Indoor Air Quality and Health in Social Housing

Abstract

Purpose

This study investigates the interplay between Indoor/Outdoor Air Quality (IAQ/OAQ), occupant behaviour, and building Air Permeability (AP) aiming to identify the key Indoor Air Pollutants (IAPs) and develop effective mitigation strategies to simultaneously address energy efficiency, IAQ, and occupant health in social housing.

Design/methodology/approach

A mixed-method approach was applied across social housing case study dwellings in the London Borough of Newham. Physical monitoring of PM_{10}, $PM_{2.5}$, CO, CO_2, TVOCs, temperature, and humidity was conducted using data loggers in three phases of: a) baseline conditions; b) air purifier intervention; and c) behavioural interventions. CONTAM multizone modelling was adopted to assess indoor/outdoor air pollutant correlations and dispersion at four AP levels (1, 5, 10, and 15 $m^3/m^2 \cdot h$@50Pa), while occupant behaviour and behavioural interventions were assessed through questionnaire surveys.

Key Findings

Daily average pollutant levels, particularly for CO and TVOCs, significantly exceeded the WHO and CIBSE guidelines (by up to 16 and 57 times, respectively), largely driven by occupant activities. Air purifiers reduced PMs however had limited impact on other air pollutants. Behavioural interventions showed limited effectiveness, with improvements not sustained over time. Higher AP generally increased concentration of IAPs, while outdoor pollutants such as $PM_{2.5}$ and NO_2 showed limited sensitivity to AP levels. CO_2 concentration levels were found to be less reliable as an indicator of the overall air quality in residential buildings. A combination of technical and behavioural interventions should be considered to simultaneously improve IAQ and public health.

Practical implications

The findings emphasise the need for integrated IAQ strategies in the context of retrofit and social housing, combining ventilation, air filtration, and occupant engagement. Housing providers should prioritise ventilation strategies while retrofit programmes should mandate effective natural/mechanical ventilation whenever significant airtightness improvements are planned. Improving occupant awareness and behaviour along with development of technological interventions, such as smart ventilation systems and VOC-targeted monitoring and controlling technologies, are essential to improve public health. The findings suggest that poor IAQ may poses much higher risk to health than outdoor air. The governmental policies should therefore shift attention towards IAQ by developing practical guidelines on ventilation rates and limiting harmful indoor air pollutants from household materials as well as on the effects of retrofit and their implications on IAQ and health.

Originality/value

This research provides a comprehensive real-world assessment of IAQ in social housing by integrating empirical monitoring, behavioural analysis, and simulation modelling within a unified framework. It contributes to the understanding of how socio-technical interactions between occupants and building systems influence IAQ and offers actionable insights for improving health outcomes in vulnerable residential environments.

Keywords: Indoor Air Quality; Outdoor Air Quality; Air Pollutants; Public Health; Retrofit; Social Housing.

Nomenclature

The following terms are used throughout this paper. Definitions are provided to assist readers from interdisciplinary backgrounds and to contextualise the specific values and concepts discussed in the methodology, results, and conclusions.

Air Permeability (AP): The measure of the airtightness of the building fabric, defined as the air leakage rate per hour per square metre of envelope area at a reference pressure differential of 50 Pa, expressed in units of $m^3/m^2.h@50Pa$. Three sub-types are distinguished: (i) the limiting air permeability, which is the worst allowable value permitted under building regulations; (ii) the design air permeability, which is the target value set at the design stage; and (iii) the assessed air permeability, which is derived from physical measurement and used to establish the Building Emission Rate and Building Primary Energy Rate. In this study, AP values of 1, 5, 10, and 15 $m^3/m^2.h@50Pa$ are simulated to represent a range from highly airtight to relatively leaky building envelopes (HM Government, 2021).

Behavioural/Technical Intervention: In the context of indoor air quality management, a behavioural intervention refers to any structured, non-engineering measure designed to modify occupant practices that contribute to indoor pollutant generation. Such interventions typically include targeted education, provision of guidance materials, and occupant-specific advice aimed at reducing activities such as indoor smoking, use of VOC-emitting products (e.g., air fresheners, cleaning agents), and cooking without adequate ventilation. Behavioural interventions are distinguished from technological interventions (e.g., air purifiers, mechanical ventilation) in that their effectiveness depends on sustained occupant compliance rather than passive or automated operation (Franchi *et al.*, 2006).

Immediately Dangerous to Life or Health (IDLH): A threshold concentration of an airborne substance defined by the US National Institute for Occupational Safety and Health (NIOSH) as the level that poses a threat of death, irreversible health effects, or impaired ability to escape from an exposure environment. IDLH values are not exposure limits or safe levels; they represent the upper ceiling above which only the most reliable respiratory protection is acceptable. In this study, IDLH values for CO (1,200 ppm) and CO_2 (40,000 ppm) are used as reference points against which peak indoor concentrations are assessed (NIOSH, 2014a; NIOSH, 2014b).

Short-Term Exposure Limit (STEL): A time-weighted average concentration to which a person can be exposed for a continuous period of up to 15 minutes without experiencing adverse health effects, provided that the long-term daily exposure limit is not exceeded. In the UK, STELs are published by the Health and Safety Executive (HSE) in EH40/2005 Workplace Exposure Limits and apply to hazardous substances in occupational settings. In this study, STELs for CO (100 ppm) and CO_2 (15,000 ppm) are used as short-term reference thresholds to assess acute exposure risks within the case study dwellings (Health and Safety Executive, 2020).

1. Introduction

Indoor air pollution is responsible for 3.8 million deaths per year (WHO, 2023) and 64% of premature deaths are linked to overall air pollution exposure (Maciejewska *et al.*, 2024). In the UK, air pollution has been identified as the greatest environmental risk to public health (Smith, 2025). The UK also has one of the highest death rates from respiratory conditions in Europe, accounting for nearly 20% of all fatalities (British Lung Foundation, n.d.). These diseases come with a significant economic burden, costing more than £11 billion each year due to ill health and decreased productivity (Public Health England, 2019). It is therefore imperative to identify the primary sources and levels of pollutants and develop strategies to improve Indoor Air Quality (IAQ) (Tran *et al.*, 2020).

Poor IAQ has been linked to building-associated illnesses, negatively impacting human health (Hromadka *et al.*, 2017) and a decline in work performance (Laumbach and Kipen, 2005). Both short- and long-term exposure to Indoor Air Pollutants (IAPs) can result in a wide range of diseases (Koivisto *et al.*, 2019). As people spend around 80% of their time indoors (European Commission: Joint Research Centre *et al.*, 2017), exposure to even low amounts of IAPs could negatively affect their health in the long term. Yet, the indoor environment is often neglected in discussions concerning environmental equity and justice (Adamkiewicz *et al.*, 2011). Additionally, although outdoor ambient air concentrations provide a general estimate of personal exposure, it is largely influenced by an individual's time-activity patterns, including the amount of time spent indoors (Ashmore and Dimitroulopoulou, 2009). Relying solely on the outdoor air data can therefore result in the misclassification of exposure (Zipprich *et al.*, 2002; Delgado-Saborit, 2012).

The assessment of IAQ and its implications for occupant health aligns with broader frameworks used to evaluate air quality impacts at a policy level. The UK Government's "Air Quality Appraisal: Damage Cost Guidance" emphasises that air pollutants, particularly $PM_{2.5}$ and NO_2, contribute significantly to the national mortality burden, equivalent to 29,000–43,000 deaths annually (Department for Environment, Food & Rural Affairs, 2023). The guidance highlights methodologies, such as damage costs and impact pathways, to quantify the societal impacts of pollutants. It also identifies key pollutants, including Sulphur dioxide (SO_2), Volatile organic compounds (VOCs), and Ammonia (NH_3), whose emissions have far-reaching effects on human health and the environment (Department for Environment, Food & Rural Affairs, 2023). By applying damage cost analyses, which assign monetary values to emissions per tonne, policymakers can better estimate the economic and health implications of air quality interventions (Department for Environment, Food & Rural Affairs, 2023).

Buildings play a key role in altering exposure to pollutants from both indoor and outdoor sources (Taylor *et al*., 2014). Pollution from outdoor sources can enter indoors through infiltration from human activities, such as vehicle traffic, which is a primary source of particulate matter (PM) and nitrogen dioxide (NO_2) (Harrison, 2018), or from natural sources like radon, which emanates from the decay of radioactive materials in the ground (Turk *et al*., 1990). The airtightness of a building, along with its number of external walls, wind exposure, and occupant window-opening habits, plays a key role in determining the infiltration of outdoor pollutants (Hänninen *et al*., 2004). Additionally, the presence of ventilation systems, both mechanical and natural, as well as the building's layout, further influence how outdoor pollutants enter the indoor environment. These factors can vary significantly across different socio-economic groups, affecting overall exposure levels (Taylor *et al*., 2014). In buildings with mechanical ventilation, pollutants may also enter actively through these systems, with the infiltration rate depending on the ventilation rate and whether filtration systems are in place. Once indoor, pollutants may undergo chemical transformations on various surfaces. For example, nitrogen dioxide (NO_2) reacting with indoor materials can produce nitrous acid (HONO), a harmful pollutant with known adverse health effects (Gligorovski, 2016; Ma *et al*., 2017). The dwelling's ventilation rate (whether passive or active), internal deposition, and air filtration systems all function as sinks for indoor pollution, helping to reduce pollutant levels. A year-long monitoring study across 124 UK homes found indoor TVOC concentrations ranging from 100 to over 8,000 µg/m³, with winter months producing higher accumulation due to reduced air change rates, reinforcing the particular vulnerability of occupants in poorly ventilated dwellings during cold seasons (Warburton *et al*., 2025).

IAQ is also heavily influenced by occupancy patterns, occupant behaviour, and ambient conditions. Typical actions in communal dwellings, such as using specific household items, cooking without enough ventilation, and smoking indoors, can release pollutants into the air (Zhou *et al*., 2022). Such activities further expose occupants to a variety of hazardous substances, reducing IAQ. A lack of awareness regarding the implications of these activities can exacerbate the problem. As reported by Mannan and Al-Ghamdi, smoking inside emits hazardous compounds that persist and damage the health of individuals who reside there, and not just smoking but even lighting items such as candles or burning incense or fume-generating products contribute to poor IAQ (Mannan and Al-Ghamdi, 2021). Besides obvious factors like smoking and cooking, certain other factors might have an impact on IAQ. Cleaning habits and poor ventilation have also been important factors in degrading IAQ. Several cleaning products, highly fragranced products, and air fresheners all add to indoor pollution. When occupants choose these devices without sufficient ventilation, they unintentionally introduce harmful pollutants into the indoor environment. Another essential component of IAQ is moisture management. It has been observed that certain behaviours such as drying clothes inside increases the humidity within, especially without ventilation or less ventilation which consequently fosters the formation of mould (Zhao *et al*., 2021). Indoor overcrowding can worsen IAQ difficulties by causing an increase in carbon dioxide levels (Semple *et al*., 2012). Recent research has increasingly adopted occupant-centric perspectives in assessing indoor environmental quality, recognising the critical role of user interactions with building systems in shaping indoor conditions (Wani *et al*., 2026). Improving IAQ in residential buildings calls for an integrated strategy that tackles both pollution sources and ventilation systems (Mendell *et al*., 2013). Effective source control measures involve minimising the use of polluting items, ensuring proper maintenance of combustion equipment, and implementing moisture control strategies (World Health Organization, 2021).

Numerous studies have examined the effects of air purifiers and ventilation strategies on IAQ in residential settings. Air purifiers with HEPA filters have been found to significantly reduce particulate matter concentrations, including $PM_{2.5}$ and PM_{10} (Sultan *et al*., 2011). However, their ability to remove gaseous pollutants like VOCs and CO is often limited, necessitating additional strategies such as source control and ventilation (Du *et al*., 2015). Emerging research has also explored sustainable material-based solutions for improving IAQ, demonstrating the potential of adsorbent materials integrated within building systems to effectively reduce indoor pollutants, particularly VOCs (Jung *et al*., 2025). Ventilation approaches, including natural ventilation through windows and mechanical ventilation systems, have been extensively studied for their role in diluting and eliminating indoor pollutants (Guo *et al*., 2004; Persily, 2016). While natural ventilation can be an effective and energy-efficient solution, its performance depends on factors like outdoor air quality, weather conditions, and building design (Dimitroulopoulou, 2012; Chenari *et al*., 2016). Beyond engineering controls, behavioural interventions and occupant education are also essential for effective IAQ management (Franchi *et al*., 2006; Whitehouse and Grigg, 2021).

In modern buildings, thermal comfort is closely linked to IAQ, which, in turn, is influenced by the building's airtightness when no active ventilation systems are in place (Fernández-Agüera *et al*., 2019). This relationship is particularly significant in lower-standard constructions, such as social housing in southern Europe, typically associated with lower-income households (Fernández-Agüera *et al*., 2019). At the core of IAQ lies the concept of Air Permeability (AP), which refers to the ease with which air can move through a building's outer shell, exerting significant influences on the indoor air environment (Tochihara and Ohnaka, 2005). This interaction between AP and IAQ is multifaceted, with permeability levels controlling the entry of outdoor pollutants and the dispersal of indoor emissions, thereby shaping the complex makeup of indoor air composition (Fisk and Rosenfeld, 2000).

