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Ten questions concerning the future of residential indoor air quality and its environmental justice implications

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ABSTRACT

Humans spend a large proportion of their time at home, where exposure to poor indoor air quality has detrimental – and often inequitably distributed – impacts on health and wellbeing. Unprecedented changes to residential indoor environments are expected in the coming decades, especially in order to meet net zero energy and greenhouse gas emissions targets. However, it is unclear how these changes will affect indoor air quality, and to what extent they will differentially impact different social groups. In this paper, we pose and address ten questions concerning the future of residential indoor air quality and its environmental justice implications. We pay attention to environmental justice in relation to indoor air quality, including distributive, procedural, recognition, capabilities, and epistemic dimensions. The ten questions specifically address: social gradients in health and exposure, and how changes in climate, policies, behaviours, technologies, populations, and demographics might affect residential indoor air quality and environmental justice. We also highlight the role that transdisciplinary research can play in improving residential indoor air quality in a more environmentally just way.

1. Introduction

The residential indoor environment is fundamentally changing, in particular due to increased rates of urbanisation, climate change, and implementation of net zero energy and greenhouse gas emissions policies to decarbonise the housing sector. Indoor air quality (IAQ) is one aspect of the residential indoor environment that will be affected, with the potential to significantly impact on health and wellbeing. Air pollution is the leading environmental risk factor for human health, and the indoor environment is a significant contributor to people's overall exposure to air pollution. On average, people spend ~90 % of their time indoors, of which ~70 % is spent in a residential environment [1–3], where concentrations of certain air pollutants can be greater than outdoors [4–6].

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IAQ refers to the indoor concentrations of air pollutants that have the potential to harm human health and wellbeing. This includes a mix of gaseous species including carbon dioxide (CO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOCs), as well as radon, and particulate matter (PM) of both organic and inorganic composition, and biological origin, such as airborne viruses, pollen, and mould. In addition to outdoor air pollution that ingresses into the indoor environment [7], there are a considerable number of indoor sources that influence IAQ including: building materials, consumer products, combustion processes (e.g. cooking, space heating using natural gas, solid fuels), airborne biological material, and occupant activities (e.g. cleaning, drying clothes indoors) [4]. There is an established body of evidence on the health effects associated with air pollution, including the onset of new diseases and exacerbation of a range of existing health conditions [8,9]. This evidence is largely based on exposure to outdoor air pollution [10,11], while evidence for health effects associated with IAQ is less established due to the complex mixture of many indoor-generated pollutants, the large variability in magnitude, frequency and duration of indoor exposures, and limited information on their toxicity [12,13]. While air pollution affects everyone, it does not do so equally, as for the same levels of exposure individuals have differing levels of sensitivity [12,13], including those with pre-existing health conditions, and children and older people [14]. Crucially, the most disadvantaged tend to be disproportionately affected by air pollution owing to a ‘triple jeopardy’ whereby they are more likely to have 1) higher exposure to air pollution, 2) a greater cumulative burden of poor health, and 3) increased risks from social determinants of health related to deprivation [15–17]. This highlights the social justice element of action on poor air quality, and forms the argument to improve air quality in an equitable way [17].

The concept of environmental justice (EJ) emerged in the United States (US), primarily in response to claims of environmental racism following the placing of industrial polluting facilities in predominantly Black neighbourhoods [18,19], and has since been widely used in air quality activism and research. Outdoor air quality has been the dominant air quality EJ issue, with associations between spatiotemporal patterns of air pollution emissions and exposures by race and ethnicity [20,21], socioeconomic status (SES) [15,16], age [22,23], sex and gender [24,25], housing status [26,27], and many other forms of social difference [28]. Research indicates that there is a disproportionate burden of outdoor air pollution on marginalised social groups [16,29], albeit with differing strengths and direction of associations for different air pollutants, and across different geographical scales (e.g. local, regional, or national) [16,30,31].

Less is understood about IAQ compared to outdoor air quality both from a natural and social science perspective [4,32], including notably how IAQ may relate to EJ. EJ framings on IAQ are starting to take shape [33–35], including through events such as the tragic death of Awaab Ishak in the United Kingdom (UK), a young boy who died as a result of chronic exposure to mould in his social housing association home [36,37], amid accusations that his parent’s concerns were ignored due to racial discrimination and prejudice by the housing authorities [38]. The spatiotemporal distribution of air quality, and associated exposures, is only one dimension of EJ [39]. To support a better understanding of future residential IAQ and its EJ implications, we take a wider conception of EJ, considering the following five dimensions (Fig. 1) [28,40,41]:

Fig. 1. Five dimensions of environmental justice.

1. *Distributive* justice: Who is exposed to better or worse IAQ, and does this vary by social groups? Who is producing emissions of air pollutants that are affecting IAQ?
2. *Procedural* justice: How are decisions that affect IAQ made? Who is involved and has influence? What processes exist to challenge decisions? Who has access to IAQ information? [28,40].
3. EJ as *recognition*: Are certain social groups the subject of discrimination or *misrecognition* leading to poor IAQ? For example, the 'environmental racism' that underpinned the emergence of EJ as a concept [19].
4. A *capabilities* perspective of EJ [42,43]: What is the capability of people to achieve good IAQ? For example, one may live and work in an area with poor air quality but have the resources to mitigate its effects, such as through filtering air [44], whereas others may have few resources to control IAQ [45].
5. *Epistemic* justice [46]: Who is respected in their capacity to know about IAQ? How are different groups' testimonies of poor IAQ received? For example, community groups' knowledge about air pollution is often seen as anecdotal based solely on subjective beliefs and experiences [47].

While five different dimensions of EJ are presented, in practice they are mutually interrelated, and occur in conjunction. In this paper, distributive justice features prominently in all 10 questions we pose, as it is central to environmental injustice. Each question further draws upon the multiple types of EJ. The clearest demonstration of the other dimensions of EJ are highlighted: procedural (Question 9), recognition (Question 1 and 7), capabilities (Question 8) and epistemic (Question 6). This paper primarily focuses on heating dominated countries, such as the UK, as well as in Northern Europe, and North America. As an authorship team based at universities in the Global North we inevitably present a partial view of what constitutes EJ for IAQ [48]. However, the authors stress the need for these principles to be advanced and refined for wider global use, such as for the billions of people – primarily in low- and middle-income countries – who are reliant on solid fuels for domestic cooking and heating, with significant health impacts primarily for women and children [49]. Nonetheless, this paper outlines a framework for understanding important social and physical dimensions that underpin EJ issues for IAQ, through providing a multidimensional EJ lens.

