations 1991 Approved Document F (Ventilation), which came into force in 1992 [55]. It mandated the installation of background ventilation in all habitable rooms and required that all kitchens and bathrooms should be provided with mechanical extract ventilation, such as an extract fan, to remove moisture and prevent condensation. Subsequent studies have identified the benefits of extract ventilation [56,57], and the lack of this provision has been associated with raised fungal spore concentrations [57] and an increased risk of mould growth [58].

These regulations were not in place at the time of construction of older properties, but they were introduced in part because of problems occurring in existing properties, particularly post war housing, which experienced problems of damp and mould [59–61]. It may be assumed that older properties may be less reliant on installed ventilation provision as infiltration/exfiltration is typically higher in older properties and this is included as part of a dwelling's overall ventilation performance. However, studies that have attempted to measure this uncontrolled ventilation have found that its effect varied spatially and temporally [62,63], resulting in rooms receiving varying amounts of ventilation. Thus, the uncontrolled, unpredictable and stochastic nature of adventitious ventilation may not adequately contribute to a controlled and planned ventilation strategy, and even if it does contribute to ventilation rates, it will impact energy consumption and carbon emissions.

It is also likely that most homes will have changed or been retrofitted over time. Where substantial retrofit is undertaken, then compliance with regulations would be required. In practice, this is a somewhat grey area, with regulations only applicable to new elements, and for most homes, improvements will be undertaken incrementally. However, most homes will have undergone some measure of improvement. Common retrofit or home improvement measures will affect air permeability and may include ventilation elements; for example, over 80 % of British homes now have double glazed windows [64]. Kitchen refurbishment is commonplace and may include some form of a cooker hood or extract fan, as will bathroom retrofits. Energy efficiency upgrades will also affect ventilation characteristics; for example, new windows, draught-proofing and thermal insulation will improve airtightness, and indeed, some of these measures are promoted on this basis [30,65]. Standards for airtightness of new buildings have improved in recent years, notably since the introduction of mandatory airtightness testing in 2002 [30,31,66]. Although older buildings may therefore have poorer airtightness, the emerging standards for energy-efficient retrofit aim to improve this and are clear about the need to also improve ventilation [67,68].

Comparison with these well-established building standards also recognises what is generally accepted as good practice – the removal of moisture at source from rooms where this is generated (kitchens and bathrooms) and the provision of controlled and properly placed vents in all habitable rooms to provide a background level of ventilation and provide make-up air for mechanical extraction whilst minimising thermal discomfort. It also recognises that whilst nearly all dwellings have windows, which may be used for ventilation, these will be predominately used for intermittent and purge ventilation, as leaving windows open for extended periods of time will give rise to excessive heat loss and draughts and may be associated with problems of noise, security and outdoor pollutants.

In summary, Building Standards requirements for ventilation provision in Britain have been developed as a means of maintaining safe, healthy and energy-efficient homes. These standards have been established for nearly 40 years and therefore are justified as a benchmark for evaluating the installed ventilation provision in this survey. Whilst not required of older homes through legislation, they are referenced in guidance and are relevant to the changing nature of the British housing stock.

To identify this provision from the survey, two dichotomous variables were defined:

1. Ventilation in kitchen and bathroom ('wet rooms') (intermittent or continuous or passive stacks or cooker hood discharging to the outside in the kitchens and bathrooms) or MVHR or PIV.
2. Provision for background ventilation via trickle vents. Variable 2 was not required for dwellings with whole-house ventilation systems such as MVHR (n = 58).

Previous ventilation research identified the lack of knowledge as a key reason for poor levels of ventilation. A further sub-variable was therefore included in the analysis: 'received information,' a dichotomous variable defined as households which had received any form of information on how to use their ventilation provision. This presents a third characterisation of homes in which there is both a minimum provision that is compliant with building standards and occupants have received advice on its use.

Further analysis based on the above is undertaken for other relevant variables, including tenure type, age of the property, and vulnerable groups. An overview is also provided for ventilation use, including barriers and drivers.

3. Results and discussion

3.1. Installed minimum ventilation provision

We find that 45 % (n = 1032) of respondents reported mechanical ventilation in both their kitchen and bathroom ("wet rooms"). 49 % (n = 909) of all homes reported trickle vents on some of the windows, of which only 29 % (n = 532) had trickle vents on all windows. Combining these results to include homes that had both extract fans in the two wet rooms and trickle vent provision on some or all windows shows that 71 % (n = 1324) of homes did not have this minimum ventilation provision. When considering homes that had trickle vents on all windows, this rises to 82 % (n = 1533).

Across all homes, only 27 % (n = 507) had received advice or information about how to use their ventilation system. Adding that further categorisation to the group with mechanical extract ventilation and trickle vents shows that only 11 % (n = 204) of homes had (1) extract ventilation provision and (2) trickle vents and (3) received advice or information about how to use their ventilation provision.