In social housing units, often characterised by ageing infrastructure and inadequate maintenance, lower AP aggravates IAQ issues, increasing residents' exposure to indoor pollutants and associated health risks (Diaz Lozano Patino and Siegel, 2018). According to Adamkiewicz *et al*. (2011), the uneven distribution of AP within buildings creates disparities in pollutant concentrations, further complicating the IAQ and potentially increasing health differences among occupants. Sealing gaps in a home or improving its airtightness is a common method to lower energy usage and enhance winter thermal comfort. However, maintaining good air quality requires a certain amount of fresh air circulation, and there are concerns that increasing airtightness could unintentionally lead to a decline in IAQ (Kempton *et al*., 2022a). According to Howieson *et al*. (2013), reducing ventilation rates to boost energy efficiency and reduce carbon emissions, without implementing a well-planned and effective ventilation strategy, is likely to create a more harmful indoor environment and can lead to serious, long-term negative effects on public health that may not be immediately apparent. Recent evidence from social housing in London has further confirmed that while energy-efficient retrofits can reduce energy consumption by up to 60%, they can simultaneously introduce risks of elevated indoor pollutant concentrations where increased airtightness is not paired with adequate ventilation upgrades, with occupant behaviour compounding these risks further (Hashemi and Dungrani, 2025). Wal *et al*. (1991) proposed that increasing the airtightness of homes leads to higher concentrations of indoor air pollutants. Similarly, large-scale monitoring of 169 energy-efficient dwellings in Switzerland found that interior thermal retrofitting without mechanical ventilation was associated with significantly elevated formaldehyde and TVOC levels, with half of all dwellings exceeding chronic TVOC exposure limits (Yang *et al*., 2020). This view is reinforced by the Building Research Establishment (British Electrotechnical and Allied Manufacturers Association, 2006), which states that as homes become more airtight, indoor pollutant sources can more significantly affect IAQ, potentially causing negative health effects if ventilation is not properly maintained (McGill *et al*., 2015).

Increased building envelope airtightness has been associated with a decline in IAQ if adequate ventilation is not implemented (Kukadia and Upton, 2019; Dimitroulopoulou *et al*., 2005; McKay *et al*., 2010). For buildings with high airtightness, mechanical ventilation is typically necessary, and it is incorporated into certain building standards (e.g., (HM Government, 2010; ASHRAE, 2019a)). However, Crawley *et al*. (2018) noted that the relationship between ventilation and airtightness is not sufficiently addressed in current standards. Additionally, the complexity of whole-house mechanical ventilation systems can lead to design or operational issues (Less *et al*., 2015). Increased airtightness in buildings, while beneficial for energy efficiency, may have complex implications for IAQ. A rapid review by Kempton *et al*. (2022b) identified 20 studies exploring the impact of airtightness on various IAQ parameters, including CO_2, $PM_{2.5}$, VOCs, formaldehyde, NO_2, and mould growth. The review highlighted the lack of consistent measurement units and methodologies, making it difficult to draw reliable correlations between airtightness and IAQ. While some studies reported a negative correlation between airtightness and CO_2 levels, as well as VOCs and formaldehyde, the overall evidence remained limited and inconsistent. Interestingly, increased airtightness was found to reduce the infiltration of outdoor pollutants like PM2.5 and NO_2 in areas with high outdoor pollution. However, the relationship between airtightness and mould growth was more complex, with some studies showing a negative correlation with relative humidity but a positive correlation with actual mould presence. These findings underscore the need for standardised measurement approaches and further studies to better understand the interplay between airtightness and IAQ in diverse building contexts (Kempton *et al*., 2022b). Understanding the nuanced interactions between AP, pollutant infiltration, and IAQ parameters becomes extremely important in formulating effective mitigation strategies and safeguarding public health (Persily, 2016). To this end, this study aims to address the complex relationship between IAQ, building design, and occupant behaviour in social housing settings. This research seeks to identify effective strategies for mitigating poor IAQ while maintaining energy-efficient building practices. Intermediate findings on other relevant issues including thermal comfort, energy efficiency, and IAQ, have previously been published in other papers (Narayanan *et al*., 2024a; Narayanan *et al*., 2024b; Basaly *et al*., 2025; Basaly *et al*., 2024).

2. Methodology

This study employs a mixed-method approach, including physical measurements using data loggers, questionnaire surveys, and modelling using the CONTAM software explained below.

2.1 Physical Measurements Using Data Loggers

The study focuses on measuring key pollutants including Particulate Matter (PM_{10} and $PM_{2.5}$), Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Total Volatile Organic Compounds (TVOCs), (using DL-1038, Figure 1. a) along with assessing temperature and humidity levels (using HOBO MX1102A, Figure 1. b) across seven Case Study Buildings (CSBs) out of 10 originally selected CSBs based on the funded project requirements (3 participants removed consent during the study hence were not included). For a period of 37 days (27th of November- 2nd of January), data loggers were placed in the living rooms and recorded measurements at 15-minute intervals. The daily average concentrations of each pollutant were analysed to evaluate IAQ and understand the influence of resident behaviour on pollutant levels. In two CSBs (Flat 4 and Flat 5), the occupants unplugged the Data Loggers during the final days of the measurements; hence, no data was recorded for this period.

Figure 1: a) DL-1038 (left); b) HOBO MX1102A CO2 (right) data logger.

Table 1 summarises the guidelines for CO (World Health Organization, 2021), CO_2 (ASHRAE, 2019b), TVOCs (CIBSE TM40, 2020; Institute of Air Quality Management, 2020), PMs (World Health Organization, 2021), Relative humidity (CIBSE, 2021) and Temperature (CIBSE, 2021). As stated in Arc's Guide to Re-entry v1.1 (Pyke, 2020), μg/m³ can be converted to ppb using a factor of 3.767, resulting in an approximate value of 80 ppb, which is used as the guideline value for assessing TVOCs. In addition to the standard 8-hour and 24-hour IAQ guideline values, short-term (15-minute) exposure limits for CO, CO_2, and TVOC were also included in the study. For CO and CO_2, the 15-minute limits are adopted from the UK's EH40/2005 Workplace Exposure Limits (WEL) (Health and Safety Executive, 2020), which provides Short-Term Exposure Limits (STEL) to protect against health risks from brief, high-level exposures. For TVOCs, a 15-minute limit of 1500 μg/m³ is estimated using a commonly accepted multiplier approach in occupational and industrial hygiene literature, where short-term limits are typically calculated as 2 to 5 times the 8-hour Time-Weighted Average (TWA) (American Conference of Governmental Industrial Hygienists, 2022). Since Chartered Institution of Building Services Engineers (CIBSE) and Building Research Establishment Environmental Assessment Method (BREEAM) recommends an 8-hour TVOC guideline of 300 μg/m³ for post-construction, pre-occupancy assessments, a multiplier of 5 was conservatively applied to derive the 15-minute limit of 1500 μg/m³ included in this table. The table also includes the IDLH (Immediately Dangerous to Life or Health) values for CO (NIOSH, 2014a) and CO_2 (NIOSH, 2014b).

Table 1: IAQ guidelines and standards (Narayanan *et al*., 2024a; Narayanan *et al*., 2024b)

Pollutant	**Guideline Value**		**IDLH**
CO	6 ppm (24 hr average)	100 ppm (15 minutes)	1200 ppm
CO_2	1000 ppm	15000 ppm (15 minutes)	40000 ppm
TVOCs	300 μg/m³ (8 hr average)	1500 μg/m³ (15 minutes)	
$PM_{2.5}$	15 μg/m³ (24 hr average)	-	
PM_{10}	45 μg/m³ (24 hr average)	-	
Relative Humidity	40-70%	-	
Temperature (Winter) – Living Areas	22-23°C	-	

2.2 Occupant Behaviour and Air Filtration

The study was divided into three phases: monitoring the pollutant levels during 1) the pre-intervention phase (current conditions; monitored for 37 days); 2) during air purifier installation (monitored for 12 days); and 3) after the behavioural interventions (monitored for 31 days). In the second phase, air purifiers (Healthy Air 500, Figure 2) were installed in the living rooms and were set to automatically adjust their speed based on the air quality in the buildings. According to the technical data sheet of the air purifier, it can remove PM2.5, TVOCs, NOx, SOx, ozone, bacteria, viruses, allergens, dust, pollen, odours, and smoke. In the third phase, tailored behavioural interventions were implemented and developed based on Phase 1's observations and the results of a questionnaire survey. The survey assessed the occupant behaviour, which was used to categorise key behavioural patterns such as ventilation practices, cooking frequency, and use of mechanical systems, and these classifications were subsequently used to inform the design of behavioural interventions and to support comparison with measured IAQ trends across the monitoring phases. Hourly average readings of each pollutant were analysed in all three phases to assess IAQ. For a more accurate comparison regarding the effectiveness of different interventions, only 12 days of the collected data (the period during which the air filtration was installed) have been presented.

Figure 2: Air Purifier (Healthy Air 500).

2.3 Modelling

CONTAM software was utilised to model the dispersion and concentration of pollutants for various AP rates. CONTAM is a software tool for multizone IAQ and ventilation analysis, created by the National Institute of Standards and Technology (NIST) (National Institute of Standards and Technology, 2021). It is designed to simulate airflow, contaminant transport, and IAQ within buildings. A detailed model of one of the CSBs, which exhibited the worst-case scenario with the highest measured concentrations of pollutants (according to the monitoring/physical measurements) was developed. The simulations were conducted for the following scenarios:

1. Building retrofit with insulation materials.
2. Occupant Behaviour: CO and TVOC generated from other indoor sources (e.g. cleaning, burning materials, cooking).
3. Correlations between Outdoor/Indoor NO_2 concentration levels.

The first scenario was to assess the effects of TVOCs generated from cavity walls and loft insulation on IAQ for different AP rates. Phenolic Foam (PF-2: 33.7 kg/m³) with a TVOC generation rate of 0.17 mg/h was considered as the input for the generated TVOCs from insulation materials (Narayanan *et al.*, 2024a). The simulations were carried out for three months (January-March). This was due to the fact that the TVOC emissions showed a gradual increase to approximately 1900 μg/m³ until day 14, followed by a decrease to approximately 1500 μg/m³, and persisted above the safe level throughout a 3-month period (Wi *et al.*, 2021). The CONTAM model for the source in the cavity is shown in Figure 3. a. In the second scenario, simulations were carried out for different AP values of 1, 5, 10, and 15 m³/m².h@50Pa for TVOC and CO to assess the impacts on IAQ. The scheduling for indoor TVOC and CO generations was based on the actual data collected from the CSB. The hourly average values of the worst day when TVOC and CO concentrations were at their peak were considered as the input for the simulations. The CONTAM model for the source indoor is shown in Figure 3. b.

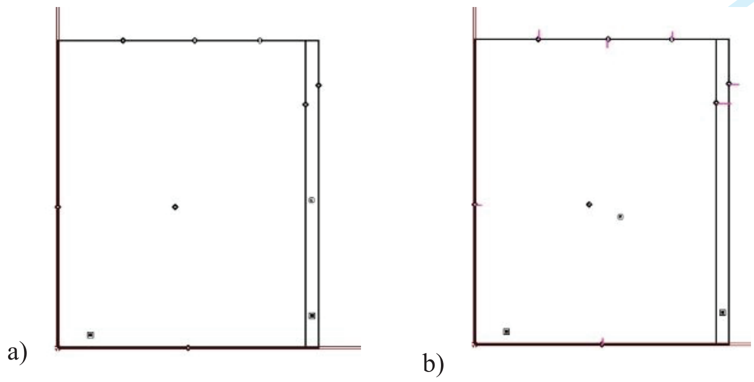


Figure 3: a) CONTAM model with pollutant source in the cavity. b) CONTAM model with pollutant source indoors

In the third scenario, the correlations between indoor/outdoor air quality at different APs were assessed. The annual outdoor NO_2 levels were collected from the closest air quality monitoring station provided by the London Borough of Newham Council. The simulations were conducted for both the entire year as well as for a zoomed-in scenario for a single day. Table 2 provides a detailed overview of the daily scheduled values/inputs for the CONTAM model. In all cases, it was assumed that windows were closed during the simulation periods. This assumption reflects the real-world conditions observed during the study. Data collection was conducted during winter, when windows are typically kept closed in the UK, and this was corroborated by the questionnaire surveys in which occupants confirmed that they keep their windows closed throughout the winter months. Furthermore, as the primary focus of the simulations was to isolate and assess the effects of building airtightness on indoor pollutant concentrations, maintaining closed windows across all scenarios ensured that infiltration through the building fabric remained the sole pathway for air exchange, enabling a consistent and controlled comparison across the four AP levels.

Table 2: Daily scheduled values for TVOC and CO inputs in the model.

