Examining the concentrations and trends in indoor air quality in existing UK social housing dwellings

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Abstract. While outdoor air quality is regulated, indoor air quality (IAQ) in homes has been relatively neglected despite the links between IAQ and health. This paper empirically examines the concentrations and trends in indoor temperature, relative humidity (RH), carbon dioxide (CO_2), Particulate Matter ($PM_{2.5}$ and PM_{10}), VOCs (EtOH) and Isobutylene across a sample of 42 existing social housing dwellings located in West Midlands (UK). Time series data were recorded continuously at 15-minute intervals from 1 February 2022 to 30 April 2022, using Airthinx sensors located in the living rooms of each dwelling. Contextual data about the physical and household characteristics were gathered using in-person surveys. Statistical analysis revealed that under heating was dominant, with eight out of 42 dwellings failing to reach the recommended 18°C indoor temperature, due to poor insulation levels and high heating costs. Mould was present in 61% of dwellings, despite mean RH values remaining below 65%. CO_2 concentrations were related with occupancy, with mean values frequently above 900ppm and as high as 3,092ppm in some dwellings, due to limited ventilation to conserve heat. High PM levels were generally associated with indoor smoking, with $PM_{2.5}$ concentration rising to 202ug/m^3, substantially above the 15ug/m^3 limit. VOCs remained low, yet indoor painting and air fresheners provided the greatest increases. The poor levels of IAQ in these dwellings makes a strong case for whole house energy retrofits that reduce unwanted heat loses, improve air-tightness and provide continuous background ventilation for removal of indoor pollutants.

Keywords. Social housing, indoor air quality, particulate matter, volatile organic compounds

1. Introduction

Humans spend 90% of their time indoors (Klepeis, et al., 2001) yet outdoor air quality has been extensively monitored and regulated through substantial guidance for many years. The World Health Organization (WHO) estimated around 3.2 million deaths during 2020 as a result of household air pollution with such extreme effects including heart disease, strokes, lower respiratory infection, chronic obstructive pulmonary disease and lung cancer. More commonly, mild symptoms include irritation of mucous membranes, headaches, dizziness, nausea, diarrhoea, rashes, abdominal and chest pain (Spengler & Sexton, 1983).

As of 2021, the social rented housing sector accounted for 17% of dwellings in the UK. Overall, 72% of social housing tenants fall in the two lowest income quintiles with the highest unemployment rate. Because of this, social housing tends to occupy those with a higher percentage of vulnerability. Moreover, social housing conditions are widely recognised as being low-quality and associated with higher indoor pollutants which can lead to adverse health implications, heightened through vulnerability and consequently described as non-decent (HM Government, 2022). Set to improve conditions, the UK Government (2022) has introduced new legislation to improve social housing with a target to reduce non-decent housing by 50% by 2030. Non-decent conditions of social housing are confounded by the fact that there is paucity of empirical data on typical concentrations of IAQ in UK homes which can be used as an indication of the extent and urgency of improvements. Studies undertaken have predominantly focused on indoor temperature, RH and CO_2 as a measure of IAQ (Pation & Siegel, 2018) with limited data surrounding PM and VOCs. Gupta and Kapsali (2016) showed poor IAQ levels in six low energy social housing dwellings due to insufficient supply of fresh air from the Mechanical Ventilation with Heat Recovery (MVHR) due to poor commissioning coupled with a lack of user comprehension. Another study by McGill, Oyedele, & McAllister (2016) measured poor levels of IAQ in four naturally ventilated and four mechanically ventilated new low energy dwellings. Stamp, et al (2022) revealed seasonal difference in IAQ concentrations of low energy homes suggesting it to be twice as bad in the winter due to natural ventilation during summer. It is evident that these studies have limited to small sample sizes between three and eight, and predominantly for low energy or new dwellings.

It is vital to measure IAQ levels in existing housing given that UK is home to the oldest housing stock in Europe (Piddington, *et al*, 2020), and 80% of existing dwellings will still be in use in 2050 (UK Green Building

Council, 2021). In an attempt to reduce energy demand of existing dwellings, large-scale retrofitting is being widely promoted, although assessment of IAQ impacts of energy retrofits is limited. Gupta and Zahiri (2022) studied IAQ levels over a short term, pre and post heat pump installation in five social housing flats. Their findings indicated indoor pollutants fell post installation due to increased window opening because of always-on heat pump-based heating system. Similar outcomes were observed by Gupta and Howard (2022) who studied IAQ of four flats which underwent a deep energy retrofit. Post retrofit comparisons showed indoor pollutant levels dropping, yet $PM_{2.5}$ and PM_{10} levels remained high, likely due to occupant activities, especially smoking. It has become evident that occupant behaviour and activities can influence IAQ (Stamp, et al., 2022).