Dwelling age is a key factor, and the introduction of requirements for ventilation in the 1985 Building Regulations has led to an increase in provision, with a statistically significant association between the age of dwellings and the provision of extract ventilation and trickle vents (Chi-square value = 194, p-value = 0.00). Table 1 illustrates this relationship. Excluding responses where the age of the dwelling was not known (n = 252), 79 % (n = 1276) of homes were reported to have been constructed before 1991, leaving 21 % (n = 333) homes constructed after 1991. Only 22 % (n = 283) of homes built before 1991 had mechanical extract and trickle vents, compared with 59 % (n = 197) built after – although an improvement, the latter indicates that 41 % of dwellings, to which the above building regulations apply, did not have this provision.

Table 1
Percentage of building ages that reported trickle vents (on all and some windows), mechanical ventilation in bathrooms and kitchens and the combination of these measures.

Construction date	Trickle vents (all and some)	Mechanical ventilation (bathroom & kitchen)	Mechanical ventilation and trickle vents
Don't know (14 % n = 252)	41 % (n = 103)	39 % (n = 97)	23 % (n = 57)
Pre 1919 (16 % n = 298)	33 % (n = 100)	38 % (n = 113)	20 % (n = 61)
1919–1944 (14 % n = 265)	42 % (n = 110)	38 % (n = 101)	21 % (n = 55)
1945–1964 (14 % n = 267)	50 % (n = 132)	43 % (n = 116)	27 % (n = 71)
1965–1980 (16 % n = 299)	46 % (n = 138)	33 % (n = 98)	18 % (n = 54)
1981–1990 (8 % n = 147)	53 % (n = 78)	43 % (n = 64)	29 % (n = 42)
1991–2015 (13 % n = 240)	71 % (n = 170)	71 % (n = 171)	56 % (n = 134)
2016 – present (5 % n = 93)	84 % (n = 78)	74 % (n = 69)	68 % (n = 63)

Given the self-reported nature of the survey, it is possible that some provision may be provided about which occupants were unaware – this is discussed more in Section 3.8. Furthermore, studies that have examined homes with ventilation provision that meets current building standards have commonly found that the standard of installation and/or the performance of the ventilation systems do not meet minimum or good practice standards [27,50,69]. Thus, it is likely that even in cases where the installed provision meets these minimum standards, that the actual performance of that provision might not achieve the performance requirements of the building regulations. There are several reasons for this, including poor design, installation errors, inadequate understanding and a lack of maintenance.

There is a statistically significant association between homes with mechanical extract ventilation and trickle vents, with tenure type (Chi-square value = 67 p-value = 0.00). Table 2 shows a higher proportion of

Table 2
Comparison of tenure type with mechanical ventilation + trickle vents, and mechanical ventilation + trickle vents + received information/advice on how to use their ventilation provision.

Tenure	Mechanical ventilation + TV	Mechanical ventilation + TV + information/advice
Own – outright (36 % n = 677)	25 %(n = 172)	9 % (n = 62)
Own - with mortgage (27 % n = 506)	32 % (n = 160)	13 %(n = 66)
Own - shared ownership (1 % n = 19)	68 % (n = 13)	21 % (n = 4)
Rented – housing association (6 % n = 110)	47 % (n = 52)	20 %(n = 22)
Rented – local authority (4 % n = 78)	49 % (n = 38)	18 % (n = 14)
Rented – private landlord (15 % n = 282)	22 % (n = 62)	9 % (n = 25)
Neither – rent free (5 % n = 85)	19 % (n = 16)	4 % (n = 3)
Neither – pay family/ friends (5 % n = 85)	21 % (n = 18)	7 % (n = 6)
Other (1 % n = 19)	32 % (n = 6)	11 % (n = 2)

owned properties (outright and with a mortgage) that did not have ventilation provision compliant with current building standards compared with properties rented from housing associations and local authorities. Furthermore there was a clear distinction between socially rented properties and privately rented properties, with the former having a much higher prevalence of ventilation that complies with current building standards. This sample, however, contained a much lower percentage of socially rented homes than in the British population.

To draw comparisons with the international literature in the introduction of this paper, the sample is presented in a different way here: trickle vents are ignored, and ventilation provision is categorised according to the literature descriptions. 60 % (n = 1066) of homes in this research had mechanical extract ventilation in bathrooms, 34 % (n = 610) had only natural ventilation (windows), 3 % (n = 55) had supply and extract ventilation (MVHR), and 2 % (n = 42) had supply ventilation (PIV). Thus, homes in this sample had a lower proportion of natural ventilation and a higher proportion of mechanical extract than Sweden, Norway and Denmark [23–25]. Furthermore, the sample had a lower proportion of supply and extract ventilation than Swedish homes and Danish bedrooms, but a higher proportion than in Norway [23–25]. Coward et al. [26] reported a lower proportion of English homes (43 % n = 1216) with extract ventilation than in this sample. However, cross-comparison is challenging as other studies are old and there is no clear universal definition for natural and extract ventilation across these studies.

