



BIRMINGHAM CITY
University

Pathways to Improving Indoor Air Quality and Occupant Health in New Homes in the UK.

Mohamed A. Barre

College of Built Environment & Engineering

Birmingham City University

Director of Studies: Associate Professor MONICA MATEO-GARCIA

Second supervisor: Dr EMMANUEL ABOAGYE-NIMO

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

September 2025

Abstract

Poor indoor air quality (IAQ) in new UK homes has become a growing concern due to its implications for human health and well-being. IAQ is increasingly important as people spend a significant portion of their time indoors. This concern is exacerbated by more airtight, energy-efficient construction, which can reduce natural ventilation and increase reliance on installed systems and occupant practices. In response, the UK Building Regulations address ventilation (Part F), while energy-efficiency requirements for new homes are set out in Part L. However, delivering these standards is complex because IAQ is influenced not only by building form and materials but also by interacting factors across design, systems, and occupancy, making it a multifaceted challenge. Therefore, effective IAQ solutions cannot be purely technical, particularly as they need to be applied to mass-market housing. This research investigates how decision-making across the home development process influences IAQ, and how a holistic, systemic approach can be implemented to address interconnected factors while avoiding unintended consequences of isolated interventions. The study aims to improve IAQ in mass-market housing by investigating pathways through which these factors interact and by identifying cost-effective solutions and mitigation strategies.

A practice-based, mixed-methods multiple-case study was conducted on six recently built UK homes. A variety of data collection techniques were employed, including extended IAQ monitoring and targeted experiments (i.e., cooking as a pollutant-generating activity). To establish a baseline, several homes were monitored during unoccupied periods. These data were triangulated with occupant surveys, daily activity diaries, and semi-structured interviews with occupants to link IAQ patterns to household practices and system use. Interviews with housing developer professionals were also conducted to investigate how decisions affecting IAQ are made throughout planning, design, construction, handover and occupation.

The findings show that IAQ outcomes result from the combined effects of pollutant-generating activities, ventilation system specification and integration, and occupant understanding and adaptation. Determining the cause of inadequate air quality was often nonlinear, as poor air quality could stem from materials and products introduced into the building, their integration, or the occupants' overall activities. The analysis of the home development process revealed that the current approach does not adequately address decision-making at all stages, instead

prioritising regulatory compliance and post-occupancy responses only after problems have arisen.

This thesis contributes empirical, behavioural, and process-based insights into IAQ in new homes and demonstrates how IAQ outcomes emerge from interconnected decisions involving building design, technologies and systems, occupant behaviour, and the home development process. It develops a Pathways Approach Framework that translates these findings into a structured, system-based decision-support approach for mass-market UK housing delivery. The impact of the work is to support more informed, holistic IAQ decision-making across planning, design, construction, handover, and use, while enabling occupants to play an active role in maintaining healthier indoor environments.

List of Abbreviations.

CO	–	Carbon Monoxide
CO ₂	–	Carbon Dioxide
EU	–	European Union
IAP	–	Indoor Air Pollution
IAQ	–	Indoor Air Quality
IEQ	–	Indoor Environmental Quality
NO _x	–	Nitrogen Oxides
NO ₂	–	Nitrogen Dioxide
O ₃	–	Ozone
PHE	–	Public Health England
PM	–	Particulate Matter
PVC	–	Polyvinyl Chloride
RH	–	Relative Humidity
SBS	–	Sick Building Syndrome
SO ₂	–	Sulphur Dioxide
VOCs	–	Volatile Organic Compounds
SVOC	–	Semi-Organic Compound
TVOC	–	Total Volatile Organic Compound
UK	–	United Kingdom
VOC	–	Volatile Organic Compound
WHO	–	World Health Organisation

Contents:

List of Abbreviations.....	4
List of tables.....	10
List of Figures.....	11
Acknowledgements.....	14
Chapter 1. Introduction.....	15
1.1 Background of Study.....	15
1.1.1 The Importance of IAQ.....	18
1.1.2 The Role of Building Practices and IAQ.....	19
1.1.3 From Conventional Solutions to a Holistic Approach.....	21
1.2 Problem Statement.....	22
1.2.1 The Problem of Health.....	23
1.2.2 The Emissions of Building Products.....	23
1.2.3 Challenges of Energy Efficiency and Ventilation.....	24
1.2.4 The Problem of Occupant Activities and Lifestyle.....	24
1.2.5 The Home Development Process and IAQ.....	25
1.3 The Research Aims, Objectives and Questions.....	26
1.4 Introduction to the Pathway Approach.....	27
1.4.1 Defining the Pathway Approach.....	27
1.5 Research Design and Scope.....	29
1.6 Thesis Structure.....	30
1.7 Chapter Conclusion.....	32
Chapter 2. Literature Review.....	33
Introduction.....	33
2.1 Indoor Pollutants and Health Effects.....	33
2.1.1 Introduction to Key Themes in IAQ Research.....	34
2.2 Indoor Pollutant Sources and Emissions Characteristics.....	35
2.2.1 Classification of Indoor Pollutants.....	36
2.2.2 Relationship between Indoor and Outdoor (I/O) Air Quality.....	40
2.2.3 Indoor Chemistry and Secondary Pollutant Formation.....	41
2.2.4 Pollutant Sources and Emission Behaviour.....	44
2.2.5 Health Effects of Indoor Pollutants.....	47
2.3 Building Design and IAQ.....	50
2.3.1 Pollutants from Building Design and Material Choices.....	50

2.4	Building Technology and Equipment.....	55
2.4.1	Ventilation Principles.....	56
2.4.2	Ventilation System Design, Performance, and Commissioning.....	59
2.4.3	Appliances and Source Control in IAQ.....	62
2.5	Occupant Behaviour: Lifestyles, Awareness, and Practices.....	65
2.5.1	Occupant Behaviour.....	65
2.5.2	Occupant Activity and Lifestyle Choices.....	66
2.5.3	Cooking Activities and IAQ.....	67
2.5.4	The Role of Occupants in IAQ Management.....	68
2.5.5	Occupant Perception, Knowledge, and Awareness.....	71
2.6	Home Development Process and IAQ.....	72
2.6.1	Industry Stakeholders and Decision-Making.....	74
2.6.2	Opportunities for Integrating IAQ Considerations.....	75
2.7	Building Regulations and Standards for IAQ.....	75
2.7.1	Standards, Legislation and Guidelines for Indoor Pollution.....	78
2.8	Research Gap and Significance.....	79
2.9	Chapter Conclusion.....	82
Chapter 3.	Methodology.....	84
	Introduction.....	84
3.1	The Conceptual Framework.....	84
3.1.1	Framework Development.....	85
3.1.2	Cross-Section of the Pathways.....	90
3.2	Research Methodology.....	93
3.3	Research Philosophy.....	94
3.3.1	Research Paradigm.....	95
3.3.2	Pragmatism.....	97
3.3.3	Approach to Theory.....	98
3.3.4	Methodological Choice.....	99
3.3.5	Research Strategy.....	100
3.3.6	Time Horizon.....	101
3.3.7	Overview of the research process.....	103
Chapter 4.	Data Collection and Analysis Methods.....	105
	Introduction.....	105
4.1	Buildings Studied. monitoring.....	105
4.2	Case Study Approach.....	106
4.2.1	Rationale for case study approach.....	107

4.2.2	Case Study Design.....	109
4.2.3	Limitations of the case study approach.	109
4.2.4	Research Sampling.	110
4.3	Recruitment of the Homes and Site Description.	112
4.3.1	Household Characteristics.....	113
4.4	Monitoring and Instrumentation.	122
4.4.1	Co-location test for the uHoo Aura sensor validation.....	126
4.4.2	Monitoring Plan and Sensors.	127
4.4.3	Selection Value.....	127
4.4.4	Units of Measurement and Threshold Values.....	128
4.5	Interviews.....	129
4.5.1	Data Collection Sequence.....	130
4.5.2	Occupant Interviews.....	131
4.6	Home Development Process Interviews.	133
4.6.1	Data Processing and Analysis.	135
4.6.2	Quantitative and Qualitative Analysis.	137
4.7	Home Development Process Analysis.	140
4.7.1	Thematic and Conceptual visualisation.	142
4.8	Triangulation.	143
4.9	Reliability and Validity.....	144
4.9.1	Reliability.....	145
4.9.2	Validity.....	145
4.9.3	Ethical Concentration.	146
4.10	Chapter Conclusion.	147
Chapter 5.	Results and Discussion.	148
Introduction	.....	148
5.1	Building design and materials.	150
Introduction	.....	150
5.1.1	Baseline pollutant levels.	150
5.1.2	Building design and indoor air pollutant movement experiment.	155
Summary of the experiment.	.....	159
5.1.3	Discussion of building design.	160
5.2	Occupation.	162
5.2.1	Influence of Occupants on IAQ.....	163
5.2.2	Cooking experiment in CS1 & CS3.....	169
5.2.3	Occupant Interview and Questionnaire Results.	172

Section summary.....	181
5.2.4 Behavioural Change Experiment – A Mixed-Methods Evaluation of Awareness and Daily Practices.....	182
5.2.5 Occupant Daily Diary.....	188
Section summary.....	193
5.3 Technology and Systems.....	194
5.3.1 Ventilation system.....	195
5.3.2 Discussion of technology and systems.....	198
Section summary.....	202
5.4 Home Development Process Results and Discussion.....	203
5.4.1 Interview Findings: Decision-Making Processes in New UK Home Development and IAQ. 204	
Section summary.....	214
5.4.2 Discussion of the research findings.....	216
5.4.3 Chapter Conclusion.....	218
Chapter 6. Developing Pathways Approach to IAQ Improvement.....	220
Introduction.....	220
6.1 Key Findings Informing the Pathways Approach.....	221
6.1.1 Home Development Process.....	221
6.1.2 Pathway 1: Site (Contextual Solution).....	222
6.1.3 Pathway 2: Building (Design & Technology).....	224
6.1.4 Pathway 3: Occupation (Behaviour & Maintenance).....	226
6.1.5 The Process of Pathways.....	228
6.2 Proposed Framework for Scalable and Adaptable IAQ Solutions.....	230
Introduction.....	230
6.2.1 Integrating the Pathways Approach in line with the RIBA Plan of Work for IAQ Solutions.....	235
Summary.....	238
6.2.2 Scenarios for Pathway Implementations.....	238
Introduction.....	238
6.3 Chapter Summary.....	243
Chapter 7. Conclusions and Recommendations.....	245
Introduction.....	245
7.1 Key findings in achieving the research aim and objectives.....	245
7.2 Key Findings in Relation to Research Questions.....	247
7.2.1 RQ1.....	247
7.1.2 RQ2.....	248

7.3	Research Overall Contribution	249
7.4	Recommendations & Implications.....	252
7.5	Main Conclusion.....	254
7.6	Main Limitations of the Study.....	256
7.7	Future Research.....	257
7.8	Final Research Journey Note.....	258
Chapter 8	References.....	260
Appendices.....		308
APPENDIX A:	Research Ethics Approval.....	308
	.....	309
APPENDIX B:	Home Occupant Information Leaflet and Consent Form	309
	.....	311
APPENDIX C:	Interview Guide for Housing Developers.....	311
APPENDIX D:	Occupant Daily Diary	313
APPENDIX E:	Occupant's IAQ Perceptions Questionnaire.....	314

List of tables.

<i>Table 2. 1: Classifications of Volatile Organic Compounds (VOCs) and associated measurement units WHO (2010).</i>	37
<i>Table 2. 2: Indoor air pollutants, sources, and associated health impacts (EPA, 2017).</i>	49
<i>Table 2. 3: Summary of reported case studies on pollutant emissions from selected building materials.</i>	52
<i>Table 2. 4: Studies investigating the impact of occupant behaviour interventions on IAQ in homes.</i> .	69
<i>Table 2 5: IAQ Labelling Schemes and Emission Limit criteria adopted across Europe.</i>	77
<i>Table 3 1: Description of research paradigms and their relationships (Sounders et al., 2009).</i>	96
<i>Table 3 2: Distinctions between deductive, inductive, and abductive research approaches and their application in this study (adapted from Saunders et al., 2016a).</i>	99
<i>Table 4 1: Household and building characteristics of the six studied homes (CS1–CS6).</i>	115
<i>Table 4 2: Specifications and operational details of sensor equipment utilised in this research.</i>	122
<i>Table 4 3: Types of uHoo smart sensors, measurement ranges, resolution, and accuracy.</i>	123
<i>Table 4 4: Pollutant measurement units and associated threshold values.</i>	129
<i>Table 4 5: Summaries of conducted interviews, chronological order, and anonymised participant details.</i>	135
<i>Table 5. 1: Comparison of pollutant concentrations between kitchens and living rooms across (CS1, CS2, and CS3).</i>	159
<i>Table 5 2: Occupancy characteristics, Lifestyle factors, and Building Usage Pattern across case studies.</i>	167
<i>Table 5. 3: Comparative Analysis of PM_{2.5}, TVOC, and CO₂ concentrations across case studies.</i> ..	181
<i>Table 5. 4: Overview of ventilation systems installed in case study homes.</i>	194
<i>Table 5 5: Interview guide structure and thematic sections.</i>	205
<i>Table 7 1: Mapping of research aims, objectives, and questions against thesis findings.</i>	246

List of Figures.

<i>Figure 2. 1: Mechanism of pollutant capture and transformation by plasterboard in indoor environments (Author’s illustration).</i>	42
<i>Figure 2. 2: Diversity of indoor air and associated reactive compounds (Wolkoff and Nielsen, 2001).</i>	44
<i>Figure 2. 3: Sources of indoor pollutants within buildings (RCP, 2016).</i>	46
<i>Figure 2. 4: Examples of common outdoor (blue) and indoor (red) pollutants and sources influencing IAQ. (Adapted from Kukadia and Upton, 2019).</i>	54
<i>Figure 3. 1: Conceptual framework illustrating key factors influencing IAQ and health in the UK home.</i>	91
<i>Figure 3. 2 : Research onion illustrating the methodological structure of the study (Saunders et al., 2016a).</i>	94
<i>Figure 3. 3: Deductive and inductive reasoning approaches in research (adapted from William, 2006).</i>	98
<i>Figure 3. 4: Research choices within the adopted methodological approach (adapted from Saunders et al., 2016a).</i>	100
<i>Figure 3. 5 : Phases of the research design process.</i>	103
<i>Figure 3. 6: Overview of the research methodology.</i>	104
<i>Figure 4. 1: Heatmap showing monitoring coverage of case-study houses throughout the entire monitoring period.</i>	106
<i>Figure 4. 2: Sampling methods employed in the study (adapted from Saunders et al., 2016a).</i>	111
<i>Figure 4. 3: Map of the UK showing the geographical distribution of the studied homes.</i>	112
<i>Figure 4. 4: Overview of research participant homes, monitoring timeline, and key specifications.</i>	113
<i>Figure 4. 5: IAQ sensor placement indicating pollutant stratification in relation to occupant breathing zone (adapted from iota.org).</i>	125
<i>Figure 4. 6: Co-location test configuration using eight uHoo Aura sensors (left).</i>	126
<i>Figure 4. 7: Co-Location test Results: Eight uHoo Aura sensors measuring IAQ parameters over 7 days (Right).</i>	126
<i>Figure 4. 8: Spearman’s correlation matrix illustrating relationships between IAQ parameters in CSI.</i>	128
<i>Figure 4. 9: NVivo nodes illustrating interview themes and code structure.</i>	141

<i>Figure 4 10: Triangulation of quantitative and qualitative data (adapted from Amaratunga et al., 2002).</i>	144
<i>Figure 5. 1: IAQ parameters (temperature, RH, TVOC, and PM2.5) in unoccupied home CS1 over a two-week analysis period.</i>	151
<i>Figure 5. 2: IAQ parameters (temperature, RH, TVOC, and PM2.5) in an unoccupied home CS2 over a two-week monitoring period.</i>	152
<i>Figure 5 3: IAQ parameters (temperature, RH, TVOC, and PM2.5) in an unoccupied home CS3 during a two-week analysis period.</i>	153
<i>Figure 5 4 Comparison of air pollutant movement between the kitchen and the living room in CS1.</i>	156
<i>Figure 5. 5: Air-pollutant movement in CS2-Birmingham: Kitchen vs Living Room.</i>	157
<i>Figure 5. 6 Comparison of air pollutant movement between the kitchen and the living room in CS3.</i>	158
<i>Figure 5. 7: IAQ analysis of occupied homes during a two-week monitoring period (first week of July and August 2022).</i>	163
<i>Figure 5. 8: Comparative IAQ analysis of occupied homes across two separate two-week monitoring periods in July and August 2022.</i>	164
<i>Figure 5. 9: Temporal variation in IAQ parameters in occupied homes during the first week of July and August 2022.</i>	165
<i>Figure 5. 10: Kitchen-based IAQ experiments using the AURA sensor during cooking activities (31 July 2022, 20:50–22:23, and 20 August 2022, 20:50–22:23).</i>	169
<i>Figure 5. 11: Short -duration kitchen experiments using the AURA sensor to assess pollutant generation during cooking (July 14, 2022, from 15:20 to 15:50, and on July 15, 2022, from 15:20 to 16:00).</i>	171
<i>Figure 5. 12: Occupant responses to Question 1 on perceived IAQ.</i>	173
<i>Figure 5. 13: Main reasons for window opening reported by occupants (CS1 to CS6).</i>	174
<i>Figure 5. 14: Factors preventing window opening among occupants.</i>	175
<i>Figure 5. 15: Window operation preferences during cooking and cleaning activities (CS1 to CS6).</i>	176
<i>Figure 5. 16: Comparison of one week without and one week with the IAQ sensor dashboard in CS5.</i>	184
<i>Figure 5. 17: Example of the occupant engagement with IAQ sensor data shared by the occupant.</i>	185
<i>Figure 5. 18: Comparison of one week without and one week with the IAQ sensor dashboard in CS6.</i>	186
<i>Figure 5. 19: Occupant daily diary logging tool.</i>	189
<i>Figure 5. 20: Weekly summaries of indoor environmental source activities across all case studies (CS1–CS6).</i>	190

Figure 5. 21: Kitchen window in a partially open position, illustrating occupant ventilation preference during cooking. 195

Figure 5. 22: Word cloud of the most frequent terms in NVivo-coded interview transcripts related to the home development process. 204

Figure 5. 23: Key decision-making points impacting IAQ throughout UK home development stages, based on the interview results. 214

Figure 5. 24: Stages of stakeholder involvement in the home development process. 215

Figure 6. 1: Integration of the Pathways Approach within the home development process. 229

Figure 6. 2: Proposed Pathways framework for improving IAQ in new UK homes. 232

Acknowledgements.

Suggesting that this doctoral thesis was solely the result of my individual effort would be unfair to the direct and indirect support I received from many throughout my journey. First and foremost, I offer my deepest gratitude to ALLAH, the Almighty, for His infinite mercy, guidance, and protection. Without His provision and sustenance, none of this would have been possible.

I sincerely appreciate my supervisory team: Dr Monica Mateo-Garcia, Prof. David Boyd, and Dr Emmanuel Abouagye-Nimo. Thank you for your unwavering support and encouragement throughout this journey. Your support, patience, guidance, and friendship have been invaluable, and I am deeply grateful for your detailed feedback on countless drafts and presentations throughout this research. I also thank Dr Callistus Gero, my fellow PhD researcher, for your encouragement and collaboration, which made this journey both productive and enjoyable. This research would not have been possible without the generous sponsorship and practical support of the industry partners: Barratt Homes, Taylor Wimpey, Redrow, Midland Heart, and Building Alliance. Special thanks to Mike Leonard of Building Alliance, who guided me through the corporate aspects of the research and provided valuable access to industry networks. Your sponsorship, insights, and willingness to facilitate access to homes for monitoring were crucial to the success of this study.

My heartfelt thanks go to my family, especially my children, for their unwavering love, support, and encouragement throughout this journey. To my son Shire, for his encouragement, for enduring the many frustrations that came his way, and for his unconditional support. To Shirwa, who constantly checked on me, prayed for me, and uplifted me during the most challenging times. To Sharmaake, Idil, and Iman, I am deeply grateful. As the first in my family to reach this academic milestone, I hope to inspire you all to pursue even greater ambitions.

I am also grateful to Birmingham City University, especially Prof. Georgios Fournalis, Head of the College of Built Environment, for approving partial funding to complete this PhD. I would also like to thank the Doctoral Research College office for their administrative support and all staff members and colleagues who have provided assistance along the way. A special word of thanks to Stephen Scaysbrook for his encouragement at the start of this journey. I also wish to acknowledge my friends and colleagues for their support. To everyone who contributed, directly or indirectly, to this journey, thank you. Your support has been invaluable in completing this thesis.

Chapter 1. Introduction.

Indoor air quality (IAQ) is an indispensable component of human health, comfort, and productivity, yet it remains one of the most complex and often overlooked aspects of the built environment. IAQ is a rapidly growing area of public health research due to modern lifestyles, which result in people spending most of their time indoors. The quality of indoor air is not a single, isolated parameter but rather the outcome of complex interactions between multiple factors.

This chapter provides an overview of the thesis, outlining the research background and highlighting the importance of Indoor Air Quality (IAQ) and the problems associated with poor IAQ. It presents the research aims, objectives, and questions, along with the study's scope, justification, and limitations. In addition, the chapter summaries of the research design and thesis structure conclude with a summary of the chapter.

1.1 Background of Study.

Over the last few decades, there has been substantial development in both the intensity of challenges to Indoor Air Quality (IAQ) and in the understanding of the relationships and causalities among the various parameters that impact IAQ. IAQ has a direct impact on occupant health, productivity, and performance (Uhde & Salthammer, 2007; Holgate, 2017). The indoor environment has never been more important, as people spend up to 90% of their time indoors (Morawska & Huang, 2022; Holgate, 2017), making indoor air quality a major public health concern (RCP & RCPCH, 2016).

Exposure to unhealthy indoor environmental conditions is identified as one of the most significant indoor health hazards affecting the global population (Kelly & Fussell, 2019). This includes air pollution and its health impacts, which contribute to premature deaths worldwide (COMEAP, 2018). As reviewed by Brook et al. (2010) and the WHO (2013), exposure to air pollution is associated with a wide range of health problems, including allergies, asthma, and other respiratory diseases. According to the WHO (2014), approximately 4.3 million deaths worldwide each year are caused by indoor air pollution, contributing significantly to the global disease burden. Furthermore, RCP (2019) reports that air pollution in the UK is associated with approximately 40,000 deaths per annum. Other studies also estimate that the number of fatalities is between 36,000 and 65,000 (COMEAP, 2018). In contrast to ambient air, indoor air

has received less attention, despite various studies indicating that pollutant levels are often several times higher indoors than outdoors (Chen and Zhao, 2011).

IAQ is a complex, multidimensional problem that is perceived differently by different people. It is closely linked with comfort alongside short- and long-term health problems. The term IAQ involves the environmental characteristics such as air temperature, relative humidity, pollutant concentrations, and ventilation rates, all of which can affect human health, comfort, and performance (EPA, 2014). There have been considerable changes in indoor air structure and characteristics due to shifts in household products, building materials, and operational practices, making IAQ exposure a dynamic problem (Weschler, 2009; Jacobs et al., 2009).

There has been a dramatic increase in the chemical content of consumer products, building materials, and furnishings, which are significant sources of air pollutants (Jacobs et al., 2009). The design and specification of buildings, including material choices, layout, and construction detailing, directly affect the presence and persistence of indoor pollutants (Woolley, 2024). Modern building design increasingly prioritises energy efficiency through improved insulation and airtightness (Ministry of Housing, 2021; Carrié et al., 2021). Additionally, the building's location context, including proximity to sources of outdoor pollution, has a substantial impact on indoor pollutant levels (Vardoulakis et al., 2020). As buildings become more airtight to conserve energy, there is a risk of unintentionally trapping indoor pollutants, particularly if ventilation is inadequate or poorly designed (Sharpe et al., 2020). While energy efficiency remains a regulatory and commercial priority, IAQ can become a secondary consideration, resulting in unintended consequences for occupant health (Dimitroulopoulou et al., 2023).

Key indoor pollutants include volatile organic compounds (VOCs), particulate matter (PM), carbon dioxide (CO₂), nitrogen dioxide (NO₂), and biological contaminants, all of which can originate from building materials, furnishings, heating systems, and occupant activities (Boogaard et al., 2022; Morawska & Huang, 2022). The complexity of IAQ stems from the numerous directions in which physical, chemical, and biological pollutants interact (Weschler, 2015). Determining exposure levels is further complicated by differences in time spent indoors and the range of occupant activities. Vulnerable groups, including children, the elderly, and people with chronic conditions, are at increased risk due to their greater exposure (Sundell, 2004).

Moreover, pollutants can affect people through inhalation, dermal absorption, or contact with clothing and surfaces (Ferguson et al., 2021).

Apart from outdoor emissions, the primary sources of indoor air pollution are combustion-emitted gases and particles, biological contaminants, and household products, including personal care items, cleaning agents, scented candles, and air fresheners (Dimitroulopoulou et al., 2023). The effectiveness of installed technologies and systems, especially ventilation and air filtration, is central to maintaining healthy IAQ (Fisk, 2018; CIBSE, 2020). However, inadequate or poorly maintained systems may fail to remove pollutants or may even exacerbate problems if operated improperly. However, technological advances have led to more sophisticated mechanical ventilation and filtration systems in new homes (CIBSE, 2020). These systems can be complex and not always user-friendly (Van Rooyen & Sharpe, 2024). The lack of adequate handover, commissioning, and user education often leads to improper use or disengagement, undermining the system's effectiveness and design intent (Dimitroulopoulou et al., 2023). Emissions of pollutants from building materials and furniture can be significant, with some studies indicating that indoor concentrations can be up to 7 times higher than outdoor concentrations (McDonald et al., 2018; Chen and Zhao, 2011). There is still limited knowledge of the chemical reactions that occur when various pollutants combine in homes, as well as of the range of gases and particles produced (Gligorovski and Abbatt 2018). Poor IAQ has been associated with concerns about occupants' health and well-being (RCP, 2019), and there is sufficient evidence that its impacts are particularly severe for vulnerable populations (Sundell, 2004).

The overall concentration of a pollutant depends not only on emission sources but also on how occupants interact with the building and its systems (Singer et al., 2020). Daily routines, including cooking, cleaning, and ventilation practices (e.g., window opening), significantly influence indoor pollutant levels (Cincinelli & Martellini, 2017). Differences in occupant knowledge, lifestyle, and cultural habits lead to variability in exposure and risk (Stazi et al., 2017). Perceptions of IAQ and motivation to engage with technological solutions are influenced by occupant experiences, expectations, and socio-economic context (Dimitroulopoulou et al., 2023).

The quality of IAQ in residential buildings is also influenced by the broader home development process, which encompasses planning, design, construction, handover, and aftercare. Decisions made by developers, designers, contractors, and policymakers influence the adoption and integration of IAQ-focused practices and technologies (Persily & Ng, 2022). Constraints such as

regulatory compliance, cost, supply chain limitations, and speed of delivery can impact material selection, system specification, and ultimately, IAQ outcomes. Moreover, the transition to net-zero and the increasing use of off-site construction methods introduce new challenges and opportunities for incorporating IAQ considerations at every stage of development (NHBC, 2023). Achieving a good IAQ is influenced by a complex interplay of regulated design practices, effective ventilation strategies, appropriate technology choices, and the active involvement of stakeholders throughout the home development process.

Given these challenges, understanding IAQ requires a multidisciplinary approach that integrates knowledge from chemistry (Wolkoff, 1995; Weschler, 2011), building physics, materials science, psychology, epidemiology, and health sciences (Samet et al., 1988; Newsham et al., 2013). While considerable work has been done on air quality and health, this knowledge is often inaccessible to design practitioners and building occupants. There is a critical need to bridge this gap by making evidence-based solutions available to building professionals, thus supporting improved IAQ in residential properties (Allen & Ibrahim, 2021).

1.1.1 The Importance of IAQ.

Good-quality indoor air is crucial for maintaining optimal health and well-being. The importance of IAQ on public health is expected to increase, as people typically spend 80 to 90% of their time indoors (Ferguson et al., 2021; WHO, 2018). As individuals spend up to 90% of their time indoors, vulnerable groups, such as children, the elderly, and those with chronic illnesses, often spend nearly all their time in enclosed spaces (Dimitroulopoulou et al., 2017). As a result, exposure to indoor pollutants is closely linked to both acute and chronic health problems, including respiratory irritation, allergies, asthma, cognitive decline, cardiovascular diseases, and even cancer (Rajagopalan et al., 2020). These risks are particularly concerning for children and pregnant women, and those with pre-existing health conditions, where pollutant exposure can lead to long-term developmental and health consequences.

The evolution of IAQ research highlights its growing importance. Early studies in the 1960s examined the health impacts of tobacco smoke (Thompson, 2018), followed by investigations into nitrogen dioxide from gas cooking appliances and formaldehyde from insulation materials (Shrubsole et al., 2019). More recent research and reviews have led to stricter guidelines and increased awareness of pollutants from building materials and household products, including VOCs, PM, and other contaminants (Morawska & Huang, 2022).

Key pollutants include volatile organic compounds (VOCs), carbon dioxide (CO₂), particulate matter, and biological contaminants like mould (ASHRAE, 2017; Morawska & Huang, 2022). Moisture plays a significant role: excessive humidity promotes mould growth, while low humidity can cause respiratory discomfort and static electricity. The optimal range of relative humidity for health and comfort is 40–60%, as deviations from this range increase the risk of respiratory infections and allergies (Arundel et al., 1986). In modern, airtight, energy-efficient buildings, the accumulation of CO₂ and VOCs can become problematic due to potential insufficient ventilation (Moreno-Rangel et al., 2020).

Indoor air pollution is not limited to obvious hazards, such as carbon monoxide from faulty heating appliances or radon, but also includes subtler risks, such as ultrafine particles and emissions from everyday materials and activities (Schweizer et al., 2006). Reports suggest that indoor air pollution can be up to 3.5 times worse than outdoor air, with homes effectively becoming “toxic boxes” due to the cumulative effects of pollution from both indoor and outdoor sources (Shrubsole et al., 2019).

Despite these risks, public awareness of IAQ remains limited compared to outdoor air quality. The UK government’s Clean Air Strategy 2019, alongside the WELL building standard and ongoing research, has emphasised the need for improved information, standards, and action on indoor air quality. Major initiatives, including the UKRI Strategic Priorities Fund and interdisciplinary collaborations, contribute to an increased understanding and management of IAQ (Averchenkova et al., 2020). The COVID-19 pandemic has further intensified interest in indoor environments, as poorly ventilated spaces have been identified as high-risk areas for airborne disease transmission, emphasising the critical role of IAQ in mitigating health risks (Agarwal et al., 2021; Allen & Ibrahim, 2021). Additionally, the push for energy efficiency, resulting in more airtight buildings, can exacerbate IAQ challenges if not balanced by adequate ventilation, highlighting the critical need to manage indoor pollutants while maintaining energy efficiency (Bhagat et al., 2020).

1.1.2 The Role of Building Practices and IAQ.

Building practices significantly influence IAQ and occupant health. New building designs often prioritise energy efficiency, including the development of low-carbon or energy-efficient buildings (Vardoulakis et al., 2015). These structures aim to minimise energy consumption and reduce carbon dioxide (CO₂) emissions, as promoted by policies like the UK’s Climate Change

Act of 2008, which targets an 80% reduction in CO₂ emissions by 2050 ([Climate Change Act, 2008](#); [Averchenkova et al., 2020](#)). Regulations and building codes are increasingly centred on energy conservation. However, prioritising energy efficiency without considering IAQ can have unintended negative consequences for building occupants ([Vardoulakis et al., 2015](#)).

Low-energy designs often result in airtight buildings that restrict natural ventilation. While reducing energy demands, this also traps pollutants such as CO₂, volatile organic compounds (VOCs), and particulate matter (PM) within the indoor environment. Indoor pollutants originate from various sources, including building materials, furniture, heating systems, and occupant activities, as well as external sources such as traffic emissions and industrial pollutants that infiltrate through openings or ventilation systems ([Vardoulakis et al., 2020](#)). For example, a strong correlation between indoor and outdoor nitrogen dioxide (NO₂) levels has been linked to urbanisation and proximity to high-traffic areas ([Hankey & Marshall, 2017](#)).

Energy-efficient strategies can exacerbate IAQ challenges by reducing air exchange rates, potentially leading to pollutant buildup. Studies, such as those by [Goodman & Davies \(2011\)](#) and [Sharpe et al. \(2014\)](#), have demonstrated that inadequate ventilation in airtight buildings results in elevated CO₂, TVOCs, and PM levels, contributing to conditions like sick building syndrome. These poor IAQ conditions are linked to significant health risks, including respiratory illnesses, increased absenteeism, and decreased productivity, with infants and students being particularly vulnerable.

Recent efforts have been made to develop efficient, cost-effective technologies that promote an indoor environment beneficial to health ([Arnesano et al., 2015](#)). The technologies implemented to enhance energy efficiency, such as mechanical ventilation with heat recovery (MVHR) systems, can also introduce new challenges. Building materials, even those labelled as green or low-energy, may emit VOCs, particularly in wood-based products, which can accumulate to harmful levels in poorly ventilated spaces ([Kim et al., 2022](#)). Reducing energy demand and improving energy efficiency are regarded as key strategies for addressing global climate change ([Anderson et al., 2015](#)). However, energy consumption is influenced not only by indoor environmental criteria and the technology employed but also significantly by occupant behaviour ([Paone & Bacher, 2018](#)). This interdependence can lead to conflict between energy-saving strategies and the need to maintain a healthy and comfortable indoor environment. Striking a balance requires aligning building design, climate control systems, and the

occupants' needs. This adaptability highlights the critical role of technology, building practices, and occupant behaviour in shaping sustainable and health-focused indoor environments.

To effectively map and address these challenges, the home development process must incorporate IAQ considerations at every stage, from initial planning and design through to construction, handover, and occupancy. As an overarching framework, the home development process shapes decisions about building practices, technology selection, and occupants' interactions with their homes. This includes selecting low-emission materials, implementing balanced ventilation systems, and monitoring indoor pollutant levels to ensure a healthy environment. While energy efficiency remains a key objective, it must align with strategies to maintain and improve IAQ, ensuring that buildings support both environmental goals and occupant health. The interplay among the home development process, building technology, and occupant behaviour is therefore crucial for creating sustainable and health-centric indoor environments, which aligns with the central theme of this research.

1.1.3 From Conventional Solutions to a Holistic Approach.

A significant limitation of conventional IAQ solutions is their inability to address diverse pollutant sources. Pollutants can originate from construction materials, furnishings, consumer products, and occupant activities, as well as from outdoor sources that infiltrate through ventilation systems. The relationship between the built environment and health is inherently complex, operating through multiple mediators and moderators (Frank et al., 2005). Identifying causal mechanisms linking the built environment to health requires a comprehensive, multidisciplinary approach. For example, understanding how exposure to indoor pollutants interacts with other environmental and behavioural factors is critical to developing effective health promotion strategies. A holistic understanding of these interactions can help avoid unintended adverse health consequences.

The home development process, from planning to occupation, significantly influences IAQ. The complex interrelationships between various actors in this process, designers, engineers, urban planners, and occupants, highlight the need for more holistic, multidisciplinary approaches to improving IAQ. Traditional, siloed solutions, in which individual components such as ventilation, material selection, and energy efficiency are addressed independently, often fail to account for their interconnectedness. This fragmented approach can result in unintended consequences, including poor IAQ and adverse health outcomes. There are

challenges to overcoming the limitations of conventional IAQ solutions, and a systemic approach must integrate building design, advanced technologies, and occupant behaviour to create environments that balance sustainability, energy efficiency, and health.

Technology plays a pivotal role in such an approach. Equally important is the integration of occupant behaviour into IAQ strategies. Educating occupants on best practices, such as using ventilation systems effectively, maintaining filters, and minimising pollutant-generating activities, enhances the overall effectiveness of IAQ management. A holistic approach ensures that buildings are designed not only to meet environmental goals but also to adapt to the dynamic needs and behaviours of occupants.

Conventional IAQ solutions are often constrained by their fragmented, narrowly focused nature. Typically, these approaches focus on isolated aspects, such as increasing ventilation rates or specifying particular building materials, without fully considering the diversity of pollutant sources, the complexity of building systems, or how occupants interact with their environment. Solutions are frequently developed in silos, for example, treating ventilation, material selection, and energy efficiency as separate challenges rather than as interconnected elements of a broader system. As a result, these conventional methods may overlook how decisions in one area, such as airtightness for energy efficiency, can unintentionally increase indoor pollutant concentrations if not balanced with adequate ventilation. Additionally, the lack of integration between advanced building technologies and everyday occupant behaviours can result in systems that are underutilised, misused, or ineffective in practice. These limitations reveal the challenges of managing IAQ in low-energy homes and highlight the complexity inherent in achieving both improved IAQ and energy conservation.

1.2 Problem Statement.

While the background has outlined the broader context and importance of IAQ, significant challenges remain in addressing IAQ within new homes in the UK. These challenges are deeply embedded in the complex interplay between the home development process, building and design choices, technological systems, and patterns of occupation. This section focuses on defining the core problems underpinning this thesis, organised around these four interrelated pathways. It highlights the gaps associated with each area: the health impacts of IAQ, emissions from building materials and products, the unintended consequences of energy efficiency and technological interventions, and the influence of occupant activities and lifestyles. This section

articulates these challenges and establishes the research rationale and the need for a more holistic and integrated approach to IAQ in the residential sector.

1.2.1 The Problem of Health.

Poor IAQ is a growing problem for building occupants, seriously affecting their health, well-being, and ability to engage in activities (RCP, 2019). The health effects of poor air quality are often not well-defined pathologies because they involve a wide range of airborne and gaseous pollutants, including VOCs, particles, and biological contaminants (Mannan & Al-Ghamdi, 2021; RCP, 2019). Effects can range from discomfort and loss of productivity to more severe outcomes, described under the term sick building syndrome (SBS), commonly characterized by a range of nonspecific symptoms thought to be linked to spending time in a building (Nakayama et al., 2019), and building-related illness (BRI), which refers to diseases caused by indoor air pollutants and often includes chest tightness, fever, muscle aches, etc. (Abdul-Wahab et al., 2015). The problem is further complicated by the fact that building occupants may suffer permanent health effects that do not manifest immediately, as many related diseases have latency periods of ten years or more. Therefore, understanding the impacts of IAQ on health and well-being requires careful consideration of pollutant sources, emission characteristics, and the specific building context.

1.2.2 The Emissions of Building Products.

Building products and systems can be sources of pollution that harm human health (Richter et al., 2021). These sources tend to occur in close proximity, often embedded in various materials, finishes, or even in the regular use of household products. The relative significance of the source is directly linked to the amount of contaminant it emits and the hazardous nature of those emissions (Vardoulakis et al., 2020). Health impacts include infections, intoxication, and asthma (Uhde & Salthammer, 2007), and Mannan & Al-Ghamdi (2021) state that approximately half of all respiratory diseases are triggered or aggravated by poor IAQ. Many pollutants are not readily detectable by occupants, increasing the risk to inhabitants' health. Therefore, there is a need to better understand the many pollutants released or generated by the majority of the building materials and products that shape our immediate surroundings. This study examines the consequences of selecting common materials and identifies intervention techniques to improve IAQ. According to Sharpe et al. (2015), the recent increase in indoor air pollutants is linked to inadequate building ventilation resulting from increased thermal insulation and improved airtightness. Among these, there is a need to focus on building materials in general,

as they account for most indoor VOC emissions, particularly in newly built or recently renovated residential buildings (Richter et al., 2021).

1.2.3 Challenges of Energy Efficiency and Ventilation.

IAQ is understood as both a developing and complex, multi-dimensional problem. To understand this complexity, it is important to define the origins and associated problems of the parameters emitted into the indoor atmosphere. In complex systems, such as housing, regulatory processes addressing energy conservation and climate change adaptation have been introduced (Guyot et al., 2018). However, the challenges of such regulations lie in the dynamic complexities between increasing energy efficiency and the rising unintended consequences of poor indoor environments (Davies and Oreszczyn, 2012).

Energy-efficient interventions in buildings are typically associated with considerable improvements in airtightness. As a result, a lack of ventilation can lead to poor air quality if the golden rule of "build tight, ventilate right" has not been followed. The context of climate change and its mitigation policies, aimed at improving thermal insulation and airtightness (Ministry of Housing, 2021), has led to reduced air exchange rates, thereby increasing energy efficiency. However, inadequate ventilation may increase indoor pollutant levels and lead to moisture within the building. This is associated with the energy-efficiency improvements in buildings, alongside inadequate mechanical ventilation and poor-quality building materials, which produce elevated concentrations of VOCs and other indoor pollutants (Belussi et al., 2019). This trend is generally observed as a result of improving airtightness and sealing up buildings to increase energy conservation. Today's high-performance buildings, such as Passivhaus (e.g., houses with high energy-efficiency standards) and super-insulated homes, can lead to unintended consequences for air quality when poorly ventilated. There are potential conflicts between energy conservation and improving indoor air quality. More is needed to be known about performance-based design, not only in terms of energy savings but also in providing healthy indoor environments.

1.2.4 The Problem of Occupant Activities and Lifestyle.

Apart from building materials, Tsoulou et al. (2021) emphasise that occupants' activities are important sources of indoor contamination, and their activity patterns can affect pollutant levels in indoor air. Occupant behaviour patterns also depend on personal understanding of indoor pollution, IAQ perception, occupants' age, lifestyle, and individual habits (Stazi et al., 2017).

Activities like cooking, cleaning, burning candles, and using gas heaters, wood stoves, and fireplaces can impact IAQ. They emit pollutants such as CO, CO₂, NO₂, TVOC and PM_{2.5} (Tang et al., 2024). Many of these pollutants are associated with health risks and reduced well-being. Understanding how everyday behaviours interact with building design and systems is essential for developing more effective strategies to manage IAQ. However, current approaches and standards often overlook the diversity of occupant behaviour, further complicating efforts to improve IAQ cost-effectively.

1.2.5 The Home Development Process and IAQ

The process of home development is a crucial yet often overlooked aspect of IAQ in new housing. While building materials, ventilation systems, and occupant behaviours directly shape indoor pollutant levels, the decisions that govern these factors are embedded in the practices of housing developers. In the UK, private developers are responsible for delivering most new homes, with estimates suggesting they account for about 80% of housing supply (HBF, 2024). This positions them as key actors whose choices, priorities, and business models can greatly influence IAQ outcomes.

Research on housing delivery reveals that developers operate within complex systems influenced by regulatory, financial, and market factors. Interventions aimed at enhancing building performance, including IAQ, must therefore consider these systemic contexts rather than focusing solely on technical solutions (Ison, 2017). Studies adopting systems-thinking perspectives have shown that changes in housing delivery cannot be achieved through isolated measures, as unintended consequences and counterintuitive outcomes frequently arise (Davies & Oreszczyn, 2012; Forrester, 1971). For example, efforts to meet energy efficiency targets may inadvertently compromise ventilation and air quality unless IAQ is explicitly addressed within design and delivery frameworks (Shrubsole et al., 2014).

From this perspective, IAQ challenges should not be seen only as issues of occupant practice or material emissions but as embedded within the organisational and economic logic of housing development. Developers' reliance on standardised, scalable construction processes often prioritises cost, speed, and regulatory compliance over environmental quality, limiting the integration of IAQ considerations (Adams et al., 2009). Addressing IAQ, therefore, requires both cooperation with developers and an understanding of their role, as recognising developers as

part of IAQ solutions highlights the importance of collaboration to make IAQ solutions practical and widely accepted.

From this perspective, IAQ challenges should not be seen only as issues of occupant practice or material emissions but as embedded within the organisational and economic logic of housing development. Developers' reliance on standardised, scalable construction processes often prioritises cost, speed, and regulatory compliance over environmental quality, limiting the integration of IAQ considerations (Letwin, 2018). Addressing IAQ, therefore, requires close cooperation with developers and a clear understanding of their decision-making processes. Emphasising developers as key players in housing delivery underscores the necessity to incorporate IAQ solutions that are practical, scalable, and aligned with mainstream construction practices, ensuring they are not marginalised in favour of other priorities.

Addressing these challenges requires integrated approaches that combine technical, behavioural, and systemic insights. Current knowledge remains fragmented and often inaccessible to practitioners. This gap highlights the need for research that unites these dimensions, making IAQ strategies more practical within the realities of housing delivery.

1.3 The Research Aims, Objectives and Questions.

Aim:

This research aims to improve IAQ in mass-market housing by investigating pathways through building design, technologies, occupant behaviours, and the home development process, and by developing cost-effective solutions and mitigation strategies.

Objectives:

- To review and synthesise the multiple factors affecting IAQ in homes.
- To measure IAQ in practice under different house types and occupant activities to determine how poor IAQ arises in real-world scenarios.
- To assess occupants' understanding of how their behaviour patterns and lifestyle choices influence IAQ.
- To examine decision-making processes in home development that impact IAQ and identify opportunities for more effective interventions.

- To propose an evidence-based framework and practical recommendations that guide designers, developers, and occupants in adopting best practices and raising awareness of IAQ.

Research Questions

- How do decision-making processes across various stages of the home development process influence IAQ, and what opportunity exists to integrate IAQ considerations from land acquisition to occupancy?
- How can a holistic and systemic approach to managing IAQ be implemented to address the complex and interconnected factors influencing it, avoiding unintended consequences of isolated interventions?

1.4 Introduction to the Pathway Approach.

The poor quality of indoor air has become a growing concern in recent years due to its direct impact on human health, cognitive function, and overall well-being (Chen & Zhao, 2011). Pollutants are increasing, and houses are becoming more airtight. The latter is a result of more energy-efficient building practices, which have increased airtightness and decreased natural ventilation in homes. In response to growing concerns about air quality, the UK government has incorporated the issue into Building Regulations Part F, which prescribes minimum ventilation levels while achieving energy efficiency in Building Regulations Part L for new homes (MHCLG, 2021; Adetuyi et al., 2024). The delivery of such standards is extremely complicated, as IAQ is not just a function of building form and materials, but also of ventilation system capabilities and occupant lifestyle. Ventilation results from mechanical extract and return systems, window openings, and the way these are controlled by occupants. Therefore, any solutions for improving IAQ can never be universal and must never be purely technical, particularly when applied to mass-market housing. The interplay among all these actors and the multiple factors affecting IAQ has created a complex, multifaceted issue that cannot be addressed through isolated interventions (Chen & Zhao, 2011).

1.4.1 Defining the Pathway Approach.

This research introduces the Pathway Approaches as a systemic and holistic framework for evaluating and improving IAQ in new UK homes. Unlike traditional IAQ assessments that focus on a single variable, such as ventilation performance or pollutant source in isolation (Wargocki et al., 2002), the Pathway Approach examines IAQ through a multi-pathway analysis

of four interconnected factors: building, Technology/Systems, Occupant Behaviour, and Home Development Process. The theme of Indoor Pollutants and Health Effects underpins all these pathways, providing essential context for understanding how each pathway influences IAQ and associated health risks. Accordingly, the literature review is organised to first explore indoor pollutants and their health effects, followed by a detailed analysis of each pathway.

- 1- Building Pathway: Evaluating how building characteristics, such as materials, interior layout, and contextual factors (e.g., the site and orientation), influence IAQ outcomes.
- 2- Technology/Systems Pathway: investigating the role of ventilation systems design, installation quality, usability and overall performance.
- 3- Occupant behaviour Pathway: Understanding how lifestyle routines, IAQ perceptions, and interaction with building and ventilation systems impact pollutant exposure and IAQ management.
- 4- . Home Development Process Pathway: This pathway examines how decisions made at various stages of the housing delivery process, from land acquisition to occupancy, impact IAQ, with a focus on gaps in regulatory frameworks and developer priorities.

By assessing these pathways collectively, this research seeks to provide a holistic perspective on IAQ, capturing the dynamic interactions between building design, technology, occupant behaviour, and industry practices, all underpinned by the health effects of indoor pollutants. The complex and dynamic interactions between various factors remain poorly understood, contributing to IAQ performance gaps in buildings. The Pathway Approach advocates for a systems-based perspective in developing assessment methods, technologies, occupant engagement strategies, and tools (Lukcsó et al., 2014). This approach would enable the formulation and implementation of more effective IAQ improvement practices. This research demonstrates that applying the pathway approach shows that adopting a systems mindset can lead to a deeper understanding of how these factors interact, offering insights into addressing IAQ performance gaps and their multiple underlying causes (McGill et al., 2015; Dimitroulopoulou, 2012).

1.5 Research Design and Scope

This research adopts a pragmatic philosophical stance, emphasising the interpretation of data from multiple methods to address real-world IAQ problems rather than engaging in theoretical philosophical positioning (Yvonne Feilzer, 2009). Findings from physical measurements and social data were incorporated to examine the practical challenge of assessing IAQ in new UK homes. Improving IAQ in residential settings remains a key challenge, not only because of the potential levels of occupant exposure and the significant time spent at home, but also because IAQ is not just a function of building form and materials, but also of ventilation system capabilities and occupant behaviour and lifestyle. Therefore, any solutions to achieving good IAQ can never be universal or purely technical, particularly when applied to mass-market housing.

To address the complexity of improving IAQ, the research used a live case study approach, monitoring IAQ in six recently built homes over an extended time, complemented by specific live experiments, particularly cooking as a pollutant-generating activity. It also utilised surveys, semi-structured interviews with building professionals and residents, and daily activity diaries for occupants to complete. To establish a baseline, half of these houses were monitored while unoccupied. The results were analysed graphically to establish patterns of poor IAQ and to identify causation by correlating IAQ changes with system function and activity. Importantly, the whole housing delivery process was studied through semi-structured interviews with 15 industry stakeholders, including housing developers, manufacturers, and building professionals, to assess key decision-making of all stages in the UK home development process in order to establish the impacts of this on factors that affect air quality and leverage points for IAQ improvement.

Achieving good IAQ is a multifaceted challenge that requires a comprehensive, holistic approach that considers the interplay among building, building technology, occupants, and environmental conditions. A critical aspect is understanding how building technologies (e.g. ventilation and heating systems), indoor environmental conditions, and the building itself interact. Importantly, it also requires understanding how all these elements interconnect and influence IAQ. Given that occupant behaviour is a key factor in this research, emphasis will be placed on occupants' perceptions of IAQ, lifestyle choices, and interactions with the building. Determining the cause of inadequate air quality is often challenging, as it can be argued that it stems from components introduced into the building, their integration, or overall occupant

activities. Determining the complex interactions and causalities among the factors that deliver good IAQ was seen as a key requirement for negotiating a successful pathway for IAQ improvement. These pathways for developing an effective IAQ strategy should be embedded in the housing delivery process. They need to consider occupant behaviour, building usage patterns, and occupants' interactions with the ventilation systems and practices. Current IAQ solutions tend to focus on technological and regulatory interventions to address IAQ problems; however, occupant knowledge and behaviour, as well as decision-making during the development process, are also crucial.