Day schedule	TVOC (ppb)	CO (ppm)
01:00:00	0	0.01
02:00:00	0.003	0.01
03:00:00	0.007	0.01
04:00:00	0.014	0.01
05:00:00	0.014	0.01
06:00:00	0.014	0.1
07:00:00	0.013	1
08:00:00	0.013	0.8
09:00:00	0.012	0.5
10:00:00	0.012	0.3
11:00:00	0.014	0.2
12:00:00	0.03	0.1
13:00:00	0.03	0.007
14:00:00	0.03	0.005
15:00:00	0.03	0.04
16:00:00	0.1	0.03
17:00:00	0.1	0.02
18:00:00	0.2	0.02
19:00:00	1	0.02
20:00:00	0.997	0.6
21:00:00	0.3	0.9
22:00:00	0.2	0.4
23:00:00	0.3	0.2
24:00:00	0.2	1

2.4 Case Study Buildings

The CSBs, shown in Figure 4, were built in the 1950s and 1960s and feature cavity walls and double-glazed windows. These buildings are situated in an urban area within the London Borough of Newham. The residents included pregnant women, the elderly, and young individuals. Their activities included smoking (vaping), burning candles or incense, and using air fresheners and household cleaning products. Regarding occupancy, most of the flats were consistently inhabited, with the exception of one, which was occasionally occupied. The occupancy details are as follows: two flats (Flat 1 and 2) housed 2 occupants each, three flats (Flat 3, 4, and 7) were single-occupancy, one flat (Flat 5) had 3 occupants, and one flat (Flat 6) had 4 occupants. The buildings consisted of 1- and 2-bedroom apartments, primarily located on the top and middle floors with a North-South orientation, except for Flat 3, which was situated underground and faced East-West. All buildings were equipped with central gas heating systems and mechanical ventilation units designed to enhance ventilation. However, these systems were not utilised by the occupants due to reasons such as noise and cold drafts.

Figure 4: External view of the CSBs (a, b), Floor plan of one of the CSBs (c).

3. Results and findings

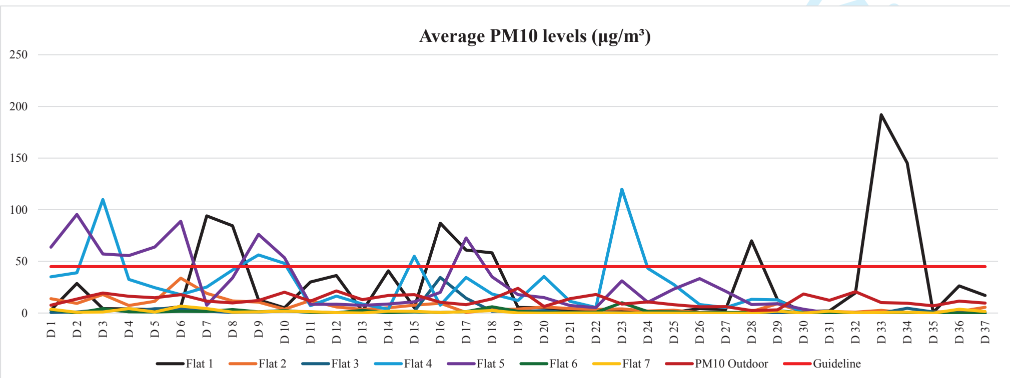
This section presents a detailed analysis of the IAPs and their levels across the CSBs. The current conditions, impacts of occupant behaviour, and air filtration on IAQ as well as AP, retrofit, and correlations between indoor/outdoor air quality are discussed.

3.1 Pollutant levels and their distribution

This section evaluates the current IAQ scenario in the CSBs by analysing pollutant levels and their variability to understand their distribution patterns.

3.1.1 Particulate Matter (PM_{10} and $PM_{2.5}$)

PM concentrations exhibited substantial variability across the CSBs. PM_{10} levels (Figure 5.a), which should not exceed the WHO guideline of 45 µg/m³, remained consistently below this threshold in some of the buildings. However, certain flats, particularly Flat 1, frequently recorded PM_{10} concentrations exceeding this limit. Flat 1, for example, reached PM_{10} levels as high as 60 µg/m³, particularly during periods of high occupant activity, such as cooking and heating in the absence of adequate ventilation. In contrast, other flats, including Flats 3, 6, and 7, maintained PM_{10} levels consistently below the guideline, suggesting that these buildings had better air circulation and fewer indoor sources of particulate matter. In terms of $PM_{2.5}$ concentrations (Figure 6. a), the situation was more stable, with none of the flats exceeding the WHO guideline of 15 µg/m³. While some flats, such as Flat 1, Flat 4 and Flat 7, occasionally recorded slightly elevated $PM_{2.5}$ levels on specific days, these readings stayed well within the acceptable range and did not surpass the specified limits. Upon analysing the outdoor PM_{10} and $PM_{2.5}$ concentrations and comparing them with indoor levels, no significant correlation was observed in the case of PM_{10}, whereas a noticeable correlation was found for $PM_{2.5}$. The outdoor PM_{10} levels were significantly lower than the indoor levels, whereas in the case of $PM_{2.5}$ the outdoor levels were higher than the levels indoors. Figure 5.b and Figure 6.b show the absolute readings of PM_{10} and $PM_{2.5}$, respectively. Some of the sudden spikes in PM_{10} levels in Flat 1 and Flat 4 were removed from the graph showing absolute levels for better consistency of the data. Peak PM_{10} readings in the most affected dwelling (Flat1, 5 and 4) exceeded the WHO 24-hour guideline of 45 µg/m³ by 33%, while most other dwellings remained well below the threshold throughout the monitoring period.



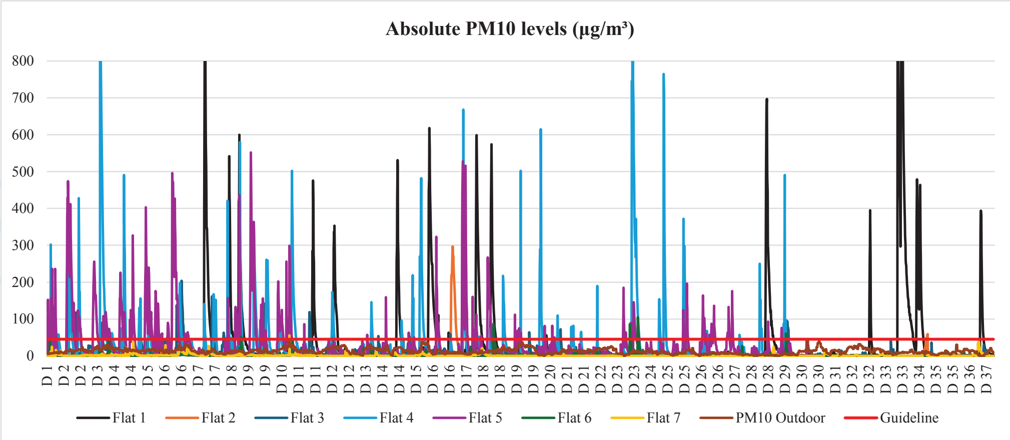


Figure 5: a) Daily average readings of PM_{10} levels (top); b) Absolute readings of PM_{10} levels (bottom) (15 minutes intervals).

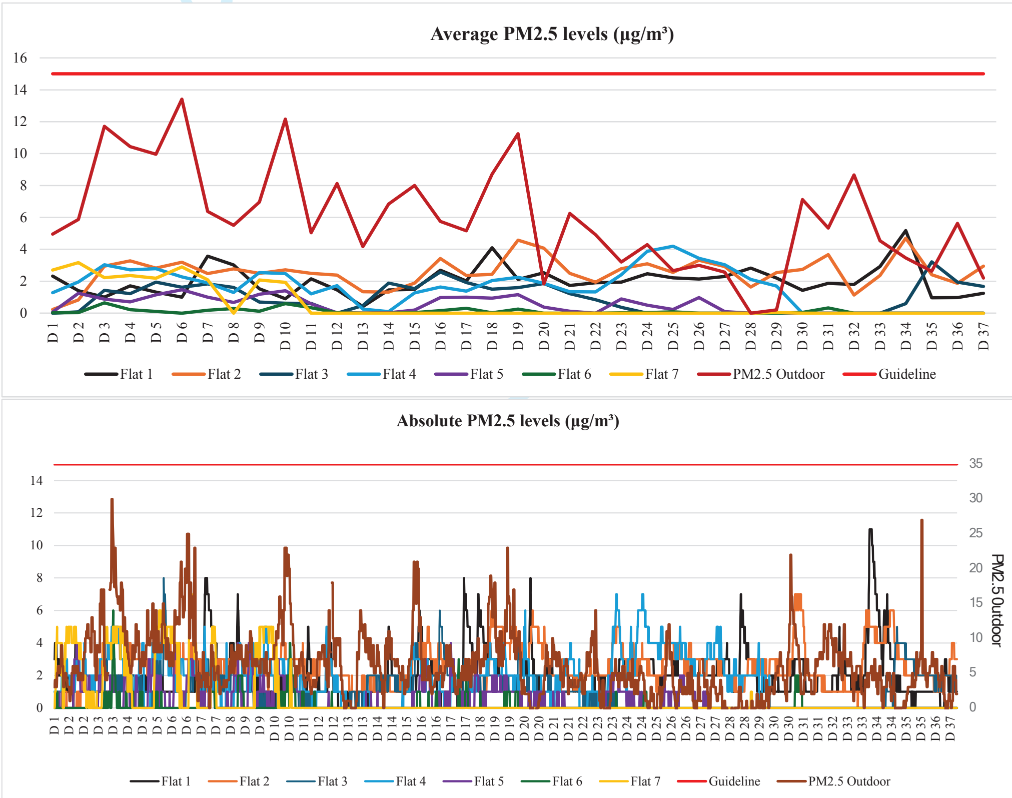


Figure 6: a) Daily average readings of $PM_{2.5}$ levels (top); b) Absolute readings of $PM_{2.5}$ levels (bottom) (15 minutes intervals).

3.1.2 Carbon Monoxide (CO)

CO levels (Figure 7. a) varied significantly across the CSBs. Flats 1, 4 and 5 consistently recorded CO levels that exceeded the WHO guideline of 6 ppm, posing potential health risks to the occupants. Flat 5 was of particular concern, recording the highest mean CO concentration of 46.22 ppm (7.7 times the WHO guideline) with 64.2% of all 15-minute readings exceeding the threshold across 28 of the 37 monitored days, and peak absolute levels reaching 626 ppm. Flat 4 also recorded persistently elevated levels with a mean of 26.00 ppm (4.3 times the guideline), exceeding the threshold on 27 of 37 days, with peak levels reaching 915 ppm on certain days, particularly during early December. CO concentrations in Flat 1 ranged from 30 to 96 ppm on average, far exceeding safe limits. This flat also experienced extreme spikes in CO concentration, with levels reaching up to 172 ppm on certain days, particularly during late December. These high levels likely resulted from inadequate ventilation, possibly related to the use of combustion-based heating appliances and cooking activities in an enclosed space. Flat 2 recorded an average of 9.31 ppm, with the daily mean exceeding the threshold on 17 of 37 days and peak absolute readings reaching 241 ppm. Although Flats 6 and 7 also experienced occasional CO spikes, these events were less frequent and less severe, and their CO levels generally remained within the safe range. Flat 3 consistently maintained CO levels below the WHO threshold. Figure 7.b shows the absolute readings of CO levels in the CSBs. The guideline value for CO in absolute readings represents the STEL (15 minutes), set at 100 ppm. None of the CSBs reached the IDLH limits as also demonstrated in Figure 7.b