3.2. Mechanical ventilation

3.2.1. Kitchen mechanical ventilation

Ventilation provision in kitchens typically consisted of extract fans and cooker hoods, although many cooker hoods were recirculating units which do not extract air to the outside. Whilst extract ventilation is predicated on moisture control, it is increasingly evident that there are health risks from pollutants generated by cooking, which include particulates from cooking processes and gases from open flame appliances [70–72].

Respondents' multiple-choice selections of ventilation systems in their kitchen show 28 % (n = 521) reported intermittent extract, 2 % (n = 45) continuous extract, 7 % (n = 121) passive stacks, 64 % (n = 1187) had cooker hoods, 18 % (n = 335) reported no ventilation system, and 3 % (n = 56) didn't know. Several respondents selected multiple options, with 15 % reporting both intermittent extract and cooker hoods, and 2 % reporting both passive stacks and cooker hoods. Of the 64 % of participants with cooker hoods, only 56 % (n = 659) were reported to extract air to the outside.

Although older buildings would not have been required to have mechanical extract ventilation at the time of construction, kitchen refurbishment is a common improvement [73], and so, forms of ventilation may be added at that time. Increased awareness of risks of moisture and pollution may also drive their adoption.

In terms of control, 28 % of all participants reported intermittent mechanical extract in their kitchens, and 86 % of those systems were manually controlled. These systems require occupants to operate them, which requires some knowledge from the occupant - as a minimum, they need to know how and when to use the system. Whilst this may be a reasonable expectation during certain activities (i.e., during cooking), it does mean that there is no automatic control of the ventilation system to manage moisture or other pollutants that are harmful to health. Recent research has demonstrated the benefits of ventilation not only during cooking but also for a period following cooking [74].

3.2.2. Bathroom mechanical ventilation

The responses to the multiple-choice question on ventilation provision in bathrooms show that 53 % (n = 979) had intermittent extract, 5 % (n = 89) had continuous extract, 7 % (n = 129) had passive stacks, 5 % (n = 93) didn't know, and 33 % (n = 614) reported no ventilation. 39 respondents reported both intermittent ventilation and passive stacks, and 4 reported continuous extract ventilation and passive stacks. 3 % (n = 55) of participants reported MVHR, and 2 % (n = 48) positive input ventilation (PIV).

For pre-1991 dwellings, 56 % (n = 720) had ventilation provision in bathrooms (intermittent or continuous mechanical ventilation or passive stack vents), rising to 88 % for post-1991 (n = 292) dwellings.

Of the participants that had intermittent extract ventilation in bathrooms, 42 % (n = 408) were manually controlled, 51 % (n = 496) were controlled by the light switch, but only 5 % (n = 53) were automatically controlled by humidistat. Typically, intermittent extract ventilation systems have a run-on timer, which keeps the fan running for a fixed period after the control mechanism is triggered, although the number of homes with this feature was not captured in this survey.

Provision for continuously running extract fans was low (5 %); however, this is becoming an increasingly common form of ventilation as it is permitted for buildings with high levels of airtightness [4,11], and of the dwellings constructed after 2016, the percentage of homes with continuously running extract fans in bathrooms doubles to 10 %.

Whilst manually controlled systems are common, it is not clear if these systems are operated in a manner that sufficiently controls moisture, damp and mould growth. In normal use, a manually controlled extract system may be operated during or immediately after bathroom use, with an expectation that most of the moisture would be removed at that time. However, moisture may continue to exist after room use, and occupants' manual control of the ventilation system may not meet this demand.

3.2.3. Mechanical ventilation behaviour

A critical dimension of ventilation effectiveness is occupant understanding and engagement with their ventilation provision. Participants were asked about the barriers and drivers for their use of mechanical ventilation systems. Table 3 shows drivers for mechanical ventilation use, with getting rid of moisture and damp being the most common, followed by getting rid of smells and smoke. Table 4 shows the barriers to mechanical ventilation use, with the cost of running the system and noise being the two biggest barriers. No barriers were noted by 45 % of the participants.

Drivers and barriers for ventilation may also be related to other aspects of the household, and 12 % (n = 216) of participants reported having a health condition that affects the way they ventilate their homes. Of these, 43 % (n = 83) had asthma, 10 % (n = 19) COPD, 8 % (n = 15) hay fever, 4 % asthma and COPD (n = 7), and 3 % (n = 5) allergies.

3.2.4. Mechanical ventilation maintenance

Depending on the type of mechanical ventilation system, appropriate maintenance is necessary to ensure the systems perform as intended. Inadequate maintenance of mechanical ventilation systems has been associated with significant sources of pollutants known to affect the health and well-being of occupants [75]. However, of those households with a mechanical ventilation system, 41 % (n = 659) had never maintained (including cleaning inside) any components of their mechanical ventilation systems, and 12 % (n = 198) didn't know. Of those

Table 3
Participant multiple choice, multiple selection responses for reasons for operating their mechanical ventilation systems.