2. Ten questions and answers concerning the future of residential indoor air quality and its environmental justice implications

2.1. Question 1: what are the interactions between social gradients in health and exposure to poor indoor air quality?

Social gradients in health refer to the phenomenon whereby "people who are less advantaged in terms of socioeconomic position have worse health (and shorter lives) than those who are more advantaged" [50, p. 2172]. To explore interactions between exposure to poor IAQ and social gradients in health, it is helpful to first understand the established health effects from air pollution, as outlined in Table 1. The list of health effects linked to these air pollutants is not exhaustive, and the weight of evidence varies between each pollution-outcome pair. While many of the health effects are derived from evidence for outdoor exposures, similarities are likely for individual chemical species. The exception is for PM, where its physiochemical properties could vary between indoor and outdoor sources. Nonetheless, health consequences of outdoor PM can be used for guiding health assessments of indoor PM.

The complex relationship between IAQ and social gradients in health is not yet fully understood. Studies directly evaluating IAQ against population characteristics such as SES, race and ethnicity, or sex and gender in high income countries are limited. Notably, people living in similar social and physical environments may experience different health effects, despite being exposed to similar levels of IAQ, due to different individual levels of sensitivity and adaptive capacity [14,63].

Table 1
Health effects associated with exposure to air pollutants commonly found in indoor air [8,9,37,51–62]. COPD = chronic obstructive pulmonary disease.

Pollutant	Health effects
Particulate matter (PM)	• **Respiratory:** e.g. airway irritation, lung inflammation, reductions in lung function, bronchitis, exacerbation of asthma, COPD, increased susceptibility to respiratory infection, respiratory mortality. • **Cardiovascular:** e.g. heart disease, heart failure, stroke, arrhythmia, increased blood pressure, embolism, cardiovascular mortality. • **Metabolic:** dyslipidaemia, metabolic syndrome, diabetes. • **Cancers:** lung, gastric, colorectal, kidney, bladder, leukaemia. • **Neurological:** impaired cognition, Alzheimer's Disease, Parkinson's Disease, links with mood disorders, stress, and antisocial behaviour. • **Birth outcomes and fertility:** in utero exposure associated with detrimental birth outcomes, low birth weight, reduced lung function and other forms of ill health that occur later in life. • **Other:** conditions of the liver, gastrointestinal tract, bone, skin, eyes, and others.
Nitrogen dioxide (NO_2)	• **Respiratory:** e.g. airway irritation, lung inflammation, reductions in lung function, exacerbation of asthma, increased susceptibility to respiratory infection, respiratory mortality. • **Cardiovascular:** heart disease, stroke, heart failure, hospital admission for acute cardiovascular events. • **Other:** associations with metabolic effects, fertility, and birth outcomes, with some similarity to PM, although the evidence is more limited and tends to be weaker than PM for effects beyond the lung.
Volatile Organic Compounds (VOCs)	• **Respiratory:** asthma, wheezing, bronchitis, respiratory tract irritation. • Irritation of the upper airway system • Cardiovascular • Neurological • Carcinogenic
Radon	• **Cancers:** lung (long-term exposure to high concentrations).
Damp or mould	• **Respiratory:** e.g. cough, wheeze and shortness of breath, increased risk of airway inflammation or infection (bronchitis, COPD, aspergillosis), development or worsening of allergic airway diseases (rhinitis, asthma) and other conditions involving airway inflammation; mortality in susceptible individuals. • Poor mental health

Certain populations may be more at risk of these health effects due to the overlap of physiological susceptibility, higher air pollution exposure, and greater risks from social determinants of health [17]. There is some evidence to suggest that populations of lower SES or minoritised ethnic communities in high income countries are more likely to experience greater exposure to indoor PM, NO_2, and VOCs [35,64–67], and to live in areas with worse outdoor air quality [13,68,69]. This includes evidence of increased health risks associated with air pollution for these populations demonstrated by hospital admissions studies [17]. Several studies in the US have also identified an increased risk of cancer from higher exposure to pollutants, such as VOCs in Black and Hispanic populations, as well as in low-income women's homes [66,70,71]. These populations may have a higher risk of developing or exacerbating health conditions, as well as being less able to mitigate their exposure due to limited adaptive capacity related to housing tenure status, lack of finance, language and cultural barriers, and less awareness of poor IAQ and its associated health risks in the first place. However, the disproportionate health burden falling on certain groups in relation to specific indoor pollutants – other than cancer with certain VOCs – are not fully established. This is a key area for future research.

These studies tend to not focus on the historical reasons underpinning why social gradients in health occur. A clear example to demonstrate the benefit of using a multidimensional EJ lens that extends beyond distributive justice is in the experiences of American Indian / American Native (AI/AN) communities in the US. These socially and culturally diverse communities experience health disparities stemming from social determinants of health such as higher poverty rates, lower median household income, and a lower level of education at all stages [72]. AI/AN populations have the lowest life expectancy at birth among all racial and ethnic groups in the US, and experience a greater health burden [72]. For example, AI/AN adults are 10 % more likely to have asthma than non-Hispanic white adults, and children are almost twice as likely [72]. Moreover, the hospitalisation rate for lower respiratory tract infections is 1.6-fold higher in AI/AN children, with a 3-fold higher rate for pneumonia admission, compared with the general US child population [73]. Early-life health conditions, such as childhood asthma, can make these individuals predisposed to further health complications arising from air pollution exposure later in life, which may persist considering households of lower SES generally experience worse IAQ [13,35].

Conceptualising EJ as recognition is useful when looking at the interactions between social gradients in health and exposure to poor IAQ for AI/AN communities. A substantial proportion (13 %) of AI/AN communities are estimated to live on tribal lands or reservations [74], stemming from the forceful expulsion from their homelands, appropriation of land by the US government, and resettlement [75]. The misrecognitions that have led to these people being the target of unwanted land uses including fossil fuel extraction, and dump sites [75,76] may also extend to indoors: more than a third of AI/AN communities live in low-quality housing, often with plumbing, maintenance, mould, and overcrowding issues, which are rooted in historical settler colonialism, injustice, and lack of resources [77,78]. Indeed, research demonstrating the social gradients in health associated with lower respiratory tract infections were linked to the increased likelihood of AI/AN children living on reservations or in rural communities, where the housing quality is systemically worse than in urban regions [73]. Similar findings have been also found in Australian Indigenous communities [79], which further exemplifies the important role of social determinants, such as housing conditions, on health inequalities.

Understanding the complex interactions between social gradients of health and IAQ is key to determining and rectifying health inequalities, and minimising environmental injustice related to potentially disproportionate health burdens resulting from poor IAQ. Such knowledge could lead both to bottom-up change through affected communities having a greater understanding of the impact of IAQ, and top-down change through equipping policy makers with relevant evidence to update policy, including building and product safety regulations. When looking at the future of residential IAQ and its EJ implications, there is a clear need to look at the context driving distributional health inequalities, including misrecognitions.

2.2. Question 2: what is understood about the inequalities in sources of indoor air pollution?

Indoor sources of air pollution play a major role – alongside ingress of outdoor air pollution – on IAQ. Indoor environments are influenced by a plethora of sources and their complex interactions through indoor air chemistry [80]. Despite growing knowledge of the numerous sources and sinks of indoor air pollutants [81], there is not yet a detailed understanding of their distribution and significance at the population level. This is partially due to large spatiotemporal variabilities of building characteristics and emissions within indoor environments, driven by hard to predict factors, such as occupant behaviour and variable ventilation rates [82]. There is also substantial difficulty and expense in monitoring IAQ with specialised, often costly, large, and potentially noisy instrumentation within confined living environments in large samples of the building stock, and/or over long periods of time.