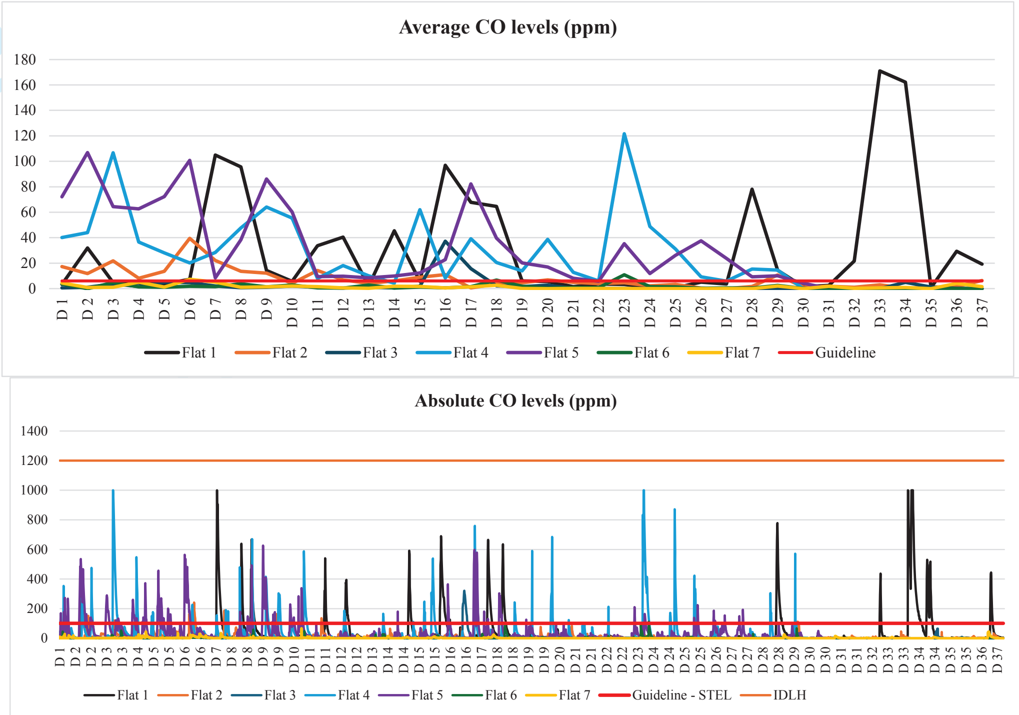
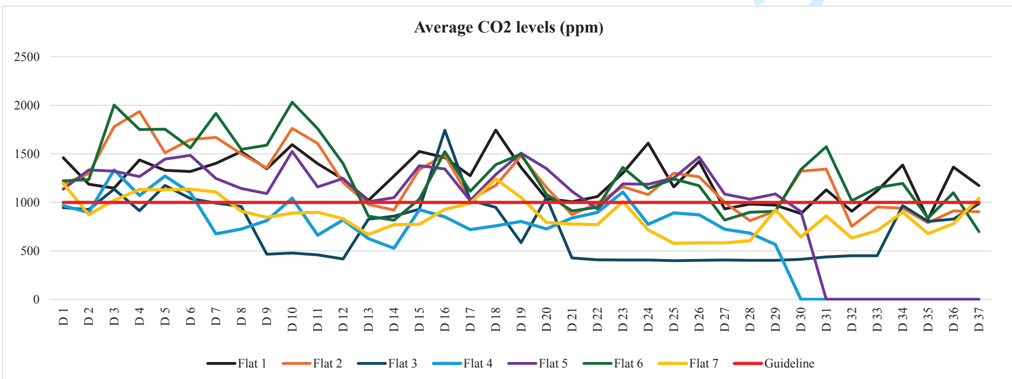


Figure 7: a) Daily average readings of CO levels (top); b) Absolute readings of CO levels (bottom) (15 minutes intervals).

3.1.3 Carbon Dioxide (CO_2)

CO_2 concentrations (Figure 8.a) fluctuated throughout the 37-day monitoring period, with several flats exceeding the ASHRAE safe limit of 1000 ppm. Although CO_2 is not classified as a pollutant, it is a reliable indicator of occupancy levels in the CSBs. The measured CO_2 concentrations provide insights into ventilation performance and human activity within the spaces. Flat 1 frequently recorded CO_2 concentrations well above this threshold, with peak levels reaching 1500 ppm. This flat exhibited persistent issues with poor ventilation, which contributed to the elevated CO_2 levels. Flat 6 also recorded occasional CO_2 spikes above the guideline, likely due to increased occupancy and a lack of proper ventilation. In comparison, Flat 3 consistently kept CO_2 levels below the recommended guideline, indicating better air exchange and fewer occupants, contributing to better IAQ in this flat. Figure 8.b shows the absolute readings of CO_2 levels in the CSBs. The guideline value for CO_2 in absolute readings is set at 15000 ppm which represents the STEL (15 minutes) and the IDLH value for CO_2 is 40000 ppm and none of the CSBs exceeds the limit.



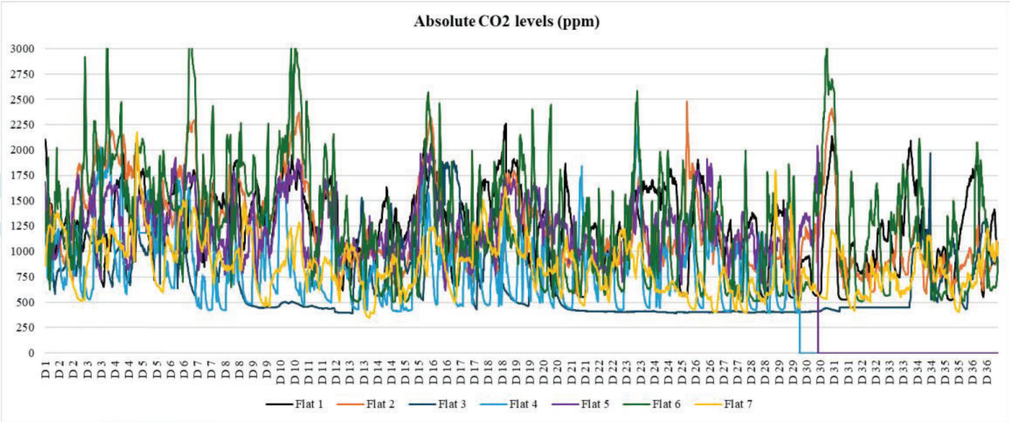
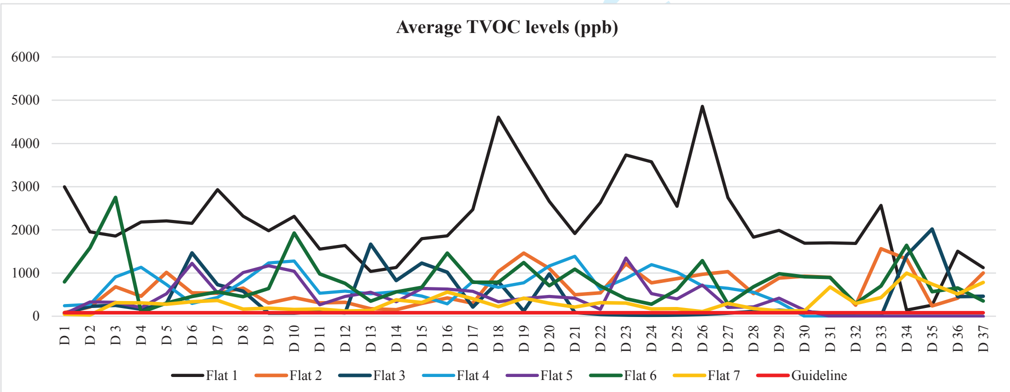


Figure 8: a) Daily average readings of CO_2 levels (top); b) Absolute readings of CO_2 levels (bottom) (15 minutes intervals).

3.1.4 Total Volatile Organic Compounds (TVOC)

TVOC levels (Figure 9.a) were highly variable across the CSBs, with several flats recording concentrations well above the CIBSE guideline of 300 µg/m³ (approximately 80 ppb). The highest TVOC concentrations were observed in Flats 1, 2, and 6. Flat 1 recorded extreme TVOC levels, with a mean of 2,186 ppb (27.3 times the guideline) and every single 15-minute reading across all 37 monitoring days exceeding the threshold, with concentrations reaching up to 4860 ppb during periods of high activity, such as when air fresheners or candles were used. Flat 2 recorded an average of 504 ppb (6.3 times the guideline), with 98.6% of readings exceeding the threshold. Similarly, Flat 6 exhibited high TVOC levels, peaking at 4610 ppb, which may have been related to recent renovations and the use of VOC-emitting products. While Flats 1 and 6 recorded some of the highest TVOC concentrations, Flat 3 also displayed periodic spikes, with an average of 387 ppb and a peak of 12,664 ppb, suggesting intermittent sources of VOCs, likely from household cleaning products or occupant activities. Despite the generally lower pollutant levels observed in Flat 3, these sporadic spikes in TVOC concentrations indicate that occupant activities can significantly impact IAQ, even in well-ventilated environments. Flat 7 recorded the lowest mean concentration at 227 ppb, though 83.8% of its readings still exceeded the guideline, confirming that no dwelling consistently maintained TVOC levels within safe limits. In some of the CSBs the TVOC levels showed sudden spikes for a very limited time which even went up to 20000 ppb (absolute levels), however those spikes were removed from the data for better consistency of the data. Figure 9.b shows the absolute readings of TVOC levels in the CSBs and the guideline value in the figure represents the STEL of 1500 µg/m³ (approximately 400 ppb).



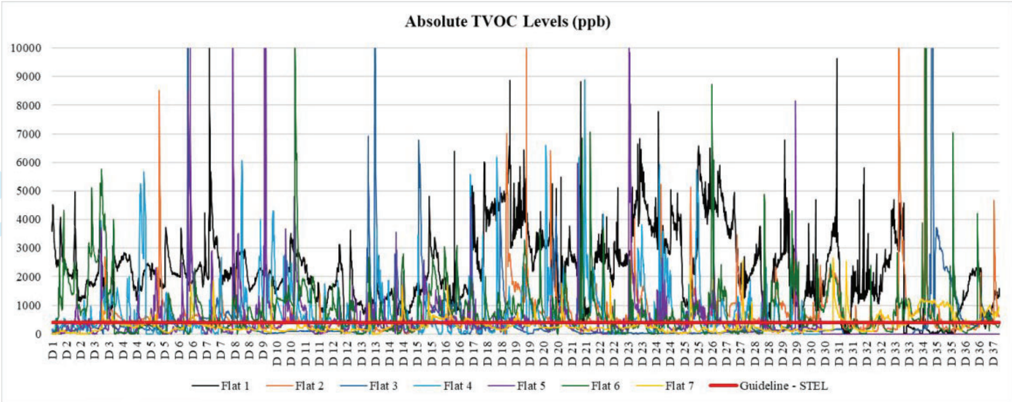


Figure 9: a) Daily average readings of TVOC levels (top); b) Absolute readings of TVOC levels (bottom) (15 minutes intervals).

3.1.5 Temperature and Humidity

The indoor temperature and humidity levels were monitored across the seven case study buildings during the 37-day observation period. According to CIBSE guidelines, the recommended winter temperature for living areas is between 22°C and 23°C, and relative humidity should be maintained between 40% and 70%. Temperature levels (Figure 10.a) varied across the buildings, with Flats 4 and 6 consistently staying within the recommended range, indicating effective thermal regulation. In contrast, Flat 1 and 3 frequently recorded temperatures below 22°C, suggesting potential discomfort due to cooler conditions, while Flat 2 and 7 exhibited frequent periods of overheating, with temperatures exceeding the upper limit of 23°C. Upon analysing the outdoor temperature levels and comparing them with indoor levels, no significant correlation was observed. Figure 10.b shows the absolute readings of Temperature levels in the CSBs.

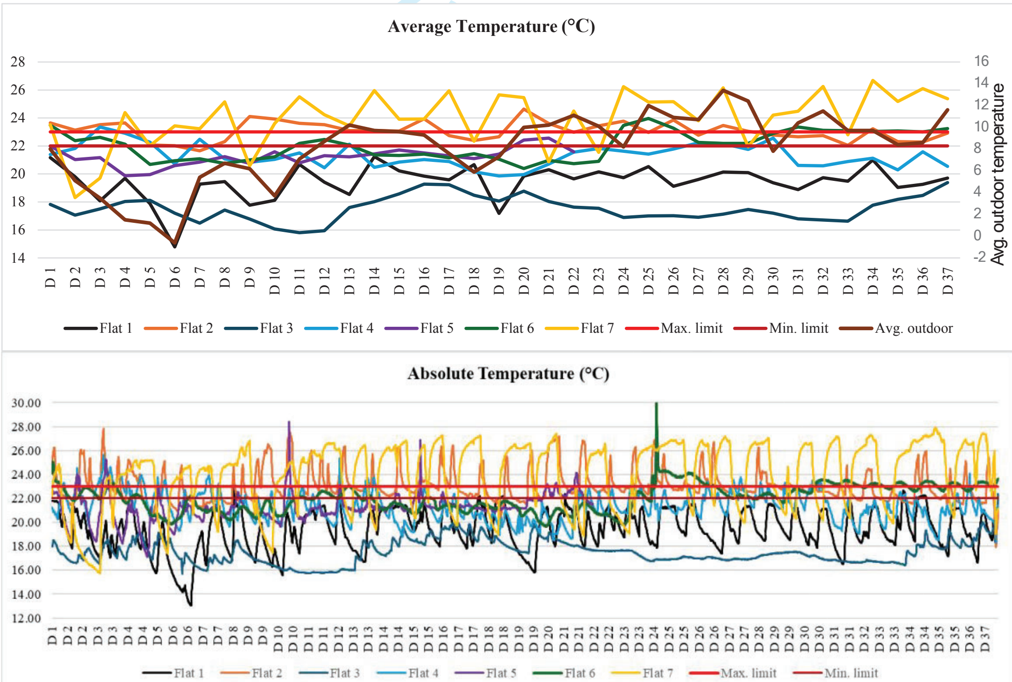


Figure 10: a) Daily average readings of temperature levels (top); b) Absolute readings of temperature levels (bottom) (15 minutes intervals).