Reason	Percentage selected
To get rid of moisture or damp	44 % (n = 700)
To get rid of smells	33 % (n = 529)
To remove smoke (i.e., from smoking, cooking, fires, etc.)	32 % (n = 501)
Don't know/can't recall	21 % (n = 327)
For fresh air/to recirculate air in the room	16 % (n = 261)
The home is too warm/hot (to cool down the house)	7 % (n = 110)
To dry clothes	5 % (n = 80)
Other open response	2 % (n = 31)

Table 4
Table showing participant multiple choice, multiple selection responses for barriers to operating their mechanical ventilation systems.

Barriers	Percentage selected
No barrier to using the mechanical ventilation system	45 % (n = 720)
Cost of electricity for running the ventilation	19 % (n = 305)
Noise from the mechanical ventilation system	13 % (n = 212)
Don't know/can't recall	12 % (n = 198)
Don't feel the need to use it	12 % (n = 195)
Concern about heat loss/cost of heating	7 % (n = 105)
Lack of maintenance/cleaning	3 % (n = 40)
Other – open response	3 % (n = 52)
Pollen/allergies	2 % (n = 24)
Don't know how to use it	2 % (n = 31)
Can't reach or operate it	1 % (n = 21)
Outdoor air pollution (including outdoor odours/smells)	1 % (n = 22)
Outdoor noise	1 % (n = 16)
Insects/pests	1 % (n = 11)
Causes draughts	1 % (n = 15)
Cools the room too much	1 % (n = 18)
Health issues	1 % (n = 13)
The mechanical ventilation system does not work	1 % (n = 23)

that had maintained their ventilation system, 28 % (n = 438) of participants had replaced filters, 22 % (n = 356) had maintained the fan, 20 % (n = 311) the grille, and 7 % (n = 113) the ductwork.

3.3. Background ventilation

Background ventilation is necessary to provide fresh air, combustion air, 'make up' air for mechanical ventilation systems and to dilute, disperse and remove water vapour and pollutants not removed by extract ventilation [4]. In older dwellings, which are typically less airtight, undesigned and unintentional leaks through the building fabric contribute to whole dwelling ventilation rates. However, as argued earlier, this uncontrolled infiltration and exfiltration can come at the expense of heat loss, energy consumption and comfort, and measures to reduce energy consumption frequently aim to reduce infiltration and exfiltration through improvements to insulation and draughtproofing. In airtight buildings, provision for background ventilation is more critical than in less airtight buildings for managing indoor air quality, particularly from pollutants from indoor sources. The survey found that 49 % (n = 902) of participants did not have trickle vents in their homes, 29 % (n = 532) had trickle vents on all windows, and 20 % (n = 377) had trickle vents on only some windows.

The survey asked participants about the frequency of interaction and found that 32 % (n = 290) of participants never change the position of the trickle vents, and 30 % (n = 276) change their position as the seasons change from winter to summer and vice versa. Frequent interaction was rarer with 11 % (n = 102) changing them every day, 10 % (n = 95) a few times a year, 4 % (n = 36) more than once a week, 2 % (n = 22) once a week, 2 % (n = 15) once a month, and finally 8 % (n = 73) did not know.

Table 5 provides an overview of which rooms were reported to have trickle vents on all or some windows and the 'normal' positions of the trickle vents in each room. 14 % (n = 138) of the participants that had trickle vents do not normally have them open in all rooms, severely limiting their intended function in a substantial number of homes. This would further reduce the percentage of homes with ventilation that complies with current building standards, but this is not included in the overall categorisation as it is due to behaviour rather than provision.

Table 5
Proportion of rooms with trickle vents and their positions. * No trickle vents in these rooms.

Room	Open	None *	Some open	Closed	Don't know
Kitchen	59 % (n = 539)	21 % (n = 190)	7 % (n = 68)	7 % (n = 64)	5 % (n = 48)
Living room	56 % (n = 505)	19 % (n = 170)	10 % (n = 93)	10 % (n = 90)	6 % (n = 51)
Main bedroom	61 % (n = 553)	17 % (n = 157)	9 % (n = 79)	7 % (n = 66)	6 % (n = 54)
Other bedrooms	54 % (n = 490)	20 % (n = 186)	11 % (n = 104)	8 % (n = 73)	6 % (n = 56)

Of the 21 % (n = 333) of homes constructed after 1991, 35 % (n = 118) reported that they either had no trickle vents, or some trickle vents were closed in one or more room in their home. This is important because research has shown that in recently constructed dwellings, ventilation rates were significantly affected by trickle vent use [33]. Hence, where occupants in recently constructed homes either do not have trickle vents or intentionally close them, this could severely limit ventilation rates in those homes, which, in turn, can result in potentially harmful exposures to pollutants from indoor sources.