IAQ is considered a critical component of the broader concept of "healthy homes." This research focuses on characterising specific IAQ parameters in new UK housing developments. The scope focuses on new residential houses built after 2013, given their enhanced thermal insulation and increased airtightness, both of which could influence IAQ and align with building regulations ([Part L, 2010](#)). To reflect real-world housing practices, this research is partnering with housing developers ([Taylor Wimpey](#), [Redrow](#), [Barratt Developments](#), and [Midland Heart Housing Association](#)) in order to focus on mass-market homes within their housing stock. Additionally, it examines the entire housing development process, from land acquisition to post-occupancy, to determine its impact on IAQ outcomes and identify opportunities for intervention. For the scope of this research, acoustics and light are excluded. The scope also includes:

- **Building Design:** Investigating the impact of architectural layout, material selection, airtightness, and spatial planning on IAQ.
- **Technology:** Assessing the performance of ventilation systems, air filtration solutions, and pollutant control measures.
- **Occupation:** Understanding how resident activities, lifestyle, daily routines, and behavioural adaptations influence IAQ.

1.6 Thesis Structure.

This thesis is organised into seven chapters, each addressing key aspects of IAQ and its improvement in residential settings. The structure is as follows:

Chapter 1: Introduction.

Provides context and background for the research, outlining the factors that affect IAQ and

their implications for health and well-being. This chapter also presents the research aim and objectives, scope, rationale, and an overview of the study.

Chapter 2: Literature Review.

Reviews and synthesises the literature relevant to IAQ in residential buildings, establishing the theoretical background and identifying research gaps. It begins with indoor pollutants and their health effects, covering sources, emission characteristics, classification, exposure, and indoor chemistry. It then examines IAQ in relation to building design, ventilation systems and technologies, occupant behaviours, and the home development process. The chapter reviews IAQ standards and regulations, highlights research gaps, and is structured around four pathways, concluding with a summary.

Chapter 3: Methodology.

This chapter describes the conceptual framework, research philosophy, methodological approach, strategy, data collection, and analysis methods. It explains the reasons for choosing a pragmatic mixed-methods approach. It also outlines the research strategy, case study design, sampling, IAQ monitoring methods, interviews with occupants and developers, and the data analysis process. Issues related to validity, reliability, ethics, and triangulation are also discussed.

Chapter 4: Data Collection and Analysis Methods.

Describes the practical implementation of the methodology. It presents the case study homes, monitoring and instrumentation, occupant and developer interviews, and the approaches to both quantitative and qualitative analysis. It also considers reliability, validity, and ethical issues, concluding with a summary.

Chapter 5: Results and Discussion.

Presents findings from IAQ monitoring, occupant behaviour studies, and stakeholder interviews. Results are discussed across four thematic areas: building design and materials, occupant practices, ventilation technologies, and the home development process. The chapter combines quantitative and qualitative insights and concludes with key discussion points.

Chapter 6: The Development of the Pathway Approach to IAQ Solutions.

Draws on the findings to develop and present the Pathway Approach framework. This chapter sets out the rationale for a systems-based approach and outlines strategies across four

pathways: Site/context, building design and technology, occupation/behaviour, and the development process. It aligns the framework with the RIBA Plan of Work, demonstrates its practical application through scenarios, and discusses its adoption in practice.

Chapter 7: Conclusions and Recommendations.

Summarises the research findings related to the aims and objectives, emphasising the contribution to knowledge and practice. It offers recommendations for industry, policymakers, and occupants, highlights limitations, and proposes directions for future research. The chapter concludes with final reflections on the research journey.

Chapter 8: References and Appendices.

Includes all references cited in the thesis and appendices with supplementary materials such as ethics approval, participant information, consent forms, interview guides, questionnaires, and additional data.

1.7 Chapter Conclusion.

The chapter has established the context and provided an overview of IAQ and its relevance. It has outlined the research aim, objectives and questions, along with the scope and rationale for the investigation. A summary of the research design and an overview of the thesis structure are presented at the start of the document, detailing the content of each subsequent chapter.

Chapter 2. Literature Review.

Introduction.

This chapter provides an in-depth review and synthesis of the literature on IAQ, establishes the theoretical background for the study, and identifies current research gaps. The review is supported by a systematic search and critical evaluation of existing studies.

The chapter begins by examining indoor pollutants and health effects, highlighting the significance of IAQ in residential environments. It then explores how building design, technologies, occupant behaviour, and the home development process influence IAQ, with the discussion structured around the four pathways that underpin this thesis. These pathways, building design, technologies, occupant behaviours, and the home development process, represent the domains where distinct IAQ challenges arise and where targeted solutions can be developed. Key themes addressed include the complexity of IAQ, sources of indoor pollutants and their health impacts, patterns of indoor exposure (e.g., emissions from building materials, household products, and occupants' activities), and core IAQ indicators, particulate matter (PM_{2.5}), total volatile organic compounds (TVOC), and carbon dioxide (CO₂). This structure establishes a foundation for the holistic, pathway-based analysis developed throughout the research.

2.1 Indoor Pollutants and Health Effects.

Indoor air in new residential buildings contains a complex mixture of pollutants from building materials, household activities, ventilation methods, and external sources. The ways these pollutants are emitted and dispersed vary. This section examines the primary types of indoor pollutants, their sources and emission patterns, and how occupants in new homes are exposed to them. Particular attention is given to widely recognised IAQ indicators, including PM_{2.5}, TVOC, and CO₂, which are crucial for assessing IAQ in residential environments. The section also reviews the classification of indoor pollutants, the characteristics and potential health effects of major contaminants, and the chemical processes that can generate secondary pollutants in indoor environments.

2.1.1 Introduction to Key Themes in IAQ Research.

The importance of IAQ has attracted growing global attention, partly due to mounting evidence of the adverse health impacts of both outdoor and indoor pollution. In the UK, outdoor air pollution is estimated to cause approximately 40,000 premature deaths each year (Holgate, 2017). Globally, premature deaths associated with outdoor air pollution are expected to increase from 3 million in 2010 to between 6 and 9 million by 2060, with the largest rises anticipated in quickly urbanising areas (OECD, 2016). However, these numbers often underestimate the total health impact, as most urban residents spend 85–90% of their time indoors (Ferguson et al., 2021). Exposure to indoor pollutants is now recognised as a major public health concern, with about 99,000 deaths per year in Europe alone attributed to indoor air pollution (RCP, 2016).

While the health effects of high outdoor air pollution levels are well-established (WHO, 2021; Chen et al., 2007), less is known about IAQ. IAQ is a rapidly expanding field of study in public health because people spend more time in enclosed spaces, certain pollutants are more prevalent, and, historically, IAQ has received less attention than outdoor air pollution (Agarwal et al., 2021). Interest in IAQ and ventilation has increased further due to the COVID-19 pandemic (Allen & Ibrahim, 2021). Although improving IAQ and reducing energy use are both vital goals for building design and operation, the impact of stringent energy conservation measures on IAQ remains uncertain. On one hand, removing sources of pollution within buildings, implementing improved ventilation systems, and reducing outdoor pollution could lower exposure. Conversely, making buildings more airtight for energy efficiency and increasing the time people spend indoors could increase occupants' exposure to pollution. How decarbonisation efforts in buildings will influence IAQ remains a fundamental, open, and empirical question as raised by Steinemann et al. (2017).

The World Health Organisation takes a comprehensive view, considering the indoor environment as a combination of physical, chemical, and biological factors, together with related occupant behaviours (Balmes, 2019). Notably, a significant portion of the global disease burden is attributable to modifiable environmental factors, further emphasising the importance of effective IAQ management (Feijó-Muñoz et al., 2019).

Defining IAQ is complex and context-dependent. IAQ is generally described as the quality of air within and around buildings and its impact on the health and comfort of occupants (EPA,

2017). The World Health Organisation takes a comprehensive view, considering the indoor environment as a combination of physical, chemical, and biological factors together with occupant behaviours (Neira & Prüss-Ustün, 2016). In particular, a large portion of the global disease burden is attributable to modifiable environmental factors, further emphasising the importance of effective IAQ management (Feijó-Muñoz et al., 2019).

The specific characterisation of IAQ often depends on how well indoor environments meet three essential criteria: maintaining safe levels of respiratory gases, diluting or removing pollutants to levels below health or discomfort thresholds, and ensuring adequate ventilation (Wilkinson et al., 2018; WHO, 2010; ASHRAE, 2010). In practical terms, IAQ is determined by the combined effects of multiple pollutants and their interactions within the building environment (GLOBALABC, 2018). To better understand these influences, several frameworks have been developed. For example, building occupants, HVAC systems, pollutant pathways, and contaminant sources can all affect IAQ, though their relevance varies by building type and context (Kubba, 2017).

IAQ is also considered a core component of the broader concept of indoor environmental quality (IEQ), which encompasses not only air quality but also thermal comfort, ventilation, acoustics, and lighting (Berardi, 2017). With urban populations and building stock expanding at unprecedented rates and existing buildings comprising the majority of the built environment, the need for a multidisciplinary approach to IAQ becomes increasingly critical (Reinhart and Cerezo Davila, 2016).

2.2 Indoor Pollutant Sources and Emissions Characteristics.

Air pollution is the presence of substances in the air that pose risks to human health, animals, vegetation, or materials (Kampa and Castanas, 2008). In the context of indoor environments, Jacobs et al. (2007) expand this definition to include chemical, physical, or biological toxins that accumulate within enclosed spaces, such as residential, commercial, and educational buildings. Multiple studies have identified a wide range of indoor pollutant sources, including gas stoves and fireplaces, as well as building materials, consumer products, furnishings, and insulation (Balmes, 2019). The relative contribution of each source to overall exposure depends on building characteristics, occupant behaviours, and ventilation system design. In addition, IAQ is often influenced by the infiltration of ambient air pollutants, which is modulated by building airtightness and the effectiveness of ventilation strategies. As Weschler (2009) observed, the

concentration and persistence of indoor pollutants are further affected by interactions with interior surfaces, chemical transformations, and removal processes such as ventilation and filtration. These complex interactions highlight the importance of a holistic approach to better understanding sources and emission characteristics of indoor air contaminants.

2.2.1 Classification of Indoor Pollutants.

A systematic classification of indoor pollutants is essential for assessing exposure risks and guiding control measures in homes. Recent studies have highlighted the diversity of chemical and physical traits, reactivity, and persistence of indoor pollutants (Logue et al., 2011; Even et al., 2019). Differentiating these substances enables targeted monitoring and a more accurate assessment of their potential health effects. Classification systems not only reflect current scientific knowledge but also help in choosing suitable sampling methods and remediation strategies (WHO, 2010). This section reviews the main frameworks for categorising indoor air pollutants, emphasising their importance to IAQ assessment and measurements.

2.2.1.1 VOCs: Types and Sources.

VOCs are a term used to classify a class of chemical compounds that are gases at room temperature and contain carbon atoms in their molecular composition. These compounds are characterised by their volatility (ability to evaporate). They are also suspected of causing various health effects, which are generally categorised as acute or chronic, depending on the dose and exposure level (Tang et al., 2016). VOCs are emitted from many common indoor sources produced by chemical reactions and play a significant role in IAQ (Weschler, 2009).

The widespread use of new products and materials has led to the release of approximately 1,000 chemicals into the air we breathe, collectively referred to as Volatile Organic Compounds (VOCs). These chemicals are toxic, diverse, and ubiquitous (Horvat et al., 2025). Emmerechts et al. (2011) noted that VOCs are a broad class of organic compounds with low boiling points (50-260 °C) that readily vaporise from liquid to vapour. VOCs are heterogeneous; some are toxic, and some are carcinogenic at high concentrations, including Formaldehyde and Benzene (Olsen et al., 1984). Furthermore, among indoor VOCs, concentrations can be influenced by several factors, including outdoor VOC levels, indoor VOC emission rates, and filtration rates (Horvat et al., 2025). EPA (2014) reported that VOC concentrations in indoor air are typically 2-5 times higher than in outdoor air. Table 2. 1 summarises VOC classifications based on boiling point, characteristics, and measurement units, following the WHO guidelines (2010). The three

categories are significant for indoor air and are all defined to fall within the common definition of indoor VOCs.

Table 2. 1: Classifications of Volatile Organic Compounds (VOCs) and associated measurement units WHO (2010).

Description	Characteristics	Measurement Units	Type of compounds
Volatile Organic Compounds (VOCs)	<ul style="list-style-type: none"> - Both gas and liquid/solid-state - The boiling point ranges from 50-100 °C to 240-260 °C 	<ul style="list-style-type: none"> - ng/L (nanogramme 10⁻⁹ g per litre of room air). - µg/m³ (microgramme 10⁻⁶ g per cubic meter of room air). 	Formaldehyde, Toluene, d-Limonene, acetone, hexanal, aldehyde, etc.
Semi-Volatile Organic Compounds (SVOCs)	<ul style="list-style-type: none"> - They are mainly semisolid/solid-state - Boiling point range 240-260 to 380-400 °C 	<ul style="list-style-type: none"> - mg/m³ (milligrams 10⁻³ g per cubic meter of room air). 	Pesticides (chlordan, plasticisers, fire retardants)
Very Volatile Organic Compounds (VVOC)	<ul style="list-style-type: none"> - Permanently gases - Boiling point range <50-100 °C. 	<ul style="list-style-type: none"> - ppm (parts per million 10⁶). - ppb (parts per billion 10⁹). 	Methyl chloride, butane propane

2.2.1.2 Types of Volatile Organic Compounds.

Regarding the numerous VOCS identified in indoor air, it is crucial to categorise them into distinct types for effective management. The classifications are influenced by several factors, including chemical characterisation (aromatic hydrocarbons, alkanes, and aldehydes), physical properties (vapour pressure and boiling points), and potential health impacts (neurotoxins, irritants, and carcinogens) (Weschler, 2009). Subsequently, the WHO (2010) developed a categorisation of indoor air pollutants, dividing them into organic chemicals to distinguish between VOCs, Semi-Volatile Organic Compounds (SVOCs), and Very Volatile Organic Compounds (VVOCs). Therefore, indoor researchers developed an interest in the interaction of SVOCs between the gas phase, particles, and dust in indoor air (Weschler & Nazaroff, 2008; Weschler & Nazaroff, 2010) as a result of identifying occupant exposure to SVOCs that occur through ingestion, inhalation and skin absorption (Weschler & Nazaroff, 2010). Regarding VVOCs, the focus is centred on Formaldehyde, following the International Agency for Research on Cancer's (IARC) classification of the pollutant as a human carcinogen (IARC, 2006). IARC classifies compounds into four groups based on scientific evidence and is part of the WHO.

Formaldehyde is recognised as one of the most hazardous indoor pollutants due to its carcinogenic properties and its sources. Formaldehyde concentrations are typically higher than

those found in outdoor environments. Studies in the literature treat it as separate from other VOCs because it is not detected by gas chromatographic methods used to quantify VOCs (Yu & Crump, 1999). WHO (2010) states that formaldehyde (HCHO) is the most important VOC due to its widespread presence in indoor environments and its well-documented health impacts. Salthammer et al. (2010) identify that indoor Formaldehyde emissions result from direct sources that emit Formaldehyde into indoor environments, as well as indirect sources that arise from pollutants emitted by individual sources and from reactions with other chemicals to produce Formaldehyde (Salthammer, 2013; Weschler, 2015). Indoor source HCHO emissions arise from additive degradation, chemical processes in wood-based building materials, furniture, and interior finishing materials (such as sealants), chemical reactions, and combustion processes (Singer et al., 2017; Kruza and Carslaw, 2019). Verrielle et al. (2015) found that many of these sources are particularly prevalent in the indoor environments of new buildings. Regarding TVOCs, it is essential to understand that analytical complexities make it difficult to determine the total number of VOCs included in TVOCs (Lee & Chung, 2011). TVOC is used as a potential indicator of good or poor IAQ. Hormigos-Jimenez et al. (2017) further state that TVOC measures can be used to calculate ventilation rates. However, TVOCs do not provide sufficient information on individual compound concentrations, their toxicity, or potential health risks to occupants. Further, TVOC measures may not include VVOC and SVOC measures (WESCHLER & SHIELDS, 2000). Therefore, this study will not only focus on TVOC measurements but will also include other pollutants, such as PM_{2.5} and CO₂, to validate its findings.

A growing number of studies have investigated VOC emissions in terms of both total and individual concentrations over the past few years (Woolley, 2024; Markowicz & Larsson, 2014). These studies often involve a material investigation chamber. In contrast, field investigations require more realistic exposure scenarios for building occupants, given indoor sources such as material installation and product use. There may be limitations in studies of VOCs from consumer products, despite standardised procedures for obtaining reliable emission data, particularly when evaluating these emissions under actual operational conditions. This is explained by Ahn et al. (2015), who, based on their findings, demonstrate that VOC emission characteristics, the frequency of generated compounds, and the extent of emissions can vary significantly during the use of consumer products, particularly when combustion is involved, resulting in substantially different exposure scenarios. On the other hand, Salthammer (2019) aimed to determine how indoor furniture and materials emit VOCs into indoor air and to identify the effects of airtightness and ventilation on VOC production (Fernández-Agüera et al., 2019). The

authors found that none of the VOCs, except benzene, exceeded guideline values when compared against airtightness. However, Fernández-Agüera et al. (2019) found significant differences in concentration in the more airtight test bedrooms than in the control bedrooms. TVOC concentrations were over three times higher in the test bedrooms (The effect of ventilation on).

2.2.1.3 Particulate Matter (PM) and its impact on respiratory health.

PM is a commonly used term for a complex mixture of invisible solid and liquid particles suspended in the atmosphere. It is currently one of the most hazardous forms of air pollution, varying in size, shape, and composition (EPA, 2014). Particulates are classified according to aerodynamic sizes: Coarse PM₁₀ (particles of ≤ 10 μm (micrometres) diameter), fine particles PM_{2.5} (particles ≤ 2.5 μm in diameter), or ultrafine particles PM_{0.1} (particles ≤ 0.1 μm in diameter). The composition of particles varies immensely and depends on numerous factors, including environmental conditions, emission sources, and location. Various studies (Raunemaa et al., 1989; Holgate, 2017) have shown a link between PM and adverse health conditions for sensitive groups, such as people with respiratory disease, asthma, and immune system deficiencies. Particles 10 μm or larger are primarily deposited in the nose and throat, whereas PM_{2.5} poses the greatest risk because it can exacerbate lung and heart conditions. According to the EPA (2017), PM concentration levels may be higher indoors than outdoors. Common sources of PM include combustion processes, outdoor air, and household products. They can also be generated indoors due to poor design, leading to inadequate air circulation and ventilation. This study focuses on PM_{2.5} in detail, as indoor PM_{2.5} concentrations, unlike those of some other pollutants, are influenced by both indoor and outdoor sources.

2.2.1.4 Carbon Dioxide (CO₂) as an indicator of indoor air freshness.

CO₂ is a concerning indoor air pollutant that can harm human well-being; yet it is a primary indoor pollutant emitted by humans, which correlates with human metabolic activities and the combustion of household appliances. Numerous studies indicate that a moderate concentration of CO₂ in indoor air tends to cause fatigue and headaches, whereas higher concentrations lead to dizziness and vomiting (Derudi et al., 2012). CO₂ has been increasing in recent years, partly due to human activities such as exhalation, tobacco smoke, and the use of fossil fuels, and is a significant factor in climate change. It is worth noting that the CO₂ Outdoor Air Value (OAV) ranges from 300 to 500 ppm. They tend to be much higher indoors, with the WHO (2010) recommending a maximum concentration of 600-1000 ppm. Indoor CO₂ concentration is a valid proxy for ventilation rate, and often measured CO₂ levels are not indicators of potential

health effects but rather of ventilation problems that could lead to health effects and are later useful for remediation.

2.2.2 Relationship between Indoor and Outdoor (I/O) Air Quality.

The relationship between indoor and outdoor air quality in residential settings is influenced by multiple factors, including outdoor pollutant levels, indoor pollutant emission rates, building location, and the effectiveness of ventilation or air-cleaning systems (Leung, 2015). Indoor air is not an isolated system; rather, it is continuously shaped by the dynamic exchange with the outdoor environment, mediated by building design, location, and occupant practices.

Outdoor air can enter buildings through three principal pathways: mechanical ventilation, natural ventilation, and infiltration. Mechanical ventilation systems, such as central air intakes, actively draw outdoor air into the building, providing controlled air exchange. Natural ventilation occurs passively through the opening of windows and doors and is affected by wind patterns, weather, and occupant behaviour. Infiltration, on the other hand, is the unintended flow of outdoor air through cracks, gaps, and other breaches in the building envelope, a process that is often greater in older or less airtight structures.

The combined action of these pathways creates a continuous network of air movement between the outside and inside, and the balance between them determines how much outdoor pollution influences indoor conditions (Boogaard et al., 2009; Leung, 2015). The Indoor/Outdoor (I/O) ratio is a key measure for quantifying this relationship, with values varying by pollutant type, building characteristics, and ventilation practices (Massey et al., 2012). For example, the I/O ratio for PM_{2.5} or VOCs may approach or exceed one in buildings with high infiltration or limited filtration, indicating significant penetration of outdoor pollutants into the indoor environment. In contrast, a lower I/O ratio may result from effective air filtration systems, closed windows, or very airtight construction (Gilbey et al., 2019).

Location and surroundings play a crucial role: dwellings situated near busy roads, industrial sites, or within urban centres are exposed to higher outdoor pollution levels, which may be transferred indoors through ventilation or infiltration (Garrett et al., 1998). In contrast, rural homes with less advanced air filtration and lower airtightness may show I/O ratios near or slightly above one, as indoor and outdoor concentrations become more closely aligned (Massey et al., 2012). However, despite higher pollutant loads, urban buildings may benefit from advanced

ventilation and filtration systems that can reduce indoor exposures to levels below those outdoors.

The type of pollutant also influences the I/O relationship. For particles such as PM_{2.5}, indoor concentrations often track outdoor concentrations, especially in homes with frequent window openings or high infiltration rates (Kuo & Shen, 2010). In contrast, ozone (O₃) typically shows lower indoor levels because it reacts rapidly with indoor surfaces. Meanwhile, nitrogen dioxide (NO₂) and ultrafine particles may vary in their penetration ability, depending on building permeability and ventilation systems (Diapouli et al., 2007).

Occupant behaviour remains a critical modifier in the relationship between indoor and outdoor air quality. Practices such as the timing of window opening, the use of kitchen or bathroom exhaust fans, and the presence of indoor sources (e.g., cooking, cleaning, smoking) can either amplify or mitigate the impact of outdoor pollution on IAQ (Kuo & Shen, 2010; Meadow et al., 2013). Several studies confirm that a substantial proportion of daily variation in indoor pollutant levels, often over 75%, can be directly attributed to fluctuations in outdoor air quality (Chen et al., 2007). Nevertheless, the exact I/O ratio and degree of correlation depend on the specific pollutant, building characteristics, and the presence of indoor sources or mitigation systems (Diapouli et al., 2007; Gilbey et al., 2019). The evidence shows that IAQ in homes is strongly influenced by outdoor pollution levels, building location and design, ventilation systems, and occupant behaviour. Understanding these interconnections is critical for comprehensively assessing exposure risks.

2.2.3 Indoor Chemistry and Secondary Pollutant Formation.

IAQ is affected not only by primary pollutants but also by complex chemical reactions that produce secondary contaminants within enclosed spaces. These secondary pollutants, formed through interactions between indoor compounds and outdoor substances that infiltrate indoors, can sometimes pose greater health risks than their original sources (Weschler, 2015; Carslaw, 2022). This section examines the primary processes that contribute to the formation of secondary pollutants indoors, assesses their impact on occupant health, and evaluates mitigation strategies to improve indoor air quality.

2.2.3.1 Process of indoor chemistry and pollutant behaviour.

Recent research trends focus on the complex interactions between VOCs and indoor materials. Numerous compounds can be generated indoors, with adsorption and desorption processes

central to the behaviour of pollutants in built environments. Adsorption refers to the adherence of gases or liquids onto the surface of a material, a process distinct from absorption, which involves the substance diffusing into the bulk of the material (Fichthorn, 1997; Parida et al., 2006). Rouquerol et al. (2014) further define adsorption as the enrichment of a material's surface by other substances, a process strongly influenced by surface area. As demonstrated by Tichenor et al. (1991) and Brown (1999), building materials can act as pollutant sinks by adsorbing gases and subsequently releasing them, a phenomenon known as the "sink effect." This means that interior finishes and furnishings not only emit VOCs but can also modulate their concentrations through sorption (adsorption and desorption), thereby impacting IAQ throughout a building's lifecycle (Molhave, 1991).

In addition to simple physical processes, a variety of chemical reactions can occur on material surfaces or in the gas phase, fundamentally changing the chemical composition of indoor air (Uhde & Salthammer, 2007; Weschler & Carslaw, 2018). These reactions include oxidation, hydrolysis, acid-base transformations, photolysis, and decomposition. Building materials and furniture are not just passive sinks or sources; they actively engage in chemical transformations that generate or consume pollutants throughout a building's operational life (Weschler, 2011).

As shown in Figure 2.1, plasterboard and similar materials can interact with indoor air pollutants through these processes. Pollutants in the air come into contact with the plasterboard via airflow, where they may be captured, transformed, or made inert, with the resulting compounds remaining trapped within the material matrix.

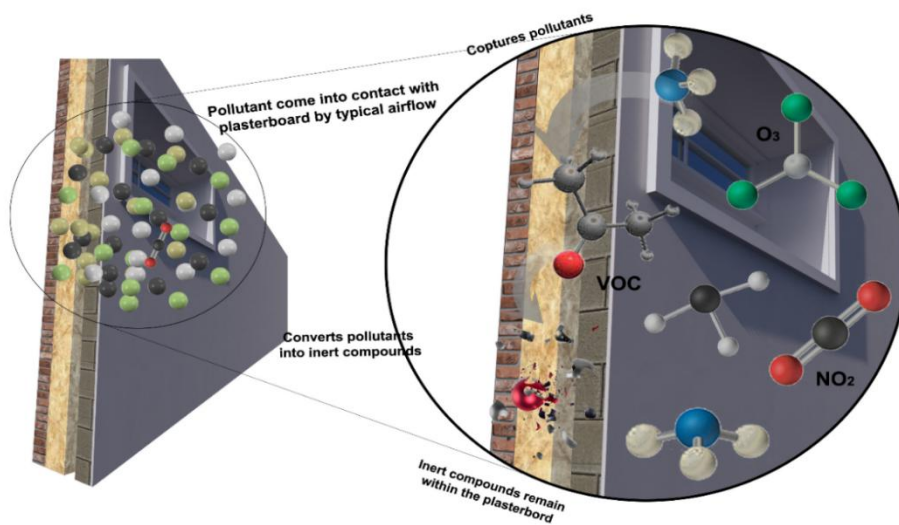


Figure 2. 1: Mechanism of pollutant capture and transformation by plasterboard in indoor environments (Author's illustration).

2.2.3.2 Indoor chemistry.

The chemical reactions occurring in indoor air and on material surfaces significantly influence the composition of indoor air (Weschler & Carslaw, 2018). While earlier studies primarily used controlled laboratory chambers, current research emphasises the importance of accounting for real-world factors such as occupant activity, hidden building spaces, and episodic events (Bekö et al., 2020; Tang et al., 2019; Weschler & Carslaw, 2018). Human presence is now recognised as a key driver of indoor chemistry, since occupants introduce reactive substances through breathing, skin oils, and everyday activities.

A particular focus has emerged on the reactions between ozone (O₃) and VOCs, particularly terpenes, because of their abundance indoors and the rapidity of their chemical transformations (Long et al., 2000; Weschler, 2004). These reactions produce a variety of secondary pollutants, including aldehydes, organic acids, and ultrafine particles, many of which form quickly enough to rival the air exchange rate in buildings (Weschler & Carslaw, 2018). The formation of these compounds is also influenced by ventilation rates, which affect both the duration of gas-phase chemistry and the dilution or accumulation of reaction products (Hernandez et al., 2020; Waring & Siegel, 2010).

Emerging research also considers how indoor chemistry unfolds in hidden spaces, such as wall cavities or beneath flooring, where conditions can differ significantly from those in the occupied zone (Weschler & Carslaw, 2018; Bekö et al., 2020). Moreover, new initiatives, including the Alfred P. Sloan Foundation's "Chemistry of Indoor Environments" and INDAIRPOLLNET, are rapidly expanding the knowledge base for indoor air chemistry (Bekö et al., 2020; Maynard, 2019).

The full range of indoor chemical changes also includes reactions involving household cleaning agents, reactions between ammonia and acidic gases, and other surface- or particle-supported interactions (Kruza & Carslaw, 2019; Uhde & Salthammer, 2007). In particular, human emissions, such as isoprene, nitric oxide, and squalene from the skin, play an important role, with recent evidence indicating that occupant presence can lower oxidant levels or increase the formation of nitrated organics (Weschler & Carslaw, 2018; Kruza et al., 2021).

As Wolkoff and Nielsen (2001) illustrate in Figure 2.2, indoor air contains a wide variety of organic and reactive species, many with molecular weights below 1000 Dalton. This complexity highlights the need for comprehensive assessment strategies, as the combined effects of building materials, ventilation systems, and occupant behaviour influence both the presence and transformation of pollutants, ultimately impacting indoor air quality and occupant health (Langer & Bekö, 2013).

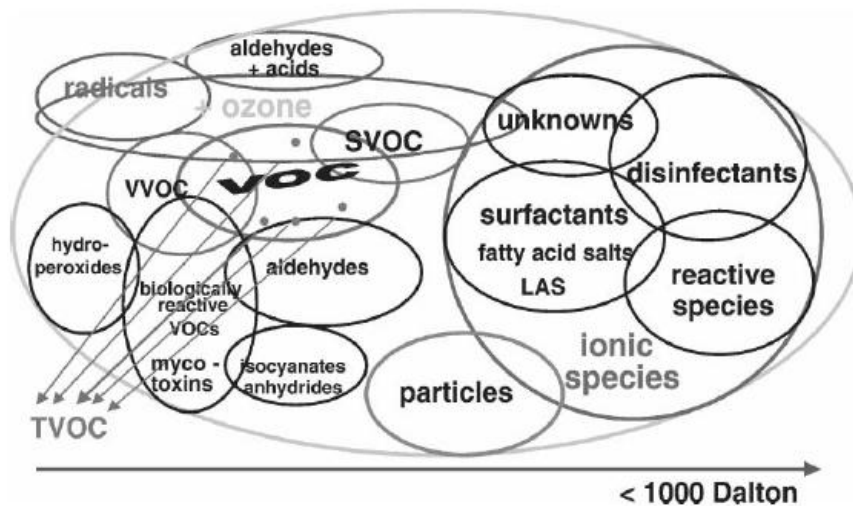


Figure 2. 2: Diversity of indoor air and associated reactive compounds (Wolkoff and Nielsen, 2001).

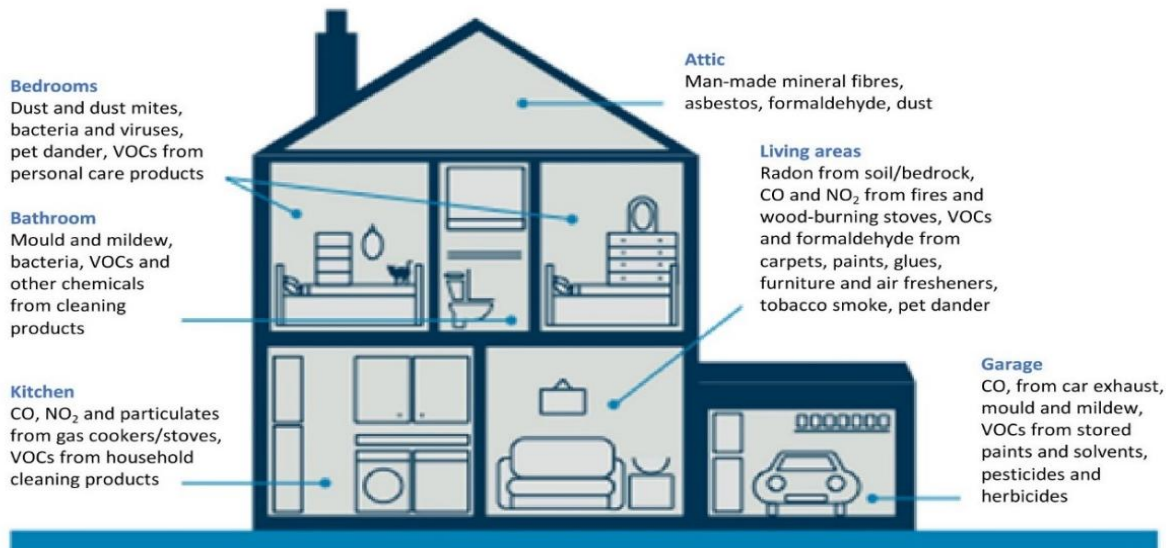
2.2.4 Pollutant Sources and Emission Behaviour.

Air pollution is generally defined as the presence of substances in the air that pose risks to human health and the environment (Kampa and Castanas, 2008). In indoor environments, these substances typically include chemical, physical, or biological agents, as described by Jacobs et al. (2010), who note their presence in various types of buildings, including homes, workplaces, schools, and transport facilities. Other studies have identified various sources of pollutants within buildings, such as gas stoves, open fireplaces, construction materials, consumer products, and furnishings, that contribute to occupant exposure to varying degrees (Wang et al., 2012; Chin et al., 2014).

Despite growing research, there is still limited evidence to fully understand the complexity of interactions between indoor and outdoor air. Chen and Zhao (2011) emphasise the importance of better understanding the impacts of outdoor emission sources, especially since indoor particulate pollution can be more hazardous than outdoor pollution. Ström et al. (2019) also reported that the influence of outdoor sources largely depends on the building's location and the density of the surrounding area.

Indoor pollutant sources involve biological, inorganic, organic, and radioactive origins. The toxicity, concentration, and duration of exposure to these pollutants can lead to a wide range of health effects, which may vary considerably between individuals (Wargocki et al., 2002). Inadequate ventilation and excessive dampness, for example, promote the growth of microorganisms, including fungi, viruses, mould, and bacteria, leading to the release of spore fragments into indoor air (Sharpe et al., 2015; Howieson, 2017). Everyday household activities, including cooking and cleaning, also generate episodic emissions that contribute to indoor pollutant levels. Inorganic contaminants such as ozone, ammonia, and combustion gases originate from both indoor and outdoor sources, including unvented fuel-fired appliances, tobacco smoke, and vehicle emissions (Wang et al., 2012). These substances frequently interact with organic compounds, released from building materials, furnishings, and household products, contributing to the formation of secondary pollutants (Weschler & Shields, 1997; Farmer et al., 2019). As Weschler & Shields (1997) argue, compounds such as ammonia and ozone are vital because of their high reactivity with unsaturated organic compounds, highlighting the complex chemistry that occurs indoors.

Organic pollutants, including aldehydes, alkenes, formaldehyde, and benzene, are continuously released from a wide range of products and materials (Chin et al., 2014). Building materials with large surface areas, such as carpets, composite wood, and adhesives, act as both sources and sinks of these emissions (Weschler & Carslaw, 2018). Emissions may be continuous or triggered by occupant activities, and focusing solely on short-term volatility risks underestimates the cumulative burden from persistent pollutants (Weschler & Carslaw, 2018). Figure 2.3 illustrates the multifaceted and dynamic origins of indoor pollutants, with emissions varying in timing, intensity, and interactions. This complexity means that indoor air quality is shaped by a network of interconnected factors, demonstrating that effective IAQ improvement cannot rely on isolated interventions; instead, it requires a holistic strategy that addresses the full spectrum of emissions and their interactions within the indoor environment (RCP, 2016). These conditions, recent changes to UK building regulations (e.g., Part L, 2010) aimed at improving energy efficiency and thermal insulation, have inadvertently reduced air exchange rates, potentially exacerbating the build-up of indoor pollutants (Mavrogianni et al., 2012; Vardoulakis et al., 2015). While such changes are beneficial for energy conservation, they may have unintended negative consequences for IAQ and occupant health, revealing a conflict between energy policies and healthy indoor environments (Shrubsole et al., 2012; Singer et al., 2020).



Sources and types of indoor pollution encountered in homes. VOCs = volatile organic compounds. Please note that these lists are not exhaustive and that the actual pollutants present, and their amounts, will vary from household to household.

Figure 2. 3: Sources of indoor pollutants within buildings (RCP, 2016).

There is an ongoing debate about the adequacy of current IAQ standards. Although CIBSE Guide A (2015) and WHO (2010) establish exposure thresholds for key pollutants, uncertainties remain regarding how these guidelines account for variability in occupant behaviour, building characteristics, and combined exposures in real-world settings (Maesano et al., 2019). Moreover, as new materials and technologies continue to develop, additional research is needed to understand their impact on emission profiles and to find the optimal balance between ventilation for energy efficiency and the effective removal of indoor contaminants.

2.2.4.1 Household Products as Sources of Indoor Pollutants.

Household products are a diverse source of indoor air contaminants, along with indoor combustion sources, ozone, and allergens (Jacobs et al., 2010), thereby influencing IAQ in residential buildings. Furthermore, personal, cleaning, and air fresheners are strongly correlated with health impairment. They may occur through inhalation of VOCs, semi-VOCs (SVOCs), particulate matter (PM), and complex mixtures of secondary air pollutants formed by reactions of chemicals in indoor air (Missia et al., 2010; Alapieti et al., 2020). A study by Wei et al. (2022) examined the chemical emissions from various household products in indoor environments. The study was based on the potential indoor concentration levels of eight selected VOCs (Toluene, Benzene, formaldehyde, xylenes, acetaldehyde, phenol, limonene, and styrene). These were assessed in three model rooms: a kitchen/family room, a children's

room, and a hall. The findings of the study highlight that the smallest room in the house (the children's room) contains the highest concentrations, as it has multiple products that may emit chemicals into the indoor air. Due to the varying emission profiles of household products, this study tries to highlight the chemical characteristics of consumer products to raise public awareness of these issues.

In cross-sectional epidemiological research, associations have been explored between respiratory symptoms, such as asthma, sensitising characteristics, and exposure to cleaning products (Howieson, 2017) and personal care products (Bédard et al., 2014). However, no consistent associations have been shown between the specific category of cleaning products, the chemicals they contain that produce significant health impacts, and the route of exposure. Additionally, some studies have reported a link between aerosol products and an increased risk of inhalation and associated health effects (Abrams, 2020).

Fragranced chemicals (terpenes), often present in household products, emit a variety of organic gas-phase compounds and aerosol products (Rohr, 2013). These chemicals have been reported to cause health problems through chemical reactions initiated by Ozone (O₃) (Wang & Waring, 2014). Research has also highlighted that a significant increase in sensory irritation of the respiratory airways and airflow restriction may be important concerns in common occupant settings regarding fragranced user products (Wolkoff, 2018).

Furthermore, to promote healthy indoor environments, additional research is needed to analyse the potential negative impacts of respiratory exposure to household products (Weschler, 2006). The results can provide risk-management guidance and inform the development of policy alternatives to integrate risk-mitigation measures that reduce toxic pollutants (Taylor et al., 2014). Product emission rates and consumer product usage patterns are crucial for reliable risk assessment, as they indicate potential health impacts on occupants (Li & Suh, 2019). Therefore, risks should be evaluated by monitoring exposure to individual product pollutants and to combined pollutants from household products throughout the day (Fang et al., 1998; Wolkoff, 2018).

2.2.5 Health Effects of Indoor Pollutants.

The quality of air within indoor spaces, where people spend most of their time, whether at home, at work, or in school, plays a crucial role in determining their health and well-being. Numerous studies have recognised a strong link between IAQ and human health outcomes (Madureira et al., 2015). Poor IAQ has been associated with a wide range of adverse health effects, some with significant long-term consequences. In particular, the WHO has reported that poor

air quality causes over 1.5 million deaths each year, ranking it as a leading contributor to the global burden of disease and disability ([World Health Organisation, 2022](#)). Understanding how IAQ affects occupants requires assessing buildings according to their type, design, and use.

This connection is exemplified in research summarised by Cincinelli and Martellini ([2017](#)), who investigated air quality in a sample of 25 homes across Macedonian cities. Their findings revealed a correlation between building features and pollutant concentrations, particularly in kitchens, which emerged as specific hotspots, with CO₂ and PM_{2.5} levels 14% and 67% higher, respectively, than in living rooms. Inadequate ventilation was identified as the primary driver of elevated CO₂ levels, while PM_{2.5} levels were influenced by the building envelope, occupant activities, and behavioural patterns, particularly cooking and cleaning ([Mannan & Al-Ghamdi, 2021](#)).

Table 2.2 summarises major indoor air pollutants commonly found in residential environments, detailing their typical sources, recommended exposure limits, and health effects. Pollutants such as TVOCs, particulate matter (PM₁₀ and PM_{2.5}), ozone, nitrogen dioxide, and carbon dioxide each present specific risks depending on concentration and exposure duration ([EPA, 2017](#)). Studies show that IAQ is influenced by a combination of emission sources, occupant behaviours, and outdoor infiltration ([Deng et al., 2024](#); [Jacobs et al., 2010](#)). TVOCs are a key source of contaminants from construction materials, furnishings, and household products, consistently linked to acute and chronic health effects ([Xue et al., 2023](#)). Particulate matter originates from both external sources (traffic, industrial emissions) and internal sources (domestic combustion), contributing to respiratory and cardiovascular risks ([Hopke et al., 2020](#)). Ozone forms indoors via chemical reactions between internal and ambient pollutants ([Vardoulakis et al., 2015](#)). Fuel combustion remains the primary source of nitrogen dioxide (NO₂), while respiration and daily activities are the main contributors to indoor CO₂ ([Fisk, 2018](#)). Indoor sources can also be categorised as intermittent or continuous, influencing exposure and mitigation strategies ([COMEAP, 2018](#)).

Table 2. 2: Indoor air pollutants, sources, and associated health impacts (EPA, 2017).

Pollutants	A major source of emissions	Time of exposure	Standard level	Health impact
Total Volatile Organic Compounds (TVOCs)	New furniture, solvents, painting, adhesives, cleaning products, insulation, and building materials.	8 hours	300 µg/m ³	Respiratory diseases, sensory irritation, fatigue, headaches, and long-term liver damage.
Particulate matter (PM₁₀)	Motor engines, industrial activities, and smoking.	24 hours	35 µg/m ³	Respiratory and cardiovascular diseases, central nervous system and reproductive dysfunctions, and cancer.
Particulate matter (PM_{2.5})	Cooking stoves, fireplaces, and outdoor air.	24 hours	150 µg/m ³	
Ground-level Ozone (O₃)	Industrial facilities, vehicular exhaust, solar gains, and chemical reactions.	1 hour	0.12 mg/m ³	Asthma and allergic triggers.
Nitrogen dioxide (NO₂)	Fuel-burning, industrial, and domestic combustion, as well as vehicular exhaust.	1 hour	100 µg/m ³	Increases the risk of respiratory infections, allergens, and liver damage.
Carbon dioxide (CO₂)	People, cooking.	8 hours	1000 ppm	Tiredness, difficulty breathing.

The health impacts of these pollutants are wide-ranging. Indoor pollutant concentrations can act as irritants, toxicants, and allergens (Sharpe et al., 2020), causing health problems such as lung cancer and cardiovascular disease (Romagnoli et al., 2014). Exposure to VOC has been linked to sensory irritation, nausea, and asthma (Wu et al., 2012; Shrubsole et al., 2019), as well as toxic and carcinogenic effects from compounds such as benzene and formaldehyde (Schieweck et al., 2018; WHO, 2010). Even at low levels of NO₂ exposure, it is linked to throat irritation and non-allergic respiratory diseases such as asthma (Guarnieri & Balmes, 2014), and higher concentrations increase the risk of cardiovascular and respiratory illnesses (Chaloulakou et al., 2008). PM exposure contributes to short-term symptoms such as coughing and wheezing (Huang et al., 2017) and long-term outcomes, including asthma (Lu & Yao, 2023), lung cancer (Lavigne et al., 2018), and stroke (Logue et al., 2012). Although not toxic by itself, CO₂ at elevated levels is associated with poor IAQ perception, headaches, and throat irritation (Persily & de Jonge, 2017). Beyond chemical and particulate exposure, biological pollutants can also affect the health and well-being of household occupants. Contaminants such as mould, house dust mites, and pollen could aggravate asthma and allergic conditions, particularly in areas with high humidity or visible mould growth (Suihko et al., 2009).

The reviewed literature revealed that indoor pollutants pose layered risks to human health, ranging from mild discomfort to severe chronic illness. Given that individuals spend up to 90% of their time indoors (EPA, 2017), it is vital to understand pollutant-specific health effects alongside their emission characteristics in order to develop strategies that improve IAQ and reduce health burdens (Missia et al., 2010).

2.3 Building Design and IAQ.

Building design and material specification play a central role in determining IAQ. This section examines how building form, construction methods, and material choices influence pollutant emissions, distribution, and occupant exposure in new homes. Framed within the thesis's pathways approach, the discussion addresses not only the direct contributions of building fabric and finishes to IAQ but also the complex interactions between airtightness, ventilation, pollutant accumulation and migration indoors. Recent trends in energy-efficient construction and evolving building practices are reviewed, along with emerging evidence of unintended IAQ consequences associated with contemporary materials and design choices. Through this lens, the section highlights the need for integrated strategies that balance both energy performance and healthy indoor environments.

2.3.1 Pollutants from Building Design and Material Choices.

Indoor pollutant concentrations are strongly influenced by a range of building-related factors, with occupant behaviour a major determinant of variability both between and within homes. Variations in building age, size, function, and construction methods also significantly influence pollutant levels, alongside geographic location (Langer and Bekö, 2013; Mannan & Al-Ghamdi, 2021). The specific properties of interior materials, the level of airtightness, and the type and performance of ventilation systems can all influence how contaminants are generated, accumulated, or removed from indoor spaces. In response to growing public concern about air quality, the UK government has addressed the issue through Building Regulations Part F, which prescribes minimum ventilation levels while achieving energy efficiency in Building Regulations Part L for new homes (Ministry of Housing, 2022).

Apart from these structural factors, building materials and products, such as engineered wood, synthetic flooring, insulation, varnishes, paints, and adhesives, are now widely recognised as major sources of indoor air pollution, especially in new or recently renovated homes. Emissions from these materials can release a variety of VOCs and aldehydes, some of which may persist for long after installation, particularly in airtight, energy-efficient dwellings (Jacobs et al., 2010; Salthammer et al., 2018). These pollutants have been associated with numerous health effects, including respiratory irritation, asthma, and cancer (Ghobakhloo et al., 2023). Moreover, emissions from materials are influenced by environmental factors such as temperature and humidity, as well as the effectiveness of building ventilation (Tang et al., 2016; Petrou et al., 2022).

Designing an effective building envelope, along with mindful occupant practices, can help limit the infiltration of outdoor pollutants. Regular inspection and maintenance are essential to prevent the deterioration of exposed materials (Mannan & Al-Ghamdi, 2021). In the UK, tightening construction standards over recent decades has led to more airtight homes, thereby reducing air exchange rates and increasing reliance on mechanical ventilation or other measures to maintain good indoor air quality (Weschler, 2009; Petrou et al., 2022). For this reason, low ventilation rates should be avoided unless effective compensatory measures are in place (Sundell et al., 2011).

The spatial arrangement of internal sources, such as kitchens or utility rooms, should also be considered in design to minimise cross-contamination within the living space (Ferdyn-Grygierek & Grygierek, 2024). As building practices evolve toward higher performance and sustainability, it is crucial to strike a balance between energy efficiency goals and the imperative for healthy indoor environments. While new designs and “green” construction methods, as well as the use of environmentally friendly products, can sometimes reduce exposure to harmful chemicals, evidence shows that such benefits are not universal and depend on the careful selection of materials and the integration of effective ventilation strategies (Mannan & Al-Ghamdi, 2021; Few et al., 2024).

2.3.1.1 Choice of low-emission materials and IAQ impact.

Managing indoor pollution at its source is a critical challenge, given the wide range of building materials that can release chemical pollutants into indoor air. A particular concern is reliance on ventilation standards, such as those outlined in Approved Document F (ADF), which provide guidance on required ventilation rates to maintain acceptable pollutant levels (HM Government, 2010). In practice, however, the intended ventilation rates are frequently not achieved, which can adversely affect occupant health.

As buildings become increasingly airtight for energy conservation, emissions from building materials and combustion products increasingly contribute to IAQ deterioration (Yu and Kim, 2011). This can also lead to higher humidity and condensation, creating favourable conditions for dust mites and other biological contaminants (Lee et al., 2008). Research consistently demonstrates a close relationship between building material emissions and occupant activities, underscoring the importance of source control in IAQ management. For example, monitoring both unoccupied and occupied new properties can reveal the relative contributions of building materials versus activities. Table 2.3 presents case studies of pollutants released by various building materials, focusing on the assessment models and monitoring methods employed, the

sources of pollutants, the primary pollutants measured, exposure durations, and recorded health effects (see Table 3).

Table 2. 3: Summary of reported case studies on pollutant emissions from selected building materials.