Against this context, this study aims to empirically measure and statistically analyse the concentrations and trends in indoor temperature, relative humidity (RH), carbon dioxide (CO_2), Particulate Matter ($PM_{2.5}$ and PM_{10}) and VOCs (EtOH and Isobutylene) across a sample of 42 existing social housing dwellings (living rooms) located in West Midlands (UK). Contextual data about the physical and household characteristics were gathered using in-person surveys. The dwellings consist of four differing housing typologies which have varying building and household characteristics. Data analysis has been divided into three levels - *sample* (all 42 dwellings), *typology* (four types, standard semi-detached, triangular semi-detached, terrace and bungalow) and *individual dwelling* to represent overall and in-depth IAQ findings. In addition, the relationship between IAQ, building characteristics and occupant activities are identified using monitoring and survey data to provide recommendation for anticipated energy retrofits.

2. Methodology

A case study based approach was adopted to gain in-depth understanding of the trends in IAQ in existing social housing dwellings in need of energy improvements. The research methodology consisted of quantitative and qualitative data collection between 1st February 2022 and 30th April 2022 using Airthinx and Hobo sensors. This included measuring time series data on indoor temperature, RH, CO_2, $PM_{2.5}$, PM_{10}, EtOH and Isobutylene at 15 minute intervals, generating approximately 340,000 pieces of data per variable. In addition to this, household and building characteristics were collected through in-person surveys with at least one resident of each dwelling. Data analysis has been divided into three levels - *sample* included all dwelling (n=42), the *typology* level which was a sub-sample of the sample level divided into four groups dependant of the built form (standard semi-detached, triangular semi-detached, terrace and bungalow) and *individual dwelling* to represent overall and in-depth IAQ findings.

Table 1 below shows the specifications of the sensors - Airthinx for internal and Hobo MX2301 for external measurements. The Airthinx sensor was located in the living room of each dwelling which was typically occupied between 19:00 and 22:00. This device was powered by mains electric, at least 1m off the floor and 1m away from a window. The device recorded temperature, RH, CO_2, $PM_{2.5}$, PM_{10}, Ethanol and Isobutylene at 15-minute intervals which transmitted data to an online portal using a mobile phone network. The Airthinx sensor has been found to be affordable and “exhibit excellent precision” (Zamora, Rice, & Koehler, 2020, p. 117615) when compared against other IAQ monitors. This is why Airthinx sensors were deemed to be appropriate for this study. The Hobo MX2301 is wireless, which stored and transmitted data to an app using Bluetooth. This device was used to concurrently record external temperature and RH at 15’ intervals.

Table 1

Specification, resolution and accuracy of monitoring devices

Device	Parameter	Range	Accuracy	Resolution
Airthinx	Temperature (°C)	0-99	± 0.5	0.1
	RH (%)	0-99	± 2	0.1
	CO_2 (ppm)	0-5000	± 50 +5% FS	1
	$PM_{2.5}$/PM_{10}(μm/ m^3)	0-500	± 10% @100 500μm/ m^3	1
	TVOC (ppm)	1-10 (EtOH)	0.15-0.5 Rs (10ppm of EtOH)/Rs (air)	0.01
		0-1 (Isobutylene)		
HOBO MX2301	Temperature (°C)	-40 - 70	±0.2	0.036
	Relative humidity (%)	0-100	±2.5-3.5 (10% to 90%); ±5 (below 10% and above 90%)	0.01

The IAQ data collected was cross related with qualitative data collected through a household survey (for each dwelling) including use of spaces, general daily routines, heating schedules and comfort preferences. A building survey was conducted for each dwelling to identify the age and construction type, the presence of insulation and window type.