Participants were asked about the barriers and drivers for the use of trickle vents, and for 54 % (n = 487) of participants, the single most important reason they open their trickle vents is for fresh air/to recirculate the air in the room, 17 % (n = 154) to remove moisture/damp, 13 % didn't know (n = 117), 10 % (n = 94) because of high indoor temperatures and to cool their home, along with smaller percentages of other responses.

A large proportion (54 % n = 488) of participants reported that they did not have any problems or concerns operating their trickle vents; however, barriers included the cost of heating (7 % n = 62), draughts (6 % n = 53), cools the room too much (6 % n = 51), insects/pests (4 % n = 32), with 6 % (n = 52) don't feel the need to use trickle vents, and 3 % don't know.

A final point is that 37 % (n = 305) of respondents had extract ventilation in their kitchen and bathroom but no trickle vents in their homes. In airtight homes, the lack of provision for make-up air may reduce the performance and effectiveness of the extract provision.

3.4. Purge ventilation and window use

Intermittent purge ventilation is necessary in homes to rapidly remove high concentrations of moisture or pollutants from occasional activities and this function is normally provided by windows in British homes [4]. However, considering the finding above that most homes did not have extract ventilation and background ventilation provision, the use of windows as a source of background ventilation and ventilation for removing moisture and pollutants from wet rooms becomes ever more critical for maintaining a comfortable and healthy indoor environment.

Most homes were provided with windows, although 6 % (n = 107) of all respondents reported that they had some rooms either without windows or windows that could not be opened. Windows have a range of functions within the home, including light, views, amenity and ventilation; however, there are several reasons why opening windows may not be desirable or practical as a permanent means of ventilation, including heat loss, security and noise. Table 6 provides an overview of how often windows were reported to be open in each room during the winter and summer, during the day and night.

Variables were derived from the data to estimate if windows were opened 'regularly' in all rooms. This variable was based on whether windows were reported to be opened (1) all the time, (2) daily or (3) a few times a week in all rooms during the day/night in the winter/summer. In the summer, 36 % (n = 676) of participants did not open their windows in all rooms regularly during the day, and at night, this rises to 73 % (n = 1362). During the day in winter, 71 % (n = 1282) of participants did not open their windows regularly, and during the night, this rises to 93 % (n = 1694).

For 57 % (n = 1058) of participants, the single main reason for opening windows was for fresh air/recirculate air in the room, 28 % (n = 523) due to high indoor temperatures and to cool the house down, 5 % (n = 87) to remove moisture/damp, 2 % (n = 41) didn't know, 3 % (n = 54) to get rid of smells, and 2 % (n = 43) for connection/contact with outdoors.

Table 6
Table showing how often the windows were open in each room, during various times of the day and during different seasons. * This room had no windows/the windows didn't open.

Season	Time	Room	Never	Twice a month or less	Once a week	Few times a week	Daily	Always open	Don't know	NA *
Winter	Day	Kitchen	18 %	24 %	6 %	18 %	23 %	3 %	3 %	4 %
Winter	Day	Living	26 %	27 %	8 %	15 %	16 %	3 %	4 %	2 %
Winter	Day	Main bedroom	14 %	21 %	7 %	15 %	29 %	9 %	3 %	1 %
Winter	Night	Kitchen	68 %	12 %	2 %	6 %	7 %	1 %	3 %	
Winter	Night	Living	69 %	13 %	4 %	5 %	5 %	1 %	3 %	
Winter	Night	Main bedroom	43 %	16 %	3 %	11 %	15 %	9 %	3 %	
Summer	Day	Kitchen	10 %	9 %	4 %	20 %	44 %	11 %	2 %	
Summer	Day	Living	8 %	9 %	5 %	23 %	41 %	11 %	2 %	
Summer	Day	Main bedroom	3 %	5 %	3 %	16 %	48 %	24 %	2 %	
Summer	Night	Kitchen	55 %	7 %	2 %	9 %	16 %	7 %	3 %	
Summer	Night	Living	52 %	7 %	2 %	11 %	18 %	7 %	3 %	
Summer	Night	Main bedroom	13 %	8 %	3 %	17 %	34 %	24 %	3 %	

For 32 % (n = 594) of participants there was no barrier to opening windows, 19 % (n = 352) the main single barrier was security, 10 % (n = 180) due to pests/insects, 9 % (n = 166) due to heat loss and the cost of heating, 8 % (n = 152) due to outdoor noise, 4 % (n = 72) due to pollen and allergies, 4 % (n = 81) didn't feel the need to open them, 4 % (n = 67) due to cooling the room(s) too much, 3 % (n = 57) due to draughts, and 3 % (n = 54) due to outdoor air pollution.

3.5. Behaviour, health, and perception of IEQ

3.5.1. Lifestyle and perceptions of IEQ

Table 7 provides a summary of how important the participants felt several different lifestyle and IEQ factors were for their health and wellbeing.