Author	Assessment model used	Monitoring equipment	Sources	Pollutant(s)	Time exposure (WHO,2010)	Health effects
Baxter et al. (2006)	Field test – Sequential model-building approach	<ul style="list-style-type: none"> Harvard Personal Environmental Monitor (PEM) X-ray fluorescence spectroscopy (XRF) 	Building materials and furnishings, cooking and heating equipment, and stored solvents	PM _{2.5}	150 µg/m ³ 24hours (average time)	Cardiovascular and respiratory health effects.
Esplugues et al. (2010)	Field test – Box-type passive samplers		The combustion process of gas and petroleum	NO ₂	100 µg/m ³ 1 hour (average time)	Respiratory health effects
Kendall et al. (2016)	Simulation – Meta-analysis	<ul style="list-style-type: none"> Direct measurements using track-etch detectors 	Soil-building concentration materials, such as stone and concrete	Radon		Lung cancer
Wang and Morrison (2006)	Field test – Secondary pollutants emission rates experiments	<ul style="list-style-type: none"> The photoacoustic infrared analyser (INOVA 1302) 	Indoor material surfaces, duct materials, carpets, and floor materials	O ₃ , VOCs, aldehydes	300 µg/m ³ 8 hours (average time)	Respiratory symptoms, allergic reactions
Missia et al. (2010)	Field test – Field and laboratory cell (FLEC) technique	<ul style="list-style-type: none"> Radiello passive samplers 	Laminate flooring, linoleum, and acrylic paints	VOCs, Benzene, Toluene		Cancer (leukaemia) risks
Tan et al. (2012)	Field test – Mass balance method	<ul style="list-style-type: none"> Electrochemical sensors 	Gas appliances, vapours from carpets, and pressed wood furniture	CO, NO ₂ , VOCs		Neurobehavioral effects, heart disease
Beko et al. (2020)	Field test – Stainless steel climate chambers	<ul style="list-style-type: none"> Innova 1312 Photoacoustic Multi-gas Monitor 	Human emissions and interactions with indoor pollutants	VOCs, NH ₃ , CO ₂	1000 ppb 8 hours (average time)	Headaches, visual disorders, and memory impairments
Kim et al. (2014)	Field test – Wireless Sensor Network Following the ZigBee standard	<ul style="list-style-type: none"> Metal Oxide Semiconductor (MOS) sensor 	Photochemical reactions, polystyrene, carpets	CO ₂ , O ₃ , VOCs, PM _{2.5}	0.12 mg/m ³ 1 hour (average time)	Headaches, loss of concentration and attention, and permanent lung damage
Moreno et al. (2018)	Field test – Wireless Sensor Network following the ATTM Standard Practice	<ul style="list-style-type: none"> GrayWolf instruments Foobot FBT0002100 devices 	Carpets, PVC flooring, adhesives, sealants, and floor varnish	Temperature, Relative Humidity (RH), PM _{2.5} , TVOCs		Exacerbations of asthma, respiratory infections
Morrison and Nazaroff (2002)	Lab test – Test chamber	<ul style="list-style-type: none"> Tenax-TA sorbent tubes 	Carpet fibres	O ₃ , VOCs (aldehydes)		Pneumonia and bronchitis, damage to the kidney and liver

		<ul style="list-style-type: none"> ● Thermal desorption gas chromatography 			
Zhou et al. (2018)	Field test – Time-resolved measurements of pollutants	<ul style="list-style-type: none"> ● Mobile analytical laboratory (MILOS) 	Polystyrene materials	NO, Nitrous acid (HONO), O ₃ , CO ₂ , RH, Temperature	Reduced lung function, respiratory symptoms
Li et al. (2020)	Field test – Stainless steel climate chambers	<ul style="list-style-type: none"> ● Picarro G2103 analyser 	Cooking, smoking, and concrete	NH ₃	Sensory irritation of the eyes and airways
Weschler et al. (2011)	Field test – Mass fraction model of squalene and cholesterol in dust	<ul style="list-style-type: none"> ● Indoor flow-controlled model SP-280 pump 	Carpets, Human emissions (skin)	Dust, SVOCs (squalene, cholesterol, five phthalate esters)	Possible permanent lung damage, triggering symptoms of allergy
Wisthaler and Weschler (2010)	Simulation – In vitro and in vivo experiments in a simulated office	<ul style="list-style-type: none"> ● Proton-transfer-reaction mass spectrometry (PTR-MS) 	Carpets, linoleum, polypropylene, and polyethylene	O ₃ , VOCs, carbonyl, carboxyl, hydroxyl, and ketone groups	Damage to the liver and kidneys, sensory and airway irritation

A considerable number of sources can emit VOCs, including building materials (Wang et al., 2022), indoor combustion sources (Liu et al., 2022), occupant emissions (Caron et al., 2020), smoking (Singer et al., 2020), and indoor chemical reactions (Weschler, 2006). Emissions from new or recently redecorated buildings are particularly important, as building materials, furnishings, and fittings are recognised as major contributors to poor IAQ (Wang et al., 2022; Brown et al., 1994). Moreover, improvements in thermal insulation often achieved with chemical-based materials can unintentionally increase harmful emissions (Naldzhiev et al., 2020). This highlights the need for robust standards and regulations to manage building material emissions, such as those promoted by NICE (2017) and the WELL Building Standard (Takigawa et al., 2009). These frameworks emphasise selecting low-emission, third-party certified materials to support good IEQ and protect occupant health. The European Environment Agency (EEA, 2020) observes the increasing adoption of emission testing and material certification, with standards focusing on emission rates and the surface area of applied materials.

2.3.1.2 Airtightness in New Energy-Efficient Homes.

Airtightness is a general term that describes how a building's envelope resists unintentional air leakage. According to Crawley et al. (2018), airtightness is determined by construction method, building complexity, number of storeys, quality of site supervision, and workmanship. In the UK, buildings constructed prior to 2006 were typically built with little focus on airtightness, as formal testing was not required, resulting in a relatively permeable legacy building stock

(Crawley et al., 2018). New construction standards now prioritise airtightness to reduce energy loss, but this has introduced new challenges for IAQ.

A key concern is that, as homes become more airtight, they may better exclude outdoor pollutants, but they also risk trapping internally generated contaminants, especially if ventilation is insufficient or improperly managed. This can lead to the accumulation of pollutants such as VOCs, PM_{2.5}, and CO₂, as well as excess humidity and condensation, which promote mould growth and material degradation (Weschler, 2009; Petrou et al., 2022). These risks are exacerbated when mechanical ventilation systems are poorly commissioned or when occupants do not fully understand how they operate, as seen in recent low-energy homes that meet higher efficiency standards (Gupta and Kapsali, 2016). The Building Research Establishment (McGill et al., 2015) has highlighted the dual challenges posed by both external and internal sources of pollution. In highly permeable buildings, outdoor pollutants easily infiltrate, whereas in highly airtight homes, internally produced pollutants become more significant when ventilation is inadequate. Figure 2.4 below illustrates the complex interplay of outdoor (shown in blue) and indoor (shown in red) pollutant sources in residential environments, highlighting how both external infiltration and internal generation influence IAQ (adapted from Kukadia and Upton, 2019):

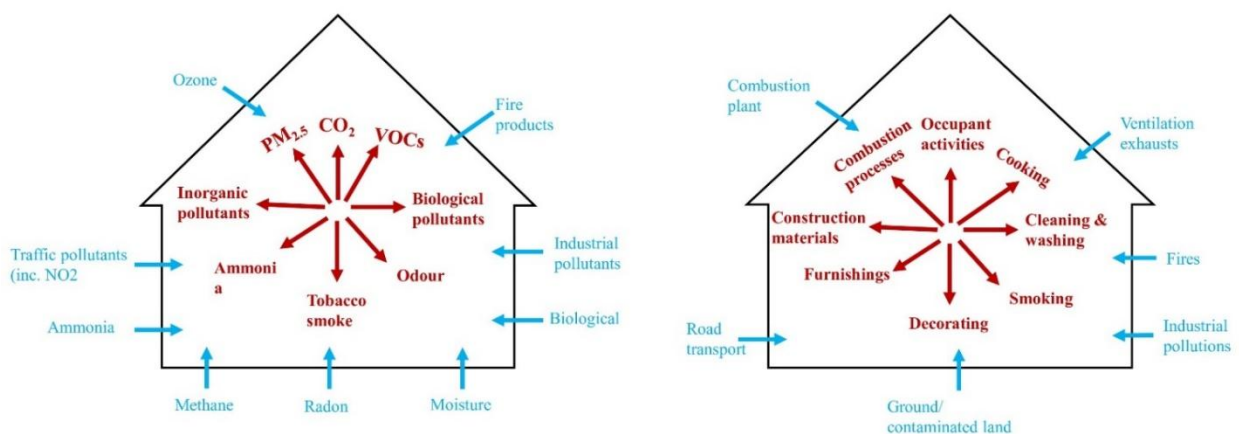


Figure 2. 4: Examples of common outdoor (blue) and indoor (red) pollutants and sources influencing IAQ. (Adapted from Kukadia and Upton, 2019).

Air permeability, a standard measure of airtightness, is commonly tested using a pressurisation or “blower-door” test, where the building envelope is subjected to various pressure differences typically within a 30 Pa range to calculate leakage rates, normalised as m³/(m²·hr) at 50 Pa (ATTMA, 2016). During this test, all intended ventilation systems are switched off to accurately quantify any unplanned leakage of the building that might occur during testing. Achieving high

levels of airtightness has become a defining feature of new energy-efficient homes. This approach minimises uncontrolled heat loss and carbon emissions but also requires carefully planned ventilation to prevent the trapping of indoor-generated pollutants. Crawley et al. (2018) highlight that finding the right balance between airtightness and adequate ventilation is vital for maintaining low energy consumption and acceptable IAQ. Therefore, building design must incorporate effective strategies to integrate ventilation systems that promote acceptable IAQ without compromising energy efficiency.

It is increasingly recognised that while airtight homes can effectively reduce the entry of external pollutants, they also risk accumulating higher concentrations of internal contaminants if ventilation is not adequately maintained (Petrou et al., 2022). This risk is particularly important in urban areas, where outdoor PM_{2.5} and PM₁₀ levels are already high, and airtight homes may further concentrate pollutants generated indoors by activities such as cooking or cleaning (Liu et al., 2022; Chen and Zhao, 2011). Another challenge associated with high airtightness is condensation. Poor ventilation and excess humidity can promote the growth of mould and other microorganisms, leading to material deterioration and adverse health effects, including asthma and eczema (Fisk et al., 2007). Factors contributing to this include insufficient heating, excessive moisture, and inadequate air renewal (Ginestet et al., 2020; Woolley, 2024).

Some studies have demonstrated that the risk of mould and moisture-related problems is substantially reduced in homes with well-designed mechanical ventilation systems. For example, Roussel et al. (2008) found higher mould concentrations in rooms lacking mechanical ventilation, and Wallner et al. (2015) observed a similar trend in a comparative study of Austrian dwellings. These findings underline the importance of optimising the design, commissioning, and operation of ventilation systems in airtight, energy-efficient homes. Only by raising occupant awareness and ensuring robust ventilation performance can the dual goals of energy efficiency and indoor environmental quality be achieved (Manousakas et al., 2020).

2.4 Building Technology and Equipment.

Integrating advanced building technologies, including ventilation systems, air filtration, and household appliances, is key to improving IAQ in new UK homes. As new construction standards promote higher airtightness for energy efficiency, reliance on both mechanical and natural ventilation strategies is crucial to ensure effective pollutant removal (Orme, 2001; Shrubsole et al., 2014). However, the success of these systems depends on both technical

performance and the ways occupants interact with and maintain them (Sharpe et al., 2015; Derbez et al., 2017).

In parallel, everyday activities such as cooking, cleaning, and the use of kitchen appliances (e.g., gas hobs, ovens, and extraction hoods) are significant episodic sources of indoor pollutants, including particulate matter and volatile organic compounds (Vardoulakis et al., 2020; Sun & Wallace, 2021). As a result, there is an increasing focus on the combined role of ventilation design, filtration technologies, and source-control measures, particularly in kitchens, to reduce IAQ risks. This section reviews current evidence on the performance and limitations of building technologies for IAQ, the interaction between system design and occupant practices, and emerging strategies to address pollutant generation from kitchen equipment and other household appliances.

2.4.1 Ventilation Principles.

Ventilation is the primary mechanism for introducing fresh air into buildings and maintaining acceptable IAQ by removing or diluting indoor contaminants (ASHRAE, 2010). In the UK, regulations such as Approved Document F (ADF) establish guidelines to ensure that new homes achieve a balance between adequate ventilation, occupant health, and energy efficiency. According to ADF, the principal goal of ventilation is to flush out ‘stale’ indoor air and replace it with ‘fresh’ outdoor air (Ministry of Housing, 2022). The selection of an appropriate ventilation strategy is determined during the building design stage. Compliance can be demonstrated by specifying whole-dwelling and extract ventilation rates, confirming that ventilation requirements are met, or by installing one of the ADF-specified systems: background ventilators with intermittent extract fans (natural ventilation), continuous mechanical extract ventilation (MEV), or mechanical ventilation with heat recovery (MVHR). Passive stack ventilation (PSV), previously designated as a separate system, is no longer an option under the latest ADF update (Ministry of Housing, 2022; EnviroVent Ltd, 2021). Ensuring that ventilation systems are properly commissioned, installed, and maintained in accordance with relevant guidelines is crucial for achieving the specified airflow rates in practice (Ministry of Housing, 2022).

The design of residential building ventilation systems is guided by interconnected principles to effectively manage indoor pollutant levels and ensure healthy indoor environments. Central to these principles is source control, which involves identifying and addressing potential pollutant

sources, such as kitchens, bathrooms, and storage areas, by removing, reducing, isolating, or directly exhausting them. This approach focuses on minimising emissions at their source before considering other measures. Once source control options are exhausted, dilution becomes the next line of defence, introducing outdoor air at specified rates to lower pollutant concentrations to acceptable levels. Internal airflows are managed to direct air from ‘clean’ spaces to more polluted areas, a concept often implemented through ‘cascade ventilation’ and intentional pressure differences between rooms (Dimitroulopoulou et al., 2023). This approach is reflected in international and national standards, although residential requirements are often less stringent than those for non-domestic buildings.

In certain high-risk situations, including recent public health emergencies, localised exposure control measures may also be necessary to further protect occupant health. Advancements in air filtration and air-cleaning technologies have become increasingly important in the context of new, low-energy-efficiency homes, particularly as internal sources of pollution become more significant (Wolkoff, 2018; Stratton & Singer, 2014). Despite advances in ventilation system design, it is widely recognised that the variability in indoor pollutant sources, often linked to occupant activities and material choices, as well as the selection of materials or appliances, can outweigh the influence of ventilation rates alone (Dimitroulopoulou et al., 2023). As a result, maintaining code-compliant ventilation rates may not always ensure acceptable IAQ, particularly in new, low-energy-efficient homes. This emphasises the need for an integrated approach that combines source control, robust, well-maintained ventilation strategies, and ongoing engagement with building occupants and designers.

2.4.1.1 Mechanical vs. Natural Ventilation.

Ventilation rate, often referred to as air changes per hour (ACH) or air exchange rate (AER), is a key factor influencing the entry and removal of both outdoor and indoor pollutants (Gallon et al., 2020). Mechanical ventilation systems (MEV, MVHR) and natural ventilation methods (background ventilators, PSV, window opening) each have their strengths and limitations. The suitable option depends on the building’s airtightness, layout, and occupant requirements.

The ventilation rate, measured as air changes per hour (ACH) or air exchange rate (AER), is a key factor in controlling the entry and removal of both outdoor and indoor pollutants (Wolkoff, 1995). Two main strategies are employed in new, airtight, energy-efficient buildings: mechanical ventilation (such as MVHR and MEV) and natural ventilation (including

background ventilators, PSV, and operable windows). The choice between these approaches depends on the building's airtightness, design, and occupant needs.

Mechanical ventilation systems, in particular MVHR, enable controlled air exchange with potential for heat recovery, helping maintain acceptable IAQ in highly airtight homes. However, their effectiveness depends not only on design but also on correct installation, commissioning, and, importantly, on occupant understanding and how occupants interact with it (Holsteijn et al., 2016). Failures at any of these stages can compromise IAQ and energy savings, as highlighted by studies that found widespread commissioning and operational problems in UK homes (Zero Carbon Hub/NHBC Foundation, 2013; Chan et al., 2019).

On the other hand, natural ventilation depends on factors such as occupant interaction and understanding, weather, and building orientation. Although it may be a cost-effective way to remove stale air, it can be unreliable for maintaining consistent IAQ, especially during winter or in urban environments (Hamilton et al., 2015). Studies indicate that when mechanical ventilation is well managed, airtight homes can achieve both energy efficiency and good IAQ (Langer et al., 2017). However, poor design, faulty installation, or inadequate user engagement can result in deteriorated IAQ (Sharpe et al., 2015).

Both approaches present challenges: poorly commissioned or malfunctioning systems can result in pollutant build-up, increased humidity, and risks such as mould and dust mites (McGill et al., 2014). Thus, a whole-system perspective that considers both the technology and users is needed to ensure that ventilation strategies are practical and user-friendly.

2.4.1.2 Ventilation and Building Energy Efficiency.

The two fundamental targets in new homes are to ensure a continuous supply of fresh air and to reduce uncontrolled air leakage through the building envelope (Younes et al., 2011). Achieving this requires striking a careful balance: while increasing building airtightness is crucial for reducing heat loss and improving energy performance, it can also increase the risk of indoor pollutant accumulation if ventilation provision is inadequate or poorly managed. Both the Royal College of Physicians (RCP, 2016) and Howieson et al. (2013) emphasise the potentially conflicting goals of improving IAQ and increasing airtightness for energy conservation, further noting that insufficient ventilation can result in elevated humidity, mould growth, condensation, and more severe asthma and allergies.

There has been an ongoing debate over whether highly airtight, energy-efficient homes negatively affect IAQ, mainly because they reduce uncontrolled air exchange. However, poor IAQ outcomes are not inherent to such buildings; they mostly occur when adequate controlled ventilation or source-control measures are not implemented. Therefore, managing both ventilation rates and pollutant sources effectively is crucial to ensure that improved energy efficiency does not compromise occupant health.

Large-scale international research, such as the EBC-IEA Annexe 68 project, has examined IAQ in low-energy residential buildings compared with that in standard homes across several countries, including Australia, Belgium, China, France, Japan, and the USA (Rode et al., 2019). Analysing data from nearly 3,000 low-energy homes and 5,000 conventional homes, the project found that while contaminant concentrations for most pollutants were generally lower in low-energy homes, certain VOCs, including formaldehyde, toluene, and others, were present at higher levels in the more energy-efficient properties. The findings suggest that emissions from new construction materials and products, commonly used in new low-energy buildings, may account for these differences.

Furthermore, a study from Ireland found that envelope retrofits designed to enhance airtightness and thermal performance could inadvertently increase indoor concentration levels of formaldehyde, PM_{2.5}, and CO₂, particularly when not accompanied by corresponding improvements in ventilation (Derbez et al., 2017). This emphasises the need for integrated retrofit approaches that combine addressing both building envelope and ventilation system upgrades. Modelling studies of NetZero energy homes have also shown that although mechanical ventilation can be sufficient to control many pollutants, including formaldehyde and acetaldehyde, comprehensive source control remains critical, especially in highly airtight homes (Ng et al., 2017). Without such measures, the benefits of energy efficiency may be offset by increased risks to IAQ and occupant well-being.

2.4.2 Ventilation System Design, Performance, and Commissioning.

Ventilation is increasingly recognised as a crucial component of healthy residential environments, and building regulations now place considerable emphasis on ensuring adequate ventilation rates in new homes. However, evidence across Europe indicates that actual ventilation performance often falls short of regulatory goals (Dimitroulopoulou, 2012). When

ventilation rates drop below the recommended threshold of 0.5 air changes per hour, indoor pollutant levels may increase to concentrations that pose greater health risks to occupants. The problem is exacerbated in homes with inadequate or poorly functioning ventilation systems, particularly in the absence of robust mechanical solutions, leading to adverse effects on occupant health and well-being (Wargocki et al., 2002).

Targeted use of mechanical extraction, particularly during high-pollutant activities such as cooking or bathing, can effectively control pollutant levels and maintain relative humidity below the threshold for mould growth, even in airtight homes (Howieson et al., 2013). However, the success of these systems greatly depends on their design and proper use in daily practice.

Building assessment schemes, such as Passivhaus and the Code for Sustainable Homes (CSH), are commonly used in the UK to evaluate the energy efficiency of buildings. However, these ratings often prioritise energy demand and design features over actual indoor air quality or occupant health (McGill et al., 2015). As a result, even highly rated, energy-efficient dwellings may have poor IAQ due to inadequate ventilation or suboptimal occupant behaviour. A strong focus on energy performance can lead to neglect of adequate outdoor air supply and pollutant dilution.

Another barrier to adequate ventilation is the so-called “performance gap” between the desired design and the actual operation of ventilation systems. Studies consistently show that mechanical ventilation is often poorly balanced, incorrectly installed, or not operated as designed by occupants (Sharpe et al., 2016; Van Rooyen & Sharpe, 2024). Proper commissioning, in accordance with guidelines, is crucial to ensure that systems deliver the correct airflow rates and achieve the desired IAQ. However, in practice, commissioning is sometimes done before a building is fully completed, and post-occupancy monitoring remains rare. This discrepancy between regulatory standards and real-world operations can lead to ventilation and IAQ problems going unnoticed and unaddressed (Van Rooyen & Sharpe, 2024). Bridging this gap requires not only improved technical oversight and system commissioning but also ongoing education and engagement with occupants to ensure that ventilation systems operate as intended.

2.4.2.1 Occupant Interactions with Ventilation Technologies.

Occupant behaviour is widely recognised as a key factor influencing IAQ in new homes (IOM, 2011). Unlike in many other building types, residents have considerable control over their

environment, and everyday activities such as cooking, bathing, cleaning, using chemicals, and smoking directly affect the formation and persistence of indoor pollutants. Occupant interactions with ventilation systems, such as opening or closing windows, adjusting or disabling mechanical systems, and neglecting maintenance, can significantly impact airflows and pollutant levels.

A growing body of research highlights that the effectiveness of even well-designed ventilation systems depends on the proper use by occupants. Studies indicate that people often do not operate these systems as intended, with inconsistent window opening, irregular use of controls, and failure to perform maintenance all affecting IAQ outcomes (Derbez et al., 2017; Guyot et al., 2018). Modelling studies assume predictable system use, yet actual behaviour varies with temperature, comfort, and cultural norms (Fabi et al., 2012). The COVID-19 pandemic exacerbated these challenges, with increased time spent indoors and heightened awareness of airborne health risks (Du & Wang, 2020). In this context, proper and regular use of ventilation systems is vital for protecting occupant health, well-being, and productivity (Al Horr et al., 2016).

A growing body of research indicates that demographic, cultural, and socioeconomic factors strongly influence how people regulate ventilation in their homes. For example, McGill et al. (2015), drawing on the Dampness in Buildings and Health (DBH) cohort, show that family size, economic status, and local customs directly affect ventilation practices and indoor moisture levels. Their findings suggest that households with more occupants and limited knowledge are more likely to experience higher humidity and an increased risk of mould growth. Fisk et al. (2007) note that daily activities, particularly in colder climates, contribute to persistent moisture, which can lead to material deterioration and health risks. Mendell (2007) expands this discussion, asserting that although moisture-related problems are well recognised, research should also focus on chemical emissions from newer building materials, including engineered wood and synthetic furnishings, which can last long after installation.

Research into domestic air pollution increasingly identifies cooking as a main source of indoor contaminants. Buonanno et al. (2009) provide detailed measurements of particulate and VOC emissions from everyday meal preparation, while more recent work by Nassikas et al. (2024) emphasises how extraction rates, appliance choices, and culinary preferences influence pollutant levels. These studies collectively illustrate that the impact of ventilation technology depends largely on occupant use, household routines, and local constraints.

Rising public health concerns about airborne disease spread during the COVID-19 pandemic have increased focus on IAQ, highlighting the connection between technical measures and daily behaviour. As a result, there is widespread consensus that ensuring healthy indoor environments now requires both reliable ventilation systems and well-informed, proactive participation from building occupants. However, significant gaps remain in understanding how variations in culture, education, and household composition influence both the adoption of new technology and the sustained use of existing systems. Tackling these complexities requires research beyond generic recommendations and an understanding of the realities of diverse domestic situations.

2.4.3 Appliances and Source Control in IAQ.

In new, low-energy homes, kitchen appliances and cooking activities are increasingly recognised as key sources of indoor air pollutants, especially PM_{2.5}, NO₂, CO, and VOCs. Using gas hobs, ovens, and other combustion appliances can significantly increase indoor pollutant levels, particularly when ventilation is inadequate or inconsistent (Logue et al., 2012; Kumar et al., 2022). Many studies now show that cooking is a primary contributor to PM_{2.5}, ultrafine particles, and VOCs in homes (Kearney et al., 2014), with gas appliances linked to higher NO₂ and CO levels, whereas electric hobs primarily generate particulates from heated oils and food (Xiang et al., 2021). Without proper extraction or source control, these emissions can build up, posing both immediate and long-term health risks (WHO, 2010).

However, the literature indicates that technology alone is insufficient: Zhang et al. (2010) and Singer et al. (2017) both report that many homes lack effective extractor hoods, or, where they are present, the devices are underused, poorly maintained, or incorrectly installed. Ducted extractor hoods vented outdoors consistently outperform recirculating models in removing cooking-related pollutants (Lunden et al., 2014), yet their adoption remains inconsistent in UK housing due to cost, design limitations, and a lack of regulatory enforcement. Moreover, Sun and Wallace (2021) emphasise that even when extraction systems are accessible, occupant behaviour often reduces their effectiveness, as many users prefer to open windows or neglect to operate hoods during cooking.

A growing body of research further shows that the effectiveness of these technical interventions ultimately depends on occupant engagement and awareness. For instance, Singer et al. (2017) highlight that a lack of user education and irregular maintenance, including failure to clean or

replace filters, can diminish system performance. The gap between technical capability and actual use remains a persistent concern, and one in which policy and practice in the UK have yet to align with best-practice recommendations. Other appliances, including gas heaters, unvented tumble dryers, and open-flame devices, can also worsen poor IAQ, especially in airtight homes where infiltration for dilution is limited. This highlights the need for a comprehensive approach to source control that combines effective technical solutions with clear, targeted user guidance.

Cooking is widely acknowledged as a primary source of PM_{2.5}, ultrafine particles, and VOCs in homes (Kearney et al., 2014). Gas appliances, in particular, contribute to NO₂ and CO emissions (Xiang et al., 2021). While the health risks of such exposures are well documented (WHO, 2010), the real-world effectiveness of technical interventions, such as extractor hoods, varies considerably. For example, Zhang et al. (2010) and Singer et al. (2017) both found that even when extractor hoods are present, their effectiveness is often reduced by poor maintenance, inconsistent use, or suboptimal installation. The literature consistently shows that ducted hoods vented outdoors are considerably more effective than recirculating models (Lunden et al., 2014), yet adoption of the former remains inconsistent, particularly in UK housing, possibly due to installation costs and design limitations. This operational gap is further compounded by occupant behaviour, with Sun & Wallace (2021) observing that many users prefer to open windows rather than use mechanical ventilation, or neglect cleaning and filter replacement, thereby impairing system performance.

In summary, effective source control in kitchens and utility areas requires both technology and user engagement.:

- Installing efficient, well-maintained extractor hoods that are vented outdoors.
- Offering clear guidance to occupants on correct appliance use and maintenance.
- Incorporating automatic or demand-controlled ventilation systems where feasible.
- Avoiding unvented combustion appliances in new, airtight homes.

Since kitchen-generated pollutants are a major contributor to poor air quality in many new homes, emphasising source control through appliance selection, proper installation, and user education is essential for maintaining good IAQ.

2.4.3.1 Innovations and Limitations in Ventilation Technology.

Understanding how ventilation technologies work in real homes requires more than just a technical assessment; it also involves considering everyday occupant behaviours and the social significance of fresh air and ventilation. Studies adopting a social practice theory perspective have emphasised the complex and routine ways occupants interact with natural and mechanical ventilation systems. For example, Zukowska et al. (2020) found that airing practices, such as opening windows, are often linked to daily routines, like waking up, cleaning, or responding to changes in humidity or odour. These behaviours evolve over time and are influenced by weather, building type, or the presence of new ventilation technology. While older, draughty homes often open windows to manage condensation, those in newer, mechanically ventilated homes may air their rooms less frequently. Tham (2016) further demonstrates how practical understandings of heat and air movement evolve through sensory experiences and are influenced by the material arrangements of the home. As people move between homes of different ages, insulation levels, or ventilation technologies, they may adopt new routines and knowledge to manage their indoor environment, whether to stay warm in an older property or improve airflow in a new, low-energy-efficient house.

Despite growing public awareness and targeted campaigns promoting good ventilation habits, the actual use and maintenance of ventilation systems can fall short of design expectations. Van Rooyen & Sharpe (2024) emphasise that ventilation-related implications, including health, freshness, and nature, are intertwined with both practical and formal knowledge. While occupants may receive guidance on optimal ventilation from public campaigns or family members, their actual practices are primarily influenced by sensory feedback, daily routines, and the design or layout of their homes. Technical aspects of ventilation systems might be overlooked or misunderstood, especially when they are not fully integrated into daily life. Gupta et al. (2018) highlight additional limitations and unintended consequences in energy-efficient homes, noting that technical ventilation systems can be easily compromised by everyday behaviours, such as blocking vents with furniture or storage, or inadvertently disrupting ductwork. These findings highlight a recurring discrepancy between the intended design of ventilation technologies and their actual application. These gaps between design intent and real-world use underscore persistent challenges and limitations, even as technical solutions become more sophisticated.

In summary, the success of innovative ventilation technologies depends on their integration into daily home life and the extent to which occupants understand and engage with them. The complexity of ventilation practices, the invisibility of airflow, and the diverse cultural and sensory meanings associated with ‘fresh air’ continue to challenge both technological effectiveness and occupant acceptance. Addressing these limitations requires improved technical design and a stronger focus on user experience, education, and the practical realities of living in new, energy-efficient homes.

2.5 Occupant Behaviour: Lifestyles, Awareness, and Practices.

Occupant behaviour is a key factor influencing IAQ in homes. This section examines how daily habits, lifestyle routines, and activity patterns affect pollutant levels and ventilation effectiveness. It also considers how occupants’ knowledge, awareness, and cultural context shape their approach to managing IAQ. The discussion will cover the impact of human behaviour, the significance of lifestyle and activities, the influence of perception and awareness, and the role of socio-cultural factors in shaping practices that affect IAQ.

2.5.1 Occupant Behaviour.

Occupant behaviour refers to the ways in which individuals interact with buildings, technologies, and their systems to achieve or maintain desirable indoor environmental conditions (Moreno-Rangel et al., 2020). Delzende et al. (2017) found that these interactions are driven by the pursuit of thermal, visual, acoustic, and air-quality comfort. Fabi et al. (2012) further refine this by emphasising that behaviour includes both conscious and unconscious actions, influenced by the occupant’s perceptions, experiences, and learned routines. These behavioural choices are not made in isolation but depend on ongoing feedback between the perceived environment and the occupant’s expectations or previous experiences.

A useful distinction within the literature is between non-adaptive and adaptive behaviours (Hong et al., 2016). Non-adaptive behaviours are characterised by routine patterns such as regular appliance use, habitual window opening, or predefined schedules for operating ventilation and lighting systems. In contrast, adaptive behaviours are intentional responses to changing environmental conditions. Examples include adjusting clothing, opening windows in response to IAQ concerns, or modifying routines to maximise comfort. This dual framework highlights the complex negotiation between occupants’ needs, preferences, and the developing indoor environment.

2.5.2 Occupant Activity and Lifestyle Choices.

Understanding the impact of occupant behaviour on IAQ requires more than technical or environmental monitoring alone. Social Practice Theory (SPT) is increasingly adopted in recent literature to frame occupant behaviour not merely as a set of isolated actions but as embedded within wider routines, social norms, and material contexts (Hong et al., 2016). Unlike behavioural models that focus on rational or reactive decision-making, SPT suggests that practices such as window opening, ventilation, and appliance use are influenced by collective habits, tacit knowledge, and social interactions (Vardoulakis et al., 2020). This perspective questions traditional IAQ models by emphasising the significance of cultural and contextual factors, suggesting that interventions should engage with these underlying routines rather than merely providing information or technology (Pourtangestani et al., 2024).

The importance of these factors is evident in variability in IAQ outcomes across households, even when physical building specifications are identical. Lifestyle choices, socioeconomic status, and education influence attitudes and behaviours towards air quality (Ferguson et al., 2021). Activities such as cooking and cleaning, the frequency and duration of window opening, and general engagement with ventilation systems all significantly impact IAQ and health, particularly among vulnerable populations (Pitarma et al., 2016). The literature underlines the need for future research and interventions to capture these behavioural dimensions, with a focus on minimising exposure to pollutants such as PM_{2.5} and TVOCs, while respecting occupant privacy and autonomy (Carslaw et al., 2025).

The literature also documents considerable variation in IAQ outcomes among households with similar building features, highlighting the influence of lifestyle, socioeconomic status, and education (Ferguson et al., 2021). Specific activities, including cooking and cleaning, as well as the frequency and timing of window openings, significantly affect pollutant levels (Pitarma et al., 2016). This is especially important for vulnerable groups, where increased exposure to PM_{2.5} and TVOCs can worsen health risks. While building regulations prescribe minimum ventilation standards, studies indicate that human behaviour often determines whether these standards are achieved in practice (Dawadi et al., 2016; Marr et al., 2012). For instance, Fabi et al. (2012) identify window opening as a common and effective method for improving ventilation. Yet, this practice varies widely depending on comfort preferences, external conditions, and cultural norms. In contrast, cooking activities are consistently identified as having the greatest impact on IAQ, exceeding other indoor pollution sources (Kim & Li, 2020; Lunden et al., 2014; Ferguson et al., 2021). This convergence in the literature underscores the need for holistic IAQ

management strategies that account for both technological solutions and the realities of occupant behaviour.

2.5.2.1 Lifestyle and Activity Patterns Affecting IAQ.

Daily routines, such as cooking, cleaning, and using household products, are key determinants of IAQ, with ventilation practices and appliance use influencing the accumulation or removal of pollutants (Caracci et al., 2022). These patterns are influenced by cultural background and socioeconomic status, so even similar homes can yield different IAQ outcomes depending on how occupants manage their indoor environments and make lifestyle choices (Dimitroulopoulou et al., 2015; Lim et al., 2021).

Empirical studies have shown that the regular use of extractor fans, opening windows at appropriate times, and maintaining appliances are essential for controlling indoor emissions (Gupta et al., 2018; Paciência et al., 2016). In contrast, neglecting these behaviours can lead to poor IAQ, regardless of a building's technical features. Targeted interventions, such as occupant education or real-time IAQ feedback, have been shown to improve daily practices and support reductions in pollutant exposure (Moreno-Rangel et al., 2020).

2.5.3 Cooking Activities and IAQ.

Cooking is a major contributor to poor IAQ in homes and is particularly relevant to this thesis, given its importance as a daily activity with substantial, variable emissions. Unlike certain indoor pollutants, such as those from smoking, cooking emissions can be addressed through both occupant choices and building design interventions. Some studies have shown that frequent cooking practices can lead to elevated pollutant concentrations, often resulting in indoor environments that exceed outdoor pollution levels during periods of active cooking (Wallace, 1996; Singer et al., 2017).

The specific types and amounts of pollutants produced during cooking depend on several factors, including the fuel source (e.g., electricity, gas, or wood), the cooking method, and the ingredients used. Gas and propane stoves, for example, have been linked to higher emissions of NO_x, CO, formaldehyde (HCHO), and other hazardous compounds. Additionally, cooking at high temperatures, frying, and the use of oils and fats can substantially increase the release of PM, VOCs, black carbon, and polycyclic aromatic hydrocarbons (PAHs) (Chen et al., 2016; Buonanno et al., 2009; Wallace, 1996). Research has highlighted that PM_{2.5} and VOCs emitted during cooking pose significant health risks, with long-term exposure linked to respiratory conditions, heart disease, and, in severe cases, cancer (Varaden et al., 2025). The health

implications emphasise the vital importance of recognising cooking as both a source of indoor pollution and an opportunity for intervention in IAQ management.

The impact of cooking-generated pollutants is also closely linked to building characteristics, particularly airtightness levels and ventilation effectiveness. While new airtight building envelopes are designed to enhance energy efficiency, they may unintentionally increase the buildup of cooking-related pollutants if ventilation rates are insufficient (Asikainen et al., 2016; Less et al., 2015). Therefore, the design and operation of ventilation systems are crucial in controlling IAQ. Studies have shown that high-efficiency range hoods are generally more effective than basic mechanical ventilation in removing particulate pollution at its source (Tang & Pfrang, 2023). However, even with higher air-change rates (e.g., 6 ACH), pollutants can spread to other areas of the home unless they are captured efficiently at the source (Sun & Wallace, 2021; Baeza-Romero et al., 2022).

The effectiveness of pollutant removal during cooking depends on the type and operation of the range hood, the building form, ventilation rates, indoor and outdoor air quality, and kitchen size (Wang et al., 2022; Zenissa et al., 2020). Ultimately, occupant behaviour, including ventilation and range hood use, remains crucial for effectively mitigating poor IAQ. Cooking activities are a significant yet often neglected source of indoor air pollution in homes. The level of exposure to pollutants from cooking depends on the occupant's lifestyle choices and habits, building design, fuel type, and ventilation effectiveness. Therefore, incorporating effective ventilation strategies and raising awareness of cleaner cooking methods are vital steps towards finding a cost-effective solution to IAQ in new homes.

2.5.4 The Role of Occupants in IAQ Management.

Intermittent indoor pollutant sources, such as NO₂ and VOCs, are primarily linked to occupant activities, including cooking and smoking (Langer et al., 2017; McGill et al., 2015). As such, Asikainen et al. (2016) demonstrated a direct relationship between the duration of these activities and pollutant concentration levels. Once the activity stops, the pollutant levels drop abruptly. Additionally, indoor pollutant concentrations are influenced by emission rates, with certain low-level VOC emissions serving as continuous sources of pollution (Chi et al., 2016). As building technology advances, particularly in thermal insulating materials (Wi et al., 2020), the indoor environment becomes increasingly comfortable, altering occupants' lifestyles and increasing the time spent indoors (Mulliner et al., 2020). This shift has led to what is now referred to as "indoor generation", where a majority of people's activities occur within indoor spaces

with complex and chemically diverse air quality (Ferguson et al., 2021). Occupant density and lifestyle choices further influence IAQ. Ferguson et al. (2021) highlight that the number of inhabitants in a home may influence indoor pollutant concentrations due to variations in indoor activities, perceptions, and living habits. Furthermore, studies have established strong associations between exposure to poor IAQ and increased morbidity and mortality (Kelly & Fussell, 2019), underscoring the critical role of occupant behaviour in IAQ management.

Occupants engage in various activities within buildings to satisfy both physical and non-physical needs, which in turn influence building operations and indoor environmental conditions. The studies in Table 4 suggest that IAQ recommendations may be less practical if they are not linked to readily available, actionable strategies for occupants. This highlights the need to include occupants in IAQ solutions. This research examines occupants' activities and motivational drivers to identify the key variables that determine perceptions of IAQ and building operation practices, while encouraging behavioural change to improve IAQ.

As summarised in Table 2.4, a range of intervention studies demonstrate that user-friendly technologies can effectively motivate occupants to adopt improved ventilation and source-control behaviours (Fang et al., 1998; Schieweck et al., 2018; Wong-Parodi et al., 2018; Kloster et al., 2022). These interventions not only provide actionable information but also promote greater engagement and responsibility among residents.

Table 2. 4: Studies investigating the impact of occupant behaviour interventions on IAQ in homes.

Article	Intervention Design	Pollutant measured	Location	Case studies	Behaviour change theory	Results
Fang et al., 1998	IoT sensor – senses pollution actions, detects pollution sources, offers recommendations for remedial action, and provides information accessed through a smartphone application.	VOCs, PM, Temperature, Humidity.	Home deployment.	Three different families in which one member smokes tobacco. Ten weeks per case study.	None specified.	The sensor served as a motivational trigger for improved IAQ behaviour, ventilation, and other related aspects. Increased awareness of IAQ competence.

Kim 2018	Evaluate the occupant's reflection on using one of the three IAQ monitoring instruments: Awair, Foodbot, and Neatmo.	Multiple pollutants.	Home deployment.	Various product reviews of home IAQ monitors.	Sense-making theory.	The reliability and interpretability of IAQ information affect sense-making. Evidence of behavioural changes to remove IAQ pollutants.
Wong-Parodi et al., 2018.	Sensor devices are available to the public, free of charge, at the local library for home use to monitor PM2.5 levels, with access to web-based platforms.	PM (Non-specific)	Home deployment.	26 participants. Three weeks of deployment. One device per participant.	None specified.	Participants' use of behavioural adaptation to mitigate risks associated with poor IAQ.
Jensen et al., 2016.	CO ₂ sensors are deployed in households to control ventilation strategy (e.g., opening windows for five minutes, two to four times daily).	CO ₂	Home deployment.	12 households.	None specified.	Occupants were found to adopt ventilation behaviour and save 5-10% energy.

These findings indicate that technological interventions, such as sensor-based feedback systems and monitoring instruments, serve as motivational triggers for behavioural change, enhancing occupants' awareness of IAQ and promoting ventilation and pollutant reduction strategies (Fang et al., 1998; Schieweck et al., 2018). Additionally, accessibility and usability influence behaviour, with sense-making theory highlighting that occupants are more likely to adopt IAQ-improving behaviours when IAQ data is reliable and easy to interpret (Schieweck et al., 2018).

2.5.4.1 Impact of specific activities on indoor pollutant levels.

Daily household activities, including cooking, cleaning, appliance use, and smoking, significantly affect IAQ by introducing various pollutants into indoor environments. Cooking, particularly with gas stoves or biomass fuels, generates high levels of PM_{2.5} and NO₂, contributing to poor respiratory health outcomes (Willers et al., 2013; Dimitroulopoulou et al., 2015). Similarly, cleaning products, air fresheners, and scented candles release VOCs that react with ozone, forming secondary pollutants that further degrade IAQ (Missia et al., 2010). Additionally,

occupant heating and cooling behaviours, such as thermostat adjustments, window operation, and use of mechanical ventilation, influence pollutant dispersion and air exchange rates, thereby affecting both thermal comfort and air freshness (Moschetti & Carlucci, 2016).

Notably, two identical homes with the same structural and mechanical designs may exhibit different IAQ conditions depending on occupants' lifestyle choices. One household might practice frequent window ventilation, use extractor fans, and limit indoor emissions, whereas another may rarely open windows, cook with high-emission appliances, or light incense and candles indoors, resulting in higher pollutant accumulation (Moschetti & Carlucci, 2016; Wang et al., 2022). These variations highlight the need for targeted behavioural interventions to encourage healthier IAQ habits. Studies suggest that improving IAQ can be achieved through tailored educational campaigns, automated IAQ feedback systems, and culturally sensitive interventions that align with occupants' routines and beliefs (Kim & Li, 2020). Recognising how lifestyle choices influence IAQ is essential for designing effective policies and interventions that empower occupants to make informed decisions about healthier indoor environments.

2.5.5 Occupant Perception, Knowledge, and Awareness.

Occupants' perceptions and awareness of IAQ play a crucial role in shaping behaviours that influence pollutant levels in residential and commercial environments. Factors such as attitudes, beliefs, socioeconomic status, education level, and cultural background influence how individuals interact with indoor spaces and respond to IAQ-related issues (Yang et al., 2020). While sensor technologies and IAQ monitoring devices are increasingly used to raise awareness, their effectiveness largely depends on how information is communicated and perceived by occupants (Kureshi et al., 2021). Despite technological advances, a gap remains in integrating behavioural psychology with real-time IAQ monitoring to promote meaningful and lasting behavioural change (Kelly & Fussell, 2019).

Several studies have explored the relationship between occupant activities and IAQ, emphasising how real-time feedback on pollutant levels can motivate behavioural change (Mumtaz et al., 2021). For example, a study by Yang et al. (2020) utilised ambient sensors in smart home installations to track motion, door openings, lighting, and temperature fluctuations, as well as PM, VOCs, and CO₂ concentrations. The results revealed a strong correlation between occupant activities and pollutant levels. Other studies have confirmed that behaviours such as

window operation, ventilation habits, and cooking frequency significantly impact indoor pollutant concentrations (Carslaw et al., 2025).

Broader socioeconomic factors and building characteristics also shape perceptions of IAQ and responses to it. Income, housing types, and social diversity influence IAQ disparities between demographic groups (Wong-Parodi et al., 2018; Vardoulakis et al., 2020). For example, low-income households are more likely to experience poor ventilation, limited access to energy-efficient appliances, and greater exposure to activities that generate pollutants, such as biomass cooking and indoor smoking (Vardoulakis et al., 2020). Cultural practices and social norms also influence ventilation routines, cooking practices, and overall awareness of indoor pollutants, leading to varied IAQ outcomes across communities and regions (Kim & Li, 2020; Lunden et al., 2014).

Developing effective communication and targeted interventions is essential to enhancing occupant perceptions of IAQ and supporting long-term improvements in indoor environments. These studies argue that unmonitored activities and low awareness can lead to prolonged exposure to pollutants and increased health risks, while effective monitoring and feedback systems can support positive behavioural change.

To address the lack of awareness about IAQ, real-time IAQ monitoring systems with interactive feedback mechanisms have been proposed as an effective strategy. Studies suggest that presenting occupants with real-time pollutant exposure data, alongside educational interventions, increases engagement in IAQ-improving behaviours, such as improved ventilation, use of air filtration systems, and reduced pollutant-generating activities (Dawadi et al., 2016). Integrating behavioural psychology models with IAQ monitoring can further optimise interventions, ensuring campaigns are tailored to diverse demographic and cultural groups (Wong-Parodi et al., 2018). Developing effective communication methods and targeted behavioural interventions will be key to enhancing occupant perception of IAQ and encouraging long-term improvements. These studies suggest that unmonitored indoor activities and a lack of IAQ awareness can lead to prolonged exposure to pollutants and increased health risks, while effective monitoring and feedback systems can support positive behaviour change.

2.6 Home Development Process and IAQ.

The development of residential buildings in the UK follows a multi-stage process structured around the Royal Institute of British Architects (RIBA) Plan of Work, which covers stages

from initial strategic definition, preparation, and concept design, through spatial and technical design, manufacturing, construction, handover, and use (RIBA, 2020). At each stage, decisions regarding site selection, building form, material specifications, and ventilation strategies directly affect IAQ.

This process is inherently collaborative, involving a wide range of different stakeholders, including developers, architects, designers, engineers, supply chain partners, regulators, and environmental consultants. Its duration and complexity often vary in relation to local planning controls, market conditions, and national policies, particularly those addressing energy efficiency and climate change. The Future Homes Standard (Ministry of Housing, 2021) has led to more stringent carbon-reduction targets, resulting in airtight homes and a greater emphasis on energy efficiency. However, without due consideration, such advances can inadvertently increase the risk of indoor pollutant accumulation (Hamilton et al., 2015; Vardoulakis et al., 2015).

A major driver for recent changes has been the escalating concern over climate change and carbon emissions. The built environment is a major contributor to global greenhouse gas (GHG) emissions, with the UK's residential sector accounting for approximately 25% of total end-user GHG emissions (IEA & OECD, 2019; DECC, 2014). Policy responses, including the Future Homes Standard, commit the sector to ambitious emission reductions by 2050 (Ministry of Housing, 2021), leading to increasingly tighter building envelopes and greater emphasis on energy performance.

While regulations and standards set minimum requirements for energy efficiency and pollutant control, the degree to which IAQ is prioritised varies across stages of development. Factors such as siting, orientation, airtightness, material selection, and the integration of ventilation systems collectively shape the IAQ of the completed home. Recent research highlights that IAQ results not solely from design or technology but from the complex interplay among regulation, construction practice, material emissions, and ultimately, occupant behaviour (Hamilton et al., 2015; Vardoulakis et al., 2015).

The home development process itself is formed by both barriers and opportunities. Fragmented regulatory oversight, multiple overlapping standards, and variable implementation of IAQ-related policies often result in inconsistent practice (Heffernan et al., 2015; Hamilton et al., 2015). Economic constraints and market dynamics further influence which IAQ interventions are adopted or overlooked (Vardoulakis et al., 2015; Macmillan et al., 2016). As homes become more

complex systems, marked by the integration of advanced technologies and systems, the importance of cross-disciplinary collaboration grows, necessitating holistic,

Understanding these interactions is crucial in the context of pathways, as conceptualised in this thesis. Decisions made at each stage, from land acquisition through post-occupancy operation, can create either barriers or opportunities for achieving good IAQ. Identifying key intervention points is essential for developing healthier, more sustainable homes (Black et al., 2021; Marshall, 2011).

2.6.1 Industry Stakeholders and Decision-Making.

A diverse group of stakeholders influences IAQ during home development, and their decisions create both opportunities and barriers. Heffernan et al. (2015) highlight that the fragmented regulatory landscape results in ventilation and pollutant-exposure limits being covered by overlapping standards rather than by a unified policy. Unlike energy standards, IAQ guidelines often lack robust enforcement, leading to ambiguity about compliance, particularly when responsibilities are divided among multiple government bodies and local authorities (Hamilton et al., 2015).

Furthermore, local authorities operate under varied regulatory frameworks, resulting in housing developments being subject to different planning requirements depending on their location. These inconsistencies limit the establishment of uniform IAQ standards across the housing sector. Therefore, a comprehensive understanding of how decisions throughout the home development process impact IAQ is crucial. Limited awareness of the interactions between building context, design, technologies, material emissions, and occupant behaviour can lead to unintended IAQ risks (Simpson et al., 2020).

Given the complexity of housing supply chains, evaluating decision-making at each stage is essential for understanding how IAQ is addressed in design and construction. Business and market constraints, alongside regulatory pressures, also influence the extent to which IAQ strategies are implemented in mass-market housing (Vardoulakis et al., 2015; Macmillan et al., 2016). Without a clear understanding of how developers operate within these constraints, it is challenging to implement scalable and cost-effective IAQ improvements. A systematic evaluation of interventions across the sector is needed to ensure that future projects prioritise IAQ.

2.6.2 Opportunities for Integrating IAQ Considerations.

The literature highlights that improving IAQ in new housing requires integration across all stages of planning, design, construction, and operation. Buildings function as interconnected systems, where decisions in one area can have unintended consequences elsewhere (ASHRAE, 2009; Sumedha, 2008). Studies highlight that a holistic approach is essential, as isolated interventions risk increasing pollutant levels or undermining other aspects of performance (Dimitroulopoulou et al., 2023).

Key opportunities include aligning site selection and orientation with outdoor pollution levels, carefully choosing low-emission materials, and ensuring rigorous commissioning of ventilation systems (Tham, 2016). Researchers also emphasise the importance of occupant awareness, as proper use of ventilation systems and informed behaviours can impact IAQ outcomes (Crawley et al., 2018). On a broader scale, urban design and passive strategies are recognised as effective for reducing infiltration of outdoor pollutants and enhancing indoor air distribution (Wieser et al., 2021).

Overall, these studies demonstrate that improving IAQ relies on interdisciplinary collaboration, early consideration of IAQ issues, and a combination of technical and behavioural approaches. These insights lay a foundation for this thesis, which develops a pathways framework to turn such opportunities into cost-effective, scalable strategies for practice.

2.7 Building Regulations and Standards for IAQ.

As reviewed in earlier sections, each pathway, covering building design, technology, occupant behaviour, and the development process, is influenced by evolving regulatory standards and guidance. As a cross-sectional theme, building regulations and standards interact with and underpin all four pathways, affecting decision-making across the residential sector. The following section provides an overview of key regulations, standards, and certification schemes relevant to IAQ in UK homes.

From the 1960s onwards, climate change policies and regulations, along with the push for increased airtightness in buildings, have aimed to reduce heat loss and regulate indoor environments. However, these measures have also affected the balance between indoor and outdoor pollutant sources that contribute to personal exposure. Buildings are susceptible to the

infiltration of external pollutants (e.g., PM_{2.5}, PM₁₀, NO_x, and radon) through the building envelope, while also generating indoor pollutants (e.g., PM_{2.5}, VOCs, CO₂, and moisture), which can promote mould growth (Shrubsole et al., 2014). As a result, IAQ varies with indoor and outdoor pollution sources, temperature and relative humidity fluctuations, and is further influenced by building form and regional meteorological conditions (Ferguson et al., 2021). Increasing research highlights the health impacts of air pollution and indoor environmental factors, reinforcing the need for improved IAQ and overall IEQ. This recognition has led to regulatory interventions, including the introduction of Building Regulations for England and Wales, particularly Part F, which address IEQ concerns.

As pollutant levels continue to rise and homes become more airtight, the challenge of maintaining good IAQ has intensified. The shift toward energy-efficient building practices has led to increased airtightness and reduced natural ventilation in residential buildings. In response to growing concerns about IAQ, the UK government has incorporated minimum ventilation requirements into Building Regulations Part F, while Part L focuses on achieving energy efficiency in new homes. However, these regulations often prioritise energy conservation over IAQ, potentially compromising indoor air conditions if ventilation remains inadequate.