Humidity levels (Figure 11.a) also showed significant variation. Flats 2, 5 and 7 maintained stable humidity levels within the acceptable range, with fluctuations between 51% and 69%. However, Flat 1, 3 and 4 periodically exceeded the upper limit of 70%, Flat 4 reaching up to 90% and Flat 1 reaching up to 73.5%, potentially creating discomfort or moisture-related issues including risk of condensation, damp and mould growth. Flat 6, while generally within the acceptable range, also approached the upper limit in a few days. The analysis of outdoor humidity levels showed a significant correlation with the indoor levels. Figure 11.b shows the absolute readings of Humidity levels in the CSBs.

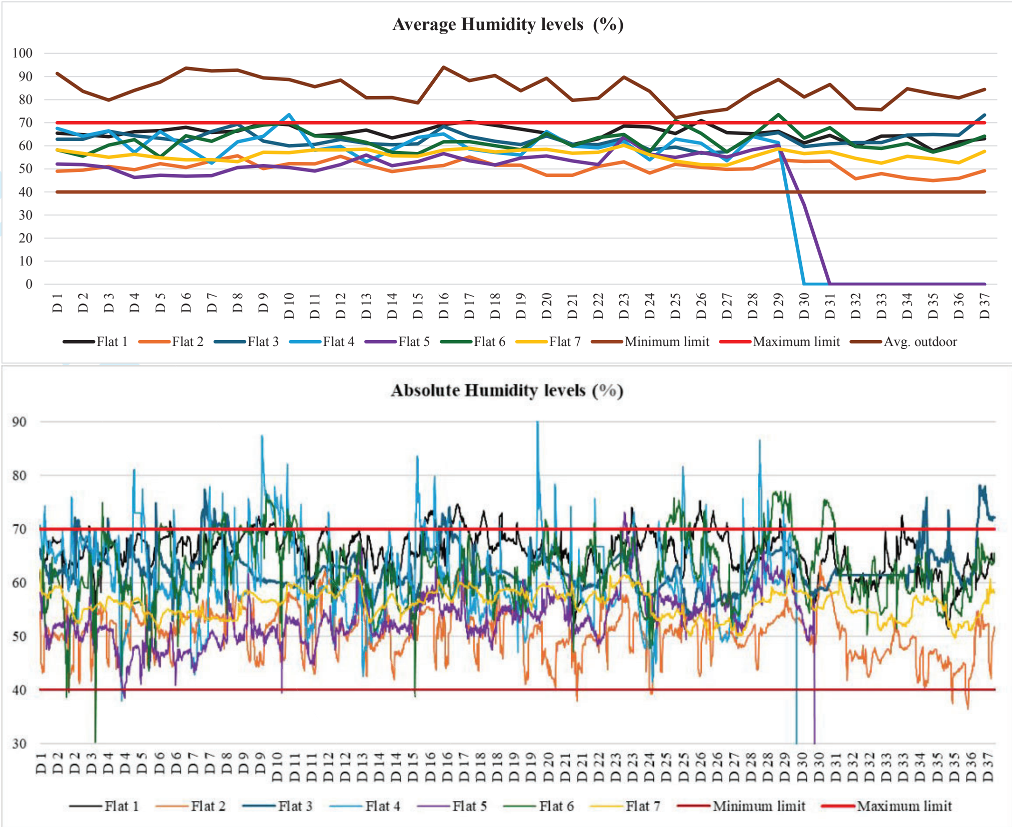


Figure 11: a) Daily average readings of Humidity levels (top); b) Absolute readings of Humidity levels (bottom) (15 minutes intervals).

3.2 Air Purifier and Occupant Behaviour

The installation of air purifiers and behavioural interventions focused on key pollutants, including CO, PM_{10}, $PM_{2.5}$, TVOCs, and humidity levels. Air purifiers had a significant positive impact on reducing CO and PM_{10} levels across all three CSBs. The reductions were notable, with CO and PM_{10} levels consistently maintained near or below recommended guidelines following installation. It should be noted that CO removal has not been identified in the technical datasheet of the Air Purifier and it is therefore unclear as to whether the reduction of CO could be directly attributed to the system. Yet, the outcomes aligns with the expected effectiveness of air purifiers in mitigating these pollutants in indoor environments. For instance, CO levels in Flat 1, which had dangerously high pre-intervention levels averaging 22.77 ppm with spikes exceeding 500 ppm (absolute reading), dropped to an average of 4.86 ppm during the air purifier phase. In Flat 2, CO levels reduced from a pre-intervention average of 4.25 ppm to 1.79 ppm, with spikes becoming less frequent and less severe. Similarly, PM_{10} levels in Flat 1 decreased from an average of 20.43 µg/m³ to 4.27 µg/m³. Flat 3 showed a similar trend, with PM_{10} levels falling from 5.13 µg/m³ pre-intervention to 1.29 µg/m³ during the air purifier phase. Despite improvements, the intervention's effect on TVOCs was less pronounced. For instance, in Flat 1, TVOC levels decreased only marginally, from an average of 3138.54 ppb pre-intervention to 2375.9 ppb, remaining significantly above the recommended guideline of 80 ppb. Similar trends were observed in Flats 2 and 3, where TVOC levels reduced significantly but continued to exceed safe limits, indicating the persistence of TVOC sources such as cleaning products, air fresheners, and occupant activities.

The pre-intervention observations and interviews with the occupants revealed direct correlations between poor IAQ and occupant behaviour. These included excessive use of cleaning materials, air fresheners and candles, limited use of trickle ventilators and/or mechanical background ventilations (due to cold draft during winter), broken and/or erroneous installation of extractor fans. The tailored behavioural interventions focused on educating occupants about reducing pollutant generation through actions such as ensuring proper ventilation during cooking and bathing, opening windows for a short period when using cleaning materials, limiting the use of VOC-emitting products, and avoiding smoking indoors. Pollutant levels were monitored for 31 days post-intervention to evaluate the effectiveness of these behavioural changes. The impact of behavioural interventions varied across the CSBs. In Flat 3, these interventions proved effective, with CO levels reducing further to an average of 2.74 ppm, and PM_{10} levels dropping to 2.46 µg/m³, consistently remaining within or near the recommended guidelines. TVOC levels in Flat 3 also decreased from 388.11 ppb during the air purifier phase to 630.45 ppb post-intervention, marking an improvement, though still above the guideline. In contrast, Flats 1 and 2 exhibited mixed results.

While behavioural interventions initially appeared to help, pollutant levels in both flats began to rise again. In Flat 1, CO levels increased significantly to an average of 51.5 ppm, with frequent spikes surpassing safe thresholds. Similarly, PM_{10} levels rose to an average of 51.17 µg/m³, and TVOC levels escalated to 4939.64 ppb, indicating a reversion to previous behaviours. Flat 2 displayed more moderate increases, with CO levels averaging 7.89 ppm, PM_{10} at 6.86 µg/m³ and TVOCs at 1040.03 ppb post-intervention.

The results suggest that while the air purifier had a substantial and immediate positive impact on pollutant levels, sustaining improvements required consistent adherence to recommended behaviours. Occupants in Flat 3 demonstrated the most compliance, likely due to a better understanding of IAQ's impact on health. In contrast, Flats 1 and 2 showed challenges in maintaining behavioural changes, highlighting the limitations of educational interventions without ongoing reinforcement. The effectiveness of these interventions varied across the CSBs and pollutants. Table 3 summarises the average values of the pollutants monitored in each flat across all three phases.

Table 3: The average values of pollutants monitored during the three phases.

Pollutants		Flats	Baseline measurement (current condition)	Air Purification Phase (After air filtration)	Behavioural response phase (After behavioural intervention)
PMs	PM_{10} µg/m³	1	20.43	4.27	51.17
		2	3.65	1.56	6.86
		3	5.13	1.29	2.46
	$PM_{2.5}$ µg/m³	1	2.35	1.11	2.49
		2	3.00	2.51	3.35
		3	1.83	1.27	1.12
CO (ppm)		1	22.77	4.86	51.5
		2	4.25	1.79	7.89
		3	5.61	1.43	2.74
TVOC (ppb)		1	3138.54	2375.9	4939.64
		2	834.75	488.96	1040.03
		3	1083.28	388.11	630.45
Humidity (%)		1	67.05	62.30	59.97
		2	50.83	50.81	51.04
		3	64.58	70.3	65.06

3.3 Air permeability and pollutant concentration

This section explores the impact of AP on pollutant concentration levels using CONTAM, a simulation tool for multizone airflow and contaminant transport. Simulations were conducted to assess how varying infiltration rates influence the accumulation and dispersion of pollutants, offering insights into the role of ventilation in maintaining IAQ.

3.3.1 TVOC concentration for building insulation (retrofit)

Simulations were conducted to demonstrate the effects of different AP levels (1, 5, 10, and 15 m³/m².h@50Pa) on the indoor TVOC concentration levels generated from a selected insulation material. As stated in Section 2.3, Phenolic Foam (PF-2: 33.7 kg/m³) with a TVOC generation rate of 0.17 mg/h was considered and simulations were carried out for three months during which the emissions are over the safe limits. This was to assess the effects of upgrading building fabrics through the installation of cavity and loft thermal insulation. The results (Figure 12) demonstrated a strong correlation between the APs and TVOC concentrations within the buildings. Generally, as expected, higher AP levels correlated with decreased TVOC concentrations, suggesting that increased air exchange in less airtight buildings facilitates the dispersion of generated pollutants from the insulation materials. The TVOC levels increased progressively as the AP decreased from 15 to 5, except for the AP level of 1 where the TVOC concentrations decreased. Further investigation is required on the reasons for this inconsistency; however, a possible explanation would be that the highly airtight buildings would allow significantly lower rates of VOCs to enter the building through the gaps and cracks in the first place, hence achieving better IAQ when it comes to correlations between outdoor/indoor air pollutants.

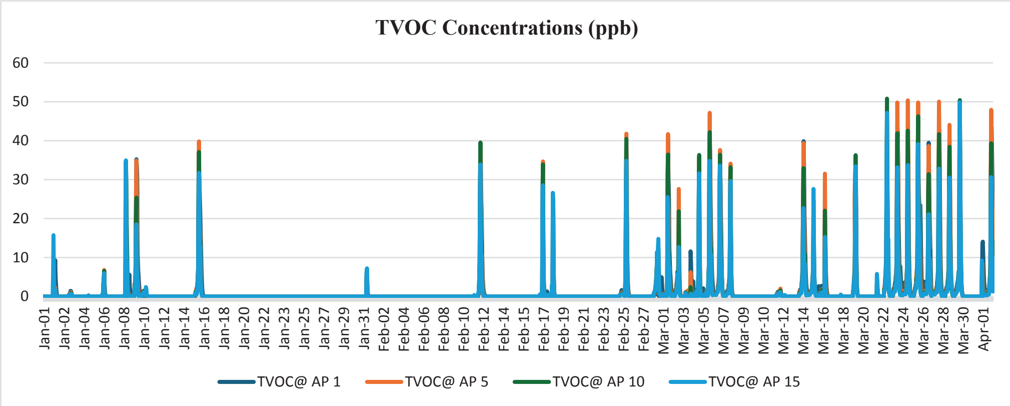


Figure 12: TVOC concentration at different Air Permeability rates.

3.3.2 TVOC levels from indoor sources

The scheduling for indoor TVOC generation was based on the actual data collected from the CSB, explaining the observed peaks in the simulated TVOC data. This pattern highlights periods of heightened indoor pollution. The analysis of TVOC levels generated from the indoor source (Figure 13) indicates distinct peaks in TVOC concentrations consistently observed at 21:00, regardless of AP level, with values ranging between 23.87 and 55.92. These peaks suggest a period of heightened TVOC emissions influenced by the occupants' activities. Lower levels of TVOC were observed for higher AP levels suggesting that increased ventilation due to air infiltration plays a significant role in the accumulation of VOCs indoors.

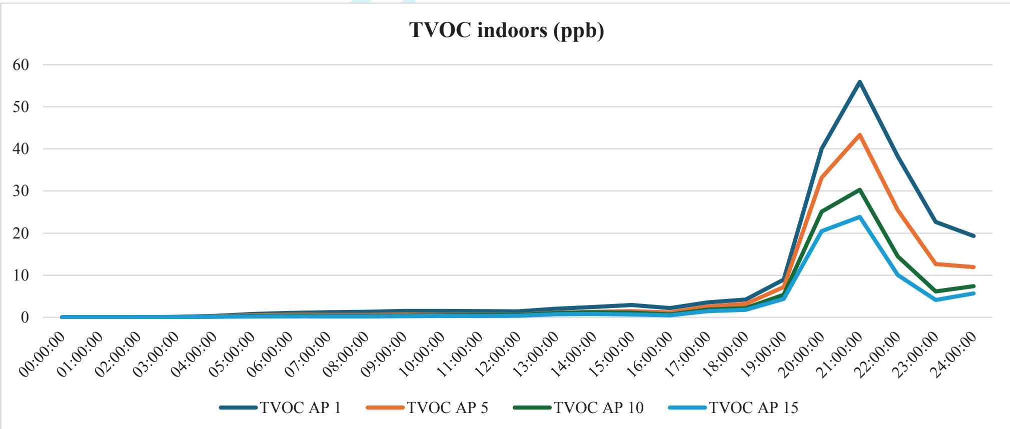


Figure 13: TVOC concentration from an indoor source.