Participants were asked about sources of indoor pollutants, and 25 % (n = 466) reported that they felt that pollution from outside their homes was the single main source, 17 % (n = 318) didn't know, 14 % (n = 259) fumes from cooking, 13 % (n = 246) from damp/mould, 11 % (n = 214) from cleaning chemicals, 6 % (n = 114) from pets, 5 % (n = 87) from personal care products, and 3 % (n = 55) from their heating system, with lower percentages of other responses.

Despite the lack of ventilation provision and the wide range of pollutant sources, respondents' perceptions of the indoor environment were generally positive - 23 % (n = 432) of participants were very satisfied with indoor air quality in their homes, 49 % (n = 913) were fairly satisfied, 20 % (n = 363) neither satisfied nor dissatisfied, 5 % (n = 88) were fairly dissatisfied, 1 % (n = 18) very dissatisfied, and 3 % (n = 47) didn't know. It is important to note that a respondent's perceived 'good' IAQ does not necessarily mean that it is healthy or safe, with other studies reporting similar satisfaction levels but poor measured IAQ [68]. 17 % (n = 317) of participants strongly agreed with the statement 'My house gets uncomfortably warm in the summer', 31 % (n = 569) tended to agree, 25 % (n = 473) neither agreed or disagreed, 20 % (n = 372) tended to disagree, 6 % (n = 105) strongly disagreed, and 1 % (n = 25) didn't know.

3.5.2. Mould and damp

A particular concern was that 22 % (n = 417) of all 1861 respondents reported that they had mould or damp on walls or surfaces in their homes. This result is similar to the 25 % of homes reported by MHCLG [27].

The analysis described below only concerns homes where the construction dates were reported by the respondents (n = 1609). 1276 homes were constructed before 1991; of these, 22 % (n = 283) had mechanical ventilation and trickle vents, and of these, 23 % (n = 65) reported mould or damp. Of the 993 homes constructed before 1991 without mechanical ventilation and trickle vents, 23 % (n = 229) reported mould or damp. Of the 333 homes constructed after 1991, 59 % (n = 197) had mechanical ventilation and trickle vents, and of these 9 % (n = 18) reported having mould or damp. Of the 136 homes constructed after 1991 without mechanical ventilation and trickle vents, 17 % (n = 23) reported to have mould or damp. These results suggest that ventilation provision alone does not play a significant role in the prevalence of mould or damp in homes constructed before 1991 but is more important in homes built after this date. In homes constructed before 1991, poor thermal performance of the fabric might be a key factor for the higher prevalence of damp and mould.

Of all the homes in this sample, 22 % (n = 417) of homes reported to have mould or damp, and of these, 75 % (n = 314) did not have mechanical ventilation and trickle vents.

Of the voluntary open responses regarding locations of damp and mould, bedrooms and bathrooms were the most common (56 %) rooms reported to have mould/damp. In terms of locations, 36 % reported mould/damp on walls, 13 % ceilings, 12 % around windows, 6 % in corners of rooms and 6 % on windows. A higher proportion of homes that had damp and mould had received information on how to use their ventilation (30 % n = 127) compared with the rest of the population. It might be anticipated that households with these issues may seek out advice, or that it may be provided by landlords, for example.

Table 7
Table showing how important the participants felt several different lifestyle/IEQ factors were for their health and wellbeing.

Factor	Very important	Fairly important	Not very important	Not at all important	Don't know
Sleeping well	72 %	26 %	2 %	0 %	0 %
Well-ventilated home	40 %	52 %	7 %	0 %	2 %
Healthy diet	43 %	48 %	7 %	1 %	0 %
Regular exercise	44 %	44 %	10 %	2 %	1 %
Clean home	38 %	51 %	10 %	1 %	1 %
Exposure to chemicals	32 %	43 %	18 %	3 %	5 %
Indoor air quality	43 %	49 %	6 %	0 %	2 %
Indoor air temperature	32 %	56 %	9 %	1 %	2 %
Indoor noise levels	36 %	46 %	15 %	2 %	1 %

3.6. Ventilation information and knowledge

As well as the physical provision for ventilation, it is important that it is used effectively, therefore, the participants were asked if they had received information/advice on how to use their ventilation and the nature of this advice. As noted in Section 3.1, only 27 % (n = 507) of participants had received information on how to use their ventilation provision; however, there is a lack of credible and authoritative advice. Of the multiple choice responses, 8 % (n = 157) reported that friends and/or family were one source of this information, 8 % (n = 150) from online, 6 % (n = 118) from tradespeople, 4 % (n = 75) were unsure where they obtained this information, 3 % (n = 61) obtained this information from advertisements, 3 % (n = 49) from their housing association/local authority, and 2 % (n = 42) from the builder/seller.

A higher proportion of households who had received information on ventilation also reported to have changed the way they ventilated their homes because of the COVID-19 pandemic (22 %) than the rest of the population (11 %). During the pandemic, there had been public information campaigns about ventilation in the home, and this may have raised awareness of the nature and importance of ventilation.