Certification schemes such as Indoor Air Comfort and Indoor Air Comfort Gold, developed by Eurofins, assess the low-VOC emissions of building materials, furniture, and decorative coatings to support IAQ. These certifications align with European voluntary specifications, emission regulations, and sustainable building certifications. The Indoor Air Comfort label covers compliance criteria such as AgBB (Germany), French and Belgian legislation, EMICODE, BREEAM, and the WELL rating system. Certification relies on environmental chamber testing, following international standards such as the ISO 16000 series and EN 717-1, to ensure harmonised emission assessment across products (Yu & Crump, 2011).

Emission testing, particularly through environmental chambers (EN 717-1), is a standard method for evaluating the emission rate of materials over time (Wei et al., 2012). Materials passing these standardised emission-rate tests qualify for use in buildings and for WELL certification labelling. Given that building materials significantly impact indoor air pollution (Ruiz-Jimenez et al., 2022), it is essential to consider secondary emission effects, such as materials acting as sinks that absorb pollutants and subsequently re-release them (Tichenor et al., 1990; Xu et al., 2012). Other factors influencing VOC concentrations include ventilation efficiency and material composition, which must be evaluated before installation to prevent exceeding

permissible pollutant limits (Kim et al., 2011). To enable comparative assessments, emission rates should be measured under controlled conditions using climate chambers (ISO 16000-9 to ISO 16000-11).

The growing sustainability agenda has driven changes in material selection and the adoption of new sustainability rating systems such as BREEAM, along with recommended design protocols from the Green Building Council and ventilation guidance from ASHRAE and CIBSE (ASHRAE, 2016; CIBSE, 2015). However, since the 1990s, while strategies to improve human health and well-being have gained recognition, their influence on the evolution of building standards has remained relatively limited. Table 2.5 below summarises emission limits required by various regulations across Europe, including Eurofins labelling criteria, the WELL standard, and WHO (2010) recommendations.

Table 2 5: IAQ Labelling Schemes and Emission Limit criteria adopted across Europe.

Organisations/Country	Key Features	TVOC Emission Limits ($\mu\text{g}/\text{m}^3$)	Relevant Standards
AgBB/DIBt: (Germany, Regulatory)	Environmental chamber test based on ISO 16000 series & EN 717-1; Evaluation limit after 28 days.	1000	CEN/TS 16516, ISO 16000 series
WHO (2010)	Indoor Air Quality Guidelines for Human Health.	300	-
M1 (Finland, Voluntary)	-	-	-
E Class (Belgium, Regulatory - Formaldehyde Only)	Construction product certification.	1000	CEN/TS 16516
Anses/AfSSET: (France, Regulatory/Voluntary)	IAQ-related chemical exposure regulation.	-	-
EMICODE (Germany, EC Series)	Flooring product emissions control.	300	CEN/TS 16516
California Department of Public Health (CDPH, USA)	Emission standard for building materials.	-	Method v1.2
Indoor Air Comfort (Eurofins)	Emission certification standard and Gold rating.	1000 (Standard), 750 (Gold)	EN-16516.1:2018

The European Economic Area EEA (2013) particularly concludes:

"The complexity of indoor pollution sources, health effects pathways and the multitude of parties responsible for generating and controlling indoor air pollution suggest that measures to improve IAQ need to be part of a comprehensive management strategy, taking account of climate and outdoor air quality, building materials and technologies, behaviour patterns, as

well as energy and sustainability policies." In the UK, chemical safety and classification are primarily driven by EU regulations. The Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) framework holds manufacturers, importers, and downstream users accountable for ensuring that chemical substances do not pose risks to human health or the environment.

2.7.1 Standards, Legislation and Guidelines for Indoor Pollution.

Unlike outdoor air, which has been subject to comprehensive regulation for decades, indoor air remains less consistently regulated (Derbez et al., 2017). While building regulations such as Part F and Part L (discussed in Section 2.7) provide minimum mandatory requirements, a broader range of voluntary standards, international guidelines, and certification schemes has developed to address indoor pollutants more directly.

Several countries have established target levels for indoor pollutants (Harrison, 2021), often based on outdoor air quality standards set by organisations such as the WHO and ASHRAE. Public Health England (PHE, 2019) introduced IAQ guidelines for pollutants to raise awareness and promote source control in the UK. Similarly, the Air Quality Strategy aligns with EU legislation aimed at reducing ambient PM_{2.5} and other pollutants (Dimitroulopoulou et al., 2023). Workplace exposure limits (WELs), derived from EU directives, provide indicative thresholds for occupational environments (Carroll et al., 2018), although their applicability to residential IAQ is more limited.

A selection of guidance documents and frameworks complements these efforts:

- WHO Global Air Quality Guidelines establish strict IAQ targets for PM, NO₂, VOCs, and other pollutants (WHO, 2010; Hoffmann et al., 2021).
- Household Fuel Combustion Guidelines provide specific recommendations for residential exposure (Bruce et al., 2015).
- NICE IAQ at Home Guidance offers practical IAQ improvements aimed at both policymakers and practitioners (NICE, 2020).
- CIBSE TM40 promotes the use of health-based IAQ metrics when assessing building performance (CIBSE, 2020).
- IAQM Guidance offers a structured IAQ assessment and mitigation method in residential environments (IAQM, 2021).

Moreover, certification schemes have become influential in shaping industry practices. Eurofins' Indoor Air Comfort and Indoor Air Comfort Gold labels certify low-emission products, standardising criteria across European and voluntary frameworks, including AgBB (Germany), French and Belgian legislation, EMICODE, BREEAM, and WELL (Yu & Crump, 2011). Certification depends on environmental chamber testing in accordance with ISO 16000 and EN 717-1 (Wei et al., 2012). Materials that pass these tests qualify for WELL certification, promoting transparent and comparable emission assessments (Kim et al., 2011; Ruiz-Jimenez et al., 2022).

The sustainability agenda has also broadened the scope of IAQ guidance. Protocols from organisations such as the Green Building Council, ASHRAE (2016), and CIBSE (2015) emphasise the incorporation of IAQ into broader performance frameworks. Table 5 summarises emission limits and criteria from leading standards and labelling schemes, including those from Eurofins, WELL, and WHO.

2.8 Research Gap and Significance.

As outlined in the preceding literature review, there is increasing concern about the complexity of indoor air pollution sources in new homes, exacerbated by fragmented stakeholder responsibilities and a lack of coordinated approaches to IAQ management. Despite extensive research on IAQ and its health impacts, practical solutions remain limited, with findings often failing to translate into effective design, construction, and occupancy strategies (Swope & Hernández, 2019). IAQ is often addressed in isolation rather than as an integral component of healthy homes, resulting in inconsistent management throughout the development process. These gaps are identified through discussion and synthesis of IAQ literature presented in this chapter, highlighting current research gaps in building design, ventilation, occupant behaviour, and housing delivery processes.

IAQ is influenced by a complex interplay of environmental conditions, material properties, ventilation strategies, occupant behaviours, and, crucially, the housing development process. The design phase establishes airtightness, ventilation, and energy-efficiency targets, yet IAQ considerations are often secondary to broader performance metrics. Construction practices, particularly material selection and assembly, contribute to pollutant accumulation, including off-gassing from synthetic materials and inadequate air infiltration rates (Potera, 2011). Technological interventions, such as MVHR systems, are designed to regulate air exchange

and remove pollutants; however, their effectiveness is often compromised by inadequate integration into the building's design or by poor installation and maintenance. After occupation, residents' use of ventilation controls, household products, and cooking practices further impact IAQ conditions in ways that are not always anticipated during design and construction (Wang et al., 2007).

Energy-efficient housing developments, while critical for reducing carbon emissions and operational costs, introduce unintended IAQ challenges. Highly insulated and airtight homes are designed to minimise heat loss but may also restrict natural air exchange, thereby increasing exposure to indoor pollutants from building materials and occupant activities (Davis et al., 2018). The regulatory emphasis on energy performance has sometimes led to IAQ being overlooked, with ventilation systems underspecified or poorly maintained, creating an imbalance between energy efficiency and occupant health. Developers whose delivery models emphasise cost and construction speed frequently meet only minimum regulatory requirements, leaving little scope for IAQ-specific innovation. This gap between design intent, technology, and real-world occupancy underscores the need for an integrated approach that incorporates IAQ considerations at every stage of home development.

An additional concern arises from the evolving nature of IAQ risks, particularly with the rise of new building materials and synthetic finishes that introduce new chemical exposures. While some regulations aim to reduce VOC emissions, knowledge remains limited regarding the cumulative impact of construction systems on indoor environments (Potera, 2011). As primary decision-makers for material specifications, developers strongly influence these risks, but IAQ considerations often remain marginal relative to economic or regulatory drivers. Outdoor pollution further complicates IAQ control, particularly in urban areas where external air quality is beyond occupants' control (Wang et al., 2007). The lack of a structured IAQ management framework spanning design, construction, and occupancy further reinforces the need for a systemic, cross-disciplinary approach.

This research addresses these gaps by examining IAQ as a dynamic system influenced not only by design, technology, and behaviour but also by the organisational and economic processes of home development. By assessing how IAQ is currently managed at each stage of housing delivery, this study will identify critical intervention points at which improvements can be embedded in regulatory frameworks, design practices, and development processes. Through a combination of IAQ monitoring in both unoccupied and occupied homes and engaging with

key stakeholders, including developers, designers, policymakers, and residents, this research proposes adaptable, cost-effective strategies to integrate IAQ into the broader housing agenda. The objective is to move beyond treating IAQ as an isolated technical issue and establish it as a fundamental component of sustainable housing development, ensuring homes are designed, built, and occupied in ways that prioritise occupant health alongside energy efficiency.

Several gaps identified in the literature review form the basis of this research:

- While some studies have examined seasonal variation and basic building characteristics (e.g. [Davis et al., 2018](#); [Wang et al., 2007](#)), there is a lack of conclusive evidence on how specific design features, such as occupancy patterns, building orientation, internal zoning, and spatial layout, interact to affect IAQ distribution across different areas of UK homes in real-world settings.
- Although occupant behaviour is widely recognised as a key factor influencing IAQ ([Wang et al., 2007](#); [Swope & Hernández, 2019](#)), few studies explore how behavioural patterns change over time in occupied homes or how they can be modified through real-time feedback and education. The potential of behaviour change as a scalable and cost-effective IAQ strategy remains underexplored.
- Previous research highlights the importance of ventilation systems in maintaining IAQ ([Sharpe et al., 2020](#); [McGill et al., 2014](#)); however, there is a lack of standardised, user-focused guidance for effective ventilation management. Many systems in new homes lack intuitive controls or clear operating instructions, leaving users uncertain about how to operate them effectively, which can result in either excessive or insufficient ventilation.
- While regulatory frameworks address energy efficiency and minimum ventilation standards ([Davis et al., 2018](#)), IAQ is rarely embedded as a central objective at the early stages of home design and construction. The fragmented nature of housing delivery means that key stakeholders, including developers, designers, ventilation manufacturers, environmental consultants, and policymakers, often work in silos, driven by different objectives, such as financial gain, regulatory compliance, aesthetic value, or energy efficiency. This lack of early, collaborative engagement is often treated as a secondary concern.

- There is little research on how the housing development process, including developer priorities, decision-making structures, and business models, affects IAQ outcomes. Understanding this process is crucial, as developers deliver most new homes in the UK and play a key role in embedding IAQ improvements into practice.

These gaps, identified through the discussion and synthesis of the literature presented in this chapter, highlight the need for a more integrated and systemic understanding of IAQ. They form the foundation for the conceptual framework developed in Chapter 3 and guide the research design and analysis detailed in subsequent chapters. Addressing these challenges is central to this research and underpins its importance for both policy and practice. This identified gap highlights the need to understand IAQ as a system influenced by interactions between building design, technologies and systems, occupant behaviour, and decision-making throughout the home development process. These aspects underpin the conceptual framework developed in Chapter 3, which transforms them into interconnected pathways to guide the empirical investigation.

2.9 Chapter Conclusion.

Over the past decade, research on IAQ has grown substantially, reflecting a rising awareness of its impact on health and well-being. This review highlights key themes, including sources of indoor pollution, assessment methods, ventilation strategies, and the challenge of balancing air quality with energy efficiency. Despite developments, gaps remain, especially regarding the complex interactions between building design, technology, occupant behaviour, and IAQ in new UK homes.

This review examined IAQ in UK homes, beginning with an exploration of IEQ principles as a foundation for IAQ analysis. The literature confirms that factors such as poor ventilation, increased airtightness, and occupant behaviours can exacerbate IAQ issues, potentially posing health risks (Moreno-Rangel et al., 2020). These findings raise the need for integrated IAQ strategies beyond single-factor interventions.

The Pathway Approach was introduced as a holistic, structured framework to improve IAQ, integrating considerations throughout the building delivery process. This approach advocates a systemic approach that links design, materials, technology, and user practices rather than

addressing IAQ in isolation. However, it is important to recognise the methodological choices and limitations inherent in this research. While a broad, practice-based approach was adopted to investigate IAQ challenges across a wide range of homes and development contexts, it was recognised that such a broad study may involve less precise or granular data than a highly focused investigation. Nonetheless, this scope was chosen to achieve greater impact on practice and to generate findings applicable more widely to mass-market housing.

This review also examined regulatory developments, such as the UK's Part F ventilation standards, and their implications for home design and occupant behaviour. Persistent gaps include limited integration of IAQ assessment methods (e.g., combining sensor data with qualitative insights) and a lack of frameworks for incorporating IAQ considerations across the design and occupancy stages.

A key challenge identified is the need for approaches that bridge high-resolution monitoring, regulatory compliance, and occupant engagement. Effective IAQ management will depend not only on technology and regulation but also on education and collaborative strategies. It is equally important to acknowledge the inherent limitations of broad research; while the findings offer generalisable insights, they may lack the precision of more narrowly focused studies.

In summary, the literature review establishes the need for integrated, systemic, and practice-informed approaches to IAQ in UK homes. The findings and gaps lay the groundwork for the next chapter, which details the methodology used to investigate these issues through both quantitative fieldwork and qualitative stakeholder engagement.

Chapter 3. Methodology.

Introduction.

This chapter outlines the research methodology adopted in this study. It also provides the basis of several philosophical research positions and reasons for selecting a specific philosophical stance, which underpins this study (Carrasco & Egbelakin, 2023). It starts by explaining the philosophical stance and research strategies that influenced the choice of methods. The chapter outlines the research design, theoretical framework, methodological approach, sampling techniques, and data collection and analysis procedures. It also provides the rationale for using a multiple-case study design and a mixed-methods approach, demonstrating how these choices support the research aims and objectives. Finally, the chapter discusses issues of validity, reliability, and the ethical considerations relevant to the study.

3.1 The Conceptual Framework.

Building on the research gap identified in Chapter 2, this conceptual framework translates the key dimensions influencing IAQ into a structured pathway model. These pathways establish the fundamental basis for both the research design and subsequent analysis.

To address the research questions, it is essential to examine the interrelated factors that influence outcomes. Miles and Huberman (1994) describe a conceptual framework as a tool that “lays out the key factors, constructs, or variables, and presumes relationships among them” (p. 440). Maxwell (1996, pp.25,37) further explains that a conceptual framework acts as a “concept map, a visual representation of the theory, reflecting the researcher’s current understanding of the phenomenon under study. A conceptual framework is not merely a collection of concepts but a structured construct in which each element plays an integral role. Bingham et al. (2024) reinforce this, stating that establishing a conceptual framework is fundamental to research, providing a structured basis for analysing relationships between concepts and applying them in practice.

Developing a conceptual framework requires a comprehensive understanding of each key element and its interrelationships. The literature review supports this process by uncovering both competing and complementary concepts (Glaser & Strauss, 2017). Morse et al. (2002) further

suggest that a better understanding of concepts and factors, coupled with holistic mapping, should be achieved to facilitate enhanced data collection through fishing up or scoping, thereby ensuring validity (Richards & Morse, 2013). Given the complexity of various elements, Van der Waldt (2020) highlights that “a *conceptual framework provides no knowledge of hard facts but rather a soft interpretation of intentions*” (p. 38), emphasising its interpretive role in research.

The framework in this study is informed by an extensive literature review and the identification of a research gap. Existing theories and models provide the foundation for mapping out key variables and their interdependencies. This study examines building characteristics and design strategies to improve IAQ, the role of home development processes in influencing indoor environmental conditions, and how occupant behaviour, perceptions, and activities contribute to these dynamics. Given the complexities of IAQ, a conceptual framework is crucial for illustrating the connections among key elements and guiding the research process.

This conceptual framework represents a tentative theory of the phenomenon under investigation and serves as the theoretical foundation for empirical study. As such, this section bridges the literature review (Chapter 2) and the methodology (Chapter 3), providing a cohesive link between theoretical constructions and research implementation.

3.1.1 Framework Development.

This research is centred around four key concepts: home development processes, building design, technology and systems, and occupant behaviour. These components collectively shape IAQ and influence the development of an Integrated Pathway Approach to IAQ solutions in UK homes.

3.1.1.1 Home development processes.

As outlined in the previous chapter, home development processes encompass a sequence of activities, including planning, design, construction, handover, and occupancy. These stages are further influenced by regulatory and policy frameworks governing IAQ standards in homes, which are critical in shaping air quality outcomes.

This framework incorporates key regulatory requirements, construction practices, and post-occupancy adaptation strategies to inform sustainable and compliant IAQ solutions. By identifying critical intervention points across all stages of home development, the framework

ensures that IAQ improvements are systematically integrated, rather than addressed as an afterthought.

Each stage of home development has distinct implications for IAQ. Planning and design decisions influence ventilation strategies, material selection, and spatial arrangements, which in turn affect pollutant dispersion and removal. Construction activities contribute to emissions from building materials, adhesives, paints, and dust, which can degrade the indoor environment post-occupancy (Logue et al., 2012). The handover and occupancy stages affect interactions with installed systems, ongoing maintenance, and occupant adaptation, all of which impact long-term IAQ (Dimitroulopoulou, 2012).

3.1.1.2 Building design.

Building design involves site context, orientation, interior layout, and material selections, all of which determine how homes interact with their environment and influence IAQ outcomes (Vardoulakis et al., 2015). These design choices influence both the sources of indoor pollutants and the ways in which air and contaminants move within the building. For instance, building orientation and layout affect solar gains, thermal conditions, and the potential for natural ventilation, while internal arrangements impact how pollutants are distributed and transferred between spaces, especially between kitchens and living areas.

Material selection further influences IAQ through the release of VOCs and other pollutants, especially in new-build homes, where off-gassing can be significant during early occupancy. Additionally, design choices affect how effectively ventilation systems are integrated and function, including airflow pathways, system accessibility, and maintenance considerations. Importantly, building design acts as a mediating layer between site context and building performance. While site conditions define external constraints, design decisions determine how these conditions are managed or mitigated within the building. As such, building design plays a crucial role in translating planning-stage constraints into practical IAQ outcomes, reinforcing the need for integrated consideration of environmental, technical, and spatial factors.

3.1.1.2.1 Site context and IAQ.

A building's geographical location and surrounding environment play a pivotal role in IAQ. Factors such as proximity to pollution sources (e.g., roads and industrial areas) can increase infiltration of outdoor pollutants into indoor environments, particularly PM^{2.5} and gaseous

pollutants (Thatcher, 1995). These external pollutant sources influence both background indoor concentrations and peak exposure levels, particularly in naturally ventilated houses or in buildings where ventilation systems draw air directly from polluted surroundings.

Local climate conditions further affect IAQ by influencing ventilation requirements, humidity control, and pollutant dispersion (Spengler & Chen, 2000). Variations in temperature, wind speed, and seasonal patterns influence both the effectiveness of natural ventilation and the performance of mechanical systems. For example, low wind speeds or unfavourable wind directions may reduce air-exchange rates, while colder conditions may discourage window opening, thereby increasing indoor pollutant accumulation.

Additionally, urban density, building orientation, and surrounding infrastructure influence airflow patterns and pollutant dispersion. High-density developments may restrict air movement and contribute to pollutant trapping, while green infrastructure can provide limited benefits for filtration and dispersion (Steinemann et al., 2017). These spatial and environmental characteristics are therefore critical in shaping baseline IAQ conditions before any building-level interventions are applied.

Importantly, site context mainly influences the planning and early design stages of the housing delivery process. Decisions made during land acquisition, site layout, and building orientation affect exposure to external pollution sources and the feasibility of ventilation strategies. Therefore, site context is a crucial constraint and opportunity for IAQ management, requiring early consideration by developers and planners. Overlooking these factors may reduce the effectiveness of subsequent technological or behavioural interventions, underscoring the need for an integrated, systems-based approach to improve IAQ.

3.1.1.2.2 Orientation and interior layout.

Building orientation determines exposure to sunlight, wind, and pressure zones, which, in turn, influence natural ventilation and indoor thermal comfort (Fisk et al., 2002). The interior layout, such as open-plan versus compartmentalised design, affects airflow, pollutant distribution, and how occupants interact with ventilation systems. While Open-plan spaces may promote air circulation, they can also facilitate the spread of pollutants (Mannan & Al-Ghamdi, 2021). Construction materials contribute to IAQ through off-gassing and particle retention (Thatcher, 1995). The use of low-emission materials, such as formaldehyde-free wood panels, lime-based plasters, and non-toxic paints, can help mitigate indoor pollutants (Logue et al., 2012). This framework incorporates design principles that support passive ventilation, reduce pollutant

retention, and optimise spatial arrangements for improved IAQ. These considerations ensure that building design plays a key role in developing effective IAQ solutions within the overall research framework.

3.1.1.3 Technology and Systems.

Technology and systems encompass ventilation systems, building appliances, operational practices, maintenance, controls and usability, all of which are necessary to enhance IAQ.

Technologies and their IAQ implications: Mechanical, natural, and hybrid ventilation systems play critical roles in diluting indoor pollutants and ensuring adequate air exchange rates (Sharpe et al., 2015). Household appliances, including kitchen appliances, electric heaters, and air purifiers, directly influence indoor pollutant levels through emissions or filtration mechanisms (Singer et al., 2017). Operational and Maintenance Practices: Proper operation and routine maintenance of ventilation systems are crucial for preventing dust accumulation and microbial growth, both of which can compromise IAQ (Wargoeki et al., 2002). Effective IAQ management increasingly relies on user-friendly, automated controls, smart ventilation, and real-time air quality monitoring (Guyot et al., 2018). Technologies should be accessible, energy-efficient, and adaptable to diverse home environments; poor usability often leads to improper system operation, thereby exacerbating IAQ issues (Sharpe et al., 2015). This section of the framework recognises that successful IAQ interventions require both appropriate technologies and the means for occupants to operate and maintain them effectively, ensuring these systems contribute positively to overall indoor environmental quality.

3.1.1.4 Occupant behaviour.

Occupant behaviour, including everyday activities, lifestyle choices, household density, perceptions, and adaptive responses, plays a pivotal role in shaping IAQ. IAQ outcomes are determined not only by structural and technological factors but also by how occupants interact with their indoor environments (Wu et al., 2024). To improve IAQ, strategies should include educational programs, user-friendly technologies, and adaptive ventilation models that encourage proactive occupant participation in IAQ management.

The impact of occupant behaviour on IAQ: Activities such as cooking, cleaning, and smoking generate indoor pollutants, particularly PM_{2.5} and VOCs (Logue et al., 2012). Household density affects ventilation requirements, CO₂ concentrations, and moisture levels, collectively placing

greater stress on the building and impacting IAQ and thermal comfort (Dimitroulopoulou, 2012). Occupant perceptions and adaptations, such as window-opening behaviours and the use of ventilation or air purification systems, further modulate IAQ (Steinmann et al., 2017). These should include education strategies, user-friendly IAQ technologies, and adaptive ventilation models to enhance occupant engagement with IAQ management.

Integrated Pathway Approach: This framework incorporates occupant behaviour as a core component for improving IAQ in new UK homes. The anticipated outcomes include improvements in health and well-being through IAQ-friendly, conscious design and technology (WHO, 2021), enhanced regulatory compliance (MHCLG, 2021), and the development of cost-effective, adaptable solutions to maintain optimal indoor environmental quality.

3.1.1.5 Indoor Pollutants and Health Effects.

This research focuses on three key parameters as independent variables: PM_{2.5}, TVOs, and CO₂. PM_{2.5} are airborne particles that penetrate deep into the respiratory system and are associated with a range of adverse health effects (Singer et al., 2017). TVOCs, chemical emissions generated from building materials and household products, have been linked to both acute and chronic health impacts (Thatcher, 1995). CO₂ serves as a proxy for ventilation effectiveness and occupancy, reflecting air-exchange rates and potential impacts on occupant comfort and cognitive function (Vardoulakis et al., 2015). These parameters were selected for their established relevance in the IAQ literature and measurable effects on occupant health and well-being, which serve as the study's independent variables. IAQ levels will be assessed through sensor-based monitoring, enabling continuous and objective data collection. Results will be compared against recognised benchmark thresholds, including WHO and IAQ UK standards, to ensure the validity and policy relevance of the findings.

By clearly defining and systematically measuring these parameters, this framework provides a structured basis for evaluating IAQ in UK homes. Integrating insights from home development processes, building design, technology and systems, and occupant behaviour, the research aims to develop scalable and adaptable solutions to improve IAQ. Thus, this conceptual framework effectively bridges the literature review (Chapter 2) and methodology (Chapter 3), ensuring a cohesive research structure.

3.1.2 Cross-Section of the Pathways.

The conceptual framework for this study is organised around a series of interconnected pathways, each representing a critical dimension of IAQ in UK homes. These pathways of home development processes, building design, technology, systems, and occupant behaviour do not function in isolation, but interact dynamically to influence IAQ outcomes. Indoor pollutants are treated as measured outcomes (indicators) rather than pathways.

At each stage, decisions and actions within one pathway influence and are influenced by those in the other pathways. For example, choices made during the design and construction phases (Pathway 1: Home Development Processes and Pathway 2: Building Design) establish the context for technology adoption and system performance (Pathway 3: Technology and Systems). These, in turn, affect and are affected by how occupants use, adapt to, and maintain their indoor environment (Pathway 4: Occupant Behaviour). The resulting patterns of pollutant generation, accumulation, and removal, and their associated health implications, feed back into earlier pathways by informing future design, technological, and behavioural interventions.

By examining the cross-section of these pathways, the research adopts a holistic, systems-thinking perspective that recognises the complexity of real-world IAQ management. This approach acknowledges that interventions targeting a single pathway, such as improving building materials or installing advanced ventilation systems, may have a limited impact unless integrated with complementary strategies across other pathways. For instance, the effectiveness of ventilation technology depends on its technical capabilities, the extent to which occupants understand and interact with the system, and the broader building context in which it is deployed.

Figure 3.1 illustrates these pathways and their cross-sectional interactions, highlighting convergence points where integrated IAQ interventions are most effective. This cross-sectional perspective underpins the research design and data analysis strategies, guiding the identification of leverage points for developing scalable, adaptable, and sustainable IAQ solutions in new UK homes. This revised conceptual framework aligns with the model presented during the viva, offering a clearer representation of pathway interactions, IAQ variables, and the influence of the home development process on IAQ outcomes.

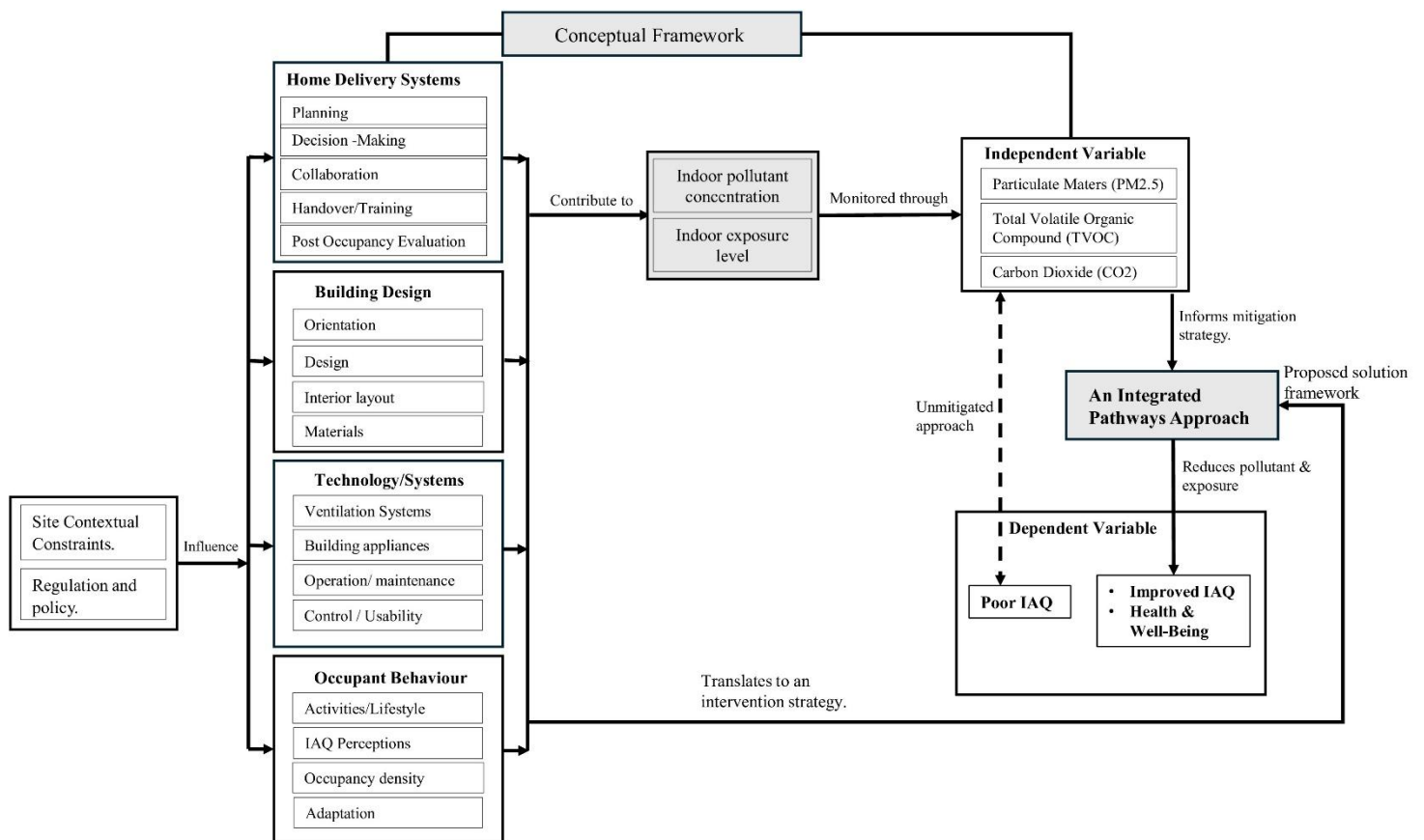


Figure 3. 1: Conceptual framework illustrating key factors influencing IAQ and health in the UK home.

The conceptual framework was developed to explain how IAQ problems emerge in residential settings through interactions between four interconnected pathways: home delivery process, building design, technology and systems, and occupant behaviour, which collectively influence IAQ outcomes. These pathways do not operate independently; rather, they interact and overlap, influencing both the generation of indoor pollutants and occupant exposure levels. As a result, each pathway contributes to indoor pollutant generation and exposure, which are measured through IAQ indicators (PM_{2.5}, TVOC, and CO₂) but also directly influence indoor pollutant concentrations and exposure levels, demonstrating how IAQ is experienced in real-world settings.

The independent variables (PM_{2.5}, TVOC, and CO₂) are used as indicators of indoor pollution and ventilation performance. The dashed, two-way arrows between the independent variables, pollutant concentrations, and IAQ outcomes represent the dynamic, feedback-driven nature of IAQ. Pollutant levels fluctuate in response to occupant activities, ventilation system operation, and environmental conditions, while occupant responses (e.g., opening windows or adjusting

systems) further influence pollutant concentrations and exposure. IAQ is therefore conceptualised as a dynamic system rather than a static condition. The framework distinguishes between unmitigated pathways, in which insufficient consideration of interactions leads to elevated pollutant levels and poor IAQ, and mitigated pathways, where integrated decision-making reduces pollutant exposure and supports improved IAQ, health, and well-being.

Within the framework, a distinction is made between the home development process and site contextual factors. The home delivery process represents the sequence of actions undertaken by developers and building professionals, including planning, decision-making, collaboration, construction, handover, and post-occupancy evaluation. The pathway identifies points at which professional decisions directly influence IAQ outcomes, including building layout, material selection, ventilation strategies, and the information provided to occupants to support IAQ awareness.

Site contextual factors, discussed in Section 3.1.1.2.1, are conceptualised as influences during the planning stage of the home development process, which define IAQ risks through external environmental conditions. These include the local outdoor pollution levels, proximity to traffic routes or industrial activities, prevailing wind patterns, and recurring environmental exposures such as smoke or odour events. Such factors influence IAQ through the infiltration of outdoor pollutants into indoor spaces, the quality of air intake into ventilation systems, and the effectiveness of natural-ventilation methods, such as opening windows. While these contextual factors may limit the effectiveness of certain IAQ strategies, they are treated as planning-stage influences rather than controllable design variables. Developers are therefore responsible for recognising and responding to site-specific constraints through informed planning and system design decisions, even where direct measurement of these conditions lies outside the empirical scope of this research.

Conceptually, the four pathways operate at different levels of the housing delivery process. The home development process operates at the organisational level, shaping the context in which design, system selection, and occupant engagement occur. Building design defines the physical and material characteristics of the houses, influencing pollutant sources, airflow, and system effectiveness. Technology and systems mediate between design intent and lived performance through ventilation, appliances, and operational usability. Occupant behaviour operates at the level of everyday practice, directly influencing pollutant generation and exposure, while being influenced by system usability, handover information, and external environmental limitations.

IAQ problems are therefore understood as emergent outcomes arising from misalignments between these pathways rather than failures within any single domain. Site context is a critical planning-stage factor influencing IAQ risk, as outdoor air quality directly affects indoor conditions through both infiltration and ventilation supply. Nearby emission sources, such as traffic, petrol stations, and industrial activities, can increase indoor pollutant levels, particularly for PM_{2.5}, nitrogen dioxide (NO₂), and certain VOCs (Baeza-Romero et al., 2022). In addition, site conditions influence the feasibility of natural ventilation, as window operation depends on weather conditions and building characteristics, which may limit effective air exchange under certain circumstances (Sharpe et al., 2020).

Although direct measurement of outdoor pollutant profiles and site-specific meteorological conditions was beyond the scope of this study, their influence is recognised as an important constraint on IAQ and a key consideration in planning and early design decisions. Effective mitigation, therefore, depends on coordinated action across pathways, forming the analytical foundation for the integrated Pathways Approach, which translates this conceptual understanding into a structured framework for managing IAQ across the housing delivery process. This framework offers the conceptual foundation for structuring the empirical analysis in Chapter 5, where IAQ outcomes are assessed through the interaction of these pathways.

3.2 Research Methodology.

The methodology defines the overall strategy and logical process underpinning this research, from the theoretical groundwork to the selection of the data collection and analysis techniques (Collis and Hussey, 2014). Creswell (2014) defines research methodology as the strategy and process of inquiry that includes the philosophical assumptions, research design, and specific methods used to collect and analyse data in a logical and systematic way. It involves logical systems based on philosophical principles that guide the research design to validate and reliably achieve its aims and objectives. As Dainty (2008) further states, research methodology encompasses the procedures employed and the underlying philosophical perspectives that inform the research.

Different research methodology frameworks exist, including the nested “research onion” model developed by Saunders et al. (2016a), which is widely used in social science and built environment research. This model (Figure 3.2) organises the research process into six concentric layers, from research philosophy at the outermost level to techniques and procedures

at the core. The research onion provides a systematic approach that begins with foundational assumptions and progresses to practical application, offering a clear structure for investigating complex, multifaceted topics such as IAQ in homes. The six-layered structure of the research onion enables a thorough investigation of IAQ by facilitating comparisons of indoor pollutant emissions across case-study homes. This research introduces the upcoming stages approach, which supports rigorous methodological planning, ensures alignment with research objectives, and clarifies each stage of the research process.

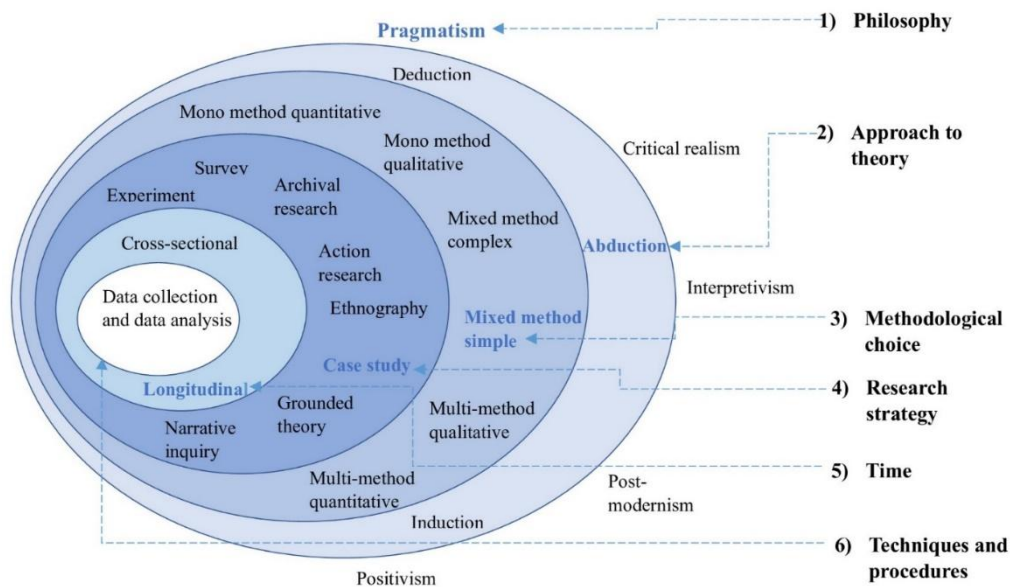


Figure 3. 2 : Research onion illustrating the methodological structure of the study (Saunders et al., 2016a).

3.3 Research Philosophy.

According to Saunders et al. (2016a), research philosophy refers to a system of beliefs and assumptions that shape an individual's perspective on the nature of knowledge. Easterby-Smith et al. (2012) added that understanding research philosophy is essential for three main reasons. It clarifies research questions and design, informs the choice of appropriate research methods, and enables researchers to select data collection and analysis techniques that extend beyond personal experience. Thus, Research philosophy is the foundation of scientific practice, reflecting individuals' interpretations and assumptions about the nature of knowledge.

This research examines both the theoretical and practical aspects of addressing complex social and technical problems in the built environment within an economic realist paradigm. Pathirage

et al. (2008) explain that research philosophy is classified into three main domains: ontological, Epistemological, and Axiological assumptions. Saunders et al. (2016a, p. 250) further noted that ontological assumptions concern the nature of reality, epistemological assumptions concern what is considered acceptable knowledge within a field of research, and axiological assumptions concern the role of the researcher's values in research procedures.

In line with these philosophical underpinnings, this research adopts a mixed-methods approach that combines qualitative and quantitative techniques to capture the complexity of indoor air quality pathways. This approach ensures that both objective measurements (e.g., sensor-based IAQ data) and subjective insights (e.g., occupant perceptions and behaviours) are systematically integrated, thereby supporting the study's aim of developing holistic, evidence-based strategies for improving IAQ in residential environments.

3.3.1 Research Paradigm.

Paradigms serve as conceptual and practical frameworks that shape how researchers understand and investigate specific problems, guiding both the formulation of research questions and the selection of methodological approaches (Patton, 2022). Each paradigm rests on philosophical assumptions, ontology (the nature of reality), epistemology (the nature and scope of knowledge), and axiology (the role of values), which collectively underpin research design (Creswell et al., 2007; Saunders et al., 2016; Dainty, 2008). Table 6 provides an overview of the main research paradigms, their philosophical stances, and typical methods, and justifies the selection of pragmatism for this study.

This research adopts a pragmatic philosophical stance, focusing on the practical resolution of complex, real-world issues related to IAQ in new residential homes. As Yvonne Feilzer (2009) highlights, pragmatism is oriented toward solving real problems and supports flexible use of various research methods. This paradigm enables the integration of objective, quantitative data (e.g., sensor-based IAQ monitoring) and subjective, qualitative insights (e.g., interviews and surveys with occupants and stakeholders), ensuring a comprehensive investigation of IAQ and associated factors (Lowe et al., 2017).

Within the pragmatic paradigm, ontology is understood as enabling the simultaneous exploration of multiple realities, accommodating both objectivist and subjectivist perspectives, and as an approach particularly well-suited to research examining both measurable pollutant concentrations and diverse stakeholder perceptions (Creswell et al., 2007; Saunders et al., 2016). Epistemologically, pragmatism draws from both positivist and interpretivist traditions,

combining empirical data collection with interpretation of social meaning and experience (Dainty, 2008). Axiologically, pragmatism acknowledges the influence of researcher values and experiences, striving to balance objectivity (through quantitative monitoring) and subjectivity (through qualitative inquiry), as noted by Patton (2022) and Saunders et al. (2009).

Moreover, this study employs a case study methodology, which aligns with the pragmatic tradition of integrating quantitative and qualitative approaches. Lowe et al. (2017) observe that pragmatic mixed-methods research benefits from in-depth case analysis. Flyvbjerg (2006) argues that the depth of context-specific insights gained from case studies provides significant value, even when generalizability is limited. By drawing on these strengths, the research comprehensively addresses its objectives, investigating the interplay among building technology, design, and occupant behaviour to inform evidence-based recommendations for improving IAQ in residential settings.

Table 3.1 Summary of major research paradigms, their ontological, epistemological, and axiological assumptions, and typical research methods, highlighting the rationale for adopting pragmatism in this research.

Table 3 1: Description of research paradigms and their relationships (Saunders et al., 2009).

Different Paradigms	Ontology (Reality of research)	Epistemology (Knowledge)	Axiology (Values of a Researcher)	Typical Research Methods
Constructivism	Built on the foundation that there are multiple realities (Relativism).	The knowledge is structured and has defined boundaries.	Values arise from social interaction and experiences. (existential)	Case study approaches are often integrated with interviews or qualitative data collection methods.
Positivism	A universal approach holds that there is a single actual reality.	Some facts are observable and perceived. Utilises hypotheses to create causal explanations.	The research has no value and reflects a detached approach by the researcher.	A top-down deductive approach. It employs research methods, including surveys and experiments.
Critical Realism	It uses causal mechanisms and objectivity to describe reality.	The knowledge that guides the research is based on relativism.	The researcher(s) adopt a value-laden approach.	It is typically accompanied by an analysis of prior methods in the literature.
Interpretivism	Incorporates various meanings and interpretations of reality.	Social interactions are what create knowledge.	The researcher's interpretations are imperative, value-laden approaches.	Small samples are investigated. It can include ethnographies (an inductive approach).
Postmodernism	Assumes that reality is socially constructed	The worldviews that underpin a specific field of knowledge constitute what is considered truth.	The research itself is grounded in values (a reflexive approach).	Typically adopts qualitative methods of data collection and analysis.

Pragmatism	Reality is based on the practical outcomes of different ideas. Adopting a flexible approach to reality permits this research to explore various ideas or phenomena simultaneously.	This research's knowledge is conceptually integrated with practical approaches, thereby justifying both positivism and interpretivism. Monitoring homes and analysing pollutants are examples of conceptual and practical knowledge in this context.	Pragmatism involves a value-driven approach, meaning the researcher's beliefs and values are incorporated into the study. Despite this, the research will include objective measures, such as monitoring, to avoid research bias.	Typical research approaches often employ a combination of methods. This aligns with the mixed-methods approach adopted in this research, enabling multiple rich data sources from strategies such as interviews, case studies, and monitoring.
-------------------	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

3.3.2 Pragmatism.

Pragmatism is a philosophical paradigm emphasising the practical resolution of research problems by integrating various perspectives and methods (Saunders et al., 2007). Rather than strictly adhering to either positivism or interpretivism, pragmatism offers a flexible approach that reconciles the dualisms of objectivism and subjectivism (Biesta, 2010) and the dichotomies between post-positivism and constructivism (Creswell et al., 2023). This paradigm prioritises empirical and context-driven approaches over purely idealistic or rationalistic methodologies (Frega, 2020).

Pragmatism recognises that knowledge is socially constructed and influenced by diverse human experiences, accommodating multiple realities and viewpoints within the research process (Morgan, 2007). This makes it particularly relevant for studies addressing complex, real-world challenges, such as IAQ, where both measurable environmental data and occupants' lived experiences are relevant. Denscombe (2008) and Mitchell (2018) highlight that pragmatism is particularly well suited to mixed-methods research, as it enables the integration of quantitative and qualitative approaches to yield actionable insights.

Adopting a pragmatic stance in this research enables the integration of both theoretical and practical perspectives, addressing the technical aspects of IAQ (e.g., pollutant monitoring) alongside the social and behavioural dimensions (e.g., occupant perceptions and developer best practices). By considering both epistemological and ontological factors, this approach facilitates a deeper understanding of how IAQ problems are experienced and interpreted by various stakeholders, and how to develop effective, scalable solutions for the built environment. Mingers (2001) aptly compares adopting a paradigm to choosing an instrument, each of which reveals certain aspects of a problem while obscuring others, highlighting the value of pragmatism's pluralistic perspective for this multifaceted research context. In conclusion, pragmatism underpins this study's methodology by bridging philosophical divides

and supporting a problem-oriented, flexible approach. This ensures that the research remains aligned with its aims: to identify, assess, and address the key pathways contributing to poor IAQ, and to propose cost-effective, scalable solutions for healthier residential environments in the UK.

3.3.3 Approach to Theory.

According to Creswell (2007), the theoretical research approach is informed by both participants' experiences and the development of a theory that explains or guides further inquiry. Research reasoning generally uses deductive, inductive, or abductive approaches (Saunders et al., 2016a). The deductive approach starts with an established theory, formulates hypotheses, and tests them through observation, moving from the general to the specific (William, 2006). In contrast, the inductive approach begins with particular observations, from which patterns are identified, and theories are developed in a bottom-up process (William, 2006). As Morgan (2014) explained, the abductive approach enables an iterative process that moves back and forth between induction and deduction to develop new theoretical insights.

Given the complex, real-world context of IAQ in residential buildings, this research adopts an abductive reasoning approach. This enables the integration of existing theoretical knowledge with empirical findings, allowing for flexible movement between data and theory, which is particularly valuable in mixed-methods research. Figure 3.3 illustrates the distinction between deductive and inductive approaches, highlighting the iterative nature of abduction.

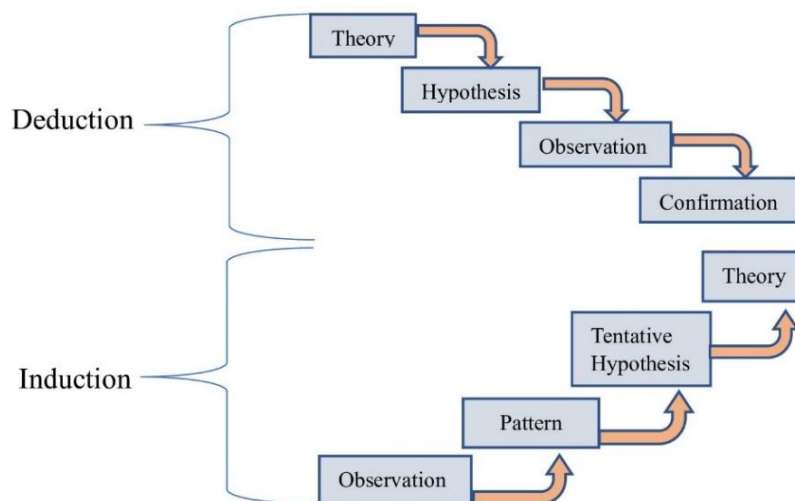


Figure 3. 3: Deductive and inductive reasoning approaches in research (adapted from William, 2006).

To reflect the methodological flexibility required by this research, deductive logic is employed in the quantitative analysis of IAQ measurements. Simultaneously, inductive reasoning guides the development of conceptual frameworks from qualitative data on occupant experiences. Abduction allows the integration of these processes, supporting the iterative refinement of both theoretical understanding and practical recommendations. Table 3.2 displays the specific applications of all methods and their respective differences.

Table 3 2: Distinctions between deductive, inductive, and abductive research approaches and their application in this study (adapted from Saunders et al., 2016a).

Approach	Main Differences
Deduction	From general knowledge to a specific topic, it aims to test a theory, and data collection is used to evaluate hypotheses derived from existing theories.
Induction	from a specific subject to more general knowledge. It aims to develop a new theory, and data collection helps create a conceptual framework.
Abduction	It falls between specific and general knowledge, and between inductive and deductive approaches. The induction method will be used to generate new knowledge about perceptions, develop a conceptual framework, identify themes, and define related tasks. At the same time, the deductive approach will focus on quantitative data collection by monitoring homes with IAQ issues across various types.

3.3.4 Methodological Choice.

Building on the pragmatic stance established in previous sections, this research adopts a mixed-methods approach that reflects an ontological view in which both objective and subjective realities are relevant, along with an epistemological perspective that incorporates both positivist and interpretivist traditions. Mixed-methods research enables the integration of quantitative and qualitative techniques, acknowledging that each provides unique insights and that neither alone is sufficient for fully addressing complex real-world problems, such as indoor air quality (Saunders et al., 2016a).

Quantitative data gathered through sensor-based monitoring offers measurable evidence of IAQ conditions and trends, which can be analysed using descriptive and inferential statistics. On the other hand, qualitative methods rely on open-ended questions and interviews to capture occupants' experiences, perceptions, and behaviours, providing non-statistical insights that enhance understanding of the factors affecting IAQ. The combination of these methods enables this research not only to identify what is occurring in the indoor environment but also to explore why these conditions arise.

As Robson (2011) and Creswell (2023) explain, mixed-methods research can be conducted using sequential, concurrent, or transformational designs. This study employs both concurrent data collection (e.g., monitoring and administering questionnaires simultaneously) and sequential approaches (e.g., follow-up interviews and data validation), aligning with the research timeline and enhancing the triangulation of findings. The mixed-methods approach is particularly well-suited to exploring the interactions among building systems, occupant behaviour, and IAQ, thereby enabling detailed and reliable analysis.

Figure 3.4 presents the research options, highlighting the mixed-methods approach as the most appropriate for this study (Saunders et al., 2016a).

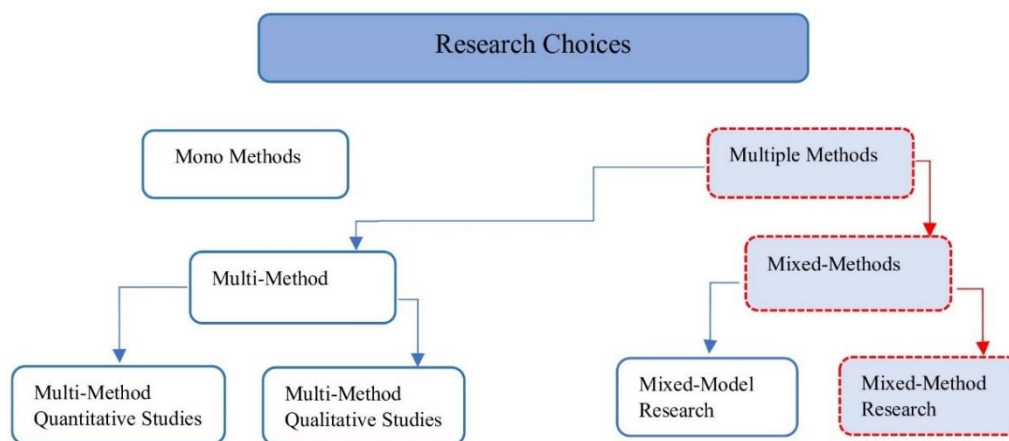


Figure 3. 4: Research choices within the adopted methodological approach (adapted from Saunders et al., 2016a).