2.1 Characteristics of dwellings

The study sample consisted of 42 social housing dwellings representing four different built forms - standard semi-detached (S), triangular semi-detached (TR), terrace (T) and bungalow (B), as shown in table 2. All case study dwellings were two storeyed, and comprised of a living room, kitchen, hallway and cupboard on the ground floor. Dwelling type TR also had another bedroom and W/C. Two to three bedrooms and family bathroom were located on the first floor. The mean number of occupants were 3.1 people per dwelling. The triangular semi-detached was the oldest dwelling type built between 1900-1929 with little insulation throughout. The standard semi-detached and bungalows were known to have the greatest level of insulation in the walls and lofts, although, residents suspected it to be inadequate. According to the UK Government approved energy rating calculation (SAP), the case study dwellings had an estimated existing design value standard air permeability of 15m^3/hm^2 @ 50Pa, indicating poor levels of airtightness. Window opening was the most common ventilation approach. The standard and triangular semi-detached dwellings commonly had wall grilles in the living rooms which some blocked up. All dwellings were heated using gas heating and used gas or electricity for cooking

Table 2

Household and building characteristics for housing typologies

Dwelling characteristics	6 Bungalows (B)	12 Standard semi-detached (S)	21 Triangular semi-detached (TR)	3 Terrace (T)
External dwelling image				
Internal dwelling image				
Number of occupants	1-2	1-7	1-6	2-4
Dwelling area	41m^2	79m^2 and 111m^2	96m^2	67m^2 and 77m^2
Age of construction	1976-1982	1930-1949 and 1950-1966	1900-1929	1950-1966
Smoking indoors	1	4	8	2
Presence of mould	4	8	12	2
Wall U-Value	0.37W/m^{2}K	0.37-0.49W/m^{2}K	0.49W/m^{2}K	0.49W/m^{2}K
Roof U-Value	0.18W/m^{2}K	0.22-0.3W/m^{2}K	0.45W/m^{2}K	0.22-0.29W/m^{2}K
Ground floor U-Value	0.78W/m^{2}K	0.78-0.87W/m^{2}K	0.75W/m^{2}K	0.77-0.78W/m^{2}K

3. Results

3.1 Temperature and Relative Humidity

During the monitoring period, external temperatures ranged from -2.9°C to 21°C. Table 3 shows the mean indoor temperature at sample level as 20.1°C, with minimum and maximum values showing significant range from 7.3°C to 37.4°C. At the typology level, type T experienced the lowest mean indoor temperature of 18.3°C, with residents expressing their concerns regarding the inadequate levels of insulation. The only source of heating on the ground floor was from the living room radiator, which due to the shape of the room, was usually covered by furnishings.

Table 3

Descriptive statistics for indoor temperature, RH and CO_2 at sample level (n: 42 dwellings)

IAQ parameter	Min	Max	Mean
Temperature (°C)	7.3	37.4	20.1
RH (%)	13	100	43
CO_2 (ppm)	400	4,999	1,198

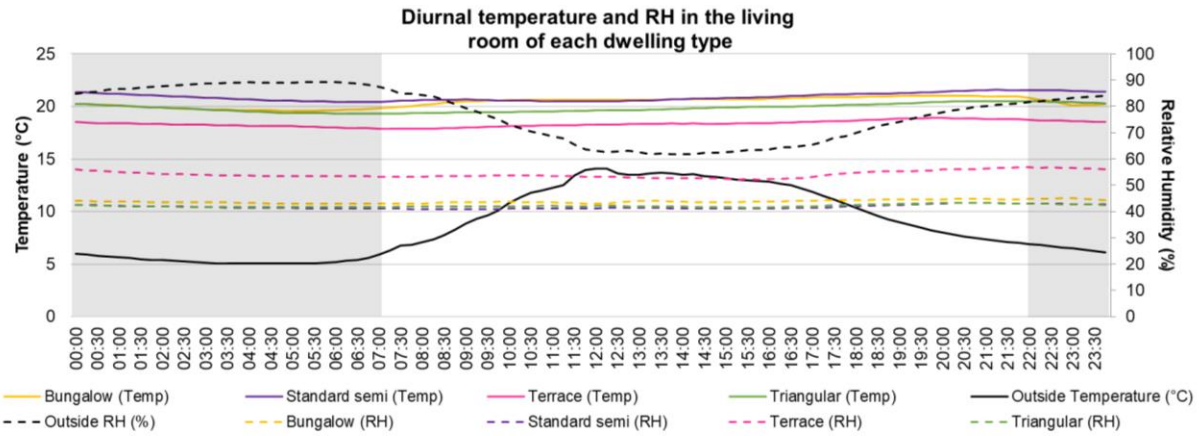
Diurnal temperature trends in the four housing typologies, in figure 1, represent typical daily temperature profiles during the monitored period. Temperatures were lowest between 04:00-09:00 hours after a prolonged period of inactivity and no heating, recognised by a notable decrease from the peak at 21:00 hours across all typologies. Dwelling type T experienced a peak diurnal temperature of 19.5°C, compared to dwelling type S at 20.7°C. These dwellings had the greatest levels of loft and cavity wall insulation suggesting a better retention of heat. Although all four dwelling typologies exceeded the 18°C limit (CIBSE, 2021), at an individual dwelling level, dwelling B03 observed a mean indoor temperature of 16.2°C while dwelling S11 experienced the lowest mean temperature of 15.8°C, primarily due to under-heating driven by high heating cost.