Nonetheless, there are specific sources of indoor air pollution where there is existing evidence on their distributions, and where changing patterns of exposure and its implications on EJ can be explored. There is some evidence of higher exposure to worse IAQ from personal care products associated with SES and race and ethnicity [83,84]. Also, indoor exposure to radon is one of the largest causes of lung cancer [56], and its geographical distributions and exposure mitigation strategies (e.g. radon sumps) are well established [56,85]. Residential radon concentrations are expected to increase in certain places as homes with energy retrofits have reduced air change rates [85–87]. Evidence on the distribution of radon across different social groups suggest that areas with lower SES have less radon [88,89]. This is likely a result of differences in dwelling typologies (e.g. detached or flats) occupied by different social groups, and that more affluent households tend to live in warmer and more airtight homes resulting in greater ingress and accumulation of radon [88]. Additionally, there is evidence that high concentrations of PM in the home can be linked to the presence of smokers, which itself is associated with factors such as low SES and poor mental health [90]. High indoor PM concentrations are also disproportionately higher for residents living in social housing, which tend to be in areas where outdoor air quality is also poor [67].

However, solely understanding EJ using a distributive lens fails to consider other social determinants of health. Health impacts from radon exposure are disproportionate, in particular for smokers, who tend to be from a lower SES background [91]. Furthermore, mismatches between absolute concentrations and effects might even be exacerbated by availability of information as there are substantial differences in private radon testing by race/ethnicity [92], and SES [93,94]. Also, even when information is publicly available, there needs to be caution in interpretation though complex social dimensions, as previous evidence suggests that it can lead people of a higher SES to move away from affected areas, and those of a lower SES to move in, attracted by the subsequent lower house prices, exacerbating inequalities [95].

The relationship between EJ and sources of indoor air pollution is therefore complex and opaque, making it currently difficult to assess distributive EJ for many indoor sources. National emissions inventories are beginning to include indoor sources [96,97], which can help to explore future differential exposures and impacts of sources of indoor air pollution. This includes who stands to benefit from planned 'just transitions' to cleaner cooking [98] that move away from the use natural gas (Question 5). However, the case of radon highlights that EJ aspects beyond distribution may be prevalent, related both to the procedures underpinning who has access to IAQ information (e.g. IAQ monitoring), and capabilities to act on that information (e.g. an ability to mitigate and/or move away from sources of poor IAQ).

2.3. Question 3: what role can ventilation play in improving indoor air quality?

Ventilation refers to the supply and removal of air to and from a space (or spaces) within the building, and is a key means of pollutant transfer between outdoors and indoors, as well as the dispersion of indoor air pollution [99]. The ventilation characteristics of a building depend on its function, location and associated building regulations, construction age, and whether / when it has been refurbished or retrofitted. Two distinct aspects of ventilation are the unintentional airflow through cracks of a building's façade (infiltration), and intentional airflow through technologies designed for this purpose (purpose-provided ventilation) [100].

Purpose-provided ventilation technologies vary in functionality and complexity, ranging from natural ventilation devices, such as windows and trickle vents, to mechanical systems that can provide a continuous supply and extract of air. The choice of purpose-provided ventilation technology depends on several factors, and many countries offer guidance or regulations on the choice of ventilation technologies [101], with an example provided in Table 2.

Actions to reach net zero are required in residential buildings which are responsible for 17 % of global energy and process-related CO_2 emissions [103]. Reducing the loss of heated (or cooled) air by improving residential building insulation and airtightness is integral to decarbonisation efforts [104]. While building airtightness can potentially offer benefits, such as improved winter thermal comfort and reduced ingress of outdoor-sourced pollutants, careful consideration towards ventilation design and specification is needed to avoid unintended consequences on IAQ [105]. In the absence of adequate compensatory purpose-provided ventilation, reducing infiltration can hinder the removal of air pollutants from indoor sources (e.g. cooking and cleaning). Additionally, reduced ventilation rates can lead to mould problems, particularly in households that are suffering from fuel/energy poverty [106,107]. This highlights a significant tension between energy and IAQ [108,109], that is only likely to increase if greater focus continues to be placed on home energy efficiency without the trade-off with IAQ being adequately considered. Evidence from the US suggests that low-income households tend to live in more leaky dwellings [110,111], placing them in a prominent position of potential conflict between energy use and IAQ. In particular, approximately 6 % of the US housing stock in 2022 was manufactured housing (MH), that is occupied by low- and middle-income households, and suffers from poor energy efficiency [112]. As a result, roughly 50 % of MH residents had a high energy burden in 2017 according to the American Council for an Energy-Efficient Economy (spent more than 6 % of their income on electricity and heating fuel costs), and 25 % were severely energy burdened with 10 % of their income spent on electricity and heating fuel costs [113]. In the UK, the private rented sector might be significantly impacted considering that it has the worst energy efficiency and the highest overcrowding amongst other tenures [114].

As the residential building stock becomes more airtight, there will be increasing need for mechanical ventilation systems (Table 2), which can in theory maintain better IAQ, especially those that filter supply air. However, some occupants might find mechanical ventilation difficult to operate, and be reluctant to use due to its noise, and operational and maintenance costs [105,115]. Newer build homes tend to be more airtight and reliant on mechanical ventilation systems: this is particularly the case in the social housing sector [114]. Therefore, this may disproportionately affect occupants of a lower SES. Likewise, a lack of maintenance of mechanical ventilation systems may further exacerbate IAQ leading to elevated concentrations of indoor-generated air pollutants such as NO_2 [116], and mould growth [117], which disproportionately affects the health of vulnerable groups [118,119]. On the other hand, for naturally ventilated residences, ventilation through opening windows may present a risk of theft and increased noise and air pollution levels in more deprived areas, and may be limited in high-rise flats through the use of window restrictors, in particular on the ground floor or flats adjacent to circulation corridors.

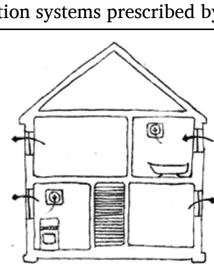
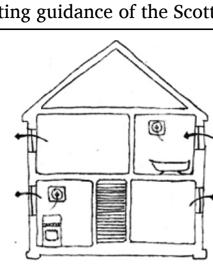
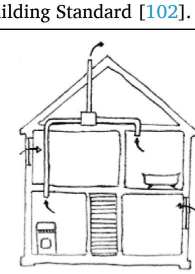
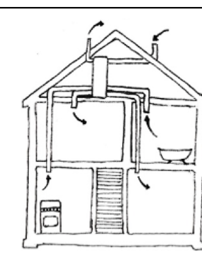
The benefits of ventilation to improve IAQ are clear. To maximise the role ventilation can play in improving IAQ and achieving EJ, greater efforts are needed to integrate effective ventilation strategies when undertaking housing energy efficiency measures. Procedurally, this includes ensuring information is available to educate people on the importance of ventilation, including how to use and maintain ventilation systems effectively, and to involve different groups of people in the design of such systems. Crucially, this must consider differential capabilities to ensure that those in private rental and social housing are not disproportionately affected.