3.3.5 Research Strategy.

The choice of research strategy depends on the nature of the research questions, philosophical stance, and practical considerations regarding data collection and analysis (Saunders et al., 2016a). As noted by Aberdeen (2013) and Creswell (2014), no single strategy is universally superior; instead, a combination of methods may be necessary to address complex, real-world phenomena, such as IAQ. This study combines observational (quasi-experimental), survey, and case study strategies within a mixed-methods framework to maximise validity and provide a comprehensive understanding of IAQ.

An observational strategy (similar to a quasi-experiment) is used to monitor IAQ in unoccupied properties, establishing a baseline for comparison with IAQ in occupied homes. This facilitates analysis of how occupant activities impact IAQ by controlling for other variables. Data collection methods for this strategy are primarily quantitative and observational. The survey

strategy is used to gather occupants' perceptions, behaviours, and knowledge regarding IAQ. Surveys and questionnaires enable the efficient collection of large-scale subjective data (Saunders et al., 2016a). Although such data may reflect respondent bias (Schwarz, 1999), subjective perceptions are vital for understanding lived experiences and complement objective measurements.

A case study strategy is used to conduct a detailed, contextual investigation of IAQ in real residential environments, employing both quantitative and qualitative data (Aberdeen, 2013; Miles & Huberman, 1994). The case study approach is especially suitable for research questions that ask “how” and “why,” and it supports the use of multiple methods to explore the complex nature of IAQ. In terms of research purpose, this study adopts a combination of exploratory and explanatory approaches. The exploratory component is used to investigate under-researched aspects of IAQ and develop an appropriate conceptual framework. In contrast, the explanatory component seeks to clarify why certain IAQ outcomes arise under specific conditions (Aberdeen, 2013). This multidimensional strategy enables a robust, flexible methodology that effectively addresses the complexity of IAQ in new residential environments.

3.3.6 Time Horizon.

The concept of time horizon in research refers to the period during which data are collected and analysed within a project (Saunders et al., 2016). While some studies adopt a longitudinal approach to examine changes over an extended period, this research is organised into sequential phases, each providing a focused, cross-sectional view of indoor air quality and related factors at defined time points. By focusing on current conditions in each research phase rather than on trends over time, this study efficiently addresses its objectives within the available timeframe and resources. The research plan is structured into five sequential phases, each linked to specific research objectives and using the most suitable data collection methods (Saunders et al., 2009; Creswell, 2014). Figure 3.5 illustrates the alignment of each phase with its corresponding completion method.

- **Phase 1:** A comprehensive literature review is conducted to understand the complex concept of IAQ and environmental quality (Objective 1). This phase establishes a thorough background on IAQ, summarises current challenges, and frames the scope for subsequent stages.

- **Phase 2:** To measure IAQ in both occupied and unoccupied homes and establish baseline data for comparison (Objective 2), observational quantitative data are collected through environmental monitoring in the studied homes. This approach enables the understanding of IAQ variations and helps identify potential sources of indoor pollutants.
- **Phase 3:** To assess how occupant behaviour patterns and decision-making processes in home development influence IAQ (Objectives 3 and 4), qualitative data are collected via interviews, questionnaires, and daily activity diaries. This phase captures the human and decision-making dimensions that affect IAQ outcomes.
- **Phase 4:** To analyse existing literature on IAQ monitoring methods, standards, and policies (Objectives 1 and 5), findings from the literature review are critically reviewed alongside the monitored IAQ data from homes. This phase helps benchmark results and identify gaps in policy or practice.
- **Phase 5:** To develop cost-effective IAQ frameworks and practical solutions (Objective 5), all collected data, both quantitative and qualitative, are synthesised and analysed. This phase consolidates insights from previous stages to propose evidence-based recommendations and frameworks for widespread implementation.

This structured, phased approach ensures that each research objective is systematically addressed through appropriate methodological steps, providing a comprehensive, coherent framework for answering the research questions.

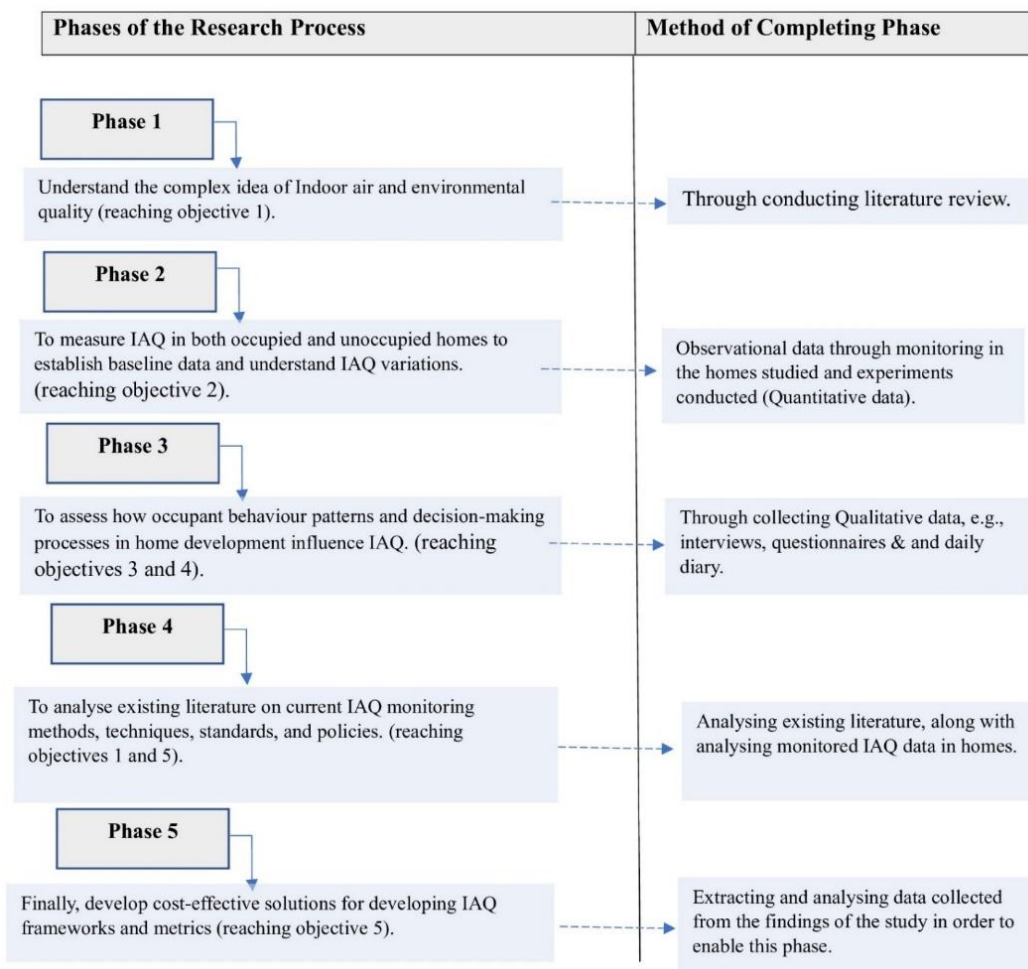


Figure 3. 5 : Phases of the research design process.

3.3.7 Overview of the research process.

Figure 10.6 presents a methodological overview of this study, illustrating the integration of mixed methods to achieve a comprehensive understanding of IAQ solutions. Both qualitative and quantitative data collection methods are employed: interviews and questionnaires are administered to building professionals and occupants, while experiments and environmental monitoring provide objective IAQ data. Triangulation is used throughout the research, integrating multiple sources and data types to enhance the reliability and validity of the findings.

The sampling strategy involves the purposeful recruitment of homes across six case studies in four locations: Birmingham, Burton-on-Trent, Chelmsford, and London, encompassing both occupied and unoccupied properties. Data analysis is conducted through a combination of parallel qualitative and quantitative approaches. NVivo 12 is utilised for content and thematic

analysis of qualitative data, whereas quantitative data are analysed using descriptive and inferential statistics to identify trends, patterns, correlations, and causal relationships.

Findings are contextualised within the existing literature and theory, thereby improving understanding and explanation of IAQ phenomena. Limitations relating to time, resources, and monitoring equipment are acknowledged. The research process culminates in the synthesis of recommendations and outcomes, providing actionable insights and pathways to effective IAQ solutions.

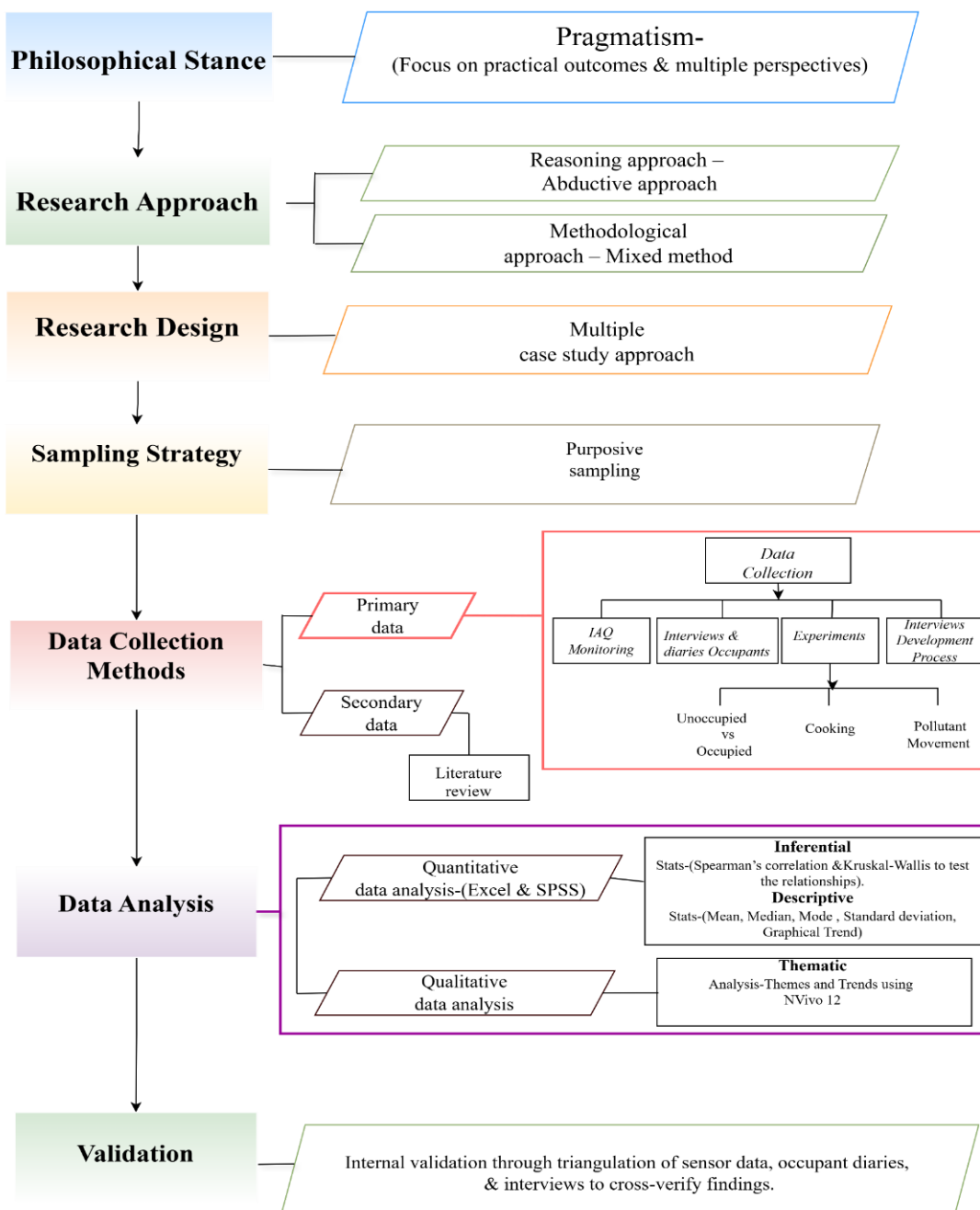


Figure 3. 6: Overview of the research methodology.

Chapter 4. Data Collection and Analysis Methods.

Introduction

The section outlines the methods used to achieve the research aims and answer the research questions. It first describes the data collection processes and then details the analytical techniques used to interpret the data.

This research combines multiple data collection methods to develop an understanding of IAQ in residential settings. Environmental monitoring provides objective, measurable data on IAQ, while interviews and questionnaires with building professionals and occupants offer valuable insights into behavioural, operational, and contextual factors. Integrating these approaches enables a thorough investigation of both the physical conditions and the human dimensions that influence IAQ. Such a multi-faceted approach is essential for producing a strong analysis and achieving meaningful insights into IAQ management and outcomes. These combined data sources also provide the empirical foundation for the pathway-based analysis presented in Chapter 5, enabling the investigation of IAQ as a system influenced by building characteristics, occupant behaviour, technologies, and development processes.

4.1 Buildings Studied. monitoring

Long-term environmental monitoring was conducted in all cases for seven months: CS5 (December 2021 to February 2022), CS6 (March 2022 to September 2022), CS4 (May 2022 to November 2022), and CS1, CS2, and CS3 (May 2022 to January 2023). This phase involved continuous minute-by-minute monitoring of indoor PM_{2.5}, TVOC, and CO₂ in the kitchens of each home. To establish a baseline, houses CS1 to CS3 were initially monitored while unoccupied, allowing the assessment of IAQ without the influence of occupant behaviour and focusing solely on the building fabric, materials, and installed systems. In contrast, houses CS4 to CS6 were monitored only when occupied, as they were not available for unoccupied monitoring. Figure 4.1 presents the data map for the entire monitoring period. The goal was to observe IAQ trends over time, account for seasonal variations, and provide an overall picture of the dataset. The long-term monitoring provided an overall context for the in-depth measurements, highlighting seasonal variations and trends. Four case studies are rented homes provided by housing associations, while the other two are privately owned and provided by

housing developers (see section 3.2.4). This diversity allows exploration of a wide range of occupants and their interactions with buildings.

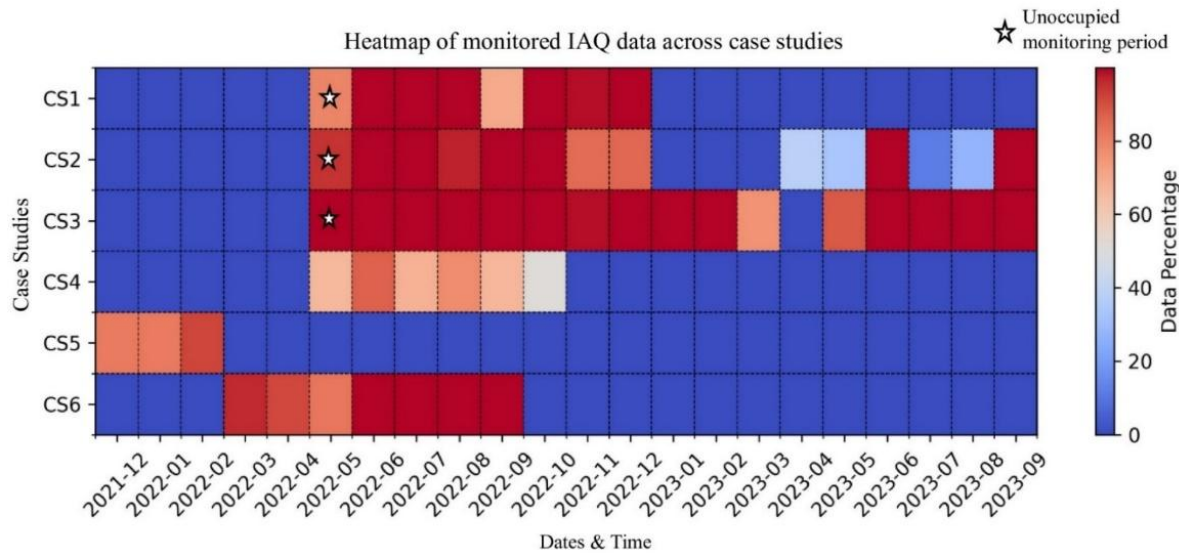


Figure 4. 1: Heatmap showing monitoring coverage of case-study houses throughout the entire monitoring period.

Figure 4.1 presents a heatmap of monitored IAQ data across case studies, illustrating the percentage of data completeness over time. Unoccupied monitoring periods are marked with stars (★), indicating two weeks in May 2022 for CS1, CS2, and CS3, and 8 weeks from December 2021 to February 2022 for CS5. While CS5 had the shortest monitoring duration of 8 weeks, the other case studies (CS1, CS2, CS3, CS4, and CS6) were monitored over approximately 7 months. The figure also highlights intermittent gaps in data collection for CS2 and CS3, which continued to occur occasionally in 2023 due to occupants switching off, reflecting the variability and challenges characteristic of the monitoring schedule for occupied homes.

4.2 Case Study Approach.

Aberdeen (2013) identifies four types of case study design: single-case study embedded, single-case study holistic, multiple-case study embedded, and multiple-case study holistic. Aberdeen (2013) further adds that a multiple-case study approach allows comparisons across cases of the same phenomenon, thereby facilitating a better understanding of the area under investigation. This multiple-case study design will enable this research to isolate variables contributing to indoor air pollution and examine them within a combined system, leading to successful, targeted solutions. Another reason for selecting a multiple-case study design is that it provides

a broad view of the topic under investigation by enabling a reliable estimation of significant IAQ-related problems.

Case study designs are also either embedded or holistic, and as stated by Saunders et al. (2016a), this highlights the unit of analysis employed in a study. On the other hand, in the pursuit of understanding the complexities of human behaviour and experiences, the goal of social science research is to employ a variety of research methods appropriate to the specific questions being asked. Researchers can explore the subject from various perspectives by utilising different approaches, as Philip describes, aiming to uncover "different truths" (Philip 1998: 262). A holistic approach is more appropriate for this research, as it investigates the phenomenon as a whole, whereas an embedded case study examines its subunits. Consequently, this research has adopted a multiple-holistic case study design. This research involved examining multiple cases across six different homes. The decision to use a multiple case study approach was driven by the need to understand both the differences and similarities among these cases (Gustafsson, 2017). Additionally, one of the research objectives was to examine how IAQ is represented in homes, and achieving a reliable assessment requires multiple cases to obtain a comprehensive understanding of the subject (Baxter & Jack, 2015). Given that the research seeks to analyse different perspectives from building professionals and occupants, a multiple-case study was the most appropriate method.

The data collection processes underpinning this case study design are described in more detail in the following sections: sampling, interviews, questionnaires, and monitoring of residential buildings. The collected data will enable the research to evaluate the relative impact of variables, such as occupant activities (e.g., cooking), on the production of combustion products. Accordingly, the multiple-holistic case study design and the data collection methods represent the most appropriate investigative techniques, as this research focuses on specific pollutant parameters, such as TVOCs, PM, and CO₂.

4.2.1 Rationale for case study approach

To justify the case study selection, it is essential to consider how the selected homes relate to the wider UK housing context and the factors influencing IAQ outcomes. A conceptual understanding of case selection is critical, as it enables the identification of relationships between key variables and supports the translation of findings into real-world applications (Miles and Huberman, 1994). In this research, the selected case studies are not intended to represent the full diversity of the UK housing stock, but rather to provide analytically relevant examples

that reflect typical characteristics of new mass-market housing. The UK housing stock varies in age, construction type, tenure, and occupancy; however, a large proportion of new housing is delivered by volume housebuilders using standardised designs and construction methods. The homes selected for this study, developed by major UK housebuilders and housing associations, reflect these common practices and are thus broadly representative of new-build residential developments. This aligns with the research objective of evaluating IAQ in typical, real-world residential settings.

The case selection was guided by purposive sampling, enabling the inclusion of homes that meet specific criteria relevant to the research objectives (Saunders et al., 2016a). These criteria included compliance with UK building regulations, variation in ventilation strategies (mechanical and natural), and diversity in property types (detached, semi-detached, and terraced). This approach allows exploration of both similarities and differences across cases, supporting a better understanding of IAQ as a system influenced by multiple interacting factors. In addition to building characteristics, occupancy profiles play a critical role in shaping IAQ outcomes. The selected homes include a range of household compositions, primarily family-based, reflecting common residential patterns in the UK. These variations enable the study to capture the influence of everyday activities, such as cooking, cleaning, and window operation, on pollutant generation and exposure.

It is widely recognised that IAQ is affected by a variety of occupant-related factors beyond general household composition. Socio-demographic variables, including gender, homeownership status, lifestyle patterns, and behaviours such as smoking, can significantly influence indoor pollutant levels. For example, cooking habits, occupancy frequency, and ventilation practices vary across households, leading to differences in pollutant concentrations and exposure. While these factors were not systematically controlled or measured in this study, their impact is acknowledged in the interpretation of results.

Therefore, this research adopts a holistic, systems-based perspective, recognising that IAQ outcomes result from interactions between building design, technologies, and occupant behaviour within specific contextual conditions. The case studies are therefore used to generate analytical insights into these interactions rather than to produce statistically generalisable findings. This approach aligns with case study research, which emphasises depth of understanding and contextual relevance (Flyvbjerg, 2006). These contextual and socio-

demographic characteristics are then used in the analysis (Chapter 5) to explain variations in IAQ performance across the case studies.

4.2.2 Case Study Design.

Careful and precise design of the case study is essential to clarify the unit of analysis and address the complexity of IAQ in residential buildings. This research employs a mixed-methods approach, integrating qualitative and quantitative data to examine the impact of building characteristics, occupant behaviour, and their interactions on IAQ. The case study framework allows for the use of varied data collection methods, including monitoring, interviews, and questionnaires, applied across six diverse homes. This diversity enriches the investigation, enabling the identification of both commonalities and differences among cases (Flyvbjerg, 2006).

Case studies are particularly suited to social science research where understanding both “what” occurs and “why” it happens is crucial (Langley and Abdallah, 2011). As Thomas (2011) describes, a case study is a design framework incorporating multiple methods rather than a single technique. This flexibility supports the examination of real-world dynamics rather than attempting to control all variables, as in the physical sciences. This practice can overlook key influences such as occupant behaviour (Oreszczyn and Lowe, 2010).

The analytical process involves two coding cycles and thematic analysis, using inductive and abductive reasoning to interpret environmental and experiential data. The case study approach offers valuable lessons that inform practice and policy by situating building performance and IAQ within the lived context of experience (Leaman et al., 2010). Table 4.1 summarises the main features of the selected case study homes.

4.2.3 Limitations of the case study approach.

It is also important to acknowledge the limitations of the generalisability of case study findings. While the multiple-case study approach offers rich, contextual insights into IAQ dynamics in real-world residential settings, the findings are inherently context-specific and are not intended to be statistically generalisable across all UK housing conditions. Rather, they provide analytically transferable insights into IAQ as a system influenced by integrating factors. Variations in climate, building age, construction methods, and regional environmental factors may influence IAQ outcomes in different ways. These contextual variations should therefore

be considered when interpreting the findings, as IAQ outcomes are influenced by both environmental conditions and occupant practices.

Moreover, temporal factors, including seasonal variations, may influence both occupancy patterns and indoor environmental conditions. For instance, differences between winter and summer can affect ventilation habits, heating usage, and pollutant generation, thereby influencing IAQ measurements and the interpretation of pollutant patterns observed during the monitoring period. In addition, the reliability of self-reported data, such as occupant activity diaries, has limitations. While these diaries offer valuable contextual information to support the interpretation of monitored data, they are subject to recall bias, reporting inconsistencies, and differences in the level of detail provided by participants. To mitigate these limitations, diary data were interpreted alongside monitored IAQ data and interview responses, enabling triangulation across multiple data sources and enhancing the robustness of the analysis.

Despite these limitations, the study provides analytical insights into interactions between building design, technologies, and occupant behaviour. The findings are intended to support conceptual understanding and guide practice, rather than to generate statistically generalisable conclusions. These limitations are acknowledged to ensure that the conclusions remain properly bounded and reflective of the study context.

4.2.4 Research Sampling.

A sample refers to a subset of participants or cases selected from a larger population for study. In this research, the unit of analysis is the individual home, chosen to examine the factors influencing IAQ. Sampling techniques are typically divided into two categories: probability sampling, in which every unit has a known probability of selection, and non-probability sampling, in which selection is based on the researcher's judgement or convenience (Saunders et al., 2016a).

Probability sampling techniques, such as random, stratified, systematic, and cluster sampling, are typically used when generalizability to the wider population is a key goal. As Sekaran (2003, p. 45) notes, "*Probability sampling designs are used when the representativeness of the sample is of importance in the interests of wider generalisability.*" By contrast, non-probability sampling methods, including purposive, snowball, self-selection, and convenience sampling, are more appropriate when time or access constraints exist, or when specific expertise is required. Saunders et al. (2016a, p. 150) further explain that "*if a researcher selected a case study*

focusing on a small group of participants chosen for a particular objective to achieve research questions, then non-probability sampling could be suited.” Figure 4.2 summarises the key differences between these two approaches.

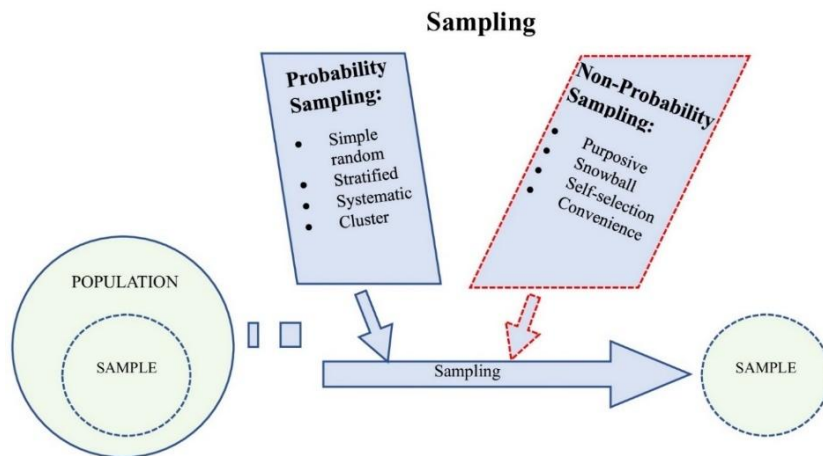


Figure 4. 2: Sampling methods employed in the study (adapted from Saunders et al., 2016a).

Figure 4.2 illustrates the two primary categories of sampling: probability and non-probability sampling. The red dotted line highlights the non-probability methods relevant to this research. The study employs purposive sampling, a nonprobability approach, to select six homes as case studies, thereby supporting an in-depth investigation of IAQ dynamics in real-world settings.

Given the detailed, case-study nature of this research, purposive sampling (a form of non-probability sampling) is the most suitable choice. This method enables the selection of six homes that meet specific criteria and involves developers and occupants. It also facilitates the inclusion of key stakeholders, such as decision-makers, technical specialists, and designers, whose knowledge and roles in the home development process directly influence IAQ (Amaratunga et al., 2002). Therefore, Purposive sampling is crucial to ensure that the selected cases generate meaningful, insightful data that address the research objectives.

4.2.4.1 Sample Size Selection.

The sample size was determined by the availability of suitable homes and occupants' willingness to participate. Six houses were selected as case studies. Most of these houses were monitored while unoccupied to assess the building fabric, materials, and technologies/systems in the absence of occupants. This allowed for the establishment of baseline data for subsequent comparison when the houses were occupied. During the selection process, key details of construction materials (wall types, insulation levels, and double glazing) and the house dimensions were collected.

- Unoccupied houses: This forms the baseline for monitoring data, reflecting indoor pollutant levels unaffected by occupant activities.
- Occupied houses: This data is compared to monitored data from unoccupied homes to evaluate the effect of occupant behaviour patterns on IAQ when occupied.

4.3 Recruitment of the Homes and Site Description.

Figure 4.3 presents a map of the UK, showing the locations of the six case study homes in this research. As indicated by the arrows, three homes are located in Birmingham, and one each in Burton-upon-Trent, Tamworth, and Chelmsford. These sites, spread across the West Midlands, East Midlands, and East Anglia, offer diverse environmental and demographic contexts. This geographical diversity enables analysis of factors affecting IAQ across different environmental conditions, thereby enhancing the relevance of the findings to a broad range of UK homes.



Figure 4. 3: Map of the UK showing the geographical distribution of the studied homes.

Participants were recruited from six homes, selected in collaboration with major UK housing developers (Redrow plc, Barratt Homes, Taylor Wimpey plc, and Midland Heart Housing Association). The selection process was guided by the availability of suitable properties, reflecting a practical, purposive sampling approach. The intention was to represent a cross-section of residential properties commonly found in UK developer portfolios, accounting for differences in house type, construction method, occupancy, and location. While the sample size limits generalisability, these homes serve as evidence-based case studies for understanding IAQ trends and challenges in the UK context.

The monitored homes were selected based on eligibility criteria, including traditional construction (brick and block), compliance with the 2013 building regulations, and inclusion of both current and future home standards (with half designed to meet the 2030 Future Home Standard). Different property types (detached, semi-detached, and terraced) were included to reflect the range of applicability of the UK housing stock.

The long-term monitoring campaign covered both winter and summer seasons, structured into two phases:

- Phase 1: Case Study 5 (Tamworth), monitored from December 2021 to February 2022
- Phase 2: Case Studies 1, 2,3,4 and 6, monitored from February to February 2023

Figure 4.4 provides an integrated overview of the six monitored homes, illustrating their types, locations, monitoring periods, and key technical specifications.

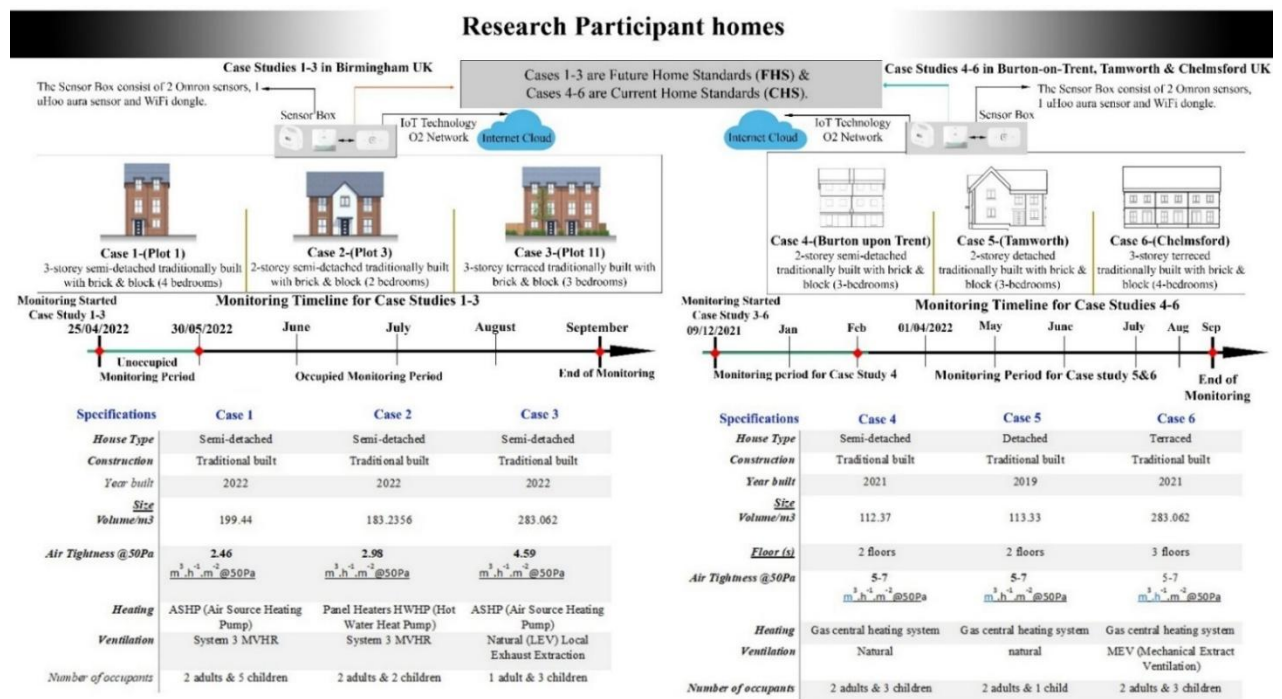


Figure 4. 4: Overview of research participant homes, monitoring timeline, and key specifications.

4.3.1 Household Characteristics.

Table 4.1 summarises the key characteristics of the six case study homes included in this research. For each home (CS1–CS6), the table details location, building form, floor volume, completion date, construction type, building airtightness, ventilation system, cooking fuel, household composition, and tenancy type. The homes represent a range of locations (Birmingham, Burton-upon-Trent, Tamworth, Chelmsford), building forms (semi-detached,

detached, mid-terrace), construction standards (Future Home Standard and 2013 Building Regulation Standard), and ventilation strategies (mechanical and natural). Household sizes and tenancy types are also included, offering a comprehensive profile for cross-case comparison. These details are vital for contextualising IAQ results and understanding variations influenced by both building and human factors.

In addition to the main building and technical characteristics, Table 4.1 has been expanded to include selected occupant-related variables such as gender composition, occupancy patterns, and smoking status. These factors are recognised in the literature as influencing indoor pollutant generation, ventilation practices, and exposure levels. Their inclusion provides additional context for interpreting IAQ measurements and supports a more holistic understanding of the interactions between building systems and occupant behaviour. While these variables were not controlled experimentally, they are considered in the analysis to explain variations observed across the case studies.

These occupant-related and contextual variables are further used in Chapter 5 to interpret variations in IAQ performance across the case studies. In particular, differences in household size, occupancy patterns, tenure type, and lifestyle factors (e.g., cooking practices and smoking behaviour) are linked to variations in pollutant generation, ventilation behaviour, and pollutant decay rates. This enables a more contextualised interpretation of IAQ outcomes, where differences between homes are not attributed solely to building or system characteristics, but to the interaction between physical, behavioural, and socio-demographic factors.

Table 4.1 also serves as the reference point for linking household occupancy characteristics to the qualitative and quantitative data collected for each case study. For each occupied home, semi-structured interviews were conducted at three stages: shortly after installation, during summer, and in winter, providing up to three interview occasions per case across the six homes. These repeated interviews were designed to capture both stable household characteristics and temporal variations in occupancy patterns, ventilation practices, and IAQ perceptions. In most cases, interviews were conducted with the primary adult occupant available at the time, while daily diaries and monitored data were used to capture the influence of other household members. This structure enables each case study to be interpreted in relation to its specific occupancy profile, as summarised in Table 4.1.

Table 4 1: Household and building characteristics of the six studied homes (CS1–CS6).

Variable	CS1	CS2	CS3	CS4	CS5	CS6
Location	Birmingham	Birmingham	Birmingham	Burton-upon-Trent	Tamworth	Chelmsford
Building form	4-bed semi-detached (3-storey)	2-bed semi-detached (2-storey)	3-bed semi-detached (2-storey)	3-bed semi-detached (2-storey)	3-bed detached (2-storey)	4-bed mid-terrace (3-storey)
Floor area/volume (m³)	199.44	187.71	283.06	245.05	294.04	315.25
Completion date	2022	2022	2022	2022	2021	2021
Construction type	Traditional (brick & block) – Future Home Standard (FHS)	Traditional (brick & block) – Future Home Standard (FHS)	Traditional (brick & block) – Future Home Standard (FHS)	Traditional (brick & block) – (2013 Reg).	Traditional (brick & block) – (2013 Reg).	Traditional (brick & block) – (2013 Reg).
Airtightness (m³·h⁻¹·m⁻² @50Pa)	2.82. M ³ ·h ⁻¹ ·m ⁻² @50pa	2.98. M ³ ·h ⁻¹ ·m ⁻² @50pa	4.59. M ³ ·h ⁻¹ ·m ⁻² @50pa	5.00. M ³ ·h ⁻¹ ·m ⁻² @50pa	5.00. M ³ ·h ⁻¹ ·m ⁻² @50pa	5.00. M ³ ·h ⁻¹ ·m ⁻² @50pa
Ventilation system	MVHR	MVHR	Natural (with extract fans in the kitchen & bathroom)	Natural (with extract fans in the kitchen & bathroom)	Natural (with extract fans in the kitchen & bathroom)	Mechanical (MV)
Fuel Supply	Electric only (no gas supply).	Electric only (no gas supply).	Electric only (no gas supply).	Gas & electric	Gas & electric	Gas & electric
Household composition	2 adults + 5 children	2 adults + 2 children	1 adult + 3 children	2 adults + 2 children	2 adults + 1 child	2 adults + 3 children
Tenure	Rented	Rented	Rented	Rented	Owner-occupied	Owner-occupied
Gender (adults)	Mixed (M/F)	Mixed (M/F)	Female-led household (Single-parent)	Mixed (M/F)	Mixed (M/F)	Mixed (M/F)
Occupancy pattern	High occupancy: (<i>Large family with teenage children; high occupancy duration and frequent activities</i>)	Moderate: (<i>Household with a baby & child; moderate activity intensity</i>)	Variable: (<i>Single-parent household; variable occupancy and routines</i>)	Moderate: (<i>Household with two young children; moderate activity intensity</i>)	Low occupancy: (<i>Both parents work, low occupancy and activity levels</i>)	Low occupancy: (<i>Both parents work, low occupancy and activity levels</i>)
Smoking status	Household smoker: No indoor smoking reported.	No smoker reported	No smoker reported	No smoker reported	No smoker reported	Household smoker: No indoor smoking reported.

ELEVATIONS:

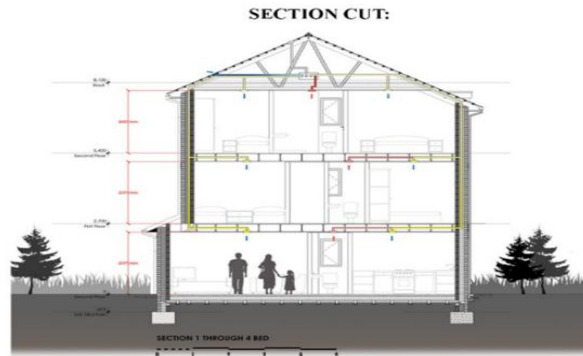
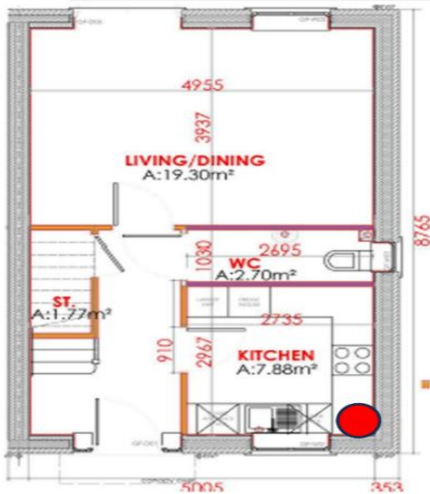


GROSVENOR ROAD (BIRMINGHAM)		
HOUSE TYPE	No.	AREA (m2)
TYPE 1	1	73.8
TYPE 2	1	72.6
TYPE 3	8	96.5
TYPE 4	2	110.7

CST1 – Building characteristics.

Plot 1 Specifications

Exterior	External facing brick / Code 4 Lead sheet with plywood Insulation Airtight polymer spray sealant Concrete Block Plasterboard with skim
Interior	Plasterboard with skim Partition Insulation / Acoustic Insulation
Floor	Reinforced sand cement screed Vapour membrane Insulation Beam and block
Window	Wood colour painted Moisture resistant MDF painted
Door	Wood colour painted
Air Permeability	1.5m2/h @50pa
Heating	Air Source Heat Pump (ASHP)
Ventilation System	Mechanical Ventilation Heat Recovery system (MVHR)
PV	Yes
Waste Water Heat Recovery	Yes
γ-value	0.028



CS1- Details of the house and some specifications	
Location	Birmingham UK
Property type	Four Bedroom Semi-detached House (three-story) (Future Home Standard Demo)
Ventilation type	Mechanical Ventilation Heat Recovery (MVHR)
Household characteristics	A family of seven – two parents and five children
Monitoring duration	May 2022 – January 2023 (phase 2)
Sensor details and location	One sensor (uHoo Aura) is positioned in the kitchen; the red dot on the floor plan represents the sensor location.



GROSVENOR ROAD (BIRMINGHAM)		
HOUSE TYPE	No.	AREA (m2)
TYPE 1	1	73.8
TYPE 2	1	72.6
TYPE 3	8	96.5
TYPE 4	2	110.7

CST2 – Building Characteristics.

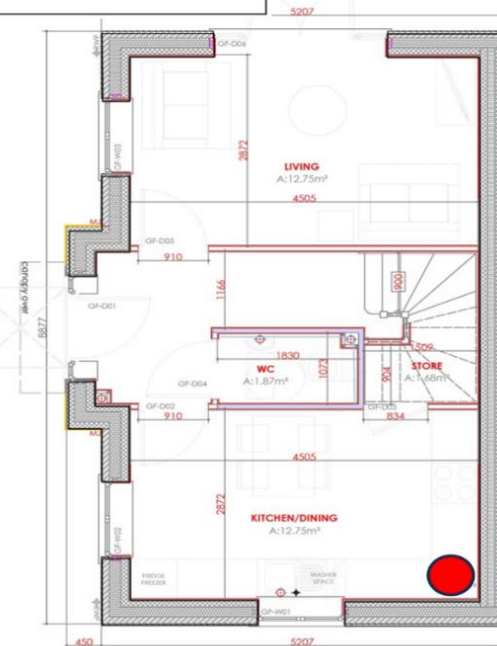
Plot 3 Specifications

Structure	External facing brick / Colour acrylic render / Code 4 Lead sheet with plywood Insulation Airtight polymer spray sealant Concrete Block Plasterboard with skim Plasterboard with skim Partition Insulation / Acoustic Insulation Plasterboard with skim
Interior Finishing	Plasterboard with skim / Wall tiling Wood / Carpet / Vinyl flooring
Window	Wood colour painted Moisture resistant MDF painted
Door	Wood colour painted
Air Permeability	2.98 m2/h @50pa
Heating	Panel Heaters Hot Water HP
Ventilation System	Mechanical Ventilation Heat Recovery system (MVHR)
PV	Yes
Waste Water Heat Recovery	Yes
y-value	0.0274

SECTION CUT:



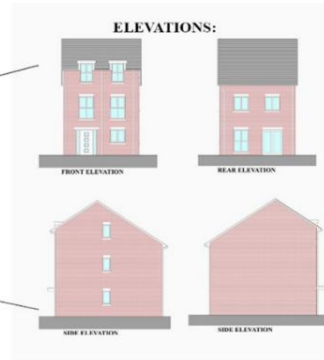
SECTION THROUGH PLOT 3



CS2- Details of the house and some specifications

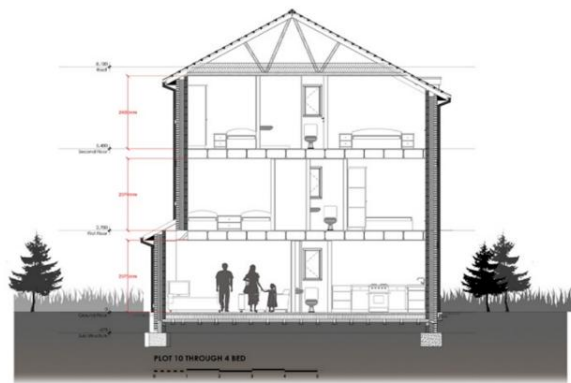
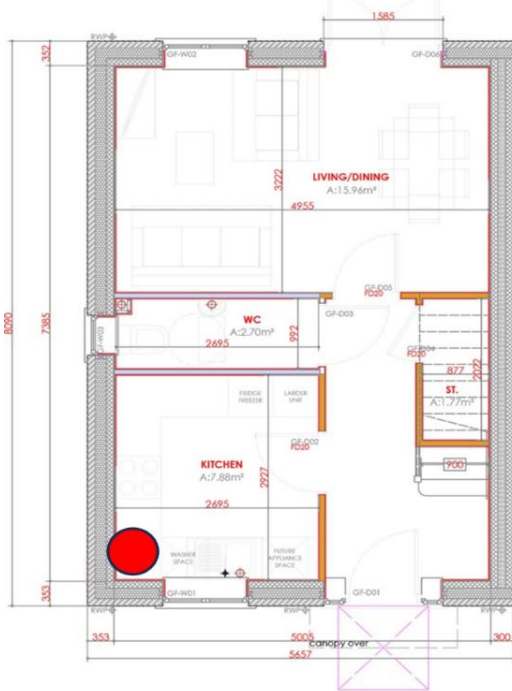
Location	Birmingham UK
Property type	Two-bedroom semi-detached House (two-story) (Future Home Standard Demo)
Ventilation type	Mechanical Ventilation Heat Recovery (MVHR)
Household characteristics	A family of four – two parents and two children
Monitoring duration	May 2022 – December 2022 (Phase 2)
Sensor details and location	One sensor (uHoo Aura) is positioned in the kitchen; the red dot on the floor plan represents the sensor location.

GROSVENOR ROAD (BIRMINGHAM)		
HOUSE TYPE	No.	AREA (m ²)
TYPE 1	1	73.8
TYPE 2	1	72.6
TYPE 3	8	96.5
TYPE 4	2	110.7



CST3 – Building characteristics.

Structure	External facing brick / Code 4 Lead sheet with plywood Insulation Airtight polymer spray sealant Concrete Block Plasterboard with skim
Interior Finishing	Plasterboard with skim / Wall tiling Wood / Carpet / Vinyl flooring
Window	Wood colour painted Moisture resistant MDF painted
Door	Wood colour painted
Air Permeability	4.6 m ² /h @50pa
Heating	Air Source Heat Pump (ASHP)
Ventilation System	De-centralised mechanical extract ventilation (dMEV)
PV	Yes
Waste Water Heat Recovery	Yes
y-value	0.028



SECTION CUT:

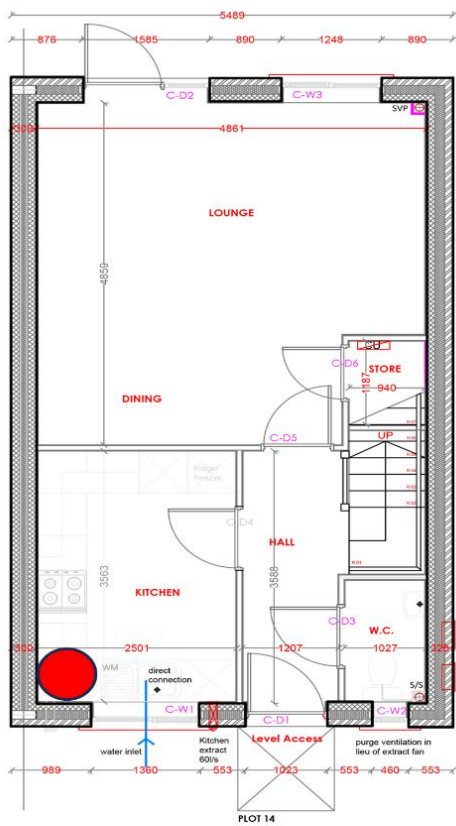
CS3- Details of the house and some specifications	
Location	Birmingham UK
Property type	Three-bedroom semi-detached House (two-story) (2013 Building Regulations)
Ventilation type	Naturally ventilated with extract fans in the kitchen and bathrooms.
Household characteristics	A family of four – one parent and three children
Monitoring duration	May 2022 – February 2023 (phase 2)
Sensor details and location	One sensor (uHoo Aura) is positioned in the kitchen; the red dot on the floor plan represents the sensor location.



ELEVATIONS:



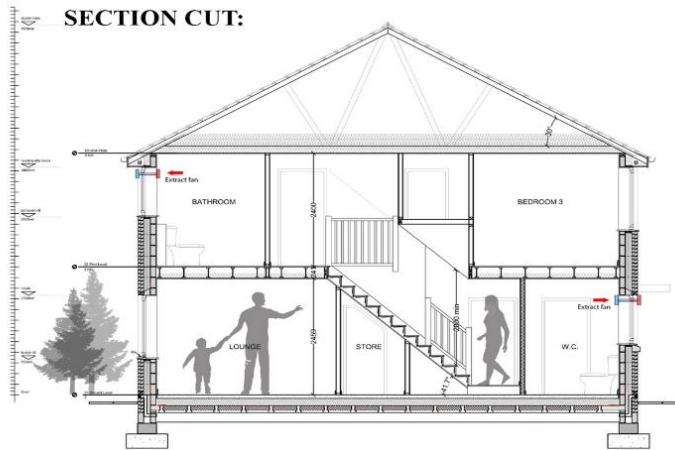
CST4 – Building Characteristics.



Specifications

Structure	External facing brick Insulation Concrete Block Plasterboard with skim Plasterboard with skim / Moisture resistant plasterboard Timber stud Partition Insulation / Acoustic Insulation Plasterboard with skim
Interior Finishing	Plasterboard with skim / Moisture resistant plasterboard / Wall tiling Carpet/ Vinyl flooring
Window	Wood colour painted
Door	Wood colour painted
Ventilation System	De-centralised mechanical extract ventilation (dMEV)
PV	No
Waste Water Heat Recovery	No

SECTION CUT:



CS4- Details of the house and some specifications	
Location	Burton upon Trent, UK
Property type	Three-bedroom semi-detached house (two-story) (Building Regulation Standard)
Ventilation type	Naturally ventilated with extract fans in the kitchen and bathrooms.
Household characteristics	A family of four – two parents and two children
Monitoring duration	March 2022 – August 2022 (phase 2)
Sensor details and location	One sensor (uHoo Aura) is positioned in the kitchen; the red dot on the floor plan represents the sensor location.

CST5 –
Building characteristics.