3.3.3 CO levels from indoor sources

Similar to the TVOC, the actual collected CO data from monitoring were used as the input for simulations. The results suggest that CO levels (Figure 14) remain relatively stable across all AP values, with readings hovering around 100 ppb. However, there was a significant increase in CO levels, peaking between 7:00 AM and 10:00 AM. During this period, CO levels spiked dramatically, reaching exceptionally high concentrations, with the highest recorded values occurring at 9:00 AM. Following the morning peak, CO levels gradually decreased throughout the afternoon and evening hours, with some fluctuations. Notably, there was a secondary increase in CO levels during the evening, particularly between 8:00 PM and 11:00 PM. This resurgence, while not as pronounced as the morning peak, still resulted in elevated CO concentrations, with the highest levels occurring at 10:00 PM. Overall, the data highlights distinct peak hours corresponding to occupants' behaviours during morning and evening. Like the VOCs, the CO levels had a reverse correlation to the AP rates, meaning that lower AP rates resulted in a higher concentration of CO.

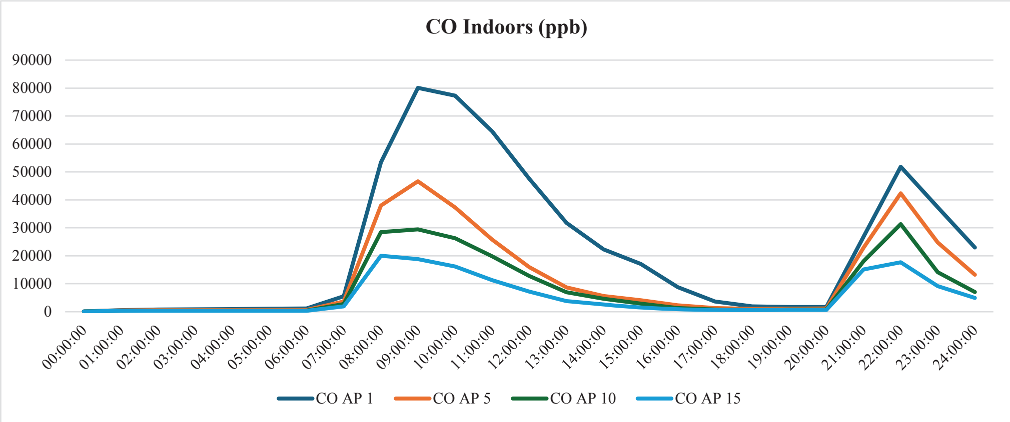
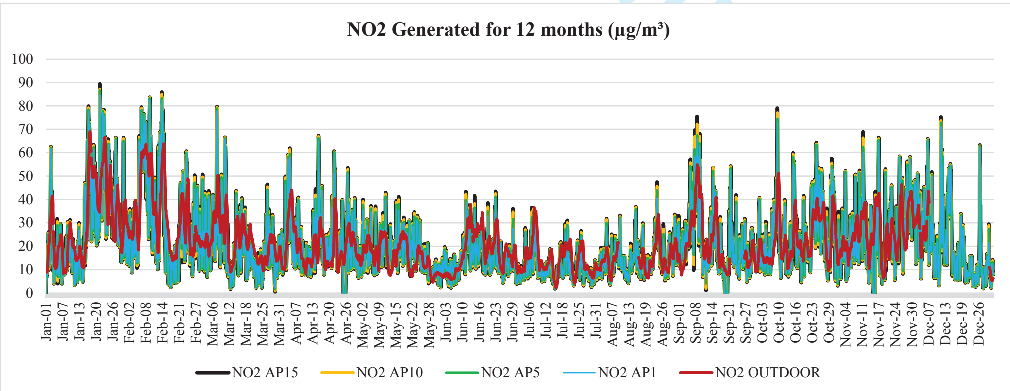


Figure 14: CO concentration from an indoor source.

3.3.4 Indoor/Outdoor air quality correlations (NO_2 and PMs)

The NO_2 levels (measured in µg/m³) were simulated across different AP values over 12 months, from January to December using the actual data collected from the local outdoor air quality stations. As stated previously, the focus of the study in this section was on the effects of building airtightness and therefore for the purpose of simulations the assumption was that the windows would always remain closed. For the NO_2, despite significant fluctuations in outdoor levels throughout the year, the indoor NO_2 concentration values for all AP levels appeared to be relatively similar, suggesting that changes in AP do not significantly affect the indoor NO_2 concentrations. This implies that external factors, such as outdoor NO_2 levels, play a more significant role in determining NO_2 concentrations than the AP alone. Figure 15.a shows higher NO_2 levels during certain periods, particularly in the winter and early spring months, pointing to seasonal influences on pollution levels. Figure 15.b shows a zoomed-in scenario for a single day (18th January) with a relatively high outdoor NO_2 demonstrating relationships between wind speed and pollution concentration levels. On this day, wind speeds ranged from 3.1 mph to 11.4 mph. From 10:00 to 14:00, when the wind speeds were relatively high (10.4 to 11.4 mph), outdoor NO_2 concentrations showed a noticeable decline, dropping from 55 µg/m³ at 10:00 to 28 µg/m³ at 14:00. This suggests that higher wind speeds promote dispersion and dilution of outdoor pollutants. Indoor NO_2 levels mirrored this trend, with concentrations decreasing during the same period. For instance, at AP 1, indoor NO_2 levels dropped from 52.3 µg/m³ at 10:00 to 24.5 µg/m³ at 14:00. On the contrary, during late evening hours (20:00 to 23:00), when wind speeds were lower (9.1 to 7.2 mph), outdoor NO_2 concentrations remained relatively high, with levels ranging from 65.9 to 55.1 µg/m³. Indoor concentrations during these hours were also elevated, though slightly lower than outdoor levels.



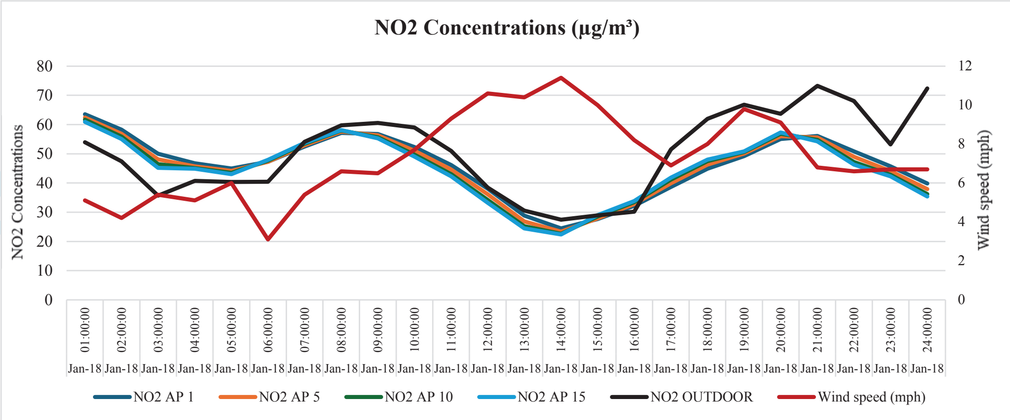


Figure 15: a) NO_2 generated for 12 months (top); b) NO_2 concentrations and wind speed (bottom).

Regarding the PMs, the analysis of PM_{10} concentrations over 12 months (Figure 16.a) shows that while there are some fluctuations, the differences across various AP levels (AP15, AP10, AP5, AP1) remain minimal. This indicates that changes in AP do not significantly impact PM_{10} levels. However, when comparing indoor with outdoor concentrations levels, a strong correlation is evident suggesting that external pollution plays a key role in determining indoor PM_{10} levels. Seasonal trends are also observed, with higher concentrations during winter and early spring, likely due to increased heating emissions and atmospheric conditions that limit pollutant dispersion.

Similarly, $PM_{2.5}$ concentrations exhibit a similar pattern (Figure 16.b), with little variation across different AP scenarios but a clear dependence on outdoor pollution levels. The data suggests that fine particulate matter can easily infiltrate indoor spaces regardless of AP, reinforcing the idea that external sources are the primary driver of indoor $PM_{2.5}$ pollution. Seasonal fluctuations are apparent, with higher levels in colder months, further emphasising the role of outdoor pollution and meteorological conditions in shaping IAQ.

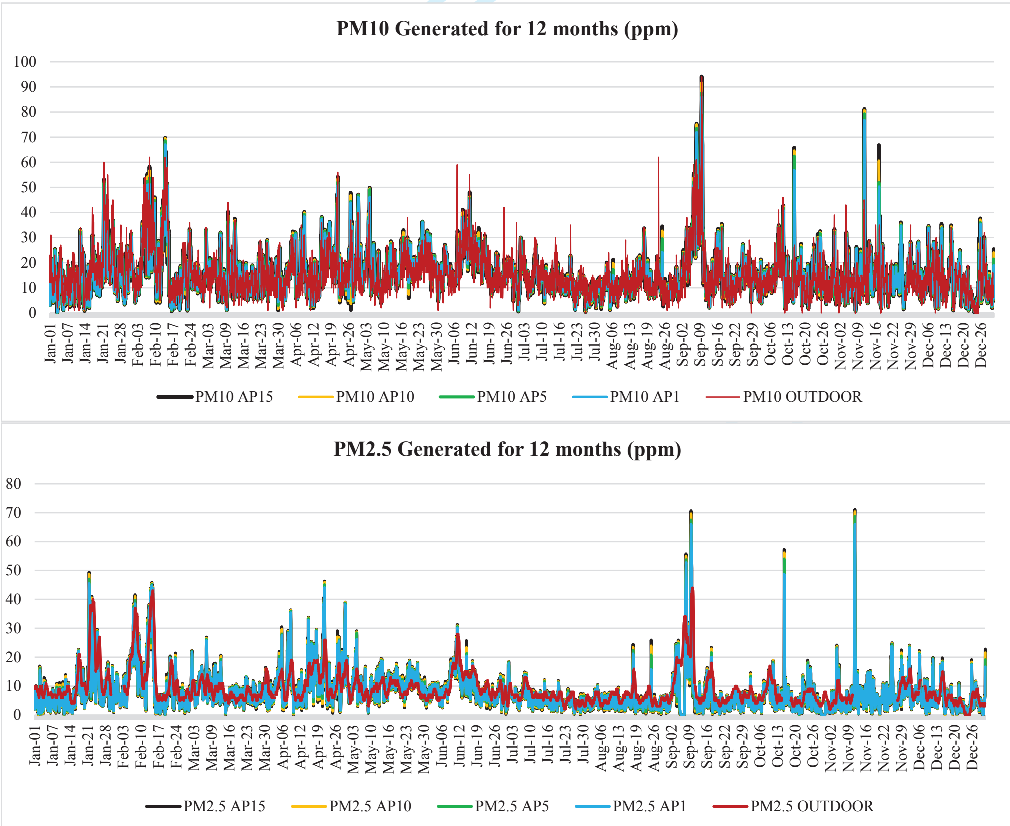


Figure 16: a) PM_{10} generated for 12 months (top); b) $PM_{2.5}$ generated for 12 months (bottom).

4. Discussion

This research explored the complex interaction between occupant behaviour, ventilation practices, building design, and Outdoor/Indoor Air Quality in social housing. The findings demonstrate how each of these factors interacts with and contributes to pollutant levels indoors, revealing both the challenges and potential solutions for maintaining healthy IAQ while balancing energy efficiency. Collected data from the three monitoring phases and CONTAM simulations shows that IAQ is primarily correlated with the occupant behaviour and ventilation habits/strategies, rather than to building airtightness alone. Pollutants such as PM_{10}, $PM_{2.5}$, CO, CO_2, and VOCs exhibited significant fluctuations due to both environmental and behavioural factors while the limited use of natural/mechanical ventilation systems led to the accumulation of indoor air pollutants. In addition to the long-term exposure considerations, the pollutants measured in the CSBs were also analysed against the Short-Term Exposure Limit (STEL) and the Immediately Dangerous to Life or Health (IDLH) values. While none of the observed pollutants exceeded the IDLH thresholds, the STEL limits were surpassed for both CO and TVOC in multiple instances indicating acute exposure risks. Daily average CO concentrations in the most affected dwelling was up to 16 times over WHO guidelines (6 ppm) with the peak absolute readings of 1.7 times over STEL guidelines (100 ppm). Daily average TVOC concentrations across most dwellings were 5–7 times the CIBSE 8-hour guideline (80 ppb), rising to over 57 times the guideline in the worst-affected dwelling. An important observation was that although the average CO_2 levels in some cases were within the acceptable limits, the rest of the IAPs were significantly higher than the recommended levels. Therefore, arguably, despite general practice, CO_2 levels may not be a suitable indicator of the overall IAQ conditions especially in residential buildings.