2.4. Question 4: how will climate change affect indoor air quality?

Climate change will impact IAQ in three main ways. First, it will directly affect outdoor air quality which will influence indoor environmental conditions. Climate change will alter the sources and transformation of many outdoor air pollutants, by influencing natural emissions (e.g., through increased wildfire risk and windblown dust emissions [120]), increasing the seasonal duration of pollen-releasing species [121,122], and altering the photochemical processes governing production and loss of atmospheric pollutants. Changes in atmospheric chemistry and transport will have complex effects on outdoor air quality at local, regional, and intercontinental scales, influencing air pollutant formation and mixing in residential areas, as well as the global background air quality. Some of the detrimental impacts of climate change on air quality may be offset by projected decreases in anthropogenic emissions [120], partly due to net zero transport policies (Question 5). However, climate change may worsen inequities in outdoor air quality, which result from pre-existing spatial patterns in air pollution sources [123]. In turn, this may also exacerbate inequities in IAQ.

Second, climate change is expected to increase temperature in indoor environments, altering photochemical processes and potentially accelerating the release (e.g. biogenic VOCs) or formation of pollutants (e.g. ozone) [124,125]. Changes in specific and relative humidity driven by climate change can also impact IAQ, with the direction of these changes and their effects expected to vary spatially. In some areas, the increased risk of floods and winter rainfall from climate change will increase microbial activity through increasing dampness in homes [126]. More vulnerable groups may be disproportionately affected, as climate-driven flood risk (a driver of dampness and mould) is likely to be worse for these populations who tend to live in more risk-prone areas [123,127], and the prevalence of mould is expected to be worse due to poorer quality housing stock. The relative complexity of assessing mould and dampness, and the high cost of collecting and analysing such measurements, has resulted in limited evidence on indoor exposure to mould or

Table 2
Purpose-provided ventilation systems prescribed by the supporting guidance of the Scottish Building Standard [102].

				
Ventilation system	**Trickle ventilation with intermittent extract**	**Decentralised mechanical extract**	**Centralised mechanical extract**	**Mechanical ventilation with supply and extract**
Recommended airtightness	$\geq 5\ m^3/m^2h$ @ 50 Pa	3 to 5 m^3/m^2h @ 50 Pa	$\leq 3\ m^3/m^2h$ @ 50 Pa	$\leq 3\ m^3/m^2h$ @ 50 Pa

other biological evidence, and corresponding associations of bioaerosol exposure and health [128]. While the evidence is mixed, it is accepted that the burden of higher mould exposure falls disproportionately on those living in social housing (as noted above) and renting privately [52], a difference in housing tenure type that is discussed in Question 8.

Third, adapting to climate change will induce changes in building design and resident behaviour that are likely to affect IAQ in a variety of ways. Increased ventilation through window opening driven by higher temperatures will, in general, reduce concentrations of indoor-sourced pollutants, although the ingress of outdoor pollutants into indoor environments will increase. The reverse effect may occur when air conditioning is used to mitigate increased temperature, as windows are kept shut during its operation resulting in limited ingress of pollutants of outdoor origin and increased accumulation of indoor-sourced pollutants [129]. However, effective filtration offers the potential to remove particulates, if filters are maintained [130]. Since resources to adapt to climate change are not equitably shared, the uptake of different measures and their associated effects on IAQ will vary between different groups. For instance, any potential IAQ benefits from the use of air conditioning [131], are likely to be greater for those of a higher SES due to increased air conditioning availabilities [132]. For lower SES groups, who tend to be exposed to greater levels of outdoor-sourced pollution [15,16], and urban heat [133], warmer summers may force them to face a dilemma between worse IAQ and summer overheating [134].

The effect of climate change on IAQ is expected to be complex and difficult to estimate quantitatively [134]. A recent study modelled the combined effects of climate change on IAQ through outdoor emissions and adaptation behaviours, finding a trade-off between increased exposures of indoor pollutants and decreased exposures of outdoor pollutants [135]. Climate change has the potential to foster new distributive environmental injustices and exacerbate existing ones. Furthermore, differential capabilities to adapt to climate change such as through air conditioning and ventilation may lead to new environmental injustices.

2.5. *Question 5: how will net zero policies affect indoor air quality?*

Net zero policies aim to significantly reduce the potential impact associated with climate change by regulating and reducing greenhouse gas emissions, primarily through low-carbon building technologies, and transport. Policies to reduce carbon emissions are hypothesised to have a potential co-benefit of improved air quality [136]: in the indoor environment, this includes through improving outdoor air quality, changing indoor sources of poor IAQ and the broader make-up of the built environment [137], and building electrification [138]. However, the extent to which these improvements will be equitably distributed is unclear [139]. Evidence from the UK suggests that policy-driven air quality improvements in the most deprived areas tend to be both smaller and slower than in the least deprived areas [140].

Low-carbon building technologies such as building fabric and heating and cooking upgrades are a significant policy priority to achieve net zero. Building fabric upgrades have the potential to alter IAQ through their effect on ventilation (Question 3). Highly energy-efficient building materials can also impact IAQ through the release of a more diverse mixture of VOCs, such as from fire retardants and plasticisers [141], paints, and insulation materials. Notwithstanding an increased interest in regenerative construction materials [142], there remains a growing production and use of plastics [143], and novel chemical entities [144]. As such, the range of materials used in building fabric upgrades is likely to change, and they are often overlooked as VOC sources [145]. Research is perpetually ongoing to determine the full extent of their potential long-term impacts on human health. However, this research is not keeping up with the speed of introducing new materials [144].

Upgrading fossil-fuel based technologies such as gas heating and cooking technologies will likely improve IAQ [146]. For instance, studies of cooking electrification have shown elimination of NO_x emissions, and less PM, alongside 50 % reductions in energy consumption [147]. However, a recent Ten Questions paper [138] has highlighted some of the challenges of cooking electrification, including both strong cultural attachments to certain cooking practices, and the potential for building owners to simply shift the costs of cooking electrification onto tenants [148]. While a lack of clean cooking infrastructure is a more acute issue in low- and middle-income countries, around 1/3 of residences in the European Union (EU) and the US use natural gas for cooking [149,150], which is a significant source of NO_2 and other indoor air pollutants [146,151], and has been attributed to as much as 12.7 % of all current childhood asthma cases in the US [152]. However, the lack of relevant data precludes robust associations between NO_2 exposures from gas cooking disaggregated by SES and race/ethnicity [153].