FRONT ELEVATION



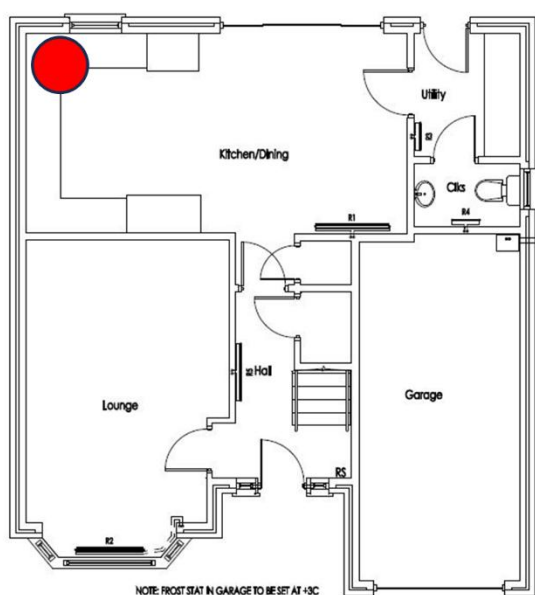
SIDE ELEVATION



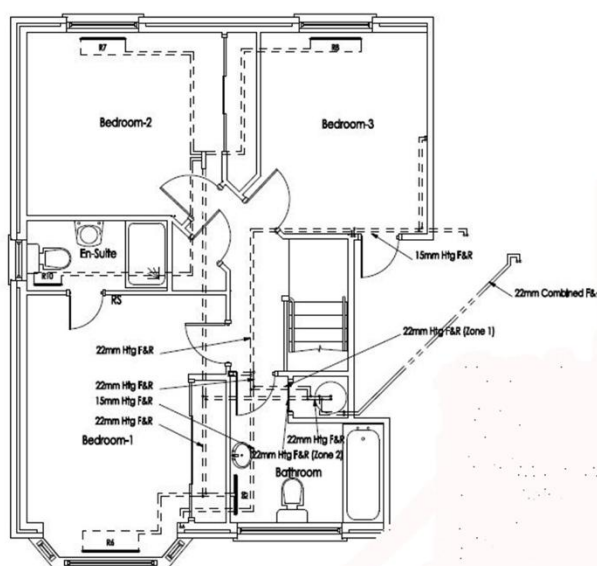
REAR ELEVATION



SIDE ELEVATION



NOTE: FROST SEAT IN GARAGE TO BE SET AT +3°C IN CONJUNCTION WITH PIPE SEAT FITTED ON COMBINED RETURN SET AT +30°C.



CS5- Details of the house and some specifications	
Location	Tamworth UK
Property type	Three Bedroom Detached House (two-story) (2013 Building Regulation Standard)
Ventilation type	Naturally ventilated with extract fans in the kitchen and bathrooms.
Household characteristics	A family of three – two parents and one child
Monitoring duration	December 2021 – February 2022 (Phase 1)
Sensor details and location	One sensor (uHoo Aura) is positioned in the kitchen; the red dot on the floor plan indicates its location.

CST6 –
Building characteristics.

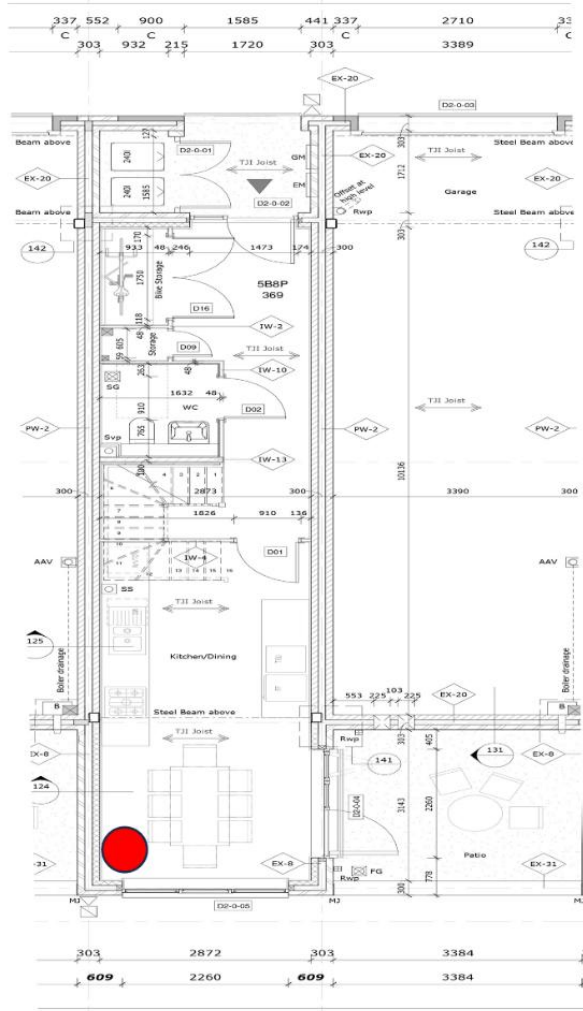


Elevation



Chelmsford Specifications

Property type	3-bedroom terraced house
Completion date	December 2020
Window facing	North-East (NE) facing
Ventilation System	MVHR
Living Room Area	17.5 m ²
Kitchen Area	19.6 m ²
Ceiling Height	2.6 m



CS6- Details of the house and some specifications	
Location	Chelmsford UK
Property type	Four-bedroom terraced townhouse (three-story) (2013 Building Regulation Standard)
Ventilation type	Naturally ventilated with kitchen and bathroom extract fans.
Household characteristics	A family of four – one parent and three children
Monitoring duration	March 2022 – September 2022 (phase 2)
Sensor details and location	One sensor (uHoo Aura) is located in the kitchen; the red dot on the floor plan indicates its location.

4.4 Monitoring and Instrumentation.

Monitoring IAQ is essential for accurately identifying IAQ problems, which can be particularly challenging in domestic buildings, as it requires high occupant compliance. Numerous variations exist among individual houses, as they depend on factors such as building characteristics, occupant behaviours, and outdoor air pollution levels, which can greatly modify indoor exposures (Ferguson et al., 2021; Fabian et al., 2011). Monitoring involves sophisticated, well-established instrumentation to meet measurement accuracy requirements, along with calibration, maintenance, and data validation, to ensure data reliability and comparability. This research utilises a combination of uHoo AURA and uHoo Smart environmental sensors to monitor a range of IAQ parameters (e.g., TVOCs, formaldehyde, PM2.5, CO₂, NO₂, temperature, and humidity) in real-time, with technical details provided in Tables 9 and 10. These sensors are RESET- and MCERTS-accredited, enabling minute-by-minute data collection with cloud-based storage for secure access and analysis.

Table 4.2 presents a detailed profile of the sensor equipment used in this research, outlining sensor specifications and operational features, including dimensions, data-logging intervals, power sources, user-interface options, and environmental certifications. Sensor specifications for all monitored parameters, including range, resolution, and accuracy, are also detailed.

Table 4 2: Specifications and operational details of sensor equipment utilised in this research.

General	
Installation	Wall-mounted
Built-in Fan	Yes
Design	
Dimensions (WxLxD)	200mm x 180mm x 57mm
Weight	800g / 1.8lbs
Data	
Log interval	Once per minute/15-minute interval
Format	Minute, Hourly average, Daily min/ max/ average + Analytics
APIs	Yes
Power	
Main Power Sources	5V-Micro-USB 48V Power over Ethernet (PoE 802.3af standard)
Backup Power Sources	3350mAh @ 3.7V Lithium-ion battery
Power Consumption	900mW (normal operation) and 1.1W (data transmission)
User Interface	



Web Dashboard	Support all major browsers.			
Mobile App	uHoo Business			
Certifications				
Environmental Performance	RoHS, REACH, WEEE, Free of SCCP and HBCDD contents RESET™ Grade B Accreditation and MCERTS			
Connectivity: Wi-Fi				
Standard	802.11 a/b/g/n @ 2.4GHz and 5GHz			
Security	WPA2-Personal (8 to 63- character password), WPA2-Enterprise (802.1x), PEAPv0 (MSCHAPv2), FIPS 140-2 Level 1 Certification			
Sensor Specifications				
<i>Parameters</i>	<i>Range</i>	<i>Resolution</i>	<i>Accuracy</i>	
TVOCs	0 to 60,000 ppb	1 ppb	± 15 %	
Formaldehyde	0 to 20,000 ppb	1 ppb	± 30 % (0 to 300 ppb) ± 10 % (300 to 20,000 ppb)	
PM2.5	0 to 1,000 µg/m ³		± 10 µg/m ³ (0 to 100 µg/m ³) ± 10 % (100 to 1000 µg/m ³)	
Carbon Dioxide (CO ₂)	400 to 10,000 ppm	1 ppm	± 300 ppm plus 3 % of the actual value	
Nitrogen Dioxide (NO ₂)	0 to 500 ppb	1 ppb	± 15 %	
Temperature	-40 to 85°C	0.1°C	± 0.5°C	-10 to 60 °C
Humidity	0 to 100%	0.1%	± 3 %	30 to 85%

Table 4.3 presents the specifications of the uHoo Smart sensors, listing the ranges, resolutions, and accuracies for each parameter, including temperature, humidity, CO₂, PM2.5, air pressure, airborne chemicals, VOCs, ozone, carbon monoxide, and nitrogen dioxide.

Table 4 3: Types of uHoo smart sensors, measurement ranges, resolution, and accuracy.

Sensor	Unit	Range	Resolution	Accuracy
Temperature	°C	-40 to 85	0.1	±0.5
Humidity	%	0 to 100	0.1	±3
Carbon Dioxide (CO ₂)	ppm	400 to 10000	1	±50
Particulate Matter (PM2.5)	µg/m ³	1 to 200	1	±15
Air Pressure	mBar	300 to 1100	0.1	±1
Airborne Chemicals (VOCs)	ppb	0 to 1200	1	±10
Ozone(O ₃)	ppb	0 to 1000	1	±10
Carbon Monoxide (CO)	ppm	0 to 1000	0.1	±2
Nitrogen Dioxide (NO ₂)	ppb	0 to 1000	1	±10

These sensors are wall-mounted and equipped with built-in fans for air sampling. Power options include a 5V Micro-USB and Power over Ethernet (PoE), with a backup lithium-ion battery to ensure continuous operation. Data can be accessed via a web dashboard or a mobile app (uHoo Business) and is securely stored in the cloud.

The proposed monitoring method targets pollutant concentrations of concern due to their effects on human health and the environment. It includes emissions from interior materials and products (TVOC, formaldehyde), combustion processes (such as cooking, cleaning, and using scented products and air fresheners) (PM_{2.5}, NO₂), and occupational data (CO₂), to facilitate statistical analysis and establish links between occupants' perceptions and measured IAQ conditions.

Indoor VOC measurement requires a better understanding of the VOC emission characteristics of building materials. Therefore, accurate measurement of VOC emission characteristics and concentrations is critical for developing improved source control, as required for occupant health and well-being (Caron et al., 2020). However, existing VOC measurement techniques are limited in the range of VOCs they can accurately quantify, and few can measure all present VOCs (Brown et al., 1994). Some studies use TVOC, the sum of VOC concentrations, as an indicator of indoor VOCs. Moreover, TVOC measurements do not quantify all VOCs in the air; they instead represent only a portion of the estimated VOCs present (Yu and Crump, 1998). The methodologies used to determine TVOC concentrations can be categorised as direct or indirect, differing in the amount of work and information required (Zhang et al., 2010).

When placing sensors in a building to collect data, it is crucial to position them at a specific height based on the building's intended use. Sensors are typically placed throughout the building in common areas; however, positioning them near induction units, floor fans, radiators, or areas with direct sunlight can compromise data accuracy. Due to deposition and resuspension, some substances can have their molecular weight cause them to gravitate towards the floor or ceiling. Depending on the pollutant being tracked, sensors should be placed accordingly. For example, methane is lighter than air, and concentrations are typically highest near the ceiling. Correspondingly, ozone is heavier than air and tends to remain near the floor. Children may be exposed to higher concentrations of pollutants, such as chlorine and ozone, near the floor. Therefore, the density of pollutant parameters needs to be accounted for when

monitoring IAQ in homes. Figure 15.5 illustrates the importance of sensor placement for IAQ monitoring.

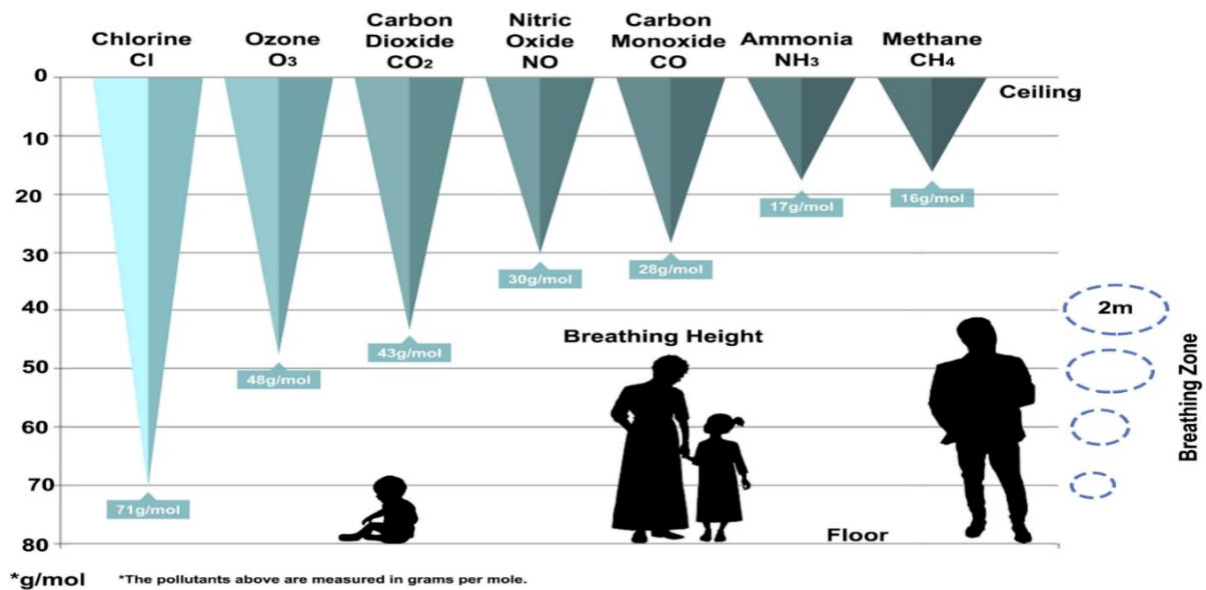


Figure 4. 5: IAQ sensor placement indicating pollutant stratification in relation to occupant breathing zone (adapted from iota.org).

The sensors in this study were positioned in accordance with ISO 1600. 1 guideline, in line with the manufacturer's recommendations, ensuring they were at least 1 m away from external walls and at least 1.5 m above the finished floor level. Care was taken to avoid direct exposure to light and heat sources, such as radiators, light bulbs, televisions, and other large electronic appliances. Additionally, the sensors were strategically placed in a non-intrusive location to ensure that regular room use was not affected. Data from the sensors was transmitted continuously throughout the monitoring period via Wi-Fi to a dedicated digital platform accessible only to the university team.

Kitchens were selected as sensor locations because cooking, particularly cooking, emits particles into the indoor environment, making it the primary source of indoor pollution in residential homes (Fleisch et al., 2019). To minimise disturbance to occupants, given that the sensors have an internal fan and noise can be disruptive during inactive periods of the day, placement in bedrooms and living rooms was avoided.

An air-pollutant movement experiment was conducted, and additional uHoo Smart sensors were used because they are less disruptive and can be easily placed in living areas. Similar to the uHoo AURA, these sensors were connected to a home Wi-Fi network, enabling data

collection and transmission to the uHoo database. The researcher had access to the data and could download historical data.

4.4.1 Co-location test for the uHoo Aura sensor validation.

A co-location test is a widely used validation method in air quality research, in which multiple sensors are co-located with or adjacent to a reference-grade instrument under identical environmental conditions to assess their accuracy, precision, and consistency (Chatzidiakou et al., 2019). This approach ensures that all units respond similarly to the same environmental changes, increasing confidence in their suitability for field deployment. To ensure the reliability and consistency of IAQ measurements, a sensor co-location test was conducted in Birmingham, UK, using the eight uHoo Aura sensors chosen as the primary measurement instruments for this research (see Table 9). The purpose of this test is to confirm that all units respond similarly to environmental changes, thereby validating their suitability for field deployment. The test was performed over a 7-day period in a controlled indoor environment, with all sensors placed together in the same room and positioned away from obstructions or direct sources of air movement (such as fans or vents), in accordance with best practice guidelines (ISO 1600- 1 guideline and the manufacturer’s recommendations). Each sensor recorded real-time data on five key IAQ parameters: CO₂, PM_{2.5}, TVOC, temperature, and relative humidity (see Section 3.5 for further details).



Figure 4. 6: Co-location test configuration using eight uHoo Aura sensors (left).

Figure 4. 7: Co-Location test Results: Eight uHoo Aura sensors measuring IAQ parameters over 7 days (Right).

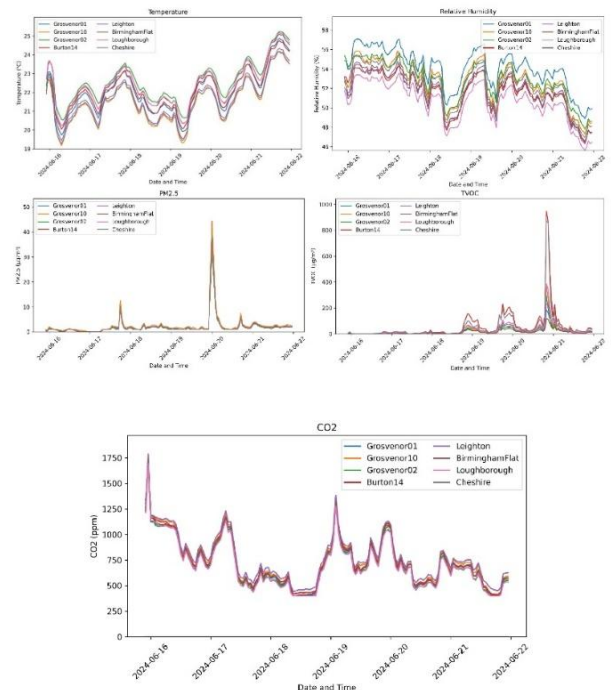


Figure 4.6 displays the eight co-located uHoo Aura sensors used in the test. Figure 4.7 shows the time-series results, demonstrating that all sensors recorded similar trends and synchronised fluctuations across all parameters over the seven days. Notably, significant spikes in PM_{2.5} and TVOC coincided across all sensors on May 19, 2024, and May 20, 2024, indicating consistent detection of transient indoor air pollution events. CO₂ measurements also followed closely aligned patterns, with increases and decreases happening at the exact times across all sensor units. Despite minor differences in absolute values, all sensors displayed similar patterns for temperature, relative humidity, PM_{2.5}, TVOC, and CO₂. Key changes and peaks were observed across units, indicating acceptable consistency and suitability for monitoring IAQ trends in this research context. Moreover, according to the manufacturer's documentation, the uHoo Aura sensors are RESET™ Grade B and MCERTS certified, providing additional confidence in their measurement accuracy and reliability for research purposes.

4.4.2 Monitoring Plan and Sensors.

All sensor data were initially extracted for analysis. The uHoo platform provides an online dashboard that allows monthly downloads of minute-by-minute data for different dates in the case studies. CS studies 1-3 were monitored from April to December 2022; CS studies 4 and 6 were monitored from March to September 2022; and CS 5 was monitored from December 2021 to February 2022. Sensor data for each monitoring period were downloaded from the uHoo online dashboard as CSV files. These CSV files were then organised into folders by home and securely stored on OneDrive to ensure data integrity and facilitate systematic analysis.

4.4.3 Selection Value.

To identify which IAQ parameters to focus on in the investigation, Spearman's rank correlation test was applied to data from one of the monitored homes (CS1). The correlations among the monitored parameters (Figure 4) revealed strong positive correlations among particulate matter variables (PM₁, PM_{2.5}, PM₄, and PM₁₀), leading to the decision to retain only PM_{2.5} for further analysis to avoid redundancy. Additionally, positive correlations were observed between TVOC and Formaldehyde, and between TVOC and CO₂. Although these associations were not particularly strong, both TVOC and CO₂ were included in the final selection because of their relevance to understanding pollutant dynamics and indoor air quality. These variables were retained because they capture multiple aspects of indoor pollutant concentrations and provide a more comprehensive understanding of pollutant dynamics within the studied homes.

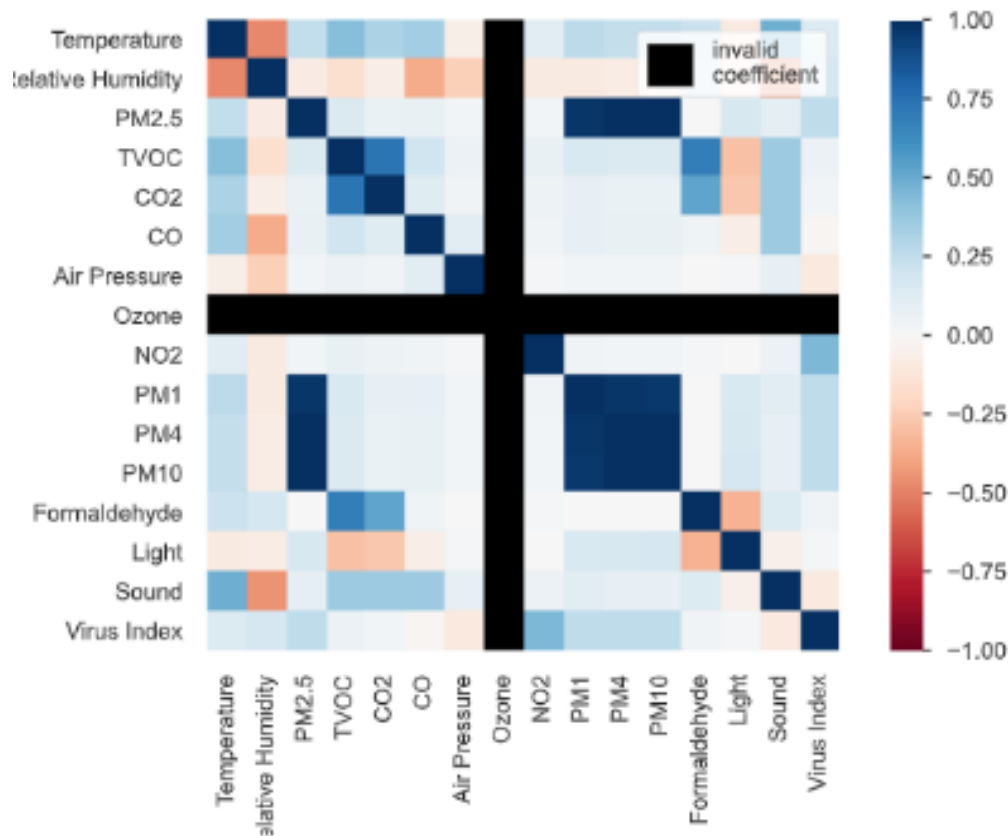


Figure 4. 8: Spearman's correlation matrix illustrating relationships between IAQ parameters in CSI.

Figure 4.8 presents the Spearman correlation results, with blue indicating positive correlations and red indicating negative ones. Based on this analysis, the final parameters selected for detailed data analysis were Temperature, Relative Humidity, CO₂, TVOC, and PM_{2.5}.

4.4.4 Units of Measurement and Threshold Values.

Table 4.4 summarises the pollutant parameters monitored in this research, along with their respective units, averaging periods, recommended thresholds, and sources of guidance. PM_{2.5} is measured in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) with a 1-day averaging period and a threshold of 15 $\mu\text{g}/\text{m}^3$, as recommended by WHO (2021). TVOCs are also measured in $\mu\text{g}/\text{m}^3$ over a 1-day period, with a threshold of 300 $\mu\text{g}/\text{m}^3$, in accordance with WHO guidance. CO₂ is monitored in parts per million (ppm) using a 1-day average, consistent with the ASHRAE 62.1:2016 standard's recommended threshold of 1000 ppm. Temperature is recorded in degrees Celsius ($^{\circ}\text{C}$), in accordance with WHO guidelines on the health impacts of low indoor temperatures. Relative humidity is measured as a percentage (%), with target levels between

40% and 60% in line with CIBSE's TM40:2020 guidance. These selected thresholds reflect current best practices for assessing IAQ impacts in the studied homes.

Table 4 4: Pollutant measurement units and associated threshold values.

Pollutant parameters	Unit	Averaging period	AQG level	Source
PM _{2.5}	µg/m ³	1 day	15	WHO guidance: 2021
TVOC	µg/m ³	1 day	300	WHO guidance: 2021
CO ₂	ppm	1 day	1000	ASHRAE standards 62.1:2016
Temperature	°C	-		WHO guidance: The health impact of low indoor temperatures: 2021
Relative Humidity	%	-	40 to 60	CIBSE: Health & wellbeing in building services TM40: 2020

4.5 Interviews.

One advantage of using interviews is that they generate data rapidly and in large quantities. On the other hand, it has its limitations and disadvantages (Aberdeen, 2013). For example, interviewees may be reluctant to respond to all that the interviewer hopes to explore. Interview techniques can be categorised into structured, semi-structured, or unstructured. Each type of interview category has its advantages and disadvantages.

This research employs semi-structured interviews, which offer the flexibility to explore participants' perspectives in depth while allowing questions to be refined as the study progresses. In addition, semi-structured interviews offer the flexibility to refine interview questions over time, following a few initial interviews, to obtain more accurate, concise, and better answers. Therefore, to gather relevant information and explore ways to improve IAQ in UK housing developments from land purchase through to occupancy, this research employs semi-structured interviews as an appropriate data collection method. Interviews with housing developers provided insights into decision-making across all phases of home development, from land purchase to occupancy, and into how these decisions influence IAQ.

All interviews were diligently recorded, transcribed verbatim, and analysed using NVivo 12 for qualitative data management. The analysis process included content analysis (Elo & Kyngäs, 2008) and sociotechnical comparison with physical monitoring data, enabling the identification of key themes and potential discrepancies or explanatory relationships between qualitative and quantitative findings. The transcription phase is a crucial aspect of the analysis, allowing the researcher to familiarise themselves with the data, as suggested by Merriam and Tisdell 2016. This included documenting and categorising the frequency of concepts, behaviours, and words into

specific themes or codes. The objective was to provide a concise summary of participants' perspectives on particular factors. The second method employed was sociotechnical analysis, which involved examining qualitative data alongside data obtained through physical monitoring. This comparative analysis aimed to identify both commonalities and disparities between datasets (e.g., instances where participant reports conflicted with monitored data). It also explored the potential for qualitative data to explain specific physical findings. However, it was imperative to remain vigilant against confirmation bias and the risk of false positives throughout this analytical process.

The coding of the 15 interview transcripts generated 6 categories or themes, as outlined in Table 17. These categories encompass land purchase and strategic planning, design and scheme orientation, construction, handover and occupation, and market dynamics and business environment. The categorisation process was informed by the conventional UK home development process and incorporated key external factors, such as regulations and market trends. These categories form the framework for presenting and discussing the interview data.

On the other hand, this section describes and justifies the technique applied in the social research conducted for this thesis. The study involved conducting semi-structured interviews and walk-throughs with residents of occupied homes, as well as extended physical monitoring. The primary goal of these interviews was to extract insights into how occupants interact with their homes, impacting factors such as IAQ, ventilation (whether intentional or not), and their overall ability to operate their homes. The interview topics covered a range of areas, including occupant activities (e.g., cooking, cleaning, and using products), opening windows and doors, and IAQ from an everyday perspective. Also, occupant diaries were utilised to identify occupants' activities and ventilation habits within the spaces.

4.5.1 Data Collection Sequence.

This section details the use of long-term monitoring to examine IAQ across a diverse set of newly built homes, each with different orientations, designs, ventilation systems, technologies, and household profiles. The purpose is to capture how these factors collectively influence IAQ over time. Long-term monitoring provides a foundation for identifying patterns of usage and behaviours that contribute to poor air quality. The study began by observing IAQ under real-life occupancy and environmental conditions, identifying the complex interactions between the built environment, occupant behaviour patterns, and pollutant levels. To gain a better

understanding, interviews and daily activity diaries were also conducted, offering qualitative context alongside the quantitative monitoring results.

Building on these findings, short-term experiments were conducted to investigate specific issues, such as how occupant activities (e.g., cooking, cleaning) and pollutant migration affect indoor environments. However, it was often difficult to determine whether inadequate air quality was due to building materials, their integration, or overall occupant activities. To clarify this, experiments were first carried out in unoccupied homes to observe how IAQ behaves in the absence of occupants and to assess the impact of building materials and systems alone. These combined methods provided valuable insights into both technical and behavioural factors influencing IAQ, highlighting the complex and multifaceted nature of IAQ challenges.

As these investigations progressed, it became evident that to better understand and address IAQ problems, it was necessary to look beyond the immediate environment and occupant behaviours. This led to a shift in perspective towards examining how buildings are conceived, designed, and delivered. By reviewing the entire home development process, the research aimed to identify where IAQ issues may originate and where opportunities for intervention could arise, even before a building is completed and occupied. This broader understanding provides a foundation for recommending systemic changes that can improve IAQ from the earliest stages of housing development.

While such a broad study may entail some loss of data precision, it offers far greater practical impact than a narrowly focused investigation. By examining IAQ across the full spectrum of building design, technology, occupant behaviour, and development processes, this research supports the development of systemic, scalable solutions for mass-market housing.

4.5.2 Occupant Interviews.

This section presents the process of gathering qualitative data through semi-structured interviews and daily diary entries completed by occupants in the six case study homes. These methods were used to capture lived experiences, behaviour patterns, and perceptions related to IAQ. The purpose was to contextualise occupant practices and identify recurring activities that may influence IAQ.

4.5.2.1 Occupant's Interview and Daily Diary.

A semi-structured interview was used to collect consistent, insightful, and comparable qualitative data, allowing participants to express their views in their own words (Barriball and While, 1994). This format also enabled the use of probing questions to clarify and explore important or unexpected issues raised during the interview discussions (Barriball and While, 1994). A fully structured interview format was considered too restrictive, as it could have limited the depth and contextual richness of the responses.

Occupants were interviewed at three stages following the installation of IAQ monitoring sensors: shortly after installation (April-June), during the summer period (July-August) and in winter (Nov-Dec). When multiple people lived in the home, the interview often focused on the primary adult respondent available at the time of data collection, while diaries and monitored patterns were used to capture the influence of other household members on IAQ. Each interview lasted approximately 20-30 minutes, depending on the level of detail the participant chose to provide. The complete list of interview questions is included in the Appendices.

4.5.2.2 Survey and Questionnaire.

A questionnaire is one of the most commonly used methods for data collection. Amaratunga et al. (2002) state that many researchers have used questionnaires as their sole data-collection method. While questionnaires can serve as a primary tool, Saunders et al. (2016a) recommend combining questionnaires with various mixed-methods research designs. Amaratunga et al. (2002) further observe that the questionnaire method offers benefits, such as saving time and money, and that it can be distributed to large numbers of respondents via electronic means.

This research used a questionnaire survey to collect quantitative data as part of the case study, supplemented with open-ended qualitative questions to enable ongoing refinements to the survey. The questionnaires were designed and distributed based on demographic factors, such as age, gender, vulnerability, and household composition. The collected data were used to categorise the data into occupants' perceptions of IAQ, behavioural patterns in the home, and the operational use of the building.

Closed questions were also included to assess specific behaviours, such as ventilation strategy implementation (i.e., window-opening practices), which were sometimes verified through direct observation by the researcher. Where possible, a Dictaphone was used to record the

interviews for accuracy. (**Appendix E**), Details the complete list of questions used to capture occupants' perceptions of IAQ and related behaviour patterns.

4.5.2.3 Occupant Daily Diary.

Participants were asked to maintain detailed records of their activity patterns during the monitoring period. An occupant diary (**Appendix D**) was provided to each participant to collect information on activities that could affect IAQ results. The occupant diary is a practical method for generating real-time occupancy data, which is validated against time-use data that describes what people do and when. Occupants were asked to record the average occupancy of the living room, kitchen, and the entire home hourly. The diary included tick-box sections to document activities such as cooking, cleaning, use of household products, and actions affecting IAQ (e.g., opening windows and doors). This was available both online (in Word format) and on paper and was condensed to one A4 page per day to minimise participant burden and increase response rates. Additionally, occupants were asked to specify which windows and doors were used for ventilation, noting the time, duration, and (if applicable) the width of the window or door opening. This detailed, structured record supports analysis of the relationship between occupant behaviour and IAQ outcomes.

4.6 Home Development Process Interviews.

Semi-structured interviews were conducted with major housing developers and key industry professionals to gain insight into their perspectives on the home delivery process. The interview questions covered a range of topics, including approaches to government policies and regulations, land acquisition, design and construction practices, the influence of environmental factors (e.g., climate change and adaptation), and operational issues in buildings (e.g., IAQ awareness, design, technology, and maintenance). The interview also addressed planning-process challenges, various design and mitigation strategies, and operational use and handover. All meetings, except one, were conducted online via Microsoft Teams, and each lasted approximately an hour. For confidentiality, Table 4.5 summarises the interview participants, maintaining anonymity; however, all were open and not reticent about their companies.

This research focuses on a better understanding of the main actor, as the major housing developer holds significant influence over the home development process. The unit of analysis is the company level, focusing on decision-making and identifying priorities and challenges. The research recognises that addressing the complexities of housing and IAQ, in particular, often requires a broader conception to effect change. Some housing problems require systemic

change. By following these lines of inquiry, the research plans to cover the full scope of the home development process, enabling the construction of the research and the analysis of its implications.

One advantage of using interviews is that they generate data rapidly and in large quantities. On the other hand, it has its barriers and disadvantages (Aberdeen, 2013). For example, interviewees may be reluctant to respond to all that the interviewer hopes to explore. Interview techniques can be categorised into structured, semi-structured, or unstructured. Each type of interview category has its advantages and disadvantages. This research employs semi-structured questioning as a more suitable approach, allowing the interviewee to provide as much information as possible about their IAQ perspective without digressing into unnecessary subjects. In addition, semi-structured interviews offer the flexibility to refine interview questions over time, after a few initial interviews, to obtain more concise and accurate answers.

The initial engagement with the home developers and other building professionals began with interviews with the developers' technical directors, manufacturers supplying to the developers, designers, and environmental and energy consultants. The main objective of the interview was to gain insight into the home development process in the UK, including where decisions are made and the implications for IAQ. In total, fifteen interviews were conducted between March and September 2021. The plan was to conduct the interviews in person to interact with the interviewees; however, due to COVID-19 pandemic restrictions, this couldn't proceed. All interviews were recorded and stored on a password-protected laptop in accordance with research ethics guidelines. All interviewees provided consent to be recorded. They explained that it would be used only for analysis. All recorded interviews were transcribed, and the dataset was reviewed to ensure consistency across responses. The short or non-descriptive responses were excluded from further coding. Then, it was analysed using NVivo 12, and the first open-coding iteration was conducted to consolidate codes into coherent groups. Through constant comparisons to check similarities and contrasts, the following five themes have been formed:

1. Planning, design, and material selection.
2. Procurement processes and supply chain logistics.
3. Government policy and regulations.
4. Market dynamics and business environment.
5. End-user education and home induction process.

Table 4 5: Summaries of conducted interviews, chronological order, and anonymised participant details.

Interviewee Code	Developers & Building Professionals	Companies' Representatives	Date Interviewed	Location
DEVELOPERS				
HD1 (<i>Housing Developer</i>)	Taylor Wimpey	Research and Development Manager Snr Technical Coordinator	16/03/2021	Online
HD2	Midland Heart	Head of Construction and Quality	17/03/2021	Online
HD3	Redrow PLC	Head of Group Technical	24/03/2021	Online
HD4	Barratt PLC	Technical and Innovation Director	06/04/2021	Online
SUPPLIERS / MANUFACTURERS				
R1 (Respondent)	H -H UK LTD	Director	26/05/2021	Online
R2	Ibstock PLC	Technical and Innovation Director	15/06/2021	Online
R3	Xtratherm LTD	Technical Director	30/07/2021	Online
R4	EnviroVent UK	Sales Director Regional Sales Manager Head of Research & Development Marketing Director	03/08/2021	In-person
ARCHITECTS / SUBCONTRACTORS / CONSULTANTS				
R5	AES Sustainability Consultants	Associate Director	17/08/2021	Online
R6	HGP - Architects	Associate Director	23/08/2021	Online
R7	Inkling LLP	Founder/Partner	05/09/2021	Online
R8	Tricas Construction LTD	Design Manager	09/09/2021	Online
R9	Acivico Group	Building Control Agent	10/09/2021	Online
R10	Thermal Economics	Head of Technical Services	13/09/2021	Online
R11	Hawk Technical	Managing Director	14/09/2021	Online

4.6.1 Data Processing and Analysis.

This chapter outlines the analytical procedures applied to both qualitative and quantitative datasets generated by the study. Using a mixed-methods design, the analysis integrates sensor-derived environmental data, interview transcripts, daily activity diaries, and survey responses. Distinct analytical techniques were employed for each data type, and the results were triangulated to develop a comprehensive understanding of the factors influencing IAQ in residential settings.

The analytical approach was guided by the study's research objectives and questions, employing statistical techniques for quantitative data and thematic/content analysis for qualitative data. This structured process enabled the interpretation of results, the identification of patterns, and the cross-validation of findings across multiple data sources. The following sections outline the specific analytical methods employed for each dataset and provide the rationale for their selection.

4.6.1.1 Data Storage.

A structural approach to data collection and storage was designed to collect data from multiple sensors across different rooms in multiple buildings. The university team could access and visualise real-time data through the manufacturer's website platform and download the historical data for analysis. The downloaded raw data were categorised into building type, building number, room type, data type, time (year-month), and resolution to facilitate efficient data management. These organised datasets were then downloaded and stored on the university's local device, ensuring a systematic data structure for easy accessibility during research analysis. To identify detailed activity patterns, data were collected at 1-minute resolution, enabling the identification of specific events and trends. Additionally, all sensors were synchronised using the UK time zone, aligning with local temporal dynamics and ensuring an accurate representation of IAQ and environmental conditions over time. The systematic approach to data collection and storage not only facilitated efficient access to information for research analysis but also captured detailed insights, thereby enhancing the depth and accuracy of the study's findings.

4.6.1.2 Data Pre-Processing.

Data preprocessing was performed to clean the dataset and ensure its suitability for analysis. The primary focus was to address missing data. Various techniques, such as interpolation, data imputation, and exclusion of records with large gaps, were employed to ensure data completeness and make it ready for analysis. Data interpolation or imputation was applied for short gaps, considering that IAQ data are sequential. For example, IAQ data such as TVOCs and PM_{2.5} can fluctuate considerably within intervals as short as 10 minutes, limiting the applicability of interpolation or imputation to shorter periods. Consequently, large gaps were excluded from the analysis because it was not possible to predict missing data over extended periods.

Detecting and addressing outliers was crucial for identifying and eliminating anomalies caused by sensor malfunctions or extreme environmental conditions. Such aberrant data could distort the results of the analysis. Outlier detection methods, such as the Interquartile Range (IQR), were utilised to identify outliers, which were then corrected if attributed to measurement errors. The outliers from the data were then removed using the IQR method. The IQR represents the middle 50% of the data lying between the 75th and 25th percentiles of a distribution. A data point qualifies as an outlier if it surpasses the 75th percentile or falls below the 25th percentile by a factor of 1.5 times the IQR. For example, if Q1 indicates the 25th percentile and Q3 represents the 75th percentile, then the IQR is calculated as $Q3 - Q1$, and the outlier is identified as a point below $[Q1 - (1.5) \text{ IQR}]$ or above $[Q3 + (1.5) \text{ IQR}]$. Despite significant short-term variations in IAQ data, such as during cooking, outliers were retained to capture essential events and maintain the integrity of the dataset.

4.6.2 Quantitative and Qualitative Analysis.

The following sub-sections describe the analytical procedures applied to the quantitative and qualitative data collected in this research. Quantitative and qualitative data were analysed separately using appropriate techniques for each dataset. Triangulation was then used to integrate findings from multiple sources, ensuring a comprehensive understanding of the factors affecting IAQ.

4.6.2.1 Quantitative Analysis.

Quantitative analysis in this research involved the systematic application of statistical techniques to interpret sensor-derived IAQ data and other numerical variables. Among the commonly employed methods were correlation, regression, and factor analysis. The initial stage of analysis involved descriptive statistics to illustrate trends in the data, following the recommendation of Amaratunga et al. (2002), who suggest that, regardless of the nature of the collected data, it is advisable to begin the analysis by examining the raw data for patterns. Both descriptive and inferential statistics were employed in this research. The analysis started with descriptive statistics, including means, medians, ranges, and standard deviations, supported by visualisation tools such as line graphs and bar charts. These methods allowed the identification of trends and patterns across the six case study homes, including differences between occupied and unoccupied states (Sekaran, 2003).

Based on these initial insights, inferential statistics were used to explore the relationships among building design, ventilation systems, and occupant behaviour, and to assess their

influence on IAQ outcomes. The Kruskal-Wallis test was used to compare the distributions of IAQ parameters across different groups. At the same time, Spearman's rank correlation coefficient was employed to assess the strength and direction of relationships between variables. These non-parametric methods were chosen due to the nature of the data and proved particularly useful for validating relationships between IAQ parameters in this study (Chapman, 2017; Saunders et al., 2016a).

Data comparison was performed within and across case-study homes, across different monitoring periods, and between operational conditions (such as cooking, cleaning, or varying occupancy status). Graphical and tabular visualisation techniques were used to clarify these comparisons and support interpretation. Where appropriate, findings from quantitative analysis were triangulated with qualitative insights from interviews and occupant diaries, thereby strengthening the validity of results and providing a better understanding of IAQ determinants in residential settings. All analyses were conducted using SPSS and Microsoft Excel, ensuring reproducibility and methodological transparency.

The Kruskal-Wallis test is a non-parametric statistical method used to compare the medians of three or more independent groups. It is particularly useful when the assumptions required for Parametric tests, such as ANOVA (e.g., normality, homogeneity of variance), are not met. This research used the Kruskal-Wallis test to determine whether there were significant differences in distributions of IAQ parameters (e.g., PM_{2.5} and TVOC levels) across different occupant activities. The test works by ranking all values, calculating the sum of ranks for each group, and comparing the variability between and within groups. Based on ranked data, the test statistic follows a chi-squared distribution (Hauke & Kossowski, 2011).

Spearman's rank correlation coefficient (ρ) is a non-parametric measure used to assess the strength and direction of monotonic relationships between two variables. Unlike Pearson's correlation, which requires interval data and normality, Spearman's correlation is suitable for ordinal data and non-normally distributed variables. In this study, Spearman's rank correlation coefficient was used to assess associations among key IAQ parameters (such as PM_{2.5}, CO₂, TVOC, temperature, and relative humidity) and to explore relationships among pollutant levels. The coefficient ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation), with values near zero indicating weak or no relationship.

4.6.2.2 Qualitative Analysis.

All interviews were diligently recorded and transcribed verbatim, allowing for deep familiarisation with the data and ensuring accuracy (Merriam and Tisdell, 2016). NVivo 12 was utilised as a data management and analysis tool throughout the qualitative analysis.

The qualitative analysis followed two main approaches. The first, content analysis (Elo and Kyngas, 2008), involved systematically coding the transcripts to identify and categorise key concepts, behaviours, and themes, and to quantify their frequency. This enabled the concise summarisation of participants' perspectives on factors influencing IAQ. The second approach was sociotechnical analysis, in which qualitative findings were used to identify alignments or discrepancies between participants' reports and measurements, and to explore how qualitative insights could explain quantitative results. Care was taken throughout the analysis to guard against confirmation bias and false positives.

The coding process, applied to 15 interview transcripts, produced 6 primary themes: land purchase and strategic planning, design and scheme orientation, construction, handover and occupation, and market dynamics and business environment. These thematic categories were informed by the conventional UK home development process and external factors such as regulatory requirements and market trends (see section).

Semi-structured interviews were conducted with various stakeholders, primarily housing developers and other building professionals, to understand the decision-making process throughout the home delivery process. Key topics included responses to government policies and regulations, land acquisition methods, design and construction practices, environmental considerations (e.g. climate adaptation), operational use of the building, planning challenges, and mitigation strategies. Most interviews were conducted online via Microsoft Teams, with one conducted in person, each lasting approximately an hour (see Table 1 for participant details).

Additionally, semi-structured interviews and walk-throughs were conducted with residents of the case study homes, and extended physical monitoring was carried out. These interviews examined how occupants interact with their homes, focusing on factors such as IAQ, ventilation habits, and operational knowledge. Interview topics included occupant activities (e.g., cooking, cleaning, product use), window and door opening, and general perceptions of IAQ. Occupant diaries were also utilised to provide detailed records of daily activities and ventilation behaviours.

The analytical approach combined quantitative and qualitative data to enable a systematic interpretation of IAQ behaviour across the case studies. Quantitative monitoring data (PM_{2.5}, TVOC, and CO₂) were analysed using time-series visualisation and descriptive statistical analysis to identify patterns, peak events, and variations between occupied and unoccupied conditions. A comparative analysis of the case studies was conducted to evaluate differences related to building characteristics, ventilation strategies, and occupancy levels.

These quantitative patterns were analysed using multiple complementary qualitative data sources. Occupant diary entries were utilised to temporally align recorded household activities (e.g., cooking, cleaning, and window opening) with pollutant peaks and decay profiles, facilitating the attribution of emission sources and behavioural triggers. Semi-structured interviews with occupants were examined thematically to capture perceptions, behavioural routines, and levels of understanding of ventilation systems and IAQ. Simultaneously, interviews with developers and building professionals offered insights into design decisions, system specifications, ventilation strategies, and handover practices within the home development process.

For the occupant-focused part of the analysis, interview transcripts were examined in relation to their specific case studies rather than combined into a single undifferentiated dataset. This allowed household-specific information on cooking routines, ventilation behaviour, occupancy patterns, and system understanding to be compared with the monitored IAQ data for the same dwelling. In this way, the qualitative analysis complemented the household and occupancy details presented in Table 4.1 and helped interpret the differences observed across case studies.

The integration of these data sources enabled a triangulated analytical approach, in which quantitative trends provided measurable evidence of IAQ variation; occupant diaries explained short-term behavioural influences; occupant interviews offered experiential and behavioural context; and professional interviews revealed upstream decision-making processes that influenced IAQ outcomes. This combined analysis supported the identification of key pathways influencing IAQ and informed the development of the Pathways Approach Framework presented in Chapter 6.

4.7 Home Development Process Analysis.

This section presents the thematic analysis of interviews with home developers and industry professionals, conducted using NVivo 12 Pro. Thematic analysis was employed to

systematically code and categorise the qualitative data, thereby identifying key factors and processes influencing IAQ in new housing developments.

Figure 4.9 illustrates the NVivo workspace used for this analysis, highlighting the main themes and sub-themes developed through the coding process.

Name	Files	References	Created By	Created On	Modified By	Modified On
Land Purchase and Strategic Planning	4	16	M	20/12/2023	M	24/12/2023 10:
Environmental Considerations	4	7	M	20/12/2023	M	24/12/2023 10:
Air pollutaion and Noise assessment	0	0	M	20/12/2023	M	24/12/2023 07:
Design and Scheme Planning	12	62	M	20/12/2023	M	24/12/2023 11:
Change in material specifications	5	6	M	20/12/2023	M	24/12/2023 11:
Ventilation decisions	7	13	M	20/12/2023	M	24/12/2023 11:
Decisions Impacting IAQ	11	26	M	20/12/2023	M	24/12/2023 11:
Scheme orientations	4	4	M	20/12/2023	M	24/12/2023 10:
Collaberative design and assessment	3	8	M	20/12/2023	M	24/12/2023 10:
Design tools	1	1	M	20/12/2023	M	24/12/2023 09:
Construction	6	20	M	20/12/2023	M	24/12/2023 07:
Gaps in skilled workers	4	5	M	20/12/2023	M	24/12/2023 10:
Quality Assessment	5	15	M	20/12/2023	M	24/12/2023 11:
Handover and Occupation	6	22	M	20/12/2023	M	24/12/2023 07:
Occupant engagement	5	10	M	20/12/2023	M	24/12/2023 11:
Occupant control of systems	4	7	M	20/12/2023	M	24/12/2023 11:
Post-Occupancy Evaluation	4	5	M	20/12/2023	M	24/12/2023 10:
Government Polciy and Regulations	6	19	M	20/12/2023	M	24/12/2023 09:
Part L and F	5	5	M	20/12/2023	M	24/12/2023 11:
Local Planning Authorities	5	13	M	20/12/2023	M	24/12/2023 11:
Market Dynamics and Business Environment	4	10	M	20/12/2023	M	24/12/2023 07:

Figure 4. 9: NVivo nodes illustrating interview themes and code structure.

The primary thematic categories (*Land Purchase and Strategic Planning, Design and Scheme Planning, Construction, Handover and Occupation, Government Policy and Regulations, and Market Dynamics and Business Environment*) represent the main stages of the home development process. Each primary node contains sub-nodes that represent more specific topics, such as *Ventilation Decisions, Decisions Impacting IAQ, and Quality Assessment*. Columns in the NVivo interface

show the number of interview files and coded references per node, along with creation and modification dates, highlighting the systematic and iterative nature of the coding process.

This NVivo setup facilitated a thorough and organised analysis, ensuring that diverse perspectives and experiences were captured. The semi-structured interviews were mainly conducted online (via Microsoft Teams), with participants including four housing developers and eleven building professionals (architects, consultants, subcontractors, and manufacturers). Table 4.5 summarises the participant roles while safeguarding confidentiality. Interview topics covered the entire spectrum of the housing delivery process, government policy and regulations, land acquisition, design and construction practices, environmental adaptation, planning challenges, and post-occupancy issues.

Thematic analysis, supported by NVivo 12, was used to identify decision-making patterns and key challenges in delivering healthy IAQ in UK homes. The analysis began by classifying the data according to the research objectives to identify cost-effective, scalable opportunities to improve IAQ within mainstream housing delivery.

4.7.1 Thematic and Conceptual visualisation.

Thematic analysis is a qualitative research method used to identify, analyse, and report patterns (themes) within qualitative data (Braun & Clarke, 2006). It offers a systematic yet flexible approach to coding and interpreting complex interview material, making it particularly suitable for research exploring decision-making processes and organisational dynamics (Nowell et al., 2017). In this study, thematic analysis was conducted using NVivo 12 software to organise, categorise, and visualise themes emerging from interviews with housing developers and building professionals.

The analysis in this section is based on semi-structured interviews with four housing developers and eleven building professionals, including architects, consultants, subcontractors, and manufacturers in senior roles within the sector. Participants were selected from various departments and had diverse levels of experience, ensuring that the collected data represented a broad range of perspectives on the home development process. Apart from one meeting, all interviews were conducted online via Microsoft Teams and typically lasted around an hour. Table 4.5 summarises the interviewees, preserves confidentiality, and indicates the range of expertise involved.

This diversity of participant backgrounds enhances the reliability and richness of the qualitative data, ensuring that the resulting themes provide a clearer understanding of decision-making and IAQ considerations in new UK housing developments. Figure 4.9 illustrates the NVivo 12 Pro workspace, showing the hierarchical structure of the main thematic categories and sub-nodes used to code and interpret the interview transcripts.

4.8 Triangulation.

The concept of triangulation, as defined by Amaratunga et al. (2002), refers to combining different data analyses within a single study to enhance the validity of findings. However, the purpose of triangulation in this research extends beyond simply validating results or testing hypotheses. Rather than pursuing a single definitive answer, this research employs triangulation to integrate diverse perspectives, incorporating insights from building professionals and occupants, as well as quantitative environmental monitoring. This approach is intended to bridge siloed debates in IAQ research and generate a more holistic and reflective understanding of the problem.