The assessments on the effectiveness of air purifiers and behavioural interventions revealed that across the three monitoring phases, the air filtration/purification resulted in a more consistent reductions in some IAPs. In Flat 1, the average CO declined from 22.77 ppm to 4.86 ppm (79% reduction) and PM_{10} from 20.43 to 4.27 µg/m³ (79% reduction), while TVOCs fell only from 3138.54 to 2375.9 ppb (24% reduction), indicating the limited effectiveness of air purification. It should be noted that the post-intervention interviews with the occupants revealed that, in some cases, occupants changed/improved their behaviour (i.e. reduced using pollutants such as air fresheners, candles etc.) particularly when the air purifies reacted to specific pollutants (i.e. automatically increased the fan/filtration speed rate). Therefore, the air purifiers may have had both direct and indirect effects on improving IAQ. On the contrary, during the Behavioural Intervention (after removing air purifiers), CO and TVOC in some flats rebounded the previous, and in some cases higher than the previously recorded levels. Some flat however sustained IAQ improvements highlighting both the opportunities and difficulties in the implementation of behavioural intervention. Additionally, the interviews revealed the reluctance of many occupants to use mechanical ventilation systems (due to concerns over noise, discomfort, cold draft, or energy consumption) contributed to poor IAQ. Such reluctances, particularly on noise and costs, may also apply to air purification systems specially in the context of social housing and vulnerable communities.

When it comes to the building airtightness, the research revealed a key challenge: buildings designed/retrofitted to achieve low air permeability, for improved energy efficiency, may trap pollutants indoors leading to poor IAQ and health outcomes. According to the results, buildings with higher AP (leakier buildings) achieved lower concentrations of VOCs and CO; however, higher AP may simultaneously result in more heat loss, poor thermal comfort, and potential risk of condensation, damp, and mould growth particularly during colder seasons. The findings therefore emphasise the need for an integrated approach that combines building airtightness for energy savings with properly designed natural/mechanical ventilation systems to ensure that pollutants do not reach harmful concentrations. Moreover, when it comes to building fabric upgrades, particularly for the wall, roof, and floor insulation, low VOC emitting materials combined with active ventilation strategies during the installation periods are essential to minimise the negative health outcomes. The building air tightness may however be less pronounced for pollutants primarily originating from outdoor sources (e.g. NO_2). The results suggested indoor concentrations remained relatively consistent across different AP levels following outdoor pollution trends.

In synthesising the findings, it becomes clear that maintaining healthy IAQ in social housing requires balancing multiple factors. For example, providing non-polluting alternatives for cooking or introducing less harmful household products could help reduce indoor pollutant loads. Additionally, structural solutions like ventilation systems and building designs with optimised natural ventilation and airtightness must be paired with efforts to improve occupant behaviour. Occupants play a significant role in shaping IAQ, and their behaviours can often negate the benefits of even the best design systems and strategies. Continuous education programmes that inform tenants about the health risks associated with poor IAQ and promote healthier practices are essential components of a comprehensive IAQ strategy. Moreover, building design should prioritise an integrated approach where both energy efficiency and IAQ are considered in tandem. Mechanical ventilation systems, natural ventilation through optimised AP and trickle ventilators, air filtration, and maintenance strategies should be incorporated into design practices to mitigate the risk of poor IAQ while achieving high energy efficiency in buildings. This research highlight the need for a multifaceted approach that includes improving ventilation systems, optimising building permeability, and engaging with occupants to encourage healthier behaviours.

5. Conclusion

This study examined the various factors influencing IAQ in social housing emphasising the three-folded relationship between indoor air quality, ventilation, and occupant behaviour. The results highlight the significant challenges posed by poor IAQ across different residential units, influenced by occupant behaviour, inadequate ventilation, and the accumulation of pollutants particularly CO, PMs, and VOCs. None of the case study apartments consistently maintained acceptable IAQ with different pollutants reaching between nearly 2 and 60 times the recommended levels. This underscores the need for targeted interventions to mitigate the risks, particularly for vulnerable occupants. The application of air purifiers, combined with tailored behavioural interventions, demonstrated the potential to reduce certain pollutants such as PMs; however, persistently high levels of VOCs revealed both technological and regulatory limitations in addressing wide ranges of VOCs, which may come from various household products and activities. Additionally, while behavioural interventions in some cases improved the conditions (for a limited period), their effectiveness diminished once technological support (i.e. air purifier with IAQ indicators) was removed. A one-off educational programme proved to be insufficient particularly for occupants with deeply embedded high-pollution-generation behaviours. Continuous educational programmes combined with IAQ monitoring systems would help to both raise occupants' awareness on IAQ and ultimately change behaviour in the long-term. More specifically, raising occupant awareness on how everyday behaviours, such as cooking without proper ventilation, burning candles, and using air fresheners and/or cleaning materials, degrade IAQ can contribute to shifting public attitudes towards the indoor environment as an active health determinant with significant societal implications given that people spend approximately 80% of their time indoors. Similarly, for housing providers and local authorities, IAQ literacy should be embedded as a recurring element of tenancy support rather than a single-point intervention.

Meanwhile, although occupants' behaviours and activities are a primary factor on IAQ conditions, there are direct correlations between buildings' physical characteristics including airtightness and IAQ. In the absence of effective and adequate ventilation strategies, airtight buildings can lead to harmful build-up of pollutants indoor. The CONTAM simulations across the four tested air permeability scenarios (1, 5, 10, and 15 $m^3/m^2.h@50Pa$) showed that reducing permeability from the leakiest to the tightest envelope approximately doubled the peak levels for TVOC accumulation while CO levels also followed the same pattern. This carries a specific implication for retrofit practices: tightening the building envelope below an AP of 5 $m^3/m^2.h@50Pa$ without simultaneously commissioning effective natural and/or mechanical ventilation is likely to worsen IAQ with direct implications on health. Retrofit programmes should therefore mandate effective and measurable ventilation strategies as a co-intervention whenever significant airtightness improvements are planned. On the other hand, integration of low emitting materials is critical to reduce VOC generation rates and maintain acceptable IAQ particularly during retrofit/installation.

When it comes to air purification and filtration systems, although effective in controlling PMs, they were insufficient as a standalone response to TVOCs and other pollutants. Therefore, air purifiers should not be prescribed as a general IAQ remedy without specifying and testing pollutant-type suitability. An important result that directly challenges the adequacy of CO_2-based ventilation standards/guidelines as a standalone governance tool, was the coexistence of acceptable CO_2 levels with severe exceedances of other pollutants such as CO and TVOC in several dwellings. This indicates that CO_2 may be an unreliable and misleading proxy for the overall IAQ conditions. The regulatory frameworks should therefore consider mandating multi-pollutant monitoring protocols, incorporating CO and TVOC sensors alongside CO_2 in order to achieve more accurate results on IAQ conditions and ventilation requirements.

In conclusion, the study underscores the need for a holistic approach to building design and retrofit where technical, behavioural, and structural factors are jointly considered. The findings suggest that, given that people spend most of their time indoors, poor IAQ may in fact pose a much higher risk to health than outdoor air. The governmental policies should therefore shift attention towards IAQ by developing practical guidelines on ventilation rates and limiting harmful indoor air pollutants from household materials as well as on the effects of various activities such as retrofit and their implications on IAQ and health. In this respect, a combination of continuous educational programmes to raise public awareness leading to meaningful long-term behaviour change, and technical intervention (e.g. enhanced retrofit materials and strategies, indoor environmental monitoring, smart mechanical ventilation systems), along with providing non-polluting alternatives for household day-to-day activities (e.g. cleaning, cooking etc.) will help to affectively address poor IAQ and its associate health outcomes. Although this study provides detailed analysis on the status of IAQ in social housing, further longitudinal research across a wider range of housing types in different regions with different socio-economic backgrounds is required to provide a more comprehensive view on the correlations between IAQ, occupant behaviour, ventilation rates/strategies, and physical characteristics of buildings, establishing more generalisable thresholds on IAQ and effective interventions to improve the conditions in social housing.

ACKNOWLEDGEMENT

This document is an output from a research project, Healthy Energy Efficient Dwellings (HEED), funded by the UK Research and Innovation (UKRI), Medical Research Council (MRC) [Grant number: MR/Y503186/1]. The authors would like to thank the Newham Council, Hyde Housing Association, and iOpt Limited, and Healthy Air Technology Ltd. for supporting the project. The authors further confirm that Grammarly was used solely for proofreading and to enhance the clarity and readability of the manuscript. No generative artificial intelligence (AI) or AI-assisted technologies (including ChatGPT or similar tools) were used in the preparation of the manuscript content, data analysis, interpretation of results, or literature review.

Funding declaration

This research was funded by the UK Research and Innovation (UKRI), Medical Research Council (MRC) [Grant number: MR/Y503186/1].

Ethics approval

Ethical approval was granted by the University of East London's Ethics Committee under the application number (ETH2223-0136).

Conflict of interest

The authors declare that there is no competing interest.

REFERENCES

Adamkiewicz, G., Zota, A.R., Fabian, M.P., Chahine, T., Julien, R., Spengler, J.D. and Levy, J.I. (2011), "Moving environmental justice indoors: understanding structural influences on residential exposure patterns in low-income communities", American Journal of Public Health, Vol. 101 No. S1, pp. S238–S245, available at: https://doi.org/10.2105/AJPH.2011.300119

American Conference of Governmental Industrial Hygienists (2022), Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs), ACGIH, available at: https://www.acgih.org/science/tlv-bei-guidelines/ (accessed 29 April 2026)

Ashmore, M. and Dimitroulopoulou, C. (2009), "Personal exposure of children to air pollution", Atmospheric Environment, Vol. 43 No. 1, pp. 128–141, available at: https://doi.org/10.1016/j.atmosenv.2008.09.024

ASHRAE (2019), Standard 62.2-2019: Ventilation and Acceptable Indoor Air Quality in Residential Buildings, ASHRAE, Atlanta, available at: https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/62_2_2019_g_20210730.pdf (accessed 29 April 2026)

Basaly, L.G., Hashemi, A., Elsharkawy, H., Newport, D. and Badawy, N.M. (2024), "Evaluating thermal comfort and overheating risks in a social housing prototype: as-built versus retrofit scenarios", Environmental Science and Sustainable Development, Vol. 9 No. 2, available at: https://doi.org/10.21625/essd.v9i2.1073

Basaly, L.G., Hashemi, A., Elsharkawy, H., Newport, D. and Badawy, N.M. (2025), "Effects of retrofit strategies on thermal comfort and energy performance in social housing for current and future weather scenarios", Buildings, Vol. 15 No. 80, available at: https://doi.org/10.3390/buildings15010080

British Electrotechnical and Allied Manufacturers Association (2006), Energy Efficient Ventilation in Dwellings – A Guide for Specifiers, BEAMA, available at: https://www.beama.org.uk/static/uploaded/0926d783-01b5-4cf1-9d53dc0198e2d0e1.pdf (accessed 29 April 2026)

British Lung Foundation (n.d.), Lung Diseaselung disease in the UK – Big Picture Statistics, available at: https://statistics.blf.org.uk/lung-disease-uk (accessed 29 April 2026)

Chartered Institution of Building Services Engineers (2020), *TM40: Health and Wellbeing in Building Services*, CIBSE, London, ISBN 978-1-912034-51-2 (PDF), 978-1-912034-50-5 (Print).

Chartered Institution of Building Services Engineers (2021), *Guide A: Environmental Design*, CIBSE Publications, London, ISBN 978-1-914583-05-6.