Net zero transport policies focusing on limiting tailpipe emissions in urban environments will have an impact on the concentrations of certain indoor air pollutants by reducing outdoor NO_x, PM, and, VOCs concentrations [137]. The phasing out of internal combustion engine vehicles, and the adoption of electric vehicles would likely reduce the atmospheric concentrations of NO_x and VOCs [154]. This could lead to an increase in street-level ozone concentrations in colder weather conditions [155]. Additionally, non-exhaust PM emissions from tyre and brake wear may be greater due to electric vehicles tending to be heavier [156]. Despite this, reducing NO_x and PM emissions is expected to have a greater positive impact on public health [157]. Notwithstanding the complicated atmospheric chemistry changes at play, the system-level effects of net zero transport policies are complex. For example, there are uncertainties on how the prioritisation of electric vehicles will impact private vehicle demand, and also whether this may effectively price out lower-income groups from owning private vehicles [158].

Net zero policies focused on low-carbon building technologies and transport are being introduced, and they will affect IAQ. In their current form, it is unclear whether net zero policies will worsen IAQ in general, or more acutely for certain social groups, exacerbating distributive injustices. To ensure that unintended consequences, such as poor IAQ and distributive injustices, are not baked in, there is a clear need for IAQ improvement strategies to be incorporated into regulations (Question 9).

2.6. *Question 6: how will the adoption of technological innovations indoors affect indoor air quality?*

A range of new technologies are being enrolled into residential environments which have the potential to significantly influence IAQ. In this question, we primarily focus on the adoption of new technologies that do not have widespread adoption yet. However, there are a range of technological innovations already in-situ within residential buildings that have the potential for a significant impact on IAQ. For example, as cooking is a substantial contributor to household indoor air pollution, technologies such as cooker hoods are an efficient and widely applicable means to improve IAQ. For example, surveys in Canada and Great Britain have shown that the majority of homes have cooker hoods [159,160]. However, their effectiveness is dependent on several factors, including whether they extract to outside or not: in the aforementioned surveys, only between 56 and 66 % of homes with cooker hoods extracted to outside, diminishing their potential to improve IAQ. Moreover, the effectiveness of cooker hoods depends on how they are used, both related to their perceived effectiveness based on removal of cooking-related odours [161], and/or how noisy they are. Previous studies suggest that noise is the main reason that cooker hoods would neither be used often, nor at the appropriate fan speed to remove indoor air pollution [160]. It is worth noting that the installation of cooker hoods in households may have its own relations to EJ, as previous research has shown that both home size, and tenure type (e.g. renter vs owner occupied) are strongly associated with cooker hood presence [160], a point we discuss in Question 8.

An example of a new technology being adopted in residential environments is air cleaning devices, which vary widely in their technology, including mechanical and electronic filtration, adsorption systems, UV irradiators, photocatalytic oxidation, and cold plasma / cold thermal plasma cleaning techniques, with mixed health effects [162–164]. These devices are unlikely to be evenly distributed, with people from higher SES groups more likely to have technologically cleaned IAQ [165], due to the high upfront costs of air cleaners [166], and ongoing costs such as electricity and filter replacements [167]. Moreover, alongside the well documented potential issues with air cleaners that produce ozone [168], some research has shown that poorly maintained filters may emit secondary VOCs [169], and encourage microbial growth [170].

Low-cost air quality sensors are also increasingly being used in the residential environment. While the use of low-cost air quality sensors has historically been focused on outdoor air quality [171,172], the increase in public awareness about IAQ following the emergence of COVID-19 has increased their use by the general public, as well as their integration into buildings to monitor IAQ in real-time. While the range of measurements and accuracy of air pollutants measured with low-cost IAQ sensors varies [173], technologies are rapidly developing that will improve their capabilities.

An increasing use of low-cost IAQ sensors in the residential environment could have clear positive EJ implications through more accurately quantifying how IAQ is distributed [174]. This could, therefore, enable people to use IAQ sensors to generate their own evidence of poor IAQ, and empower them to reduce their exposure to poor IAQ through behaviour change. Currently, users of low-cost IAQ sensors tend to be wealthier [175], which could lead to an evidence gap for IAQ in the homes that need monitoring the most. However, even if low-cost IAQ sensors were freely available to all, many groups may not have the capability (time, awareness, and understanding) to meaningfully engage with the data. Furthermore, there may be mismatches in how IAQ data are used and interpreted between, for example, building occupants and owners. Research has shown that citizen scientists have often struggled to communicate the importance and impact of short-term spikes of air pollution as they do not align with existing expert frameworks of chronic and acute exposure [47,176]. In short, this raises the issue of whether the availability of IAQ sensors actually leads to a more just outcome if different groups fundamentally disagree about the significance and meaning of the data: a clear potential case of epistemic injustice.

Another EJ consideration relates to the type of actions IAQ measurements can potentially lead to. Raising awareness of an IAQ problem without a means or willingness to fix it could potentially have a negative impact on the home occupant's mental health [177], contributing to an IAQ triple jeopardy of health, as well as leading to disengagement with the issue [178,179]. Moreover, despite the best intentions of researchers, IAQ measurements and data can perpetuate harmful narratives about a people or a place. This can inadvertently entrench misrecognition by solely defining some places as 'dirty', rather than focusing on the wider societal reasons driving poor IAQ [39,47]. For example, in some cases this may be historical injustices over hundreds of years such as colonisation and racism [180]. Additionally, an over-reliance on low-cost IAQ sensors may even perpetuate a 'data treadmill' [181], whereby a requirement for more precise data to be generated is used as an excuse for a lack of remedial action [182], when the problem is somewhat already evident, such as through different ways of knowing IAQ, including seeing visible mould or a broken extractor fan, or through the impacts of exposure on the body [183,184].

Technological innovations have the potential to directly, or indirectly, improve IAQ. However, it is critical that the adoption of such technologies is equitably distributed. In the particular case of low-cost IAQ sensors, careful consideration is necessary to ensure that actions resulting from their use do not inadvertently perpetuate epistemic injustices, as "not even the strongest sensor with the highest-resolution open-source real-time data will be enough to magically manifest environmental justice, especially if that injustice is built on a firm foundation of inequality and oppression" [185, p. 239].

2.7. Question 7: how will future population shifts and demographic changes impact indoor air quality?

Changes in population demographics may heighten the importance of poor IAQ for population health. The world population is ageing rapidly, particularly in higher-income countries: more than one in five people in the EU are aged 65 and over [186], and in the last decade in the US, this age group increased by 38.6 % [187]. This increase is projected to be accompanied by a rise in non-communicable diseases, particularly cardiovascular disease (CVD) [188,189]. CVD remains the most common cause of death in the EU [4] and if the disease is to rise at its current prevalence rates across different demographics, lower socio-economic and ethnic minority status groups may be more greatly affected [190,191]. The onset of CVD and other non-communicable diseases, may also encourage a more sedentary lifestyle, which further exacerbates several health conditions [192], leading to people spending more time at home, making the indoor environment an even more important site of exposure.