Mixed-method research design can be classified into four categories: sequential explanatory, sequential exploratory, concurrent triangulation, and concurrent nested (Creswell, 2014). This research adopts a sequential exploratory design, in which qualitative data are first collected and analysed, followed by the collection and analysis of quantitative data (Aberdeen, 2013). Using multiple data collection methods enables a better understanding of the phenomenon than using a single method.

As shown in Figure 4.10, this research's triangulation approach combines both quantitative and qualitative data streams. Quantitative data are categorised into monitoring and instrumentation. Monitoring involves longitudinal measurements across all seasons, using data from unoccupied homes as a baseline for comparison with occupied homes. Instrumentation includes the use of real-time cloud-based sensors, with SPSS and Excel used for analysing quantitative data. Qualitative data consists of interviews with building professionals and occupants, analysed using NVivo software.

Both data types are integrated during the analysis and interpretation stages to address different research questions and objectives. The combination of methods enhances data triangulation and provides a deeper insight into IAQ phenomena, overcoming the limitations of any single method (Amaratunga et al., 2002). This approach ensures that weaknesses in one method are

compensated by strengths in another, as supported by triangulation theory. As Nau (1995) and Fossey et al. (2002) emphasise, qualitative data can help clarify the meaning behind quantitative findings, and the integration of both methods enriches the study's conclusions. Rather than seeking resolution or finality, triangulation here provides an opportunity to reveal variances, identify knowledge gaps, and contextualise findings across stakeholder groups.

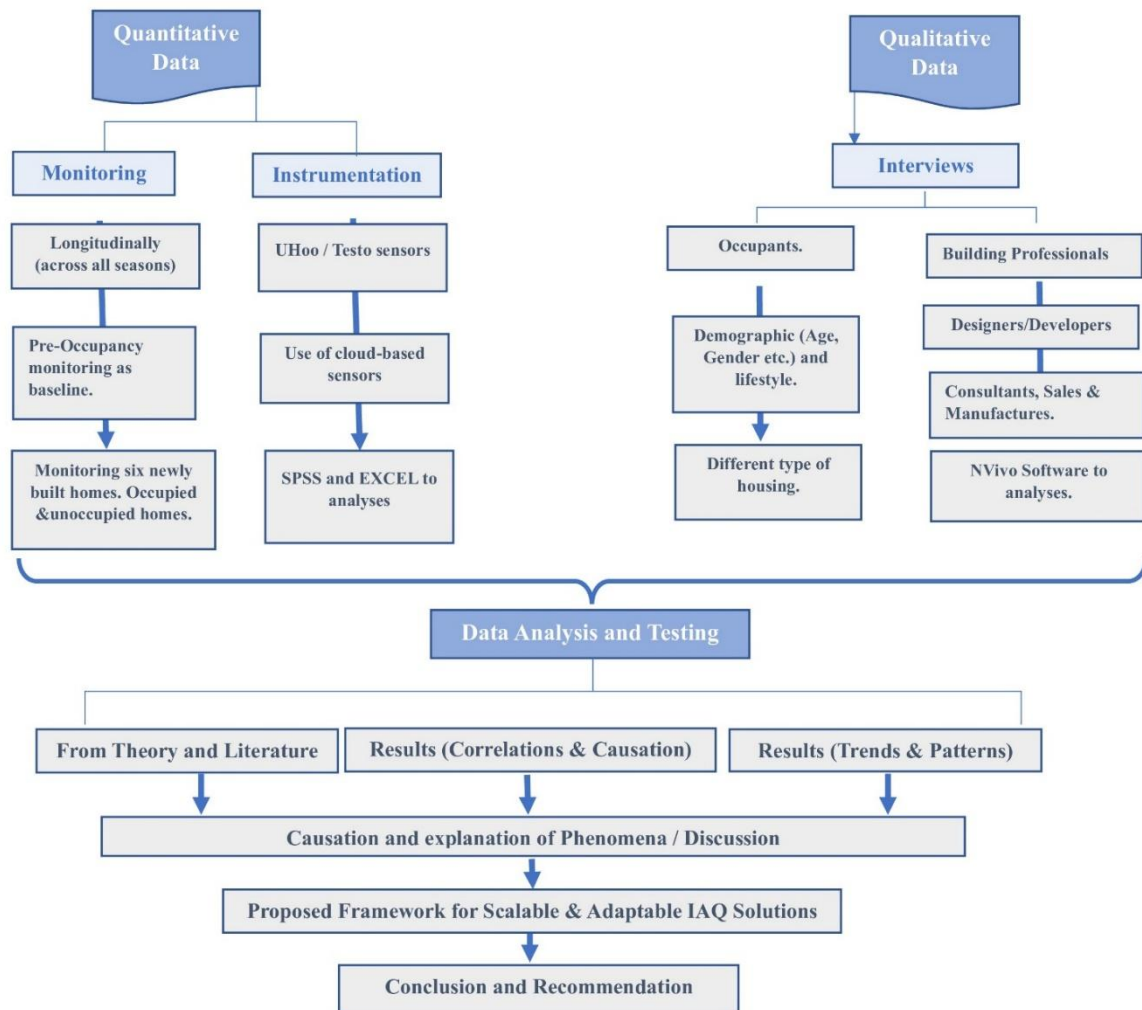


Figure 4 10: Triangulation of quantitative and qualitative data (adapted from Amaratunga et al., 2002).

4.9 Reliability and Validity.

Ensuring the reliability and validity of research findings is essential to producing credible results, especially in research spanning multiple domains, data types, and methodological approaches. Given the multi-pathways approach used in this thesis, which includes building design, technology, occupant behaviour, and the broader development process, particular care has been taken to ensure the methodological rigour supporting all phases of the study. This

section discusses strategies to maximise reliability and validity within a complex, practice-based inquiry.

4.9.1 Reliability.

To minimise the risk of drawing incorrect conclusions and to ensure the credibility of the research, it is vital to avoid bias at every stage of the research process. Reliability assesses how consistent the study results will remain if the same study were repeated under similar conditions by different researchers, and the probability that these results are reproducible (Gibbs, 2018).

Throughout this thesis, reliability was strengthened by using consistent procedures for both quantitative and qualitative data collection and analysis. For sensor-based IAQ monitoring, consistency was maintained by using the same equipment (uHoo sensors), conducting co-location testing, synchronising data downloads, and following the manufacturer's guidelines. Reliability was supported in the qualitative part through piloting interview guides, verbatim transcription, and systematic coding in NVivo. Recognising that a broad, real-world study may introduce variability in the data, the focus was on methodological transparency and repeatability to ensure that the findings are dependable and can be reproduced in similar settings.

4.9.2 Validity.

Before the data analysis, the research methods were examined for reliability and validity. As Saunders et al. (2016a, p. 202) stated, "*Validity is the extent to which data collection method or methods accurately measure what they were intended to measure.*" This research addressed validity by carefully aligning the research questions, data collection instruments, and analysis techniques with the study's practical objectives. For quantitative data, instrument calibration, co-location testing, and the use of accredited sensors (RESET™ and MCERTS) helped ensure measurement accuracy. For qualitative data, validity was enhanced by piloting and refining interview protocols, ensuring interview questions were directly relevant to the study aims, and employing triangulation by comparing findings across multiple data sources and perspectives. This multi-method approach not only increases the credibility of the research outcomes but also ensures that the findings accurately reflect the phenomena under investigation.

4.9.3 Ethical Concentration.

Given the nature of this research, ethical considerations are paramount. Ethical approval was obtained from Birmingham City University prior to conducting the research (**Appendix A**). The research fully complied with the requirements of the General Data Protection Regulation (GDPR), ensuring all data was collected, stored, and managed in accordance with current legal and ethical standards.

All participants were treated with respect and courtesy throughout the research. Before taking part, each participant received a clear, plain-language information sheet explaining the study's aims, objectives, what would be required of them, how their data would be managed, and their rights as participants. Participants were informed that their involvement was entirely voluntary, that they could withdraw from the study at any time without consequences, and that channels were available to raise any concerns or complaints.

The research employed an 'informed consent' strategy (Swift, 2022), ensuring that all participants were clearly informed about what would be asked of them, how their data would be handled, and any potential consequences of their participation. "Informed" indicates that participants understood what participation involved, including data handling and any associated risks. "Consent" refers to the process by which participants were informed of their rights and, where applicable, signed a consent form. Full consent was secured before any monitoring, interviews, or surveys were undertaken in participants' homes.

All data were handled with strict confidentiality and stored securely on password-protected devices accessible only to the research team. To further safeguard privacy, no personally identifying information was included in any reports or publications, ensuring participants' anonymity at all stages. Risk assessments were conducted prior to site visits to ensure the safety of both participants and the researcher. Participants were assured that the research would not intrude into personal activities beyond what was necessary for IAQ research, and that the main goal was to enhance understanding, not to observe individual behaviour.

Upon completion of the study, participants were offered a plain-English summary of the findings as a token of appreciation and to support their understanding of good IAQ practices in

their homes. All Ethical safeguards were upheld throughout, in line with the university's guidelines and the commitments made to each participant.

4.10 Chapter Conclusion.

This chapter provides a detailed and justifiable explanation of the methodological approach adopted to address the research questions outlined in Chapter 1. A multiple-case study design grounded in mixed methods was selected to investigate the complex, interacting factors influencing IAQ in new UK homes. This approach intentionally integrates technical and social perspectives, combining environmental monitoring, qualitative interviews, daily activity diaries, and surveys to gather not only physical IAQ measurements but also occupants' lived experiences and behaviours.

The rationale for this comprehensive strategy stems from the recognition that IAQ outcomes are shaped by a combination of building characteristics, occupant activities, and broader development processes. This research can explore patterns, draw comparisons across different homes, and generate practically relevant insights for the industry and policymakers by triangulating quantitative and qualitative data.

The chapter also clarifies the data analysis procedures and the steps taken to ensure reliability, validity, and ethical integrity throughout the research process. By documenting the research design, data collection, and analysis strategies, this chapter provides a clear foundation for the results and discussion presented in the following chapters. The following sections will draw on this methodological framework to present and interpret the study's key findings, address each research question, and outline its implications for IAQ management in residential settings.

The integration of quantitative monitoring data with qualitative insights from interviews, questionnaires, and occupant diaries offers a comprehensive empirical dataset. These data are analysed in Chapter 5 using the pathway-based framework developed in Chapter 3, enabling the identification of how interactions between building design, systems, occupant behaviour, and the home development process influence IAQ outcomes.

Chapter 5. Results and Discussion.

Introduction

This chapter presents and evaluates the key findings from the data analysis. As outlined in previous chapters, the data were derived from monitored IAQ measurements in both unoccupied and occupied homes, supported occupant diaries, and semi-structured interviews. The findings are further contextualised through triangulation with insights from the literature review.

The literature review identified three key gaps in understanding IAQ in new energy-efficient homes:

1. The influence of occupant behaviour as a critical yet frequently overlooked factor.
2. The importance of the decision-making process during home delivery beyond technological and regulatory considerations.
3. The interplay between design, construction, and occupancy influences the adequacy of IAQ in such homes.

The analysis presented in this chapter adopts an integrated approach, combining quantitative pattern recognition with qualitative interpretation of occupant behaviour and system interactions. To address these gaps, four research areas, or “pathways”, are established. These pathways are derived from the conceptual framework outlined in Chapter 3 and are used here to structure the analysis and interpretation of the empirical findings. These pathways reflect the complexity and multidisciplinary nature of IAQ and provide a practical and scalable basis for improving air quality in mass-market housing.

The findings are structured according to these pathways, which are further developed in Chapter 6:

- Building as a System (Pathway 1: Building Design and Materials): Establishes baseline IAQ conditions in unoccupied homes and evaluates the influence of materials and spatial configuration.

- Occupation (Pathway 2: Occupant Behaviour): Examines the impact of daily activities, lifestyle, and occupant perception on IAQ, supported by interviews, questionnaires, and diaries.
- Technology and Systems (Pathway 3: Ventilation and Technology): Evaluates ventilation strategies, including mechanical systems and window operation, their effectiveness in managing IAQ.
- Home Development Process (Pathway 4: Development Practices): Explores how planning, design, construction, and handover stages influence IAQ outcomes.

The research involved monitoring six newly built homes over an extended period, alongside controlled experiments and data collection from occupants and industry professionals. This multi-method approach enables a holistic understanding of IAQ across the identified pathways and supports the development of the framework presented in Chapter 6.

As outlined in Table 4.1, differences in IAQ performance across the six case studies were influenced by variations in occupancy patterns and household characteristics. Homes with higher occupancy levels and more frequent household activities showed greater variability and elevated pollutant peaks, particularly related to cooking and ventilation practices. Differences in ventilation systems, occupant understanding, and behavioural adaptation further influenced pollutant concentration and decay rates. These findings reinforce the interpretation of IAQ as an outcome of interconnected pathways, where building design, technologies, and occupant behaviour collectively shape indoor environmental conditions. These interpretations are further supported by staged occupant interviews and diary records from each case, which provide case-specific explanations for how household routines, ventilation practices, and occupancy patterns contributed to the monitored IAQ behaviour.

Within each section, findings are presented through an integrated analytical structure. Quantitative results from IAQ monitoring are interpreted directly, supported by qualitative evidence from occupant diaries and interviews with occupants and building professionals. These interpretations are then positioned within the existing body of knowledge through targeted comparison with relevant literature, thereby strengthening the analytical depth of the discussion.

This approach ensures that results, interpretation, and discussion are not treated as separate elements but are combined within each thematic pathway to provide a coherent, evidence-based analysis.

5.1 Building design and materials.

Introduction.

This section covers the aspects of the first pathway of the Pathway Approach and the results. While buildings may have freedom in design, the selection of building materials, along with their shape, size, and orientation, must be carefully planned, as these factors significantly impact IAQ (Langer et al., 2015). This includes assessing pollutant concentrations without occupants present, evaluating the performance of building design and interior layout in relation to IAQ, and understanding the effects of building materials. Evaluating IAQ in unoccupied buildings provides a baseline for isolating the impact of building design and materials on air quality in the absence of occupants. The analysis and evaluation of these measures focus on three key aspects: Baseline pollutant level evaluation, the impact of building design, and the effectiveness of materials.

5.1.1 Baseline pollutant levels.

The primary goal of this analysis is to establish baseline IAQ data by evaluating the houses when unoccupied and comparing these results with those during occupied periods.

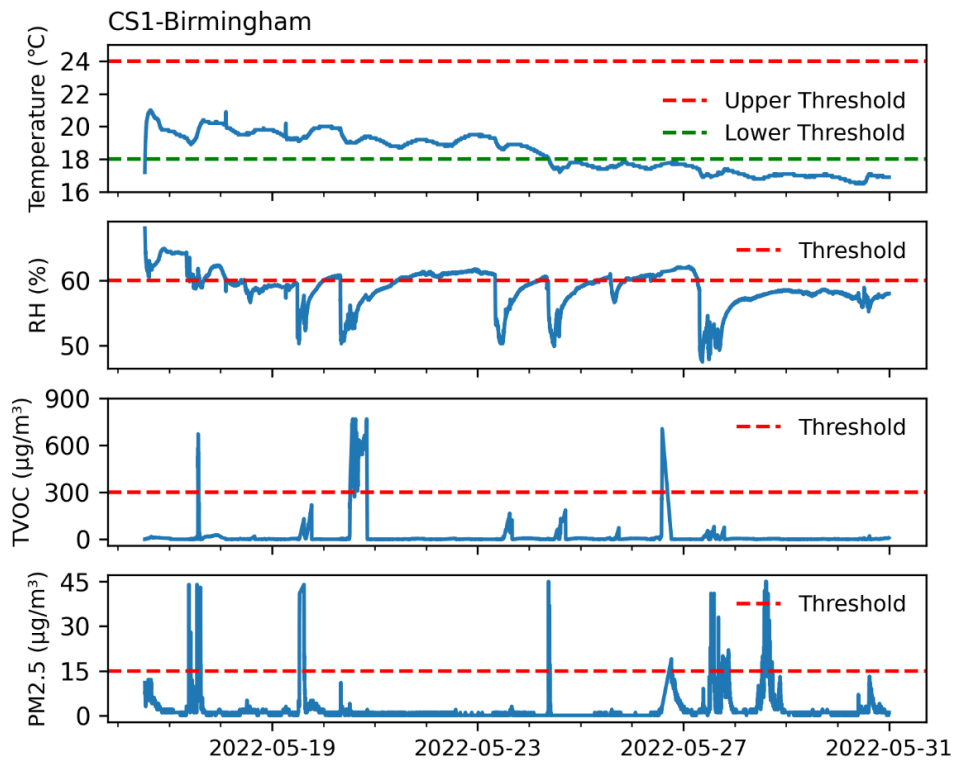


Figure 5. 1: IAQ parameters (temperature, RH, TVOC, and PM2.5) in unoccupied home CS1 over a two-week analysis period.

Figure 5.1 presents the baseline IAQ analysis for an unoccupied home (CS1-Birmingham), showing temperature alongside TVOC, PM2.5, and relative humidity (RH) levels from May 12th to 30th, 2022, before occupation. TVOC levels exhibit significant spikes, reaching up to $2000 \mu\text{g}/\text{m}^3$, and PM2.5 levels also peak at up to $400 \mu\text{g}/\text{m}^3$, followed by a rapid decline. These peaks correspond to occasional builder activities. Overall, TVOC and PM2.5 remain below the recommended threshold values. RH remains relatively stable between 40% and 60%, while temperature fluctuates slightly, remaining within an acceptable range of 16°C to 24°C .

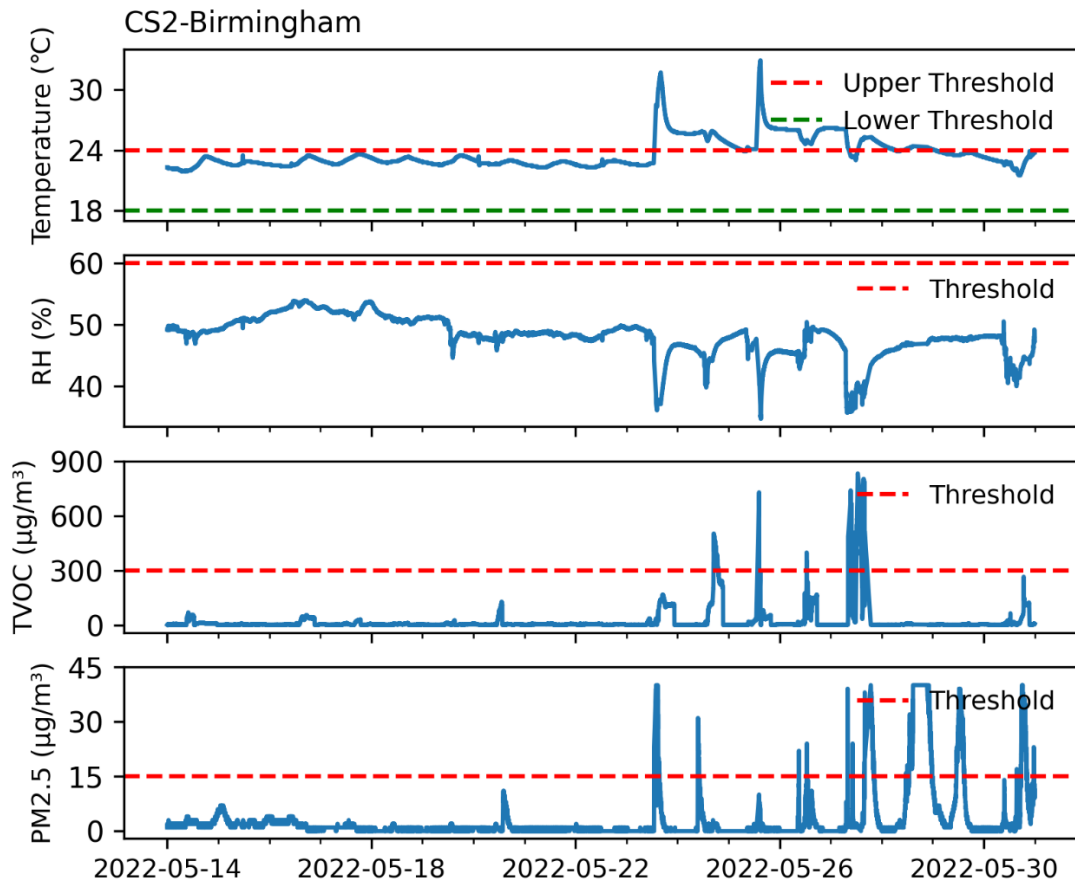


Figure 5. 2: IAQ parameters (temperature, RH, TVOC, and PM2.5) in an unoccupied home CS2 over a two-week monitoring period.

Figure 5.2 presents the baseline IAQ analysis for an unoccupied home (CS2-Birmingham), displaying temperature alongside TVOC, PM2.5, and relative humidity (RH) levels over a two-week period from May 14 to May 30, 2022, before occupation. TVOC levels spike to 2000 $\mu\text{g}/\text{m}^3$, and PM2.5 levels also peak at 400 $\mu\text{g}/\text{m}^3$, then decline rapidly. These peaks correspond to occasional builder activities. Overall, TVOC and PM2.5 remain below the recommended threshold values. RH remains relatively stable between 40% and 60%, while temperature fluctuates slightly, remaining within the 16°C to 24°C range.

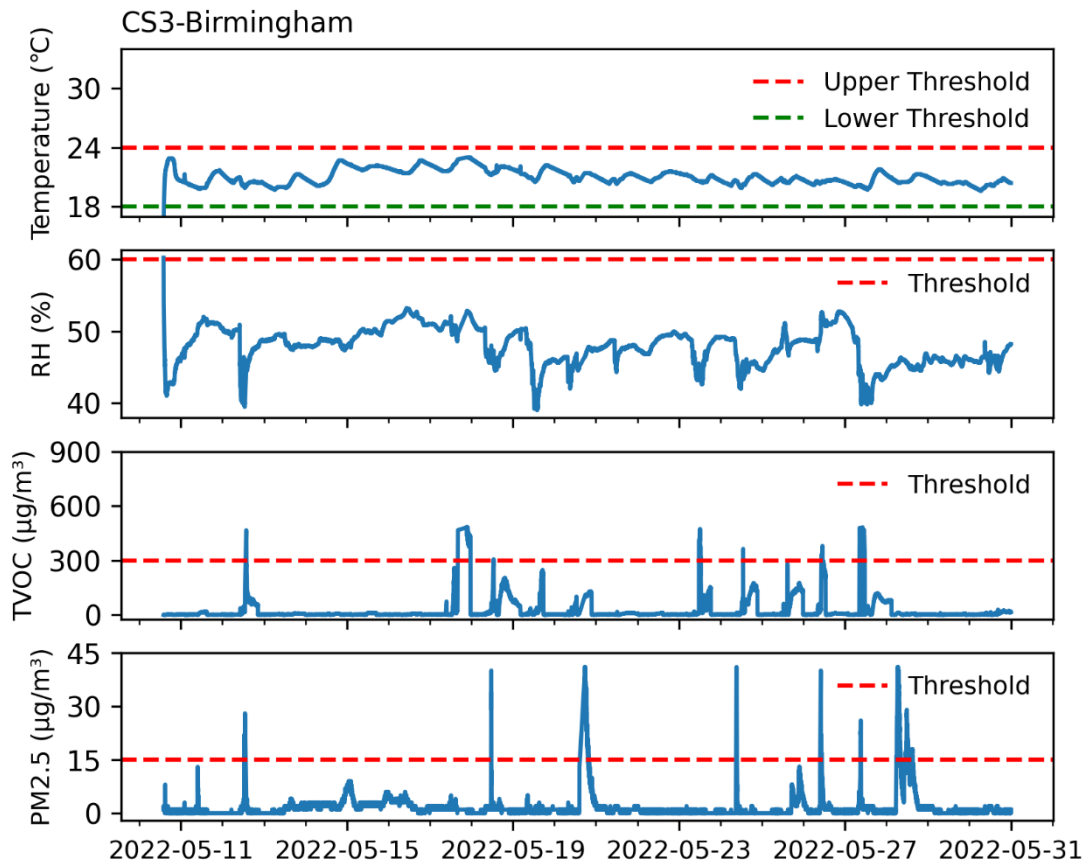


Figure 5 3: IAQ parameters (temperature, RH, TVOC, and PM2.5) in an unoccupied home CS3 during a two-week analysis period.

Figure 5.3 presents a two-week analysis of IAQ metrics for an unoccupied home (CS3-Birmingham) from May 11 to May 30, 2022, prior to occupation. The graph shows the temperature alongside TVOC, PM2.5, and RH levels. TVOC levels exhibit significant spikes, reaching up to $600 \mu\text{g}/\text{m}^3$, and PM2.5 levels peak at up to $45 \mu\text{g}/\text{m}^3$, both of which then decay rapidly, corresponding to builder activities. Overall, as in previous cases, TVOC and PM2.5 remain below the recommended threshold values for most of the period. RH levels fluctuate between 40% and 60%, while temperatures range from 18°C to 24°C , maintaining stable indoor conditions.

The graphs show relatively stable temperature readings throughout the monitoring period, with minor fluctuations. TVOC levels are consistently low, remaining below the exposure threshold, with occasional spikes associated with specific events, such as construction work. PM2.5 levels are also low, staying below the exposure threshold for most of the monitoring period, with occasional spikes likely due to external factors or construction activities. The results indicate that TVOC and PM2.5 levels were below the exposure threshold, with levels almost zero for most of the monitoring period. This suggests that building materials have a negligible influence

on IAQ under these conditions. The occasional spikes in TVOC and PM_{2.5} levels correspond to construction work, highlighting the impact of specific external activities. Overall, the IAQ remains within acceptable limits when no occupants are present.

The analysis of unoccupied houses provides a clear baseline for comparison with periods when the houses are occupied. The findings will be further discussed in Section 5.1.3, once these homes are occupied, allowing a comparative analysis of the impact of occupancy on IAQ.

The graphs show relatively stable temperature readings throughout the monitoring period, with minor fluctuations. TVOC levels are consistently low, remaining below the exposure threshold, with occasional spikes associated with specific events, such as construction work. Similarly, PM_{2.5} levels are predominantly low, remaining below the exposure threshold for most of the monitoring period, with occasional spikes likely due to external factors or construction activities. These results indicate that TVOC and PM_{2.5} levels were below the exposure threshold, with nearly zero concentrations for most of the monitoring period. This suggests that building materials have a negligible influence on IAQ under these conditions. The occasional spikes in TVOC and PM_{2.5} levels correspond to construction work, highlighting the impact of specific external activities. Overall, the IAQ remains within acceptable limits when the building is unoccupied.

These findings reveal that TVOC and PM_{2.5} concentrations remained consistently low in unoccupied homes, with only short-term spikes associated with construction activities. This suggests that, in the absence of occupant-related sources, building materials have a negligible impact on IAQ under normal conditions. This interpretation aligns with Defra (2022) and Al Horr et al. (2016), who report that unoccupied buildings tend to maintain stable IAQ due to the absence of occupant-driven emissions. These findings further demonstrate that short-term construction-related activities can introduce temporary peaks in pollutant concentrations, highlighting that IAQ is influenced by dynamic interactions rather than static building conditions alone.

Although some studies, such as Wang et al. (2024) and Wei et al. (2015), report that low-emission materials help sustain good IAQ, this study's findings indicate that their overall effect is secondary to variations during occupancy. These findings highlight the importance of viewing IAQ as a system influenced by multiple interacting factors rather than solely material choice.

The analysis of unoccupied houses provides a clear baseline for comparison with periods when the houses are occupied. The findings will be further discussed in Section 4.5.1, once these homes are occupied, allowing a comparative analysis of the impact of occupancy on IAQ.

5.1.2 Building design and indoor air pollutant movement experiment.

This experiment was conducted in occupied homes to analyse the movement and distribution of air pollutants between the kitchen and living room. The primary objectives were to evaluate pollutant generation patterns, particularly in high-emission areas such as the kitchen, and to identify effective mitigation strategies to improve IAQ. The experiment also aimed to assess how designing interior layouts influences pollutant dispersion and helps mitigate pollutant movement within the home.

An extra sensor was installed in the living room of each studied home to provide comparative data on pollutant concentrations in spaces adjacent to the kitchen. The experiment monitored TVOC, PM_{2.5}, and CO₂ levels over time. Since the kitchen is a primary source of indoor pollutants from cooking, higher pollutant concentrations were anticipated than in the living room.

The graphs for CS1, CS2, and CS3-Birmingham provide valuable insights into:

- The generation and peak concentrations of pollutants in the kitchen.
- The movement and dispersion of pollutants from the kitchen to other rooms, particularly the living room.
- The role of interior design and layout in facilitating or mitigating pollutant movement.
- The effectiveness of natural and mechanical ventilation in reducing pollutant levels.

By combining pollutant monitoring with interior design analysis, this study aims to inform strategies to optimise residential layouts and ventilation systems, thereby improving IAQ and reducing pollutant exposure in occupied homes.

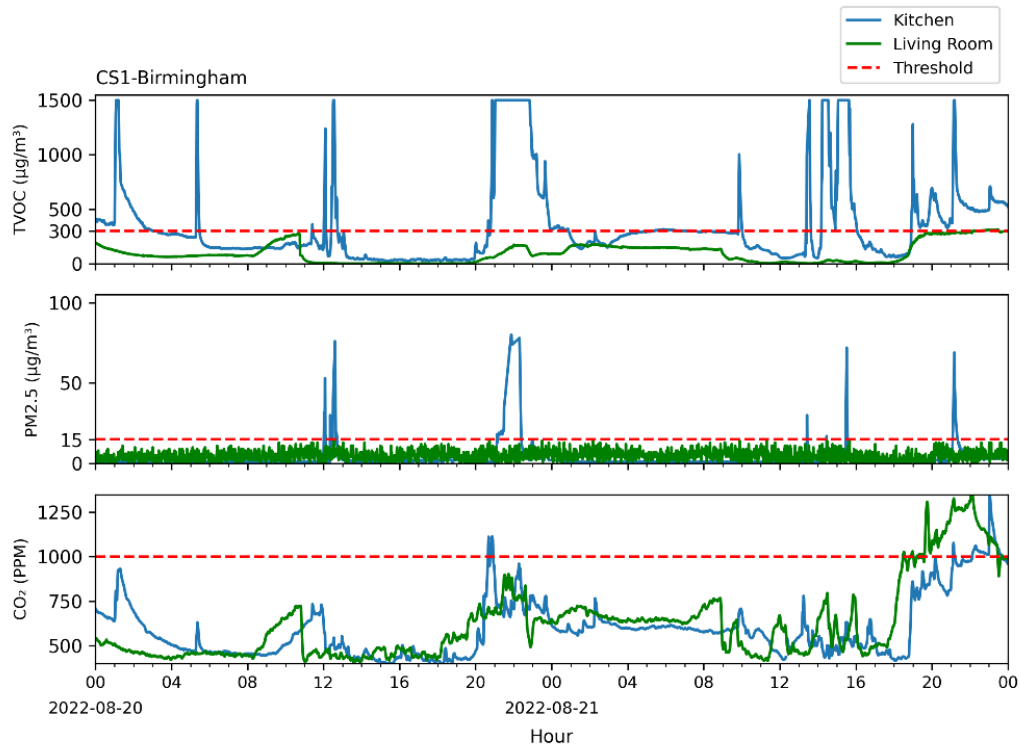


Figure 5.4 Comparison of air pollutant movement between the kitchen and the living room in CS1.

Figure 5.4 shows the movement and distribution of indoor air pollutants, including TVOC, PM_{2.5}, and CO₂, between the kitchen and living room in CS1-Birmingham during a 24-hour monitoring period (20th–21st August 2022). The analysis highlights the impact of the enclosed kitchen design on pollutant containment and movement. High spikes in TVOC levels were recorded in the kitchen, frequently exceeding the 300 µg/m³ threshold during cooking or periods of high activity, confirming the kitchen as the primary source of pollutant generation. In contrast, TVOC concentrations in the living room remained low, with no significant exceedances, indicating that the enclosed kitchen effectively restricted the migration of pollutants. Similarly, PM_{2.5} levels occasionally spiked in the kitchen, exceeding the 35 µg/m³ threshold during cooking. In contrast, levels in the living room stayed below the threshold, further demonstrating effective containment of particulates within the kitchen. CO₂ levels in both rooms remained below the 1000 ppm threshold for most of the day, demonstrating adequate ventilation; however, a gradual increase was observed in the evening, particularly in the living room, likely due to occupant presence and reduced ventilation efficiency.

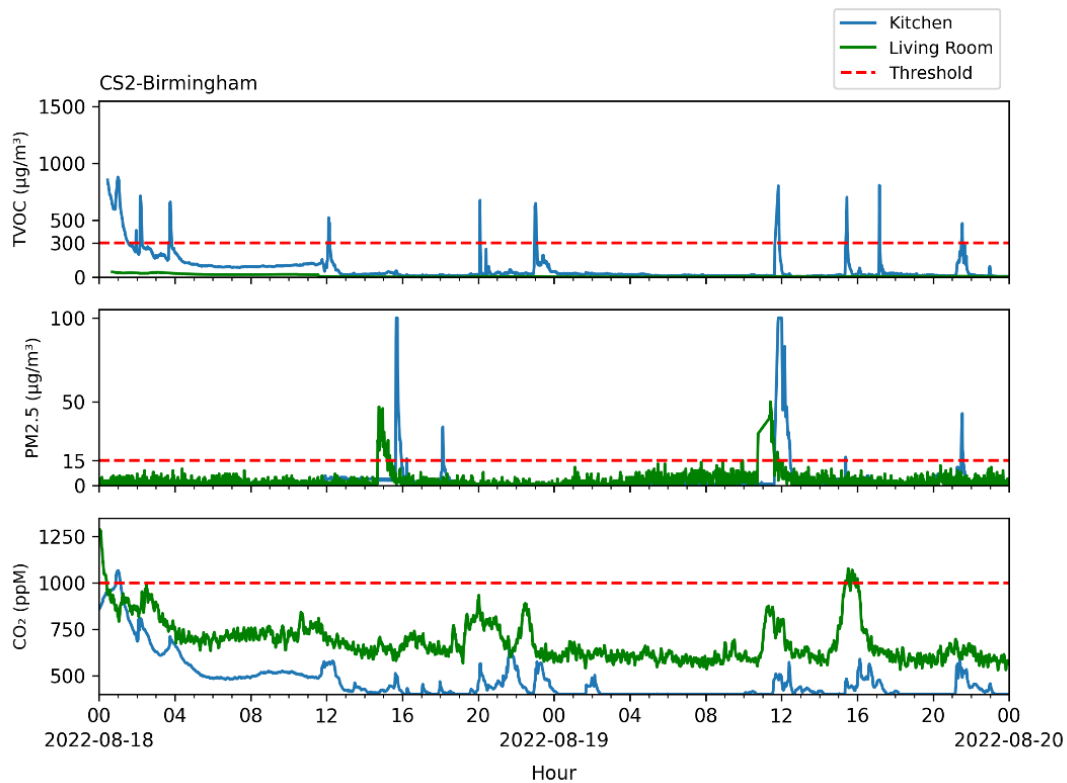


Figure 5. 5: Air-pollutant movement in CS2-Birmingham: Kitchen vs Living Room.

Figure 5.5 shows the air pollutant movement analysis for CS2-Birmingham over 48 hours (18th–20th August 2022), focusing on TVOC, PM2.5, and CO₂ levels in the kitchen and living room. The kitchen consistently exhibited higher TVOC and PM2.5 levels during high-activity periods, with TVOC frequently exceeding the 300 µg/m³ threshold and PM2.5 occasionally exceeding the 35 µg/m³ threshold, particularly during cooking. These findings confirm that the kitchen is the primary source of volatile organic compound emissions and airborne particulates. In contrast, pollutant levels in the living room remained significantly lower, with minimal spikes, suggesting effective containment of pollutants within the kitchen, likely due to the enclosed design and ventilation strategies. CO₂ levels in both rooms remained below the 1000 ppm threshold for most of the day. Still, they showed a gradual increase, peaking in the evening, especially in the living room, likely attributed to occupant presence and reduced ventilation efficiency during these hours. This analysis underscores the vital role of kitchen design and ventilation in preventing pollutant migration and ensuring acceptable indoor air quality in residential spaces.

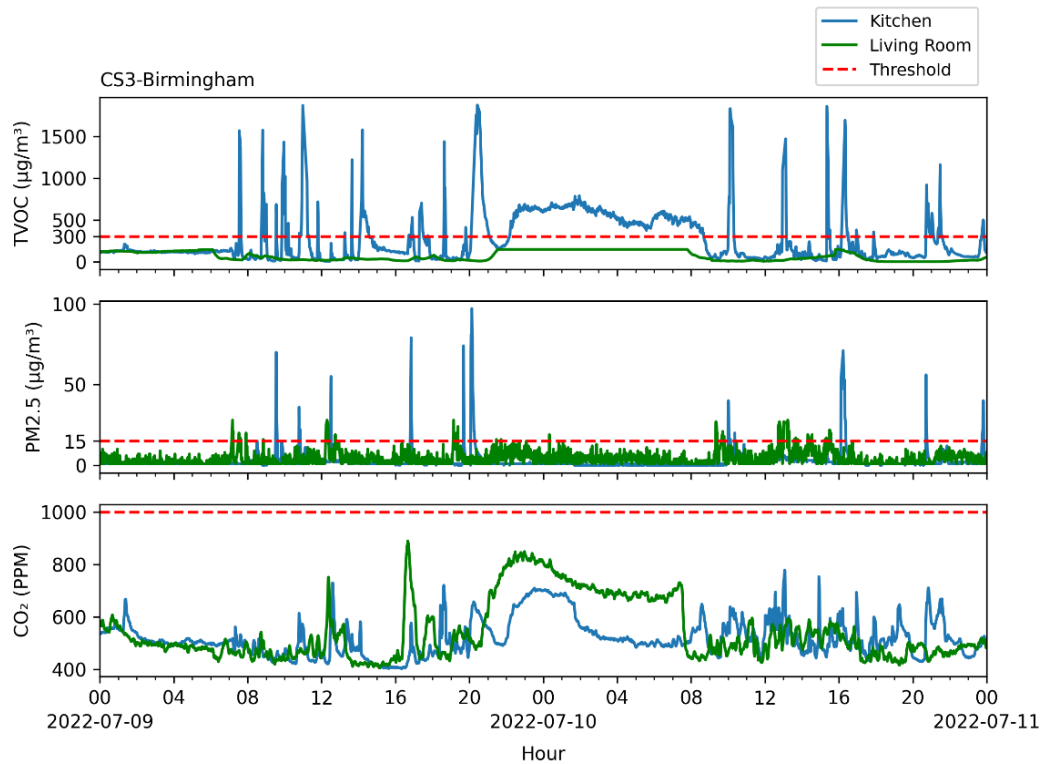


Figure 5.6 Comparison of air pollutant movement between the kitchen and the living room in CS3.

Figure 5.6 presents the air pollutant movement analysis for CS3-Birmingham over a 48-hour period (9th–11th July 2022), highlighting TVOC, PM_{2.5}, and CO₂ levels in the kitchen and living room. The kitchen consistently recorded higher pollutant levels, with frequent, significant TVOC spikes exceeding the 300 µg/m³ threshold during cooking and other high-activity periods, confirming it as the primary source of emissions. During similar activities, PM_{2.5} levels in the kitchen occasionally exceeded the 15 µg/m³ threshold, though these spikes were short-lived and confined to the kitchen. In contrast, the living room exhibited significantly lower pollutant levels, with TVOC and PM_{2.5} rarely exceeding their respective thresholds, indicating effective containment of pollutants within the kitchen, likely due to the enclosed design and ventilation strategies. CO₂ levels in both rooms remained below the 1000 ppm threshold for most of the period but gradually increased throughout the day, particularly in the living room during extended occupancy, highlighting the influence of occupant presence and reduced ventilation. This analysis highlights the importance of interior design and ventilation in preventing pollutant migration and maintaining acceptable IAQ.

Summary of the experiment.

Table 5. 1: Comparison of pollutant concentrations between kitchens and living rooms across (CS1, CS2, and CS3).

Parameter	CS1: Kitchen Median	CS1: Kitchen Max	CS1: Living Room Median	CS1: Living Room Max	CS2: Kitchen Median	CS2: Kitchen Max	CS2: Living Room Median	CS2: Living Room Max	CS3: Kitchen Median	CS3: Kitchen Max	CS3: Living Room Median	CS3: Living Room Max
PM2.5($\mu\text{g}/\text{m}^3$)	5	100	2	50	10	200	5	100	8	150	4	75
TVOC ($\mu\text{g}/\text{m}^3$)	400	2000	100	300	500	1800	150	400	300	1900	120	350
CO2 (ppm)	600	1200	550	1000	700	1100	650	950	650	1150	600	1000

Table 5.1 illustrates the pollutant levels of PM2.5, TVOC, and CO₂ in kitchens and living rooms across three case studies (CS1, CS2, and CS3). Across all parameters, the kitchens consistently exhibit higher concentrations than the living rooms. For PM2.5, kitchens recorded median values ranging from 5 to 10 $\mu\text{g}/\text{m}^3$, with maximum levels up to 200 $\mu\text{g}/\text{m}^3$. In contrast, living rooms showed lower medians, ranging from 2 $\mu\text{g}/\text{m}^3$ to 5 $\mu\text{g}/\text{m}^3$, with maximum levels not exceeding 100 $\mu\text{g}/\text{m}^3$. These elevated PM2.5 levels in kitchens are primarily attributed to cooking activities, a significant source of particulate matter emissions. Similar trends are reported in the literature, in which cooking, especially frying, has been identified as a primary contributor to indoor PM2.5 levels (Martins & Carrilho da Graça, 2018).

For TVOC, the kitchens displayed significantly higher levels, with medians ranging from 300 $\mu\text{g}/\text{m}^3$ to 500 $\mu\text{g}/\text{m}^3$ and maximum values exceeding 1900 $\mu\text{g}/\text{m}^3$. In living rooms, median TVOC levels ranged from 100 $\mu\text{g}/\text{m}^3$ to 150 $\mu\text{g}/\text{m}^3$, with maximum values below 400 $\mu\text{g}/\text{m}^3$. These findings suggest that kitchens are the primary source of volatile organic compound emissions, particularly during cooking. The literature supports this observation, noting that gas stoves and other cooking methods emit a range of VOCs, contributing to higher TVOC levels (Tang et al., 2024). Despite these elevated levels, the enclosed kitchen design effectively contained pollutants, limiting their movement to living areas.

CO₂ levels showed minor differences between kitchens and living rooms. Median CO₂ values ranged from 600 ppm to 700 ppm in kitchens and 550 ppm to 650 ppm in living rooms. Maximum levels occasionally exceeded 1000 ppm in kitchens, underscoring the need for enhanced ventilation during extended occupancy or cooking. Similar CO₂ levels in both spaces

can be attributed to shared occupancy patterns. Research indicates that maintaining CO₂ levels below 1000 ppm is crucial for ensuring adequate ventilation and occupant comfort (WHO, 2021).

The comparison highlights the importance of kitchen design in managing IAQ. The enclosed designs in these studies effectively contained pollutants, preventing significant migration to living rooms. This containment is particularly crucial for PM_{2.5} and TVOC, where pollutant levels in living rooms consistently remained below thresholds despite high kitchen emissions.

The analysis demonstrates the role of kitchen design in containing pollutant migration. Lower pollutant levels were recorded in the living room compared to the kitchen across all cases (Figures 5.4–5.6), supported by diary entries indicating that cooking activities were confined to the kitchen during peak times.

These findings align with Dimitroulopoulou et al. (2017), who emphasise the importance of spatial separation in controlling the spread of pollutants. The results further show that this containment is influenced by real-life occupancy conditions, where behaviours such as door operation and ventilation practices influence pollutant distribution within the home. Future research should explore pollutant dynamics in homes with open-plan kitchen designs to assess whether pollutants disperse more readily into adjacent living spaces. Such studies would provide valuable insights into the impact of kitchen layouts on IAQ and help develop better architectural practices for healthier living environments. Understanding the trade-offs between open and enclosed designs can guide the optimisation of ventilation and pollutant containment strategies.

5.1.3 Discussion of building design.

The comparison highlights the importance of kitchen design in managing IAQ. The experiment in this study highlights the effectiveness of enclosed kitchens in mitigating the migration of pollutants throughout the house. Elevated pollutant levels, particularly PM_{2.5} and TVOC, were observed in kitchens during cooking. However, these pollutants were effectively contained, with minimal migration to living rooms or other spaces. This finding emphasises that enclosed kitchens can act as barriers, compartmentalising pollutants and reducing exposure risks in adjacent areas. These results align with studies showing that enclosed designs, when coupled with adequate ventilation, mitigate the spread of indoor pollutants (Dimitroulopoulou et al., 2017).

Air migration within buildings is another critical factor influencing IAQ. Pressure differentials caused by higher temperatures can drive internal airflows, moving pollutants between spaces. This phenomenon, known as the stack effect, is particularly pronounced in taller buildings, where vertical airflow can transport pollutants between floors, and it also affects single-story homes. The findings reinforce the importance of properly pressurising pollutant-generating spaces, such as kitchens, to prevent cross-contamination. Enclosed kitchens further enhance this containment by reducing the movement of unintended pollutants to the rest of the house (McGill et al., 2015; Nazaroff & Weschler, 2020)

The interaction between airflow and pollutant decay was evident in this study. For example, pollutants like CO₂ remained elevated overnight when doors and windows were closed, only decaying once these openings were reopened. Open kitchen windows during cooking accelerated pollutant decay, highlighting the importance of ventilation in removing airborne contaminants (Hussein et al., 2006). These findings also support earlier work suggesting that ventilation design should be integrated into the conceptual phase of building design to address IAQ issues proactively (Persily, 2015). By incorporating such airflow strategies with spatial planning and activity zoning, designers can effectively manage IAQ while accommodating the functional needs of different building spaces.

The design of building spaces is critical in determining indoor environmental performance (Hansen, 2018). Careful consideration of spatial layout during the design phase is essential to mitigate the adverse effects of poor IAQ. To minimise their impact during occupancy, contributors to IAQ in homes, including building configuration and design characteristics, must be addressed during the conceptual and design stages. The interactions among occupants, building elements, and environmental factors significantly affect both IAQ and occupant well-being.

Building design encompasses detailed plans and technical characteristics (Juhásová Šenitková, 2016). In residential buildings, these elements include spatial dimensions, interior layouts, building envelopes, ventilation systems, and furnishings. For instance, door design influences airflow, as undercut gaps of 10 mm promote pollutant dispersion and adequate ventilation (Cao et al., 2014). Factors such as cooking, cleaning, and burning scented candles require targeted design considerations to minimise exposure. Spatial planning, which separates pollutant sources from primary living areas and installs air quality monitors, can alert residents to unhealthy levels and guide mitigation strategies.

In conclusion, this study's findings provide insights into the relationship between kitchen design and pollutant dynamics in homes. Enclosed kitchens demonstrated the ability to limit pollutant migration, offering a potential design strategy for managing IAQ. However, these findings are specific to enclosed kitchens and should serve as a basis for comparative research involving open-plan designs. Future studies could assess whether pollutants in open-plan layouts spread more readily to adjacent spaces, offering a broader understanding of the impact of kitchen design on IAQ. These insights emphasise the importance of ventilation strategies and spatial planning in residential design, offering architects and designers valuable considerations for creating healthier, more functional indoor environments.

5.2 Occupation.

This section of the research examines the critical role occupants play in shaping IAQ in residential environments. Occupants directly affect IAQ through their daily activities, behavioural patterns, lifestyle choices, and time spent indoors. These human factors contribute to both the generation of indoor pollutants, such as those produced during cooking, cleaning, or the use of household products, and to their mitigation, depending on how ventilation systems are operated and how indoor environments are managed.

Using data drawn from daily activity diaries, occupant interviews and surveys, and a series of controlled cooking experiments, this section explores how occupants act as sources of pollutants, receptors of exposure, and active modifiers of the indoor environment. Case studies CS1 through CS6 illustrate a range of behaviours and routines that shape IAQ outcomes across different households. This section also considers the influence of awareness and educational interventions on occupant practices, highlighting the potential for behaviour-focused strategies to improve IAQ in newly built, low-carbon homes.

Additionally, a behavioural change experiment was conducted to examine whether presenting real-time sensor data to an occupant could influence their ventilation and cooking-related behaviours. The purpose was to assess whether raising awareness of pollutant levels, particularly TVOC, CO₂, and PM_{2.5}, would lead to actions that improve IAQ, such as adjusting ventilation use or modifying high-emission activities. This intervention provided insight into how feedback mechanisms can empower occupants to make informed decisions that support healthier indoor environments.

Finally, this section explores the broader implications of occupant awareness and education, emphasising the importance of incorporating behavioural considerations into IAQ management strategies, particularly in airtight, low-carbon homes.

5.2.1 Influence of Occupants on IAQ.

The primary goal of this analysis is to compare these results with the baseline established when the house was unoccupied, thereby understanding the impact of occupant activities on IAQ. Figure 5.7 displays the variations in TVOC, PM_{2.5}, temperature, and RH over a specified period when the house is occupied.

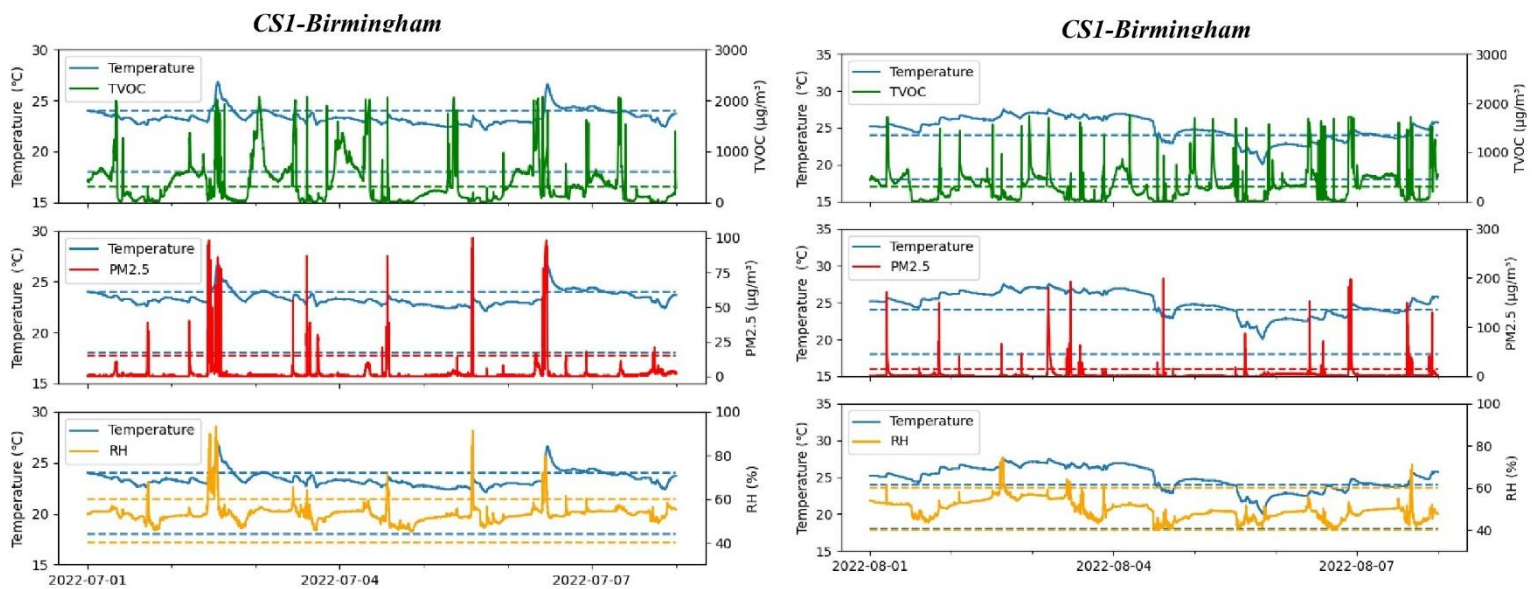


Figure 5. 7: IAQ analysis of occupied homes during a two-week monitoring period (first week of July and August 2022).