Indoor temperatures below 18°C were recorded in 85% of dwellings (36 out of 42), of which 9% (3 out of 36) experienced temperatures <18°C at least 85% of the time. Residents of these dwellings were generally classed as vulnerable due to age or existing health conditions. Temperatures below 10°C were observed in eight dwellings, five were associated with TR dwellings which were 100 years old. If prolonged exposure to such temperatures occur, significant health implications may be experienced. The worst case was TR13 which encountered daily indoor temperatures <10°C, nearly 29 times over the monitoring period due to extensive window opening.

Internal diurnal RH profiles showed no correlation with external RH. In table 3, at the sample level, mean indoor RH levels were found to be 43%. At typology level, as shown in figure 1, all dwelling types had a stable means and a range of 14%. Typology T experienced the highest RH at 56%. At an individual dwelling level, mould was prevalent amongst 61% of dwellings (26 out of 42). Residents in dwellings TR11 and TR14 believed that presence of mould contributed to deterioration of their respiratory system, with mould spreading to fabrics and furnishings. Under heating of these dwellings was contributing to this along with inadequate ventilation and insulation, resulting in warm indoor air hitting cold surfaces and condensing.

Figure 1

Daily indoor and outdoor temperature and RH profiles across the four typologies of dwellings



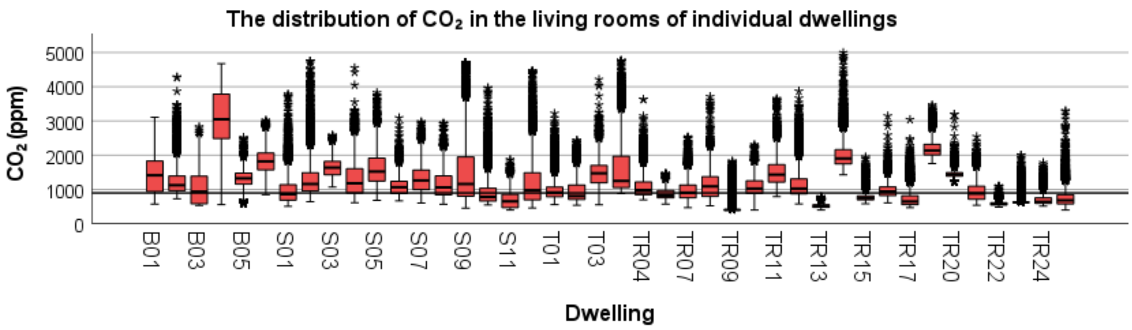
3.3 Carbon Dioxide

Throughout the monitoring period, indoor CO_2 concentrations showed significant variation, reaching the devices maximum capacity at 4,999ppm. The mean concentration of CO_2 levels at sample level (table 3) were 1,198ppm, exceeding the recommended limit of 900ppm for medium air quality (CIBSE, 2021) by 300ppm. The diurnal CO_2 profile at sample level showed a direct relationship to room occupancy – with CO_2 levels increasing from 15:00 at 1,107ppm and peaking to 1,496ppm at 21:30. Occupant activities at this time would have included cooking in the kitchen, children playing, watching TV and relaxing. This profile was also observed at the typology level with the exception of dwelling type B who was occupied by retired residents spending most of their day in the living room. For this reason, dwelling type B experienced a small increase of 141ppm from 06:15am to 09:00am when residents got up. Perhaps expected, this dwelling type also had the greatest mean of 1,692ppm due to constant occupancy and inadequate ventilation. Dwelling type TR had the lowest mean of 1,058ppm.