Exacerbated by the COVID-19 pandemic [193], and facilitated by a lack of outdoor spaces and greater access to electronic devices, children in many higher-income settings are already spending more time indoors than previous generations [194]. Inequalities in sedentary lifestyles have been shown for children [195,196], and urbanisation is a key contributor: greater urbanisation coincides with reduced green space, and children with less green space access are more likely to display sedentary behaviour [197]. Several studies have found access to green space is not equally distributed across a number of European and US cities, which is linked to property price driven 'green gentrification' [198–200]. Moreover, even when green space is accessible in lower-income settings, the area is less likely to be safe [201–203].

Denser living arrangements, including multi-unit housing, are widely used to house the growing urban population. Despite higher density urban environments tending to produce fewer carbon emissions [204], greater population densities are associated with worse outdoor air quality [205,206]. This increases the infiltration of polluted outdoor air into dwellings, and also reduces the effectiveness of natural ventilation to disperse indoor-sourced air pollution [35]. Apartments or flat-style accommodation also share a number of party walls, floors, and ceilings with neighbouring units [35]. This can lead to the ingress of air pollution from adjacent homes via shared ventilation ducts, with fewer external walls through which outdoor air is exchanged. As the demand for housing in urban areas outstrips the supply of available units, single-unit housing – which is generally associated with better IAQ [35] – becomes available to only those on higher incomes.

Conceptualising EJ as recognition is useful when looking at the potential future treatment of climate refugees. However, before looking forwards it is helpful to look backwards. Present day outdoor air pollution distributional injustices (with obvious implications for IAQ) have been traced back to misrecognition predominantly based on race and ethnicity, and SES. This includes the historical US policy of 'redlining', a racially discriminatory mortgage appraisal practice which graded neighbourhoods based on their creditworthiness, giving worse grades to Black and immigrant communities, leading to social segregation [207]. Likewise, the construction of highways in predominantly Black and lower SES communities in the US have entrenched disproportionately greater exposure to air pollution [208–210]. A potential source of future social segregation in higher-income areas is climate-induced migration: In the next century, tens of millions of people are projected to be displaced due to the impacts of climate change [211]. While little is known about the living conditions of future climate refugees, many refugees presently face animosity and barriers to accessing safe and affordable housing, often resulting in refugees occupying insecure and poor quality housing [212]. A tragic example of this was the aforementioned death of Awaab Ishak. Awaab's parents had recently moved to the UK from Sudan [213], and had called on the housing association to “Stop providing unfair treatment to people coming from abroad who are refugees or asylum seekers” [38], exemplifying how refugee misrecognition and poor IAQ may interact through the provision of housing.

Future population shifts and demographic changes will have an impact on IAQ through an ageing and more sedentary population spending more time indoors, alongside increased urbanisation and climate migration. However, these impacts will likely have unequal effects due to different distributions of pre-existing illness, access to green space, and patterns of misrecognition.

2.8. Question 8: what role can individual behaviour change play in improving indoor air quality?

IAQ is strongly driven by the behaviours of building occupants through everyday practices such as cooking, cleaning, and opening windows [214]. Therefore, behavioural changes are an important part of both reducing indoor air pollutant emissions and exposures [215]. As such, the necessity of individual behaviour change to reduce exposure to poor air quality has been highlighted [216–220]. For IAQ, b behaviour change has the potential to reduce emissions and exposures including through for example, not smoking indoors [221], improving ventilation practices [218], using back burners during cooking [222], modulating the frequency and use of certain consumer products [4], and using a dehumidifier while drying clothes indoors [4].

While these actions are undeniably important, the framing of IAQ as a matter of ‘personal care’ [223] that is solely the responsibility of the building occupants is overly simplistic. Behaviours are not an individual choice that occur in a vacuum: they are influenced by social and political contexts, including social hierarchies and power relations [224]. It is important to note that most proponents of behaviour change acknowledge that it should be complementary to a broader systemic, long-term, and multisectoral change [220]. However, attempts to improve public health, such as through improving IAQ, are often critiqued for ‘lifestyle’ drift, where they start by aiming to address upstream social determinants of health, but end up focused on downstream factors such as lifestyle, and promoting behaviour change [225]. This leaves the larger upstream factors unaddressed, resulting in “addressing the proximal causes of the disease but being blind to the causes of the causes” [224, p. 3]. Nonetheless, for IAQ, even if all reasonable actions to reduce emissions and exposures have occurred upstream, there are still likely to be situations where some need to consider individual actions. For example, that may be in response to forest fires, dust storms, or a heightened susceptibility to certain aspects of IAQ that are relatively harmless for less susceptible individuals [226]. Likewise, for the increasing trend of – predominantly – higher-income communities using wood burning stoves for primarily social desirability and aesthetic reasons [4], coming at great expense to their own IAQ [227]. It is critical that until wider upstream IAQ improvements can be achieved “personal-level actions should be considered as temporary, supplementary solutions” [220, p. 24]. Attempts to change behaviour are unlikely to improve IAQ unless several factors are considered.

People cannot change their behaviour if they do not have an awareness of the problem. An obstacle to raising awareness of IAQ is it is often invisible in nature. Tomsho et al. [228] found that a lack of sensory awareness (e.g., taste, smell, and/or visual prompts) of IAQ made people less likely to search out information on IAQ, and engage in behaviour change. A UK study found that access to air quality information to inform behaviour change was ‘sociodemographically stratified’ which may contribute to distributive injustices [229]. If IAQ information is not readily available, the burden of responsibility falls on the public. For example, consumers currently possess sole responsibility for the IAQ impacts of household and personal care products, and personal furnishings in their homes, both in terms of product choice and how they are used. As the general public mostly do not have the knowledge that these products may degrade IAQ, and products do not label their IAQ impacts, consumers have a limited ability to make informed purchase and use decisions, which can more broadly be considered as informed consent [230]. However, even equipped with the relevant knowledge, there are still significant barriers to behaviour change improving IAQ.

Behaviour change is also unlikely to improve IAQ unless differential capabilities are considered [231]. Fig. 2 illustrates a scale of capability for behaviour change based on housing tenure type. Note that there is a hard tenure type / activity capability barrier between housing ownership and non-ownership, where behaviour changes to improve IAQ cannot be accessed and/or achieved. For example, current public health messaging mainly focuses on encouraging occupants to open their windows or use continuous mechanical ventilation, particularly during poor IAQ events such as cooking [232]. However, this fails to acknowledge the ventilation and cooking infrastructure available that either facilitate or prohibit the necessary practices required to improve IAQ.