One aspect of increasing awareness of ventilation is the use of IAQ sensors to provide objective information on IAQ, commonly CO_2 sensors. A higher proportion of homes that had received information on ventilation also had an IAQ sensor (9 %) than the rest of the population (5 %).

There is also a greater use of MVHR systems in recently constructed homes, although the overall percentage is small (3 %). A higher proportion of homes that had MVHR (69 %) had also received information on how to use their ventilation provision than homes without MVHR (26 %).

3.7. Policy discussion

This research indicates a concerning lack of ventilation provision in British homes. If extrapolated to the 27.8 million dwellings in Great Britain [28], this would leave 19.7 million dwellings without ventilation provision to extract moisture and pollutants from wet rooms and purpose provided provision for background ventilation. The same extrapolation would also suggest that 6.1 million dwellings may suffer from damp and mould.

Dwelling age is a significant factor for ventilation provision. Dwellings constructed before 1991 were not required to provide extract and background ventilation at the time of construction. In these buildings open fires, high ceilings, gaps in fabric and window design provided liberal ventilation rates, but at the expense of high heat loss and poor thermal comfort. However, many of these houses will have been modified over time to become more airtight. Regulatory change, such as the Clean Air Acts of 1956 and 1968, reduced the use of open fires, and energy-saving campaigns to reduce draughts and heat loss first introduced during the 1970's oil crisis resulted in a reduction of ventilation in British homes. As a result, post war housing experienced damp and mould issues, leading to the introduction of regulations and standards in 1985 to control moisture in new homes. An even greater shift is happening now, as the need to address climate change is leading to changes in design and construction, with increasing levels of insulation and mandated airtightness, and these requirements will be increasingly applied to existing dwellings.

The lack of ventilation provision in older dwellings highlights a flaw with the current regulatory framework, where new building standards are not applied retrospectively. Exceptions occur when new standards are applied to older buildings where there is a clear health risk; however, this is typically triggered by tragic events, such as the Legionnaires disease outbreak [76] and the Grenfell Tower fire [77]. Of equal concern is the large number of post-1991 homes that appear to not to comply with the standards to which they should have been constructed.

Given the known associations between ventilation and health, the findings from this survey support the need for development of appropriate policies to ensure adequate ventilation in all homes, including existing homes. Although the Government has recently issued advice to landlords concerning the risks of damp and mould [15], the Housing Health and Safety Rating System [78] and emerging retrofit standards such as PAS2035 [67] remain as guidance, not regulation, and thus, may not drive widespread adoption. Given the current statutory requirements for energy efficiency in the context of climate change, we argue that improvements in ventilation provision must be linked to energy-efficiency improvements, and these ventilation improvements are likely to be more cost-effective when combined with other refurbishment work.

In the winter following this survey, fuel costs in the UK rose significantly, leading to a 'cost-of-living crisis'. This crisis may lead vulnerable households to prioritise heating over ventilation, but for the fuel-poor, this has always been a dilemma. The combination of high energy costs, poor ventilation provision, poor understanding of the importance of ventilation and poor knowledge of how to ventilate homes presents a higher risk for reduced ventilation, an increased risk of exposure to harmful IEQ and an increased risk of harm from this exposure.

As well as the physical provision, most respondents had received little information on how to ventilate their homes, and when they did, this was from disparate and unauthoritative sources. Ensuring that occupants have better advice on how to use and maintain their ventilation provision is critical, but this is predicated on homes having suitable installed and operational ventilation provision. For rented properties, this could be achieved through placing responsibility on landlords to ensure working and maintained ventilation provision. Furthermore, the NICE review of Indoor Air Quality at home [79] recommended that those with inspection responsibilities, such as Environmental Health Officers and landlords, are made aware of ventilation provision and its importance. The issue of ventilation provision is harder to address in private homes, but its importance for health can be highlighted through public health messaging. Whilst there was public health information about ventilation during the COVID-19 pandemic, this was generic and focussed on reducing transmission risk, not managing exposure to pollutants, energy and health. In practice, ventilation advice should be clear, targeted and based on provision. Public health messaging on ventilation can be relatively cheap when compared with installing ventilation provision and could have an immediate impact on reducing harm in the public.

To perform effectively whilst in use, most ventilation provision must be maintained. At present, there are no mandatory requirements for testing or maintaining ventilation systems during their serviceable life in homes in Britain. A lack of maintenance was evident in this survey, and this finding supports the need for developing mandatory requirements for the testing and maintenance of ventilation provision, which could be considered alongside other safety checks in homes. In the construction industry, it is often not clear who is responsible for the installation of ventilation components and systems, with work being undertaken by various trades. Given its importance for both energy and health, and particularly with the emergence of more complex systems such as MVHR, we suggest that there may be scope for a new dedicated trade for ventilation installation and maintenance.