Figure 2 shows interquartile ranges (IQR) for CO_2 for individual dwellings. TR dwellings experienced the greatest median CO_2 levels below 900ppm compared to B and S types, which had IQR's close to 1000ppm and median CO_2 levels greater than 900ppm. At individual dwelling level, there were some outliers. Dwelling B04 had the highest mean CO_2 level of 3,092ppm with a lower quartile close to 2,500ppm and upper quartile of 3,800ppm, due to prolonged occupancy and limited window opening. Dwellings TR14 and TR18 also experienced higher than expected interquartile ranges. In TR18, residents kept their curtains closed at all times and internal door also shut, thereby restricting ventilation and air flow. TR14 experienced the worst case of mould throughout the sample. Mould is known to consume oxygen and release CO_2, perhaps suggesting why indoor CO_2 levels remained high.

Figure 2

The distribution of Carbon Dioxide in the living rooms of individual dwellings compared against CIBSEs guide for medium air quality of 900ppm



3.4 Indoor pollutants, $PM_{2.5}$, PM_{10}, Ethanol and Isobutylene

At the sample level, as shown in table 4, mean concentrations of $PM_{2.5}$ and PM_{10} were 31.8ug/m³ and 37.1ug/m³, $PM_{2.5}$ was over double the 24-hour recommended WHO limit of 15ug/m³ (2021), but PM_{10} remained below 45ug/m³. However, maximum values of PM_{10} were very high at 2,125ug/m³ and 2,592ug/m³. Such high levels were unlikely to be due to external concentrations, but rather driven by occupant activities such as indoor tobacco smoking and cooking in unventilated spaces. Typology TR had the smallest means of 20.7ug/m³ for $PM_{2.5}$ and 23.7ug/m³ for PM_{10}, even though, 7 dwellings (33%) were associated with indoor smoking. In comparison, dwelling type T experienced the highest means of 117ug/m³ and 140ug/m³, since 66% of dwellings (2 out of 3) in this typology were associated with indoor smoking, which is the greatest sources of indoor PM (Ni, Shi, & Qu, 2020).

Daily profiles suggested external PM levels were responsible for some indoor PM spikes derived from exhaust emissions. With the exception of this, other PM levels arose as a result of human activities. At an individual level, approximately 19 dwellings had $PM_{2.5}$ mean concentrations greater than 15ug/m³ - 68% (13 out of 19) were associated with indoor smoking where dwelling T02 reached a mean of 202ug/m³. Residents of this dwelling worked opposing shift patterns and smoked in the living room at all times over a 24-hour period, not allowing internal air to be refreshed. Non-smoking households using gas as their cooking sources without an extractor fan in the kitchen accounted for 26% (5 out of 19). The remaining 6% (one out of 19) was associated with location, near to a main road with $PM_{2.5}$ extracted from exhausts, as well as household activities including candle burning, aerosol usage and cleaning products (Zhang, et al., 2021). In addition to the exceedance of WHO $PM_{2.5}$ recommended levels, 10 dwellings had mean PM_{10} concentrations greater than 45ug/m³. Unsurprisingly 90% (9 out of 10) of these were associated with indoor smoking. In dwelling T03 with an open plan living room/kitchen, gas cooking without extractor fan resulted in mean concentrations of PM_{10} reaching 116ug/m³. Daily trends for this dwelling showed concentrations to be highest during the evening which cooking would have taken place and scented candles lit to disguise cooking odours.

Ethanol (EtOH) and Isobutylene were also monitored. At the sample level, the maximum capability of the monitors were reached for both parameters, as shown in table 4. Neither parameter has recommended limits for exposure in domestic environments. Industry guidance stated EtOH should be below 1800ppm to avoid short term health effects (Public Health England, 2015) and Isobutylene should be <250ppm averaged over an eight hour period (TCP group, 2012). At typology level, dwelling type T experienced the lowest concentrations with means of 0.1ppm (EtOH) and

0.02ppm (Isobutylene) compared to other typology means of 1ppm and 0.1ppm. Such differences could be due to building and construction materials used such as plaster/fibre boards, adhesives, wood-based panels and insulation (Weigl, et al., 2014) which have less VOCs than other construction materials.

At an individual level, nine out of 42 dwellings (21%) experienced higher than typical VOC concentrations. Dwelling TR13 experienced the highest mean EtOH and Isobutylene concentrations of 4.8ppm and 0.5ppm, this dwelling was undergoing extensive internal redecoration and painting, which is a common source of VOCs (The Air Quality Expert Group, 2022). Dwelling S10 also experienced concentrations of 4ppm for EtOH and 0.5ppm for Isobutylene due to constant use of plug-in air fresheners.