Chenari, B., Dias Carrilho, J. and Gameiro da Silva, M. (2016), “Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review”, *Renewable and Sustainable Energy Reviews*, Vol. 59, pp. 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074

Crawley, J., Wingfield, J. and Elwell, C. (2018), "The relationship between airtightness and ventilation in new UK dwellings", Building Services Engineering Research and Technology, Vol. 40 No. 3, pp. 274–289, available at: https://doi.org/10.1177/0143624418822199

Delgado-Saborit, J.M. (2012), "Use of real-time sensors to characterise human exposures to combustion related pollutants", Journal of Environmental Monitoring, Vol. 14 No. 7, pp. 1824–1837, available at: https://doi.org/10.1039/c2em30148a

Department for Environment, Food and Rural Affairs (2023), Air Quality Appraisal: Damage Cost Guidance, GOV.UK, available at: https://www.gov.uk/government/publications/assess-the-impact-of-air-quality/air-quality-appraisal-damage-cost-guidance (accessed 29 April 2026)

Diaz Lozano Patino, E. and Siegel, J.A. (2018), "Indoor environmental quality in social housing: a literature review", Building and Environment, Vol. 131, pp. 1–11, available at: https://doi.org/10.1016/j.buildenv.2018.01.013

Dimitroulopoulou, C. (2012), "Ventilation in European dwellings: a review", Building and Environment, Vol. 47, pp. 109–125, available at: https://doi.org/10.1016/j.buildenv.2011.07.016

Dimitroulopoulou, C., Crump, D., Coward, S.K.D., Brown, B., Squire, R., Mann, H. and Ross, D. (2005), Ventilation, Air Tightness and Indoor Air Quality in New Homes, BR477, BRE Bookshop, Watford, ISBN 9781860816833

Du, L., Batterman, S., Godwin, C. and Rowe, Z. (2015), "Air exchange rates and migration of VOCs in basements and residences", Indoor Air, Vol. 25 No. 6, pp. 676–687, available at: https://doi.org/10.1111/ina.12178

European Commission: Joint Research Centre, Marin Ferrer, M., Poljanšek, K., Clark, I. and De Groeve, T. (2017), Science for Disaster Risk Management 2017: Knowing Better and Losing Less, Publications Office of the European Union, Luxembourg, available at: https://data.europa.eu/doi/10.2788/842809

Fernández-Agüera, J., Domínguez-Amarillo, S., Alonso, C. and Martín-Consuegra, F. (2019), "Thermal comfort and indoor air quality in low-income housing in Spain: the influence of airtightness and occupant behaviour", Energy and Buildings, Vol. 199, pp. 102–114, available at: https://doi.org/10.1016/j.enbuild.2019.06.052

Fisk, W.J. and Rosenfeld, A.H. (2000), "Health and productivity gains from better indoor environments and their relationship with building energy efficiency", Annual Review of Energy and the Environment, Vol. 25 No. 1, pp. 537–566, available at: https://doi.org/10.1146/annurev.energy.25.1.537

Franchi, M., Carrer, P., Kotzias, D., Rameckers, E.M., Seppänen, O., van Bronswijk, J.E., Viegi, G., Gilder, J.A. and Valovirta, E. (2006), "Working towards healthy air in dwellings in Europe", Allergy, Vol. 61 No. 7, pp. 864–868, available at: https://doi.org/10.1111/j.1398-9995.2006.01106.x

Gligorovski, S. (2016), "Nitrous acid (HONO): an emerging indoor pollutant", Journal of Photochemistry and Photobiology A: Chemistry, Vol. 314, pp. 1–5, available at: https://doi.org/10.1016/j.jphotochem.2015.06.008

Guo, H., Lee, S.C., Chan, L.Y. and Li, W.M. (2004), "Risk assessment of exposure to volatile organic compounds in different indoor environments", Environmental Research, Vol. 94 No. 1, pp. 57–66, available at: https://doi.org/10.1016/s0013-9351(03)00035-5

Hänninen, O., Lebret, E., Ilacqua, V., Katsouyanni, K., Künzli, N., Srám, R. and Jantunen, M. (2004), "Infiltration of ambient PM2.5 and levels of indoor generated non-ETS PM2.5 in residences of four European cities", Atmospheric Environment, Vol. 38 No. 37, pp. 6411–6423, available at: https://doi.org/10.1016/j.atmosenv.2004.07.015

Harrison, R. (2018), Associations of Long-Term Average Concentrations of Nitrogen Dioxide with Mortality, COMEAP, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734799/COMEAP_NO2_Report.pdf (accessed 29 April 2026)

Hashemi, A. and Dungrani, M. (2025), "Indoor environmental quality and health implications of building retrofit and occupant behaviour in social housing", *Sustainability*, Vol. 17 No. 1, p. 264. https://doi.org/10.3390/su17010264

Health and Safety Executive (2020), EH40/2005 Workplace Exposure Limits: Containing the List of Workplace Exposure Limits for Use with the Control of Substances Hazardous to Health Regulations 2002 (as amended), 4th ed., The Stationery Office, available at: https://www.hse.gov.uk/pubns/books/eh40.htm (accessed 29 April 2026)

HM Government (2010), Approved Document F: Ventilation, 2010 ed., available at: https://www.gov.uk/government/publications/ventilation-approved-document-f (accessed 29 April 2026)

HM Government (2021), Approved Document L: Conservation of Fuel and Power, Volume 1: Dwellings, 2021 edition incorporating 2023 amendments, HM Government, London, ISBN 978-1-914124-78-5, available at: https://assets.publishing.service.gov.uk/media/662a2e3e55e1582b6ca7e592/Approved_Document_L__Conservation_of_fuel_and_power__Volume_1_Dwellings__2021_edition_incorporating_2023_amendments.pdf (accessed 29 April 2026)

Howieson, S., Sharpe, T. and Farren, P. (2013), "Building tight – ventilating right? How are new air tightness standards affecting indoor air quality in dwellings?", Building Services Engineering Research and Technology, Vol. 35 No. 5, pp. 475–487, available at: https://doi.org/10.1177/0143624413510307

Hromadka, J., Korposh, S., Partridge, M.C., James, S.W., Davis, F., Crump, D. and Tatam, R.P. (2017), "Multi-parameter measurements using optical fibre long period gratings for indoor air quality monitoring", Sensors and Actuators B: Chemical, Vol. 244, pp. 217–225, available at: https://doi.org/10.1016/j.snb.2016.12.050

Institute of Air Quality Management (2020), Appendix: Indoor Air Quality Assessment Levels, IAQM, available at: https://iaqm.co.uk/wp-content/uploads/2013/02/Interim-PS-IAQ-Assessment-Levels-Appendix_20200617-1.pdf (accessed 29 April 2026)

Jung, C., El Samanoudy, G. and Mahmoud, N.S.A. (2025), "Sustainable indoor air quality solutions: evaluating charcoal-based adsorbent materials in construction", Smart and Sustainable Built Environment, available at: https://doi.org/10.1108/SASBE-02-2025-0087

Kempton, L., Daly, D., Kokogiannakis, G. and Dewsbury, M. (2022), "A rapid review of the impact of increasing airtightness on indoor air quality", Journal of Building Engineering, Vol. 57, 104798, available at: https://doi.org/10.1016/j.jobe.2022.104798

Koivisto, A.J., Kling, K.I., Hänninen, O., Jayjock, M., Löndahl, J., Wierzbicka, A., Fonseca, A.S., Uhrbrand, K., Boor, B.E., Jiménez, A.S., Hämeri, K., Maso, M.D., Arnold, S.F., Jensen, K.A., Viana, M., Morawska, L. and Hussein, T. (2019), "Source specific exposure and risk assessment for indoor aerosols", Science of the Total Environment, Vol. 668, pp. 13–24, available at: https://doi.org/10.1016/j.scitotenv.2019.02.398

Kukadia, V. and Upton, S. (2019), Ensuring Good Indoor Air Quality in Buildings, BRE Trust, Watford, available at: https://bregroup.com/documents/d/bre-group/Ensuring-Good-IAQ-in-Buildings-Trust-report_compressed-2 (accessed 29 April 2026)

Laumbach, R.J. and Kipen, H.M. (2005), "Bioaerosols and sick building syndrome: particles, inflammation, and allergy", Current Opinion in Allergy and Clinical Immunology, Vol. 5 No. 2, pp. 135–139, available at: https://doi.org/10.1097/01.all.0000162305.05105.d0

Less, B., Mullen, N., Singer, B. and Walker, I. (2015), "Indoor air quality in 24 California residences designed as high-performance homes", Science and Technology for the Built Environment, Vol. 21 No. 1, pp. 14–24, available at: https://doi.org/10.1080/10789669.2014.961850

Ma, Q., Wang, T., Liu, C., He, H., Wang, Z., Wang, W. and Liang, Y. (2017), "SO2 initiates the efficient conversion of NO2 to HONO on MgO surface", Environmental Science and Technology, Vol. 51 No. 7, pp. 3982–3990, available at: https://doi.org/10.1021/acs.est.6b05952

Maciejewska, M., Azizah, A. and Szczurek, A. (2024), "IAQ prediction in apartments using machine learning techniques and sensor data", Applied Sciences, Vol. 14 No. 10, 4249, available at: https://doi.org/10.3390/app14104249

Mannan, M. and Al-Ghamdi, S.G. (2021), "Indoor air quality in buildings: a comprehensive review on the factors influencing air pollution in residential and commercial structure", International Journal of Environmental Research and Public Health, Vol. 18 No. 6, 3276, available at: https://doi.org/10.3390/ijerph18063276

McGill, G., Oyedele, L.O. and McAllister, K. (2015), "An investigation of indoor air quality, thermal comfort and sick building syndrome symptoms in UK energy efficient homes", Smart and Sustainable Built Environment, Vol. 4 No. 2, pp. 146–161, available at: https://doi.org/10.1108/SASBE-01-2015-0003

McKay, S., Ross, D., Mawditt, I. and Kirk, S. (2010), Ventilation and Indoor Air Quality in Part F 2006 Homes, Department for Communities and Local Government, Report BD2702, available at: https://www.gov.uk/government/publications/ventilation-and-indoor-air-quality-in-new-homes (accessed 29 April 2026)

Mendell, M.J., Eliseeva, E.A., Davies, M.M., Spears, M., Lobscheid, A., Fisk, W.J. and Apte, M.G. (2013), "Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools", Indoor Air, Vol. 23 No. 6, pp. 515–528, available at: https://doi.org/10.1111/ina.12042

Narayanan, V.V., Hashemi, A., Elsharkawy, H. and Newport, D.J. (2024), "Comparative assessment of insulation materials for improving indoor air quality in building retrofit", Environmental Science and Sustainable Development, Vol. 9 No. 2, available at: https://doi.org/10.21625/essd.v9i2.1071

Narayanan, V.V., Shaikh, R.R., Hashemi, A., Elsharkawy, H., Newport, D. and Basaly, L.G. (2024), "Analysing indoor air pollution: a study on pollutant levels and air quality assessment in social housing properties", Environmental and Sustainability Studies, Vol. 9 No. 3, available at: https://doi.org/10.21625/essd.v9i3.1072

National Institute of Standards and Technology (2021), CONTAM: Multizone Airflow and Contaminant Transport Analysis Software, NIST, available at: https://www.nist.gov/services-resources/software/contam (accessed 29 November 2024)

NIOSH (2014a), Documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs): Carbon Monoxide, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Atlanta, GA, available at: https://www.cdc.gov/niosh/idlh/630080.html (accessed 29 April 2026)

NIOSH (2014b), Documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs): Carbon Dioxide, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Atlanta, GA, available at: https://www.cdc.gov/niosh/idlh/124389.html (accessed 29 April 2026)

Persily, A.K. (2016), "Field measurement of ventilation rates", Indoor Air, Vol. 26 No. 1, pp. 97–111, available at: https://doi.org/10.1111/ina.12193

Public Health England (2019), Respiratory Disease: Applying All Our Health, Public Health England, London, available at: https://www.gov.uk/government/publications/respiratory-disease-applying-all-our-health/respiratory-disease-applying-all-our-health (accessed 29 April 2026)

Pyke, C.R. (2020), Guide to Arc Re-Entry v1.1, ArcSkoru LLC, Washington, DC, available at: https://www.arcskoru.com/sites/default/files/Arc%20Guide%20to%20Re-Entry.pdf (accessed 29 April 2026)

Semple, S., Garden, C., Coggins, M., Galea, K.S., Whelan, P., Cowie, H., Sánchez-Jiménez, A., Thorne, P.S., Hurley, J.F. and Ayres, J.G. (2012), "Contribution of solid fuel, gas combustion, or tobacco smoke to indoor air pollutant concentrations in Irish and Scottish homes", Indoor Air, Vol. 22 No. 3, pp. 212–223, available at: https://doi.org/10.1111/j.1600-0668.2011.00755.x

Smith, L. (2025), Air Quality: Policies, Proposals and Concerns, House of Commons Library Research Briefing, available at: https://commonslibrary.parliament.uk/research-briefings/cbp-8302/ (accessed 29 April 2026)

Sultan, Z., Nilsson, G.J. and Magee, R. (2011), "Removal of ultrafine particles in indoor air: performance of various portable air cleaner technologies", HVAC&R Research, Vol. 17 No. 4, pp. 513–525, available at: https://doi.org/10.1080/10789669.2011.579219

Taylor, J., Shrubsole, C., Davies, M., Biddulph, P., Das, P., Hamilton, I., Vardoulakis, S., Mavrogianni, A., Jones, B. and Oikonomou, E. (2014), "The modifying effect of the building envelope on population exposure to PM2.5 from outdoor sources", Indoor Air, Vol. 24 No. 6, pp. 639–651, available at: https://doi.org/10.1111/ina.12116

Tochihara, Y. and Ohnaka, T. (Eds.) (2005), *Environmental Ergonomics: The Ergonomics of Human Comfort, Health and Performance in the Thermal Environment*, Elsevier, Oxford. https://doi.org/10.1016/B978-008044465-9/50000-4

Tran, V.V., Park, D. and Lee, Y. (2020), "Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality", International Journal of Environmental Research and Public Health, Vol. 17 No. 8, 2927, available at: https://doi.org/10.3390/ijerph17082927

Turk, B.H., Prill, R.J., Fisk, W.J., Grimsrud, D.T., Moed, B.A. and Sextro, R.G. (1990), "Effectiveness of radon control techniques in fifteen homes", *Journal of the Air & Waste Management Association*, Vol. 40 No. 5, pp. 723–734. https://doi.org/10.1080/10473289.1990.10466721