In the survey, 72 % of respondents were very or fairly satisfied with IAQ; however, this does not necessarily correlate with healthy IAQ [69], as humans are unable to detect many harmful pollutants. Wider adoption of low-cost indoor air quality sensors (for example, humidity and CO_2) could provide objective information to occupants on IAQ and/or directly control ventilation to address this gap. Many social landlords are adopting this strategy to help manage their stock, but sensors are also available to owner-occupiers. This is a low-cost intervention and could be adopted more widely, including in retrofit standards.

Managing energy consumption, ensuring adequate ventilation and providing a safe and comfortable environment in homes are interlinked and remain a challenge for the future, particularly for the refurbishment and retrofitting of the old stock of British homes. It is critical that future policy and funding mechanisms associated with the zero-carbon agenda and retrofitting of existing homes include ventilation to avoid unintended consequences and protect the health of the public.

3.8. Limitations

The results of the survey are dependent on participants self-reported ventilation provision, which in turn relies on their knowledge and awareness of these systems. To reduce response error, the questionnaire was carefully written in plain English, and where necessary, it contained images and descriptive prompts. Furthermore, if the participants did not know the answer to a question, the questionnaire was designed to allow them to respond that they did not know instead of guessing. The participants responses were not validated - future physical surveys could validate the responses and findings of this research.

The questionnaires were completed by the participants during the summer, which could bias the results towards the summer ('time of observation bias') and reduce the accuracy of the results pertaining to the prior winter ('recall bias').

4. Conclusions

Suitable ventilation provision and effective advice on its use is needed to ensure safe, healthy, comfortable, and energy efficient homes. Despite the importance of ventilation, the provision of ventilation and its use in British homes is poorly characterised. This paper presents the first large scale survey of ventilation provision and use in British homes.

Findings show that 71 % of homes did not have minimum ventilation provision based on long-standing building regulations, and of those, only 27 % of households had received information or advice on how to use that provision. This lack of ventilation provision was highest in older homes, but the survey also provides evidence of poor compliance with building regulations on a much wider scale than considered previously.

Given the findings of this research, there are several recommended actions for Government agencies, public health agencies and academics. These are summarised below:

It is recommended that the Department for Energy Security and Net Zero (DESNZ) and the Department for Levelling Up, Housing and Communities (DLUHC):

1. Develop new policy to ensure existing homes have suitable ventilation for protecting against the health risks of poor ventilation. This policy should consider ongoing inspections and maintenance of ventilation provision in existing homes.
2. Revise and enhance Energy Performance Certificates (EPC) to include reporting on ventilation and the health aspects/implications of ventilation/IEQ.
3. Ensure that policy and standards for refurbishment and retrofit of existing homes include mandated requirements for providing suitable ventilation to protect occupants against the health risks of poor ventilation. These standards should consider the use of indoor air quality sensors for providing objective information to occupants.
4. Ensure that ventilation provision in new homes complies with current regulations – findings presented here suggest otherwise for a large number of recently constructed homes.

It is recommended that the UK Health Security Agency (UKHSA) and the Office for Health Improvement and Disparities (OHID) develop and disseminate appropriate advice and information to the public on the importance of ventilation for health and specific advice for occupants on when and how to ventilate their homes to minimise exposure to harmful IEQ. Furthermore, findings of this research may be used to estimate the burden of disease due to the lack of ventilation provision, the results of which could strengthen the evidence for other recommendations made here.

The results of this research can be used by academics for reducing the uncertainty associated with modelling assumptions for ventilation provision and behaviour in British homes. This could assist in reducing the performance gap associated with energy and IEQ modelling.

Research by others frequently reports poor ventilation rates, and when combined with the findings of this research (lacking ventilation provision, poor knowledge and prevalence of mould), it highlights the urgent need for detailed empirical investigations of actual indoor environmental quality and ventilation performance in occupied British homes at scale. This future research could be undertaken in a subsample of this sample to enable exposure and the burden of disease to be estimated for the British population.

A future detailed analysis of this dataset is proposed to identify correlations and relationships across the different variables, including specific analysis of vulnerable groups and homes that reported damp and mould. Additional analysis will also identify the proportions and numbers of buildings of different ages, archetypes and locations to inform retrofit strategies and standards.

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Ethical approval statement

YouGov (third party research organisation) was appointed by the Authors to administer an online questionnaire to a sample of their panel in Great Britain. The YouGov panel members have all entered into an agreement with YouGov, containing details of privacy and how and why data will be used.

For this research, selected members of the YouGov panel were invited by email and voluntarily chose to take part in the survey. Consent was implied and managed through the YouGov privacy agreement with the panel members.

The data was fully anonymised and managed in accordance with GDPR regulations. The questionnaire did not collect or use any special category data; therefore, YouGov rely on 'legitimate interests' as the legal grounds for processing this data.

CRediT authorship contribution statement

Cairan Van Rooyen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tim Sharpe:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Cairan Van Rooyen reports financial support was provided by Future Urban Ventilation Network. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data will be available on the Future Urban Ventilation Network open repository: https://sites.google.com/view/futureurbanventilationnetwork/open-repository.

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Appendix A. Supplementary data

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