Table 4

Descriptive statistics for $PM_{2.5}$, PM_{10}, EtOH and Isobutylene at sample level

IAQ parameter	Min	Max	Mean
$PM_{2.5}$ (ug/m³)	0	2,125	31.8
PM_{10} (ug/m³)	0	2,592	37.1
EtOH (ppm)	0	10	0.9
Isobutylene (ppm)	0	1	0.1

3.5 Cross relating IAQ parameters

The relationship between different IAQ parameters has been calculated using Pearson's Correlation Coefficient and presented in table 5. Unsurprisingly $PM_{2.5}$ and PM_{10} had a strong positive correlation, similar to that of EtOH and Isobutylene which had a correlation coefficient of 0.99. In fact, all correlations were found to be greater than 0.95 indicating that if one IAQ parameter was high, it was likely that other IAQ parameters were also having a similar trend.

At the typology level, there were notable differences. While the Pearson Coefficient between CO_2, PM_{10} and EtOH for dwelling types TR, S and T remained >0.8, in dwelling type B, a weak correlation (-0.21 to 0.23) was observed. This typology was occupied continually by retired residents leading to rise in CO_2 but often corresponded to low levels of activity resulting in lower PM_{10} and EtOH levels.

Indoor CO_2 concentration which indicate ventilation levels, is often used as proxy for IAQ. The relationship between CO_2, PMs and VOCs is under researched. Figure 3 presents the relationship between diurnal CO_2 and PM_{10} and EtOH levels across the sample. Similarities in profiles of CO_2 - PM_{10} and CO_2-EtOH were observed with strong positive correlations with some inconsistencies at the lower end due to differing occupant behaviours/activities.

Table 5

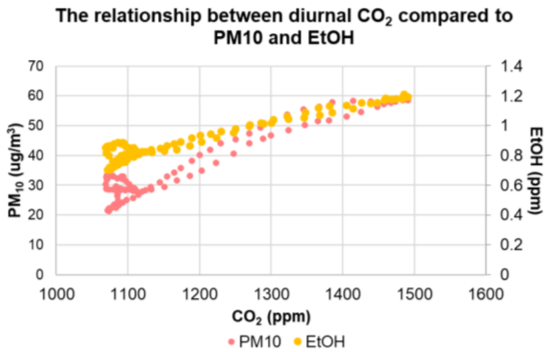
Pearson's Correlation Coefficient between CO_2, PM_{10} and EtOH at sample level.

	CO_2	$PM_{2.5}$	PM_{10}	EtOH	Isobut-ylene
CO_2	1	0.96	0.96	0.96	0.95
$PM_{2.5}$	0.96	1	1	0.98	0.98
PM_{10}	0.96	1	1	0.98	0.98
EtOH	0.96	0.98	0.98	1	0.99
Isobu-tylene	0.95	0.98	0.98	0.99	1

Levels of CO_2, in figure 3, correlate well with human occupancy, because of this, the trends suggests PM_{10} and EtOH are also related with occupant activities including cooking, tobacco smoking, aerosols, candle burning, fragrances and use of domestic cleaning products. Overall the strong correlation of CO_2 with other parameters confirmed that inadequate ventilation can lead to rise in multiple indoor pollutants that can be largely discovered through indoor CO_2 measurement in domestic environments.

Figure 3

Relationship between diurnal CO_2, to PM_{10} and EtOH



4. Discussion

The detailed longitudinal assessment of IAQ parameters in a sample of UK social housing dwellings over three heating season months revealed overall poor levels of IAQ with potential health implications for occupants. Under heating was found to be commonplace with eight out of 42 dwellings (19%) failing to meet the recommended minimum mean indoor temperature of 18°C. Three of these eight (7% overall) recorded temperatures <18°C for >85% of the time. Prolonged exposure to below recommended temperatures can exacerbate chronic illness including respiratory and cardiovascular issues, a particular concern in young children, many of whom occupy dwellings in this study. Six out of 42 dwellings (14%) experienced indoor temperatures below 10°C which can lead to a drop in the body's core temperatures and be life threatening. The main causes of under heating were rising cost of heating, buildings poor ability to retain heat due to inadequate level of insulation combined with ineffective heating systems. Since the fieldwork was undertaken before the 2022 'cost of living crisis' in the UK which led to 196% increase in gas and 107% increase in electricity prices (Bolton & Stewart, 2022), under heating would further exacerbate in these dwellings leading to serious health outcomes.