Fig. 2 is a heuristic, and circumstances will clearly not be the same

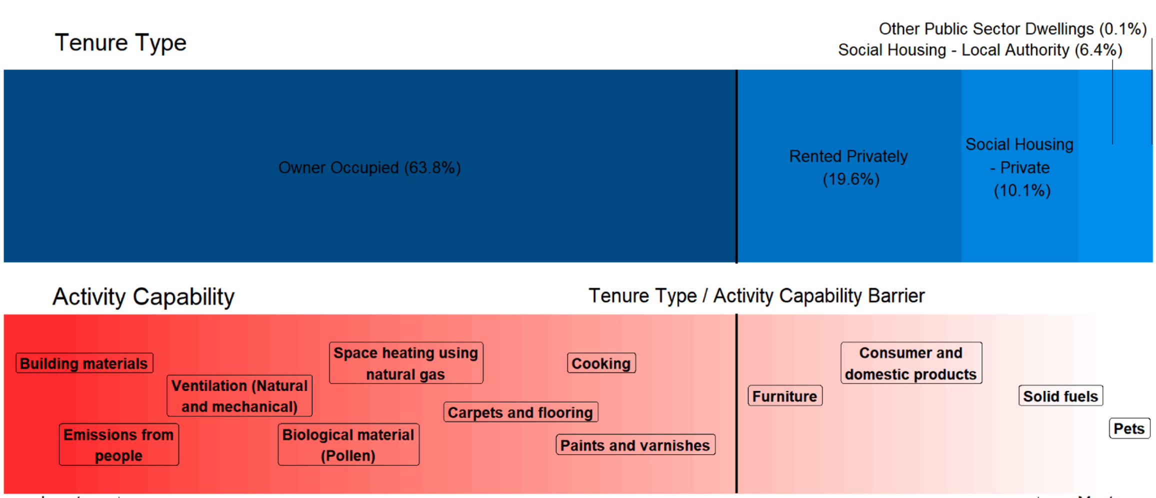


Fig. 2. Tenure type in England 2021 based on ONS [233], and behavioural change capability scale. Boxes on the lower scale show different behaviour change activities that could improve IAQ outlined in the AQEG IAQ report [4]. These include: chemical emissions from the fabric of buildings, space heating using natural gas, emissions from the use of consumer and domestic products, emissions indoors from cooking in homes, emissions from the use of solid fuel, airborne biological material present within buildings, and emissions from people. The top of the bar indicates tenure type, and the bottom (from right to left), decreasing limits of capability. There is a Capability Barrier between the Tenure Types that illustrates the different capabilities to access behaviour changes.

for all within each tenure type outlined. For example, fuel poor populations may have the physical infrastructure in place to achieve adequate ventilation to improve IAQ, albeit at the expense of maintaining a safe indoor temperature. In addition, many of those living in owner occupied residences also have a limited capability to change their behaviour, such as children and lodgers. However, property ownership is not the only barrier to behaviour change. Instead, there are a range of different social and physical solutions and barriers to behaviour change [215].

While occupant behaviour clearly influences IAQ, treating IAQ as solely the responsibility of building occupants is overly simplistic. To improve IAQ in an environmentally just manner, system-level factors that shape behaviours, as well as differential capabilities to achieve behaviour change must also be addressed. This is important to avoid lifestyle drift, in particular as framing improving IAQ as solely a question of behaviour can shape societal understandings of responsibility for poor IAQ [234], inadvertently placing it onto the individual [47].

2.9. Question 9: how should indoor air quality improvement strategies be incorporated into regulations?

Given the harmful effects of poor IAQ on public health, progressive regulation should aim to improve IAQ and address exposure inequities instead of just treating their health outcomes. Existing regulations that aim to improve IAQ often rely on technical and behavioural assumptions with high levels of uncertainty, and limited monitoring and enforcement.

Despite research and advocacy that spans decades, most countries do not regulate IAQ directly. Instead, regulations typically focus on ventilation provision and controlling emissions from specific products and technologies [105]. The introduction of regulations that set IAQ limit values, as done for outdoors, is the most direct way of legislating exposure to indoor air pollution. However, the development of such regulations is faced with many challenges. Morawska et al. [235] recognised these challenges but argued that they could be overcome in the case of public buildings, but not in the homes where monitoring and enforcement is infeasible.

Several countries have building regulations in place to guide the levels and means of ventilation provision which differ in approach and comprehensiveness [101,105]. However, evidence suggests that homes built in line with the building regulations may not always provide intended ventilation levels [236], resulting in the accumulation of air pollutants and biological agents with potentially severe consequences for the occupants. This performance gap may arise from poor design and installation, incorrect assumptions about the effectiveness of ventilation systems, and discrepancies between assumed and actual operation by the occupants [161]. Furthermore, the performance gap may differ between countries, in part due to differences in the resources available to enforce the implementation of building regulations.

While source control may in theory be the most effective way of improving IAQ, total elimination of the generation of indoor pollutants is not possible. Nonetheless, policy can play a critical role in regulating products and technologies whose use results in pollutant exposure that poses a risk to public health. The introduction of "Smoke Control Areas" in the UK [237] restricted how solid fuel devices are used within the home through financial penalties for releasing smoke from their chimney, using non-approved technologies in designated areas, and/or burning inappropriate materials. While this is an example where the use of a technology was restricted, depending on the balance of risks and benefits, an outright ban may be preferred. This was the case for technologies that employed ozone-depleting substances such as chlorofluorocarbons (CFCs), such as fridges.[1] Regulation may also be used to control the emissions from construction products as is the case in Germany and France [62]. Alongside regulating product and technology use, policy or advisory interventions can be introduced, which are not reliant on public responsibility or capability towards IAQ improvement, and focus instead on encouraging manufacturers to reduce the emissions of their products. For example, all new cosmetic products must pass a safety assessment by a qualified assessor [238]. Incorporating emissions testing in this prior-to-sale safety assessment would require manufacturers to consider IAQ impacts during product formulation: for example, reducing solvent or propellant ingredients to reduce VOCs, without the need for outright bans, as was the case for CFCs. Manufacturers could be required to take greater responsibility by testing their products for IAQ effects and advising consumers of their findings by labelling their products accordingly. However, stringent regulation will be required to minimise potential 'greenwashing' [239], as might be the case for air fresheners or air 'purifiers'.[2]

Devising effective regulation requires coordinated action across government departments at the national level that is implementable at the local level. The complex contextual factors affecting residential IAQ, including psychological, social, and financial dimensions as outlined in Questions 1 and 8, should also be considered in any attempt to improve existing regulatory frameworks. Further, to strive towards EJ, regulation should: consider the differing needs, preferences, and capabilities of individuals by involving them during its development; avoid shifting the entire responsibility of IAQ onto the individual; not be overly restrictive on how the public use products and technologies within their homes; and be monitored, reviewed, and refined regularly to identify issues and ensure that the intended outcomes are met. Achieving the latter requires an active approach to evidence generation, especially where large-scale changes to the built environment – such as through net zero policies – may influence IAQ. In the absence of such monitoring, adverse effects could be locked in [240], disproportionately impacting individuals with underlying health conditions, and those incapable of taking remedial actions.

Governments have the power – and responsibility – to not only improve IAQ, but also reduce the potential for environmental injustices related to IAQ. Their aim should be to find an appropriate balance of regulating building design, in addition to what products and technologies are available, and how they are used within the home. To strive towards procedural justice, coordinated action with different levels of involvement from different actors is required that ensure different social groups are given equal opportunities for good IAQ (Question 10). Finally, adequate monitoring and enforcement are also required to ensure that policy changes are implemented, and do not disproportionately impact certain groups, contributing to distributive injustices.

2.10. Question 10: how can a transdisciplinary approach lead to better indoor air quality?

To help improve IAQ in an environmentally just way researchers need to engage in transdisciplinary research that combines the expertise of multiple academic disciplines, private and public sectors, and the general public, to include all affected by the problem and involved in delivering the solutions.

Transdisciplinary research is "an integrative process whereby scholars and practitioners from both academic disciplines and non-academic fields work jointly […] to yield innovative solutions to particular scientific and societal problems" [241, p. 6]. Methods to outline a transdisciplinary approach are numerous [242,243], and provide a framework for transdisciplinary action to deal with complex problems [244]. These approaches use a range of methods including participatory workshops, document review, and interviews [245,246],

[1] Recent work has quantified the benefit of the latter regulation in mitigating climate change [256,257].

[2] In both cases, the names of air *fresheners* and air *purifiers* imply a non-defined improvement of IAQ.

which focus on setting a long-term desired outcome (such as improved IAQ). Subsequently, contextual factors and the roles of actors are established, as well as measures and indicators to achieve success. This approach is often presented in a diagram or narrative summary for guidance and reflection [242,247].

Such transdisciplinary approaches have been used in a variety of relevant settings [242,248–250], but generally not when considering residential IAQ and EJ. As improving IAQ requires actions across different academic disciplines, individual occupants, communities, and all different levels of government [244], a transdisciplinary approach would be both necessary and transformational. Indeed, previous guidance for residential IAQ has highlighted the myriad of sectors that need to be involved to improve IAQ, outlined in Fig. 3 [117].

With a long-term desired outcome for the future of residential IAQ to be more environmentally just, such a framing enables the consolidated actions that a range of different sectors need to take to achieve this outcome. Reflecting on the role of the research community, input from a wide range of disciplines is required to understand the complex interactions between climate, policies, buildings, technologies, and behaviours that influence future residential IAQ and its health and equity outcomes. Through working across disciplines, the research community can develop new knowledge on how to improve IAQ through technological, behaviour, and policy innovations. Alongside this, the research community can establish evidence on who is exposed to poor IAQ and where, to make visible inequalities in IAQ sources, exposures, and health impacts. In doing so, researchers can transgress boundaries between academia and policy to encourage further action from policymakers to ensure that clean air innovations are integrated into other policy initiatives (such as on climate change adaptation) and regulations that maximise co-benefits and minimise unintended consequences. Likewise, researchers can provide information to inform public information campaigns both to raise awareness of IAQ, and to change public attitudes and behaviours so residents can improve their IAQ [219,221,251,252]: while recognising that information alone is not sufficient for behaviour change, that behaviours are shaped by social and political contexts, and that differential needs and capabilities exist.

Knowledge produced in a transdisciplinary way will enable EJ to feature prominently, including through co-producing research with affected communities to ensure that the local context, lived experience, and priorities of affected communities are factored into the research's design, reporting, and recommended solutions [47,179,253]. This includes recognising that scientific knowledge is but one way of knowing IAQ, and that IAQ also has place-specific cultural relations and meanings [75,254]. Many IAQ researchers will not have the experience or expertise in transdisciplinary research, including working across disciplines, and effectively interfacing between business, government, and civil society. Indeed, previous transdisciplinary research on air quality has highlighted its challenges [253,255]. However, we believe that transdisciplinary research has the potential to deliver improved and more equitable IAQ, especially in the context of the residential indoor environment fundamentally changing in the future.

3. Conclusion

Changes in social gradients in health, sources of indoor air pollution, ventilation, climate change, net zero policies, technological innovations indoors, population shifts and demographic changes, behaviours, and regulatory air quality improvement strategies are likely to have significant impacts on residential IAQ, an important driver of health and wellbeing in the built environment. However, it is uncertain how these

Fig. 3. Different sectors required to improve indoor air quality, as outlined by the UK National Institute for Health and Care Excellence (NICE) [117].

changes will differentially impact different social groups and EJ. This Ten Questions paper has explored the implications of future residential IAQ on EJ, through paying attention to diverse aspects of EJ including distributive, procedural, recognition, capabilities, and epistemic dimensions.

While there is a lack of comprehensive knowledge on the distributions of IAQ across different social groups – especially in comparison to outdoor air quality – there is the potential for a triple jeopardy of health. IAQ research and action towards EJ should be underpinned by a multidimensional approach that does not only consider the distribution of poor IAQ, but instead also considers differential vulnerabilities to poor IAQ, capabilities to improve it, and the wider historical and social context driving unequal patterns of poor IAQ. IAQ is as much a social problem as it is a physical one: this necessitates a transdisciplinary approach to co-produce socially relevant knowledge and solutions through interfacing with all groups affected by poor IAQ, and responsible for delivering good IAQ. In doing so, this can place appropriate responsibility for poor IAQ in the right places.

CRediT authorship contribution statement

D. Booker: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **G. Petrou:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **L. Chatzidiakou:** Writing – review & editing, Writing – original draft, Conceptualization. **D. Das:** Writing – review & editing, Writing – original draft, Conceptualization. **F. Farooq:** Writing – review & editing, Writing – original draft, Conceptualization. **L. Ferguson:** Writing – review & editing, Writing – original draft, Conceptualization. **OE.I. Jutila:** Writing – review & editing, Writing – original draft, Conceptualization. **K. Milczewska:** Writing – review & editing, Writing – original draft, Conceptualization. **M. Modlich:** Writing – review & editing, Writing – original draft, Conceptualization. **A. Moreno-Rangel:** Writing – review & editing, Writing – original draft, Conceptualization. **S.K. Thakrar:** Writing – review & editing, Writing – original draft, Conceptualization. **A.M. Yeoman:** Writing – review & editing, Writing – original draft, Conceptualization. **M. Davies:** Writing – review & editing, Funding acquisition. **M.I. Mead:** Writing – review & editing, Funding acquisition. **M.R. Miller:** Writing – review & editing. **O. Wild:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Z. Shi:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **A. Mavrogianni:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **R.M. Doherty:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Anna Mavrogianni reports financial support was provided by UK Research and Innovation Natural Environment Research Council. Douglas Booker reports a relationship with National Air Quality Testing Services Ltd. that includes: board membership, employment, and equity or stocks. Malina Modlich reports a relationship with Environmental Protection Scotland that includes: board membership. Anna Mavrogianni reports a relationship with Elsevier that includes: board membership. Anna Mavrogianni: - Associate Editor, Energy and Buildings, - Editorial Board Member, Sustainable Cities and Society - Editorial Board Member, Carbon Neutral Technologies. 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.

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Data availability

No data was used for the research described in the article.

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