Due to under heating and poor levels of ventilation, there was widespread prevalence of mould across 60% of dwellings (26 out of 42). In one of these, residents' respiratory health had deteriorated with mould growing over furnishings, despite frequent cleaning. Occupancy of dwellings was found to strongly correlate with increase in indoor CO_2 levels. As a result, retired or unemployed residents experienced higher CO_2 levels (CO_2 levels > 3,000ppm in some dwellings) due to extended occupancy confounded by inadequate ventilation resulting from limited window opening, closing of trickle vents and covering of wall grilles to conserve heat.

Such indoor conditions make a strong case for deploying whole-house energy efficient retrofit measures in these dwellings that minimise unwanted heat losses and dramatically improve airtightness, while providing continuous background ventilation. The building fabric (walls, roof, floor, windows) needs to be thermally upgraded with improved levels of insulation (external wall insulation, loft insulation, high-performance triple glazed windows with trickle vents, suspended floor insulation), along with a more efficient heating system and controls. To ensure adequate levels of ventilation for good IAQ, in line with PAS 2035:2019 (BSI, 2019), mechanical ventilation with heat recovery (MVHR) should be installed to provide continuous fresh air and removal of stale, damp air.

High levels of PM were related with occupant activities and limited indoor-outdoor exchange of air. Indoor smoking was prevalent in 15 dwellings which experienced higher than recommended $PM_{2.5}$ and PM_{10} levels. In one dwelling, mean concentration of PM_{10} reached 248ug/m^3 which was 203ug/m^3 over the WHO limit (2021). It was concerning that although 54% of dwellings used gas for cooking, only 12% had extractor fans in kitchens. Since most of these dwellings had separate kitchens, the monitoring devices in the living rooms may not have detected the full magnitude of PM levels. This reinforces the need for installing mechanical extraction in kitchens with boost functionality.

Although indoor VOCs stayed relatively low in most of the dwellings, concentrations of VOCs were found to be high in a dwelling undergoing decorating and dwellings with constant use of air fresheners and scented candles. This indicates the need for social housing provides to raise awareness and educate residents about the relationship between their personal activities, IAQ and health. Guidance is required on increasing ventilation while using scented candles, air fresheners and cleaning products. Use of low emitting materials when replacing furniture or flooring should be encouraged.

The link between IAQ and occupant activities also reinforces the need for examining more precisely the timing of occupant activities in relation to indoor pollutants. Time-of-use surveys and diaries can be used at least for a sample of dwellings, alongside surveys and researcher observations.

5. Conclusion

This paper has empirically examined the concentrations and trends in indoor temperature, RH, CO_2, $PM_{2.5}$, PM_{10}, EtOH and Isobutylene across a sample of 42 existing social housing dwellings located in West Midlands (UK). Statistical analysis revealed under heating to be widespread with 19%, or eight out of 42 dwellings failing to reach the recommended mean indoor temperature of 18°C due to poor insulation and high heating costs. Mould was present in 61% of dwellings (26 out of 42) despite mean RH values remaining below 65%. CO_2 concentrations were related to occupancy, with mean values frequently above 900ppm and as high as 3,092ppm in some dwellings, due to limited ventilation to conserve heat. High PM levels were generally associated with indoor smoking, with $PM_{2.5}$ concentration rising to 202ug/m^3, substantially above the 15ug/m^3 limit. VOCs remained low, yet indoor painting and air fresheners provided the greatest increases.

The poor levels of IAQ in these dwellings can been used to inform the anticipated whole house energy retrofits that should be designed to reduce unwanted heat loses, improve air-tightness and provide continuous background ventilation for removal of indoor pollutants. The monitoring of IAQ is expected to continue post-retrofit to identify any unintended consequences on IAQ or occupant health.

Since the study has revealed the poor state of IAQ in a sample of social housing dwellings with vulnerable occupants and those on low income, it is vital that such a study is expanded to the wider housing stock (including private housing) before large-scale retrofit programmes are planned and implemented. Findings from a nationwide IAQ monitoring programme can inform the selection of retrofit measures and public engagement on the link between personal activities, IAQ and health. Without such a programme, occupants of social housing that often have vulnerable groups and those on low income, may continue to be exposed to higher indoor air pollution and adverse health impacts.

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