These observed spikes in TVOC and PM_{2.5} concentrations are directly linked with occupant activities such as cooking and cleaning, as evidenced by diary records. This verifies that occupant behaviour is the primary factor driving short-term variation in IAQ. This finding aligns with existing literature identifying household activities, particularly cooking, as major contributors to indoor pollutant levels (Wargocki, 2010). This study expands this understanding by demonstrating how the frequency and repetition of these activities in daily domestic settings increase their cumulative impact on IAQ over time.

The temperature and TVOC levels in Figure 5.7 show fluctuations in temperature readings throughout the monitoring period, indicating changes associated with occupant activities. TVOC concentrations show significant variability, with frequent spikes reaching up to 2000 $\mu\text{g}/\text{m}^3$. These spikes correlate with occupant activities such as cooking, cleaning, or using products that emit VOCs. This suggests that occupant interactions significantly impact the indoor environment. The PM2.5 levels also demonstrate similar variability, with occasional spikes reaching up to 100 $\mu\text{g}/\text{m}^3$. These spikes are likely linked to indoor sources, such as cooking combustion or the resuspension of settled dust from movement or cleaning. In contrast to the stable and compliant value observed in the unoccupied baseline, PM2.5 levels frequently exceed the threshold, highlighting the impact of occupant activities. This illustrates the significant impact that daily routines and household tasks have on indoor particulate matter concentrations. While temperature and RH are not the primary focus of this study, their inclusion provides contextual insight. Variations in RH, for instance, often coincide with periods of increased pollutant levels, further supporting the interpretation of occupant-driven indoor environmental changes. The data demonstrate that routine household behaviours have a measurable, often substantial influence on IAQ.

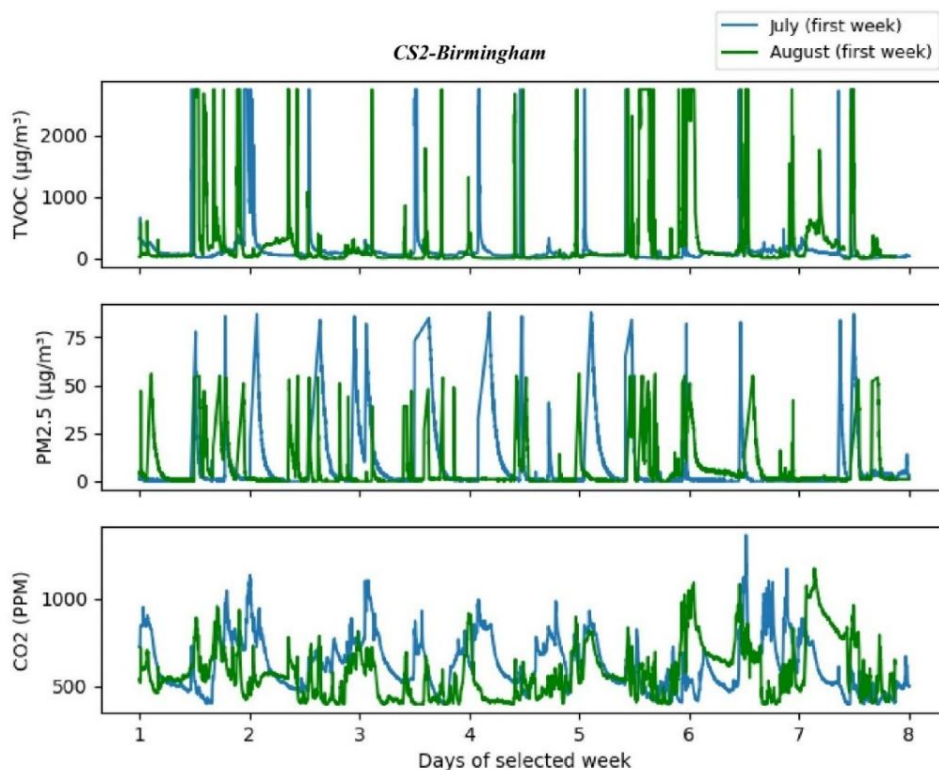


Figure 5. 8: Comparative IAQ analysis of occupied homes across two separate two-week monitoring periods in July and August 2022.

Figure 5.8 shows the IAQ metrics measured in CS2-Birmingham over the first week of July and August, focusing on TVOCs, PM2.5, and CO2 levels.

TVOC levels fluctuated significantly in July, with several spikes reaching up to 2000 $\mu\text{g}/\text{m}^3$. August displayed a similar pattern, with frequent spikes hitting 2000 $\mu\text{g}/\text{m}^3$. However, the spikes in August appeared more frequent and prolonged than those in July. This suggests that regular household activities introduce VOCs into the air in both months. PM2.5 levels showed frequent peaks in both months, often reaching 75 $\mu\text{g}/\text{m}^3$. The consistent peaks in PM2.5 indicate regular particulate-generating activities, such as cooking or cleaning, happening in both July and August. CO2 levels fluctuated regularly, generally between 500 ppm and 1000 ppm. These fluctuations suggest variations in occupancy and ventilation rates that were consistent across the two months.

Overall, the IAQ data for CS2-Birmingham reveals consistent patterns in pollutant levels across the first week of July and August. Significant spikes in TVOCs and PM2.5 indicate regular pollutant-generating activities, while CO2 levels show regular occupancy and ventilation patterns. This suggests that the indoor activities influencing air quality remained similar across both months. This analysis confirms that occupant interaction has a substantial impact on IAQ, with effects more pronounced than during unoccupied periods.

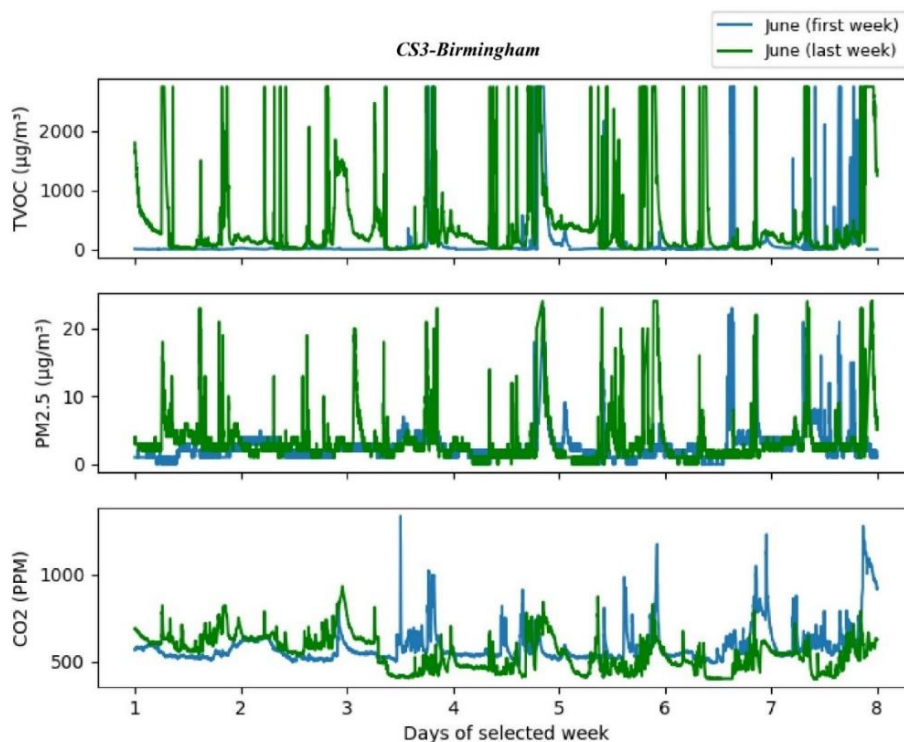


Figure 5. 9: Temporal variation in IAQ parameters in occupied homes during the first week of July and August 2022.

Figure 5.9 illustrates the IAQ metrics measured in CS3-Birmingham during the first and last weeks of June, focusing on TVOCs, PM2.5, and CO2 levels. During the first week of June, TVOC levels remained relatively low, with occasional peaks reaching 1,000 $\mu\text{g}/\text{m}^3$, suggesting

that intermittent activities introduce VOCs into the indoor environment. In contrast, the last week of June shows a marked increase in both the frequency and magnitude of TVOC spikes, with several peaks reaching up to 2000 $\mu\text{g}/\text{m}^3$, indicating increased VOC emissions, such as increased use of cleaning products or cooking. PM_{2.5} levels were generally low during the first week, with most values below 10 $\mu\text{g}/\text{m}^3$ and occasional peaks reaching 20 $\mu\text{g}/\text{m}^3$, suggesting limited particulate-generating activities. However, the last week of June shows a noticeable increase in PM_{2.5} levels, with more frequent and higher peaks of up to 20 $\mu\text{g}/\text{m}^3$, indicating increased particulate-generating behaviours, likely linked to cooking or vacuuming, particularly in the absence of adequate extraction or ventilation. CO₂ levels fluctuated between 500 ppm and 1000 ppm across both weeks. However, the last week exhibited more frequent and sustained peaks near or above 1000 ppm. These trends suggest increased occupancy duration or reduced ventilation efficiency, both supported by qualitative data indicating that the kitchen door was consistently kept closed during cooking and that there was limited understanding of the ventilation system.

Overall, the CS3 data show that indoor pollutant levels were significantly higher in the last week of June. This trend highlights the critical role of occupant activities, rather than static building materials, as primary contributors to IAQ variation. Daily behaviours such as cooking, cleaning, and product use significantly affect indoor pollutant concentrations. Based on this baseline analysis, we can infer that occupant interactions and activities have a more pronounced impact on IAQ than building materials. When the house is occupied, activities such as cooking, cleaning, and using household products are expected to increase indoor pollutant levels. This underscores the importance of occupant behaviour in managing IAQ and emphasises the need for adequate ventilation and air-quality monitoring during occupied periods. The rationale for analysing temperature and relative humidity is that they correlate with emissions from building materials. While the primary focus of this analysis is on TVOC, PM_{2.5}, and CO₂, it is essential to note that temperature and RH also influence pollutant dynamics. These environmental conditions can affect the emission rates of VOCs from building materials. Elevated temperatures may accelerate the off-gassing of chemicals, while high RH can increase the release of moisture-sensitive pollutants. Therefore, although building materials contribute to baseline pollutant levels, the more significant fluctuations are primarily driven by occupant activity, particularly during occupied periods.

Table 5 2: Occupancy characteristics, Lifestyle factors, and Building Usage Pattern across case studies.

Location	Birmingham UK			Burton upon Trent	Tamworth	Chelmsford
Cases	CS1	CS2	CS3	CS4	CS5	CS6
Building introduction	- Shown around on moving in day with the systems explained.	- Shown around on moving in day with the systems explained.	- Shown around on moving in day with the systems explained.	- Shown around on moving-in day with the systems explained	- All systems are shown before moving in.	- All systems are shown before moving in. Manuals were completed
Building use	- Doesn't fully understand the heating & MVHR systems. - Initially, hot water wasn't working, and no boost for the MVHR.	- Doesn't fully understand the heating & MVHR systems. Initially, high bills stem from a misunderstanding of the systems.	- Doesn't fully understand the heating systems. - Adaptation of the heating systems took time.	- Understand systems and that everything works well.	- The systems are understood well, but some require fixing.	- It took time to learn how to operate heating and MV systems.
Maintenance & support	- The hot water problem was quickly solved. - Assumes the responsibility lies with the housing association.	- System problems were not dealt with quickly. - Assumes the responsibility lies with the housing association.	- Assumes the responsibility lies with the housing association.	- Quick help service responses. - Assumes the responsibility lies with the housing association.	- All equipment manuals were in place after moving in, and support was very helpful.	I am still learning the systems after six months, but support is very helpful.
Daily presence at home before 4 pm	-Most days at home.	-Most days at home.	-Most days at home.	-Most days at home.	- No one at home before 5 pm.	- No one at home before 5 pm.
Pets	-No	-No	-Yes	-No	-Yes	-Yes
Indoor smoking	-No, but there is a smoker in the household.	-No	-No	-No	-No	-No, but there is a smoker in the household.
Cooking equipment type	Cooker, microwave, toaster, air fryer, portable grill. -No Gas supply (FHS).	We have a cooker, a Microwave, a kettle, an air fryer, and an instant pot. We cook twice a day and use the microwave and the Instant Pot in between. -No Gas supply (FHS).	Cooker, Toaster, Microwave, Oven, Kettle. -No Gas supply (FHS).	-Cooker, Oven (gas), Microwave, and Kettle.	-Cooker, Oven (gas), Grill(electric), Microwave, and Kettle.	-Cooker, Oven, Grill (gas), Microwave, and Kettle.
Cleaning	-We clean the kitchen surfaces daily with spray products, sweep and vacuum three or four times a week, and use bleach on surfaces and floors. The staircase carpet is vacuumed daily. The living room, corridors, and bedrooms are laminated, and the kitchen and toilets are vinyl.	We vacuum, sweep, and mop daily and three times a week. We use only natural products, including bleach.	-Vacuuming, mopping, and cleaning surfaces (using spray products, bleach for toilets, and furniture polishing products).	-Vacuuming, mopping, using spray products, and sometimes bleach for toilets.	-Vacuuming, mopping, using spray products, and sometimes bleach for toilets.	-Vacuuming, mopping, and using natural spray products.
Window opening	-Yes	-Yes	-Yes	-Yes	-No	-No
Opening the kitchen door while cooking	-Sometimes open.	-No, always closed.	-No, always closed.	-Sometimes open.	-Yes, always open.	-Yes, always open.
Lighting candles	-Yes, we use it sometimes in the living room and bedrooms. We also use traditional oud sticks. Air freshener in toilets.	-Yes, in the kitchen to get rid of food smells.	-Yes, three or four times a week (Living room and corridors).	-Yes, once a week (living room, corridor).	-Yes, most of the time, in the living room.	-Yes, the living area
Air fresheners	-Yes (toilets).	-Yes (toilets).	-Yes (toilets).	-Yes (toilets) and uses diffusers.	-Yes, (toilets) and uses a diffuser (corridor).	-Yes (toilets) and uses diffusers.

Table 5.2, derived from occupant interviews and questionnaires, presents a detailed comparative analysis of six case studies (CS1-CS6) that illustrates variations in occupancy patterns, building use, and lifestyle behaviours relevant to indoor environmental quality. It encompasses key parameters such as tenure type, system orientation, system usage, maintenance and support, daily occupancy, presence of pets or smokers, cooking equipment, cleaning routines, ventilation behaviours, and the use of fragranced products. CS1-CS4 represent rented properties, whereas CS5 and CS6 are owner-occupied. Owner-occupied households received more comprehensive introductions to the systems, which appear to enhance their understanding of and utilisation of mechanical ventilation and heating systems. In contrast, occupants in CS1 to CS3 reported confusion or incorrect utilisation of these systems, often leading to discomfort, inefficiency, or increased energy costs.

Maintenance experiences also varied: CS1-CS3 reported delayed responses or unresolved issues, whereas CS4-CS6 benefited from more effective, timely support. Daily occupancy patterns indicate that CS1, CS2, and CS4 are more often at home during the day, which may increase exposure to indoor pollutants and underscore the importance of adequate ventilation. Behavioural contributors to IAQ include the presence of pets (CS3, CS5, and CS6) and smokers in the household (CS1 and CS6), both of which introduce airborne particulates and odours. Cooking behaviours vary by case: CS4 and CS6 use gas appliances, which have implications for indoor combustion-related emissions.

Cleaning routines reflect individual preferences and perceived hygiene standards, ranging from intensive daily cleaning using both chemical and natural products (CS1, CS2) to more selective, natural approaches (CS6). Ventilation-related behaviours also differ; for instance, CS1 and CS2 regularly open windows, whereas CS5 and CS6 do not, which may reduce passive air exchange. Similarly, kitchen door management during cooking varies; some households always leave it open (CS5, CS6), while others keep it closed (CS2, CS3), which may either mitigate or trap cooking pollutants.

The use of candles and air fresheners is common in most households, often for scent or ambience; however, these practices may introduce TVOCs into the indoor environment. Diffusers are particularly utilised in CS5 and CS6, further contributing to airborne chemical burdens.

This comparative analysis highlights the diversity in occupant lifestyles and building usage patterns, particularly concerning how residents interact with systems, manage indoor sources of pollution, and ventilate their homes. These behaviours significantly influence IAQ outcomes, reinforcing the necessity for occupant-centred approaches to indoor environmental management and system design.

5.2.2 Cooking experiment in CS1 & CS3.

The purpose of the experiment is to compare different ventilation strategies and assess their effectiveness in reducing cooking-related concentration levels in the kitchen. Figures 36 and 37 illustrate two cooking scenarios in CS1 and CS3, respectively, and compare the impact of ventilation strategies on IAQ. Occupants were also asked to complete a structured open questionnaire prior to monitoring. This was used to gather information about their perceptions of IAQ and daily activities that could affect it.

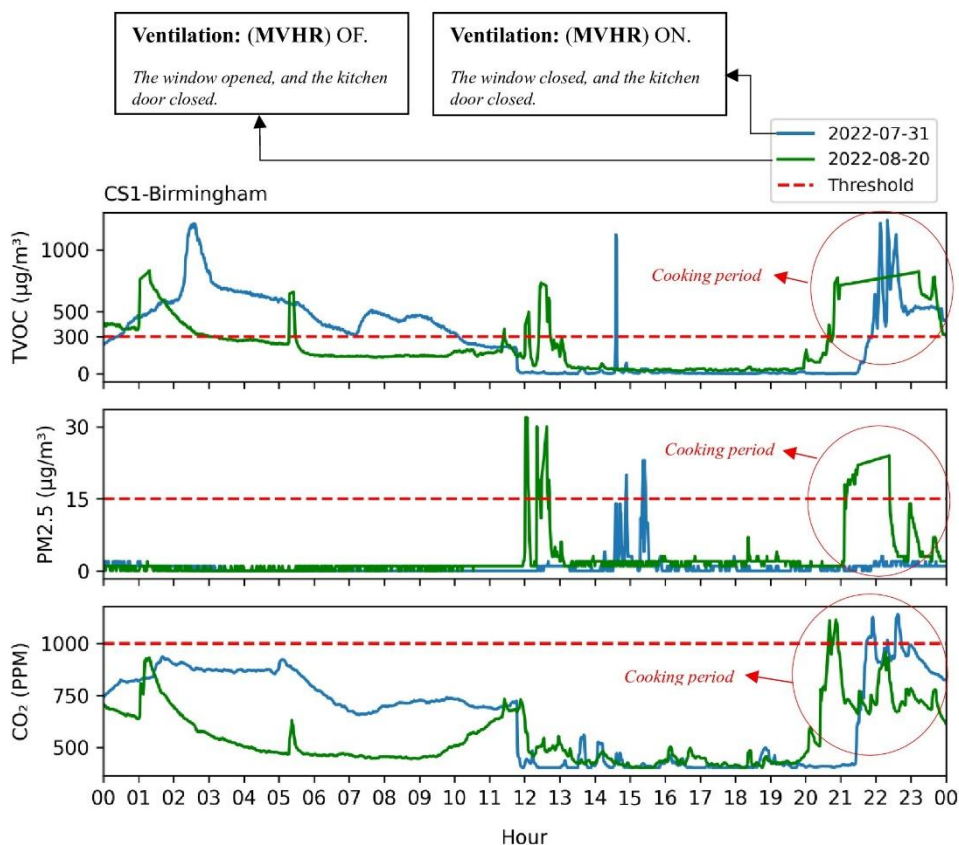


Figure 5.10: Kitchen-based IAQ experiments using the AURA sensor during cooking activities (31 July 2022, 20:50–22:23, and 20 August 2022, 20:50–22:23).

Figure 5.10 presents IAQ data collected during a controlled cooking experiment in CS1–Birmingham, comparing the effects of different ventilation strategies on pollutant levels. The

same cooking activity, preparing rice and sauce on the hob and roasting chicken in the oven, was conducted on two separate dates under different ventilation conditions. The AURA sensor was utilised in the kitchen, while the uHoo Smart sensor was positioned in the living room. Cooking took place on both July 31, 2022, and August 20, 2022, from 20:50 to 22:23.

On 31 July 2022, the MVHR system was on (without boost), with the kitchen window and door closed. During cooking, TVOC and PM_{2.5} concentrations increased but remained at moderate levels. TVOC peaked slightly above 600 µg/m³, while PM_{2.5} largely stayed below the 25 µg/m³ threshold. Pollutant levels diluted relatively quickly after cooking ended, indicating that the MVHR provided continuous background ventilation. CO₂ levels remained below 1000 ppm, suggesting adequate air exchange throughout the period.

On 20 August 2022, the MVHR system was off, while the kitchen window was open, and the door remained closed. The same dishes were cooked during the same timeframe. TVOC and PM_{2.5} levels spiked higher in this scenario and remained elevated for longer durations. TVOC exceeded 1000 µg/m³, while PM_{2.5} exceeded 25 µg/m³, indicating greater pollutant accumulation and slower dilution. CO₂ levels also rose more significantly during the cooking period, even with the window open, suggesting that the natural ventilation setup provided less consistent airflow.

Although the second scenario allowed for natural ventilation, the data suggest that relying solely on window openings, particularly with the door closed, was less effective than mechanical ventilation. The occupant reported that food odour lingered longer on 20 August, while it diluted more quickly on 31 July, consistent with the sensor data.

The comparison between the two cooking scenarios in CS1 demonstrates that MVHR operation, even without the boost function and with windows and doors closed, was more effective at controlling indoor air pollutants than natural ventilation through window opening. TVOC, PM_{2.5}, and CO₂ levels were consistently lower and diluted more quickly when the MVHR was activated. In contrast, relying solely on window ventilation resulted in higher pollutant peaks and slower decay. These findings highlight the importance of using mechanical ventilation systems as intended to maintain healthy indoor air quality during cooking activities in newly built low-carbon homes.

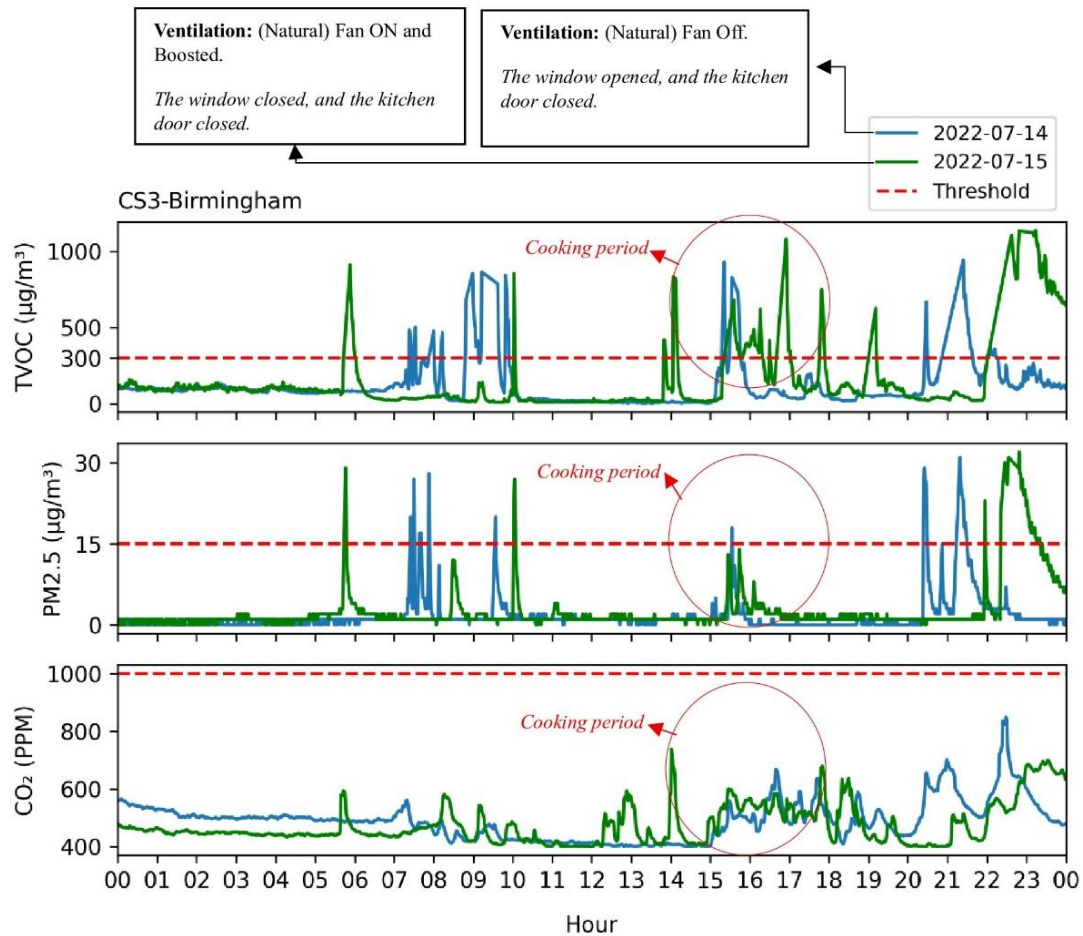


Figure 5. 11: Short -duration kitchen experiments using the AURA sensor to assess pollutant generation during cooking (July 14, 2022, from 15:20 to 15:50, and on July 15, 2022, from 15:20 to 16:00).

On Day 1, Figure 5.11 shows in CS3 that the cooking scenario used a ventilation approach with the kitchen windows open, the door closed, and the extract fan off. This experiment took place on 14 July 2022, from 15:20 to 15:50. The cooking activities included preparing rice and sauce on the hob and roasting chicken in the oven. After completing the cooking, the occupant left the kitchen with the windows still open and the door closed. Fifteen minutes later, the occupant noticed that the smell of food had gradually diminished, indicating effective dilution of cooking-related odours.

On Day 2, the cooking scenario employed a different ventilation approach: the kitchen windows and door were closed, and the extract fan was turned on with the boost function activated. This experiment took place on July 15, 2022, from 15:20 to 16:00, using the same cooking method as on Day 1. After completing the cooking, the occupant left the kitchen with the window and door still closed. Fifteen minutes later, the occupant noted that the food smell

lingered, suggesting that the extract fan alone was insufficient for removing the odour and may not have effectively diluted the cooking-related pollutants.

The comparison between the two scenarios highlights notable differences in ventilation performance. Contrary to expectations, indoor pollutant levels, including TVOC and PM2.5, were higher and more persistent when the extract fan was used with windows and doors closed (Day 2). In contrast, natural ventilation via an open window (Day 1) enabled quicker pollutant dilution and odour clearance. These findings suggest that mechanical extraction alone, even in boost mode, may not provide adequate ventilation unless supported by sufficient airflow, such as through open windows or doors. This outcome highlights the importance of integrating extraction systems with natural ventilation to maintain good indoor air quality in naturally ventilated homes, particularly during activities that generate pollutants, such as cooking.

5.2.3 Occupant Interview and Questionnaire Results.

Semi-structured interviews and questionnaires were conducted with occupants of all six newly built homes to explore behaviours and activities that influence IAQ, particularly those associated with pollutant generation. The questionnaires collected data on lifestyle practices, ventilation system use, heating schedules, and the frequency of activities that generate pollutants, including cooking, cleaning, and the use of household products. Following the questionnaire, occupants participated in brief, structured interviews to expand their responses and provide additional insights into their perceptions of IAQ during summer and winter, employing validated methods from Moreno-Rangel et al. (2023). This combined qualitative and quantitative approach provided a rich context about occupant routines and decisions, clarifying their influence on IAQ across different home designs and ventilation systems. The following figures (Figures 32 to 35) illustrate selected questionnaire results, which are subsequently complemented by illustrative quotes drawn from occupant interviews.

5.2.3.1 *Questionnaire Results: Occupant Behaviours and IAQ Perceptions.*

This section presents quantitative findings from occupant questionnaires conducted at the start of the monitoring period. The results are illustrated in Figures 39 to 42, highlighting the occupant behaviours and perceptions that influence IAQ.

The questionnaires were conducted to evaluate occupants' perceptions of IAQ, using both bipolar and unipolar rating scales. One of the key questions asked was, "How do you rate the quality of the air inside your home?" This question also formed part of the structured interviews conducted at the beginning of the monitoring campaign. The bipolar scale was used to capture directional perceptions, where higher positive ratings indicated better perceived IAQ. Responses were collected from one participant per household across all case studies (see Chapter 3 for demographic details).

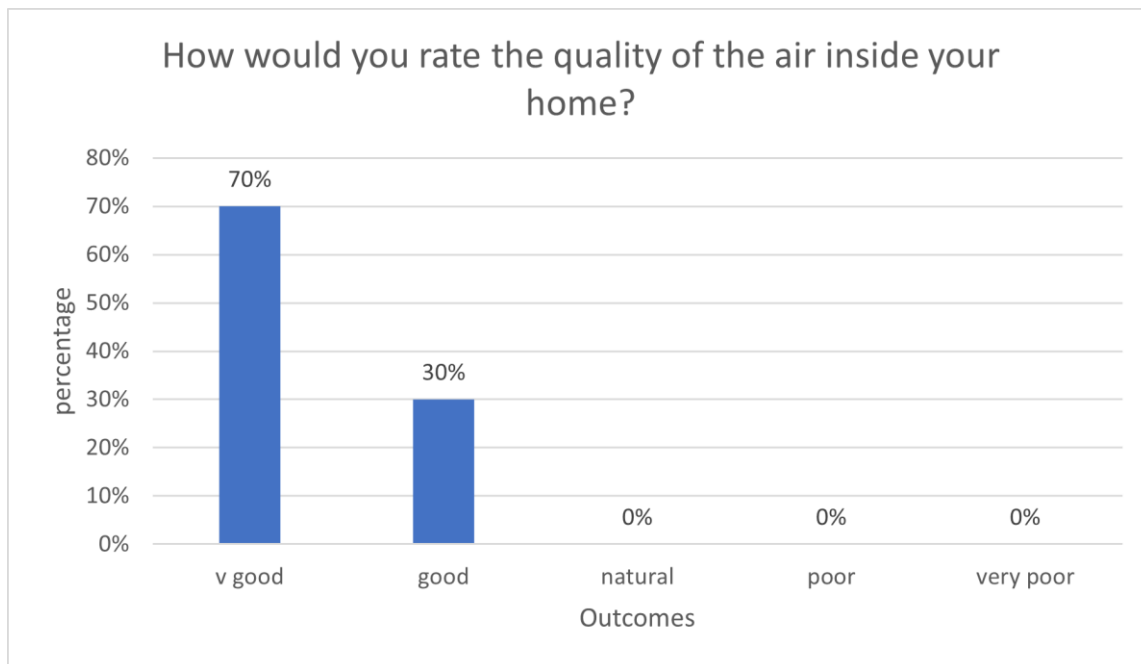


Figure 5. 12: Occupant responses to Question 1 on perceived IAQ.

Figure 5.12 shows that 70% of participants rated their IAQ as “very good,” and 30% as “good.” No occupants selected “neutral,” “poor,” or “very poor,” indicating satisfaction with their home's IAQ. However, this positive subjective perception contrasts with objective sensor data, which, in several cases, indicated poorer IAQ levels. This discrepancy highlights a significant challenge in IAQ studies: occupants often cannot perceive harmful pollutants such as VOCs and PM_{2.5}, which are typically odourless and invisible. Therefore, continuous objective monitoring is essential, as subjective comfort may not accurately reflect actual IAQ conditions.

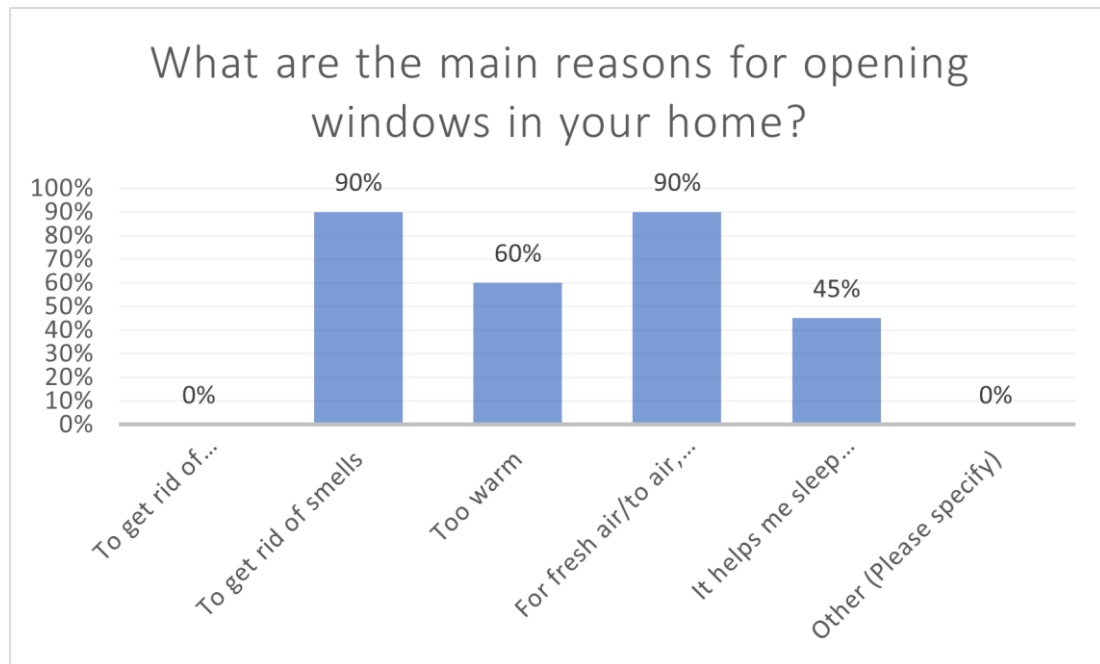


Figure 5. 13: Main reasons for window opening reported by occupants (CS1 to CS6).

Figure 5.13 shows the responses from occupants of CS1 to CS6 regarding the main reasons for opening windows in their homes. The data indicates that 90% of respondents mentioned eliminating unpleasant odours and bringing in fresh air as the primary reasons for opening windows. This shows a strong preference for using natural ventilation to eliminate odours and improve IAQ. Additionally, 60% of respondents open windows because their homes are too warm, indicating that thermal comfort is a significant factor. Interestingly, 45% of occupants reported that opening windows helps them sleep, suggesting that fresh air or a cooler environment may improve sleep quality. The absence of responses in the "To get rid of..." and "Other (*Please specify*)" categories suggests that the provided reasons capture the respondents' primary motivations for opening windows.

These results reveal a general reliance on natural ventilation, despite the availability of mechanical ventilation systems, such as MVHR. This behaviour highlights the need for improved occupant education on the utilisation and benefits of installed ventilation technologies to optimise IAQ and energy efficiency. Overall, the responses demonstrate a strong preference for natural ventilation to maintain good air quality and comfort. They identify potential areas for improvement in occupant education and system design to enhance the effectiveness of mechanical ventilation solutions.

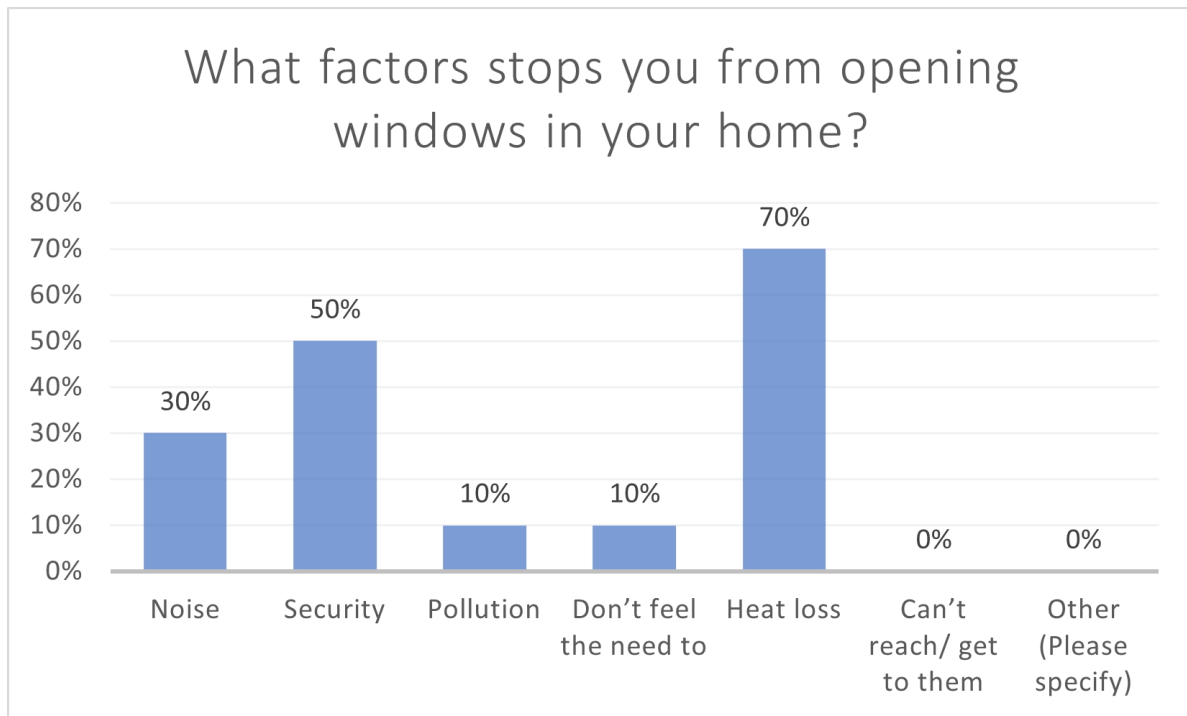


Figure 5. 14: Factors preventing window opening among occupants.

Figure 5.14 shows the primary barriers to window opening identified by occupants across CS1-CS6. The most significant concern, cited by 70% of respondents, was heat loss, highlighting occupants' awareness of energy efficiency and associated heating costs. Security issues, noted by 50%, underscored safety concerns and emphasised the importance of secure ventilation strategies. Additionally, noise pollution (30%) emerged as a notable deterrent, particularly in urban areas, suggesting a need for improved acoustic insulation or alternative ventilation methods. Smaller percentages (10%) mentioned external pollution and a perceived lack of need for additional ventilation. These diverse findings demonstrate the complexity and subjective nature of occupants' decision-making regarding ventilation behaviour. They emphasise the importance of considering occupant preferences, comfort, security, and energy efficiency when designing effective, acceptable ventilation systems for modern new homes.

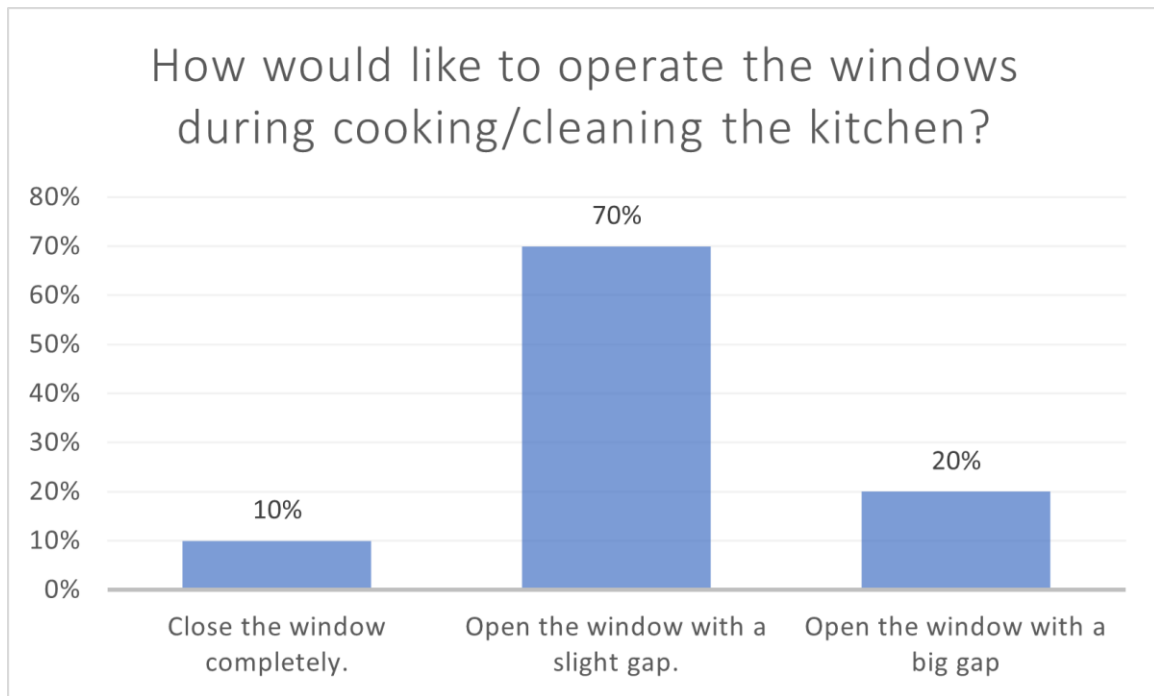


Figure 5. 15: Window operation preferences during cooking and cleaning activities (CS1 to CS6).

Figure 5.15 presents occupant responses from CS1 to CS6 regarding their preferred window operation habits during cooking and cleaning in the kitchen. The data show that a small proportion (10%) prefer to keep windows completely closed, likely relying solely on mechanical ventilation or other methods to manage IAQ. Most respondents (70%) prefer opening the window slightly, striking a balance between fresh air, thermal comfort, and energy efficiency. A further 20% prefer a wider gap, indicating a preference for increased natural ventilation to more effectively remove pollutants and odours generated during cooking and cleaning.

Overall, the majority of occupants (90%) prefer at least partial window opening during kitchen activities, indicating a strong reliance on natural ventilation to maintain IAQ. This behavioural trend highlights the need for occupant education on the optimal use of combined natural and mechanical ventilation strategies to effectively manage IAQ while minimising energy consumption.

5.2.3.2 Interview Results: Measuring the Impact of Occupant Lifestyle Choices and Habits on IAQ through Qualitative Analysis.

This section presents qualitative insights derived from brief, semi-structured interviews conducted with occupants after they completed the questionnaire. The interviews were designed to build upon the structured questionnaire responses by exploring underlying habits, motivations, and personal experiences in greater depth. This complementary approach provided a deeper understanding of occupant behaviours related to IAQ, particularly pollutant-generating activities, ventilation use, and perceptions of air quality. Selected illustrative quotes are included to highlight patterns and contextual differences across the six case studies.

The occupants of CS1 demonstrated an awareness of IAQ, frequently noting that “*the air quality in this house is good*” and later reaffirming it as “*perfect.*” Their ventilation habits are shaped by past experiences, as they stated, “*even though we know that we have MVHR and we have been told that we don’t need to open the windows, we feel opening windows in the morning and afternoon to get some fresh air.*” Despite having an MVHR system, they still regularly open windows and doors due to habits formed in their previous homes. Cooking is a daily activity, with more intensive sessions on weekends. During these times, ventilation is managed by opening windows rather than relying on MVHR, as the system was not fully understood. Additionally, there was no boost button in this case.

The occupants also reported frequent use of air fresheners, “*daily or sometimes every other day in every room, including traditional scented sticks to get a pleasant odour.*” Cleaning is performed rigorously, with daily vacuuming and surface cleaning, especially in the kitchen. Despite receiving an initial system demonstration, they admitted to struggling with the complex heating system and expressed a desire for additional training. This case highlights how habitual behaviours, prior housing experiences, and family routines strongly influence occupants' interactions with the indoor environment and their management of IAQ.

The occupants of CS2 rated the indoor air quality as “*very good,*” but frequently opened windows to “*get fresh air,*” particularly during and after cooking. They noted that “*IAQ is very important to prevent mould and condensation,*” reflecting awareness of its role in maintaining a healthy home. Cooking occurred up to three times daily, with full meals prepared on the hob, in the oven, microwave, rice cooker, and instant cooker. The occupant explained, “*I cook three times a day because I prepare a fresh meal for the children and my husband,*” indicating a high

frequency of cooking, a source of pollutant generation. Cleaning was performed daily using bleach and multi-surface sprays, with mopping “every day in the kitchen and two to three times a week in the rest of the home.” Scented candles and oud sticks were used “*twice a week, and air fresheners were applied in the toilet every day in the bathrooms,*” primarily “*to get rid of food smells and steam.*”

Despite having an MVHR system, the occupant said, “*I don’t think it’s enough to get rid of the food smell and the steam from bathrooms,*” particularly without a boost function. As a result, they relied on opening windows while cooking, stating, “*I always open the window in the kitchen when I cook.*” However, this practice conflicted with concerns about energy efficiency and security, noting, “*I don’t like to open the window at night or in the winter season because of the cold and safety.*”

This case highlights how intensive cooking practices increase the need for adequate ventilation and how habitual reliance on window openings can compromise energy efficiency. It also highlights the importance of occupant education, such as encouraging low-emission cooking techniques, using natural cleaning alternatives, and minimising reliance on scented products that merely mask underlying IAQ issues. Addressing these behaviours could help improve air quality and reduce unnecessary energy consumption in homes equipped with mechanical ventilation systems.

The occupant of CS3 rated the indoor air quality as “*very good*” and stated, “*We have no problems with IAQ,*” indicating a generally positive perception. However, IAQ was also described as “*very important as it might affect us,*” reflecting awareness of its health implications. Cooking took place twice daily, using the hob, oven, air fryer, and portable grills. The occupant noted, “*We primarily use air fryers and portable grills because I have teenagers,*” suggesting convenience-driven appliance choices that may vary in pollutant output. Cleaning was conducted rigorously: “*We clean daily with surface wiping in the kitchen using spray products and bleach in the bathrooms.*” The rest of the house was vacuumed and swept daily, with mopping “*occurring twice weekly.*” Scented candles, traditional oud sticks (used twice weekly), and air fresheners in toilets were also mentioned: “*We use it to get rid of the food smell and smell nice*”, potentially contributing to elevated indoor pollutant levels.

Despite the presence of a Continuous Mechanical Extract (CME) fan system equipped with a boost cord and a humidity sensor (which triggers at 60% RH), the occupant relied heavily on

opening the window, stating, “*We open the window with a slight gap in the summer season, and always during cooking, regardless of the season.*” Security concerns and heat loss were cited as reasons for limiting window use at other times. This reliance on window ventilation suggests a limited trust in, or understanding of, the mechanical system’s intended function. It reflects a behavioural preference for manual control over automated systems, even at the potential cost of energy inefficiencies or compromised IAQ. The regular use of strong cleaning products and scented items, combined with inconsistent mechanical ventilation, highlights the need for occupant education on pollutant sources and the importance of using installed ventilation systems correctly.

The occupant of CS4 rated the indoor air quality as “*very good*” and stated that it is in “*good condition, with no problems,*” indicating overall satisfaction with their home environment. Although no specific concerns were raised, the occupant acknowledged that IAQ is “*quite important,*” particularly for preventing mould and condensation. Cooking typically takes place in the evenings every other day, with simpler meals like “*scrambled eggs and beans for the children, and more intensive cooking, such as roasting and frying, every other Sunday.*” Daily kitchen cleaning includes wiping surfaces with spray products and mopping the floor most evenings. On weekends, the occupant performs more thorough cleaning routines, including vacuuming and using bleach in the bathrooms. Scented candles are occasionally used in the living room, while air fresheners and diffusers are frequently used in the kitchen and bathroom “*to get rid of cooking smells.*”

This is a naturally ventilated home, so occupants primarily rely on opening windows for airflow and odour control. They prefer to “*open the window with a slight gap during cooking and cleaning.*” However, several barriers to frequent window use were cited, including “*noise, security, pollution, heat loss, and even we don’t feel the need to.*” This highlights the subjective and situational nature of window-opening behaviour and suggests that, while natural ventilation is the only available option, it is used selectively based on comfort and risk perception. Additionally, reliance on air fresheners and diffusers may mask indoor pollutants rather than address their root causes, underscoring the need for greater awareness of pollutant sources and for effective ventilation strategies in naturally ventilated homes.

The occupant of CS5 rated the indoor air quality as “*very good,*” although it was noted that the air “*sometimes tends to become stuffy,*” indicating general satisfaction with occasional discomfort. IAQ was considered “*quite important,*” particularly in relation to preventing mould

and condensation. Cooking typically takes place most evenings, with meals often prepared in advance for multiple days. Ventilation during cooking and cleaning is primarily managed by opening windows, with the occupant reporting a preference to “*open the window with a slight gap*” to allow fresh air in while retaining indoor warmth.

Daily cleaning occurs in the evening, especially after cooking, using surface sprays and wipes, with the kitchen floor mopped regularly. On weekends, the occupant undertakes more thorough cleaning, including vacuuming and using bleach in the bathrooms. Scented candles are used in the living room and corridors, while air fresheners and diffusers are applied in the kitchen and bathrooms “*to get rid of cooking smells.*”

Although this home relies entirely on natural ventilation, the occupant expressed some reluctance to open windows more frequently, citing “*security, heat loss, and a sense of not always needing to ventilate.*” These responses demonstrate a nuanced approach to managing IAQ, striking a balance between comfort, energy concerns, and safety. The regular use of odour-masking products suggests a possible lack of awareness of their contribution to pollution. This case highlights the importance of enhancing occupant understanding of how everyday behaviours affect IAQ and of how informed decisions can effectively mitigate indoor pollution, even in naturally ventilated homes.

The interview data from CS6 offer valuable insights into occupant behaviour influencing IAQ. The occupant described IAQ as “*generally pretty good,*” though they noted that the kitchen can “*get a bit stuffy and retain cooking smells*” during activities like roasting or frying. Cooking occurred mainly in the evenings, with occasional batch preparation. Cleaning was frequent and involved both natural products: “*surfaces are sprayed and wiped with Ecover after each use.*” Air fresheners and diffusers were used throughout the home to manage odours, particularly due to pet ownership. Although no major IAQ concerns were reported, the occupant stressed the importance of mechanical extraction in bathrooms without windows. Overall, CS6 demonstrated an informed and proactive approach to maintaining indoor air quality through daily routines and awareness of ventilation.

To complement the qualitative insights from interviews and questionnaires, Table 5.3 presents a comparative summary of pollutant concentrations across the five case-study homes. These data illustrate the tangible impact of daily habits and ventilation behaviours on IAQ and reinforce the variation in outcomes attributable to occupant practices.

Table 5. 3: Comparative Analysis of PM2.5, TVOC, and CO2 concentrations across case studies.

Case Study	PM2.5 Median ($\mu\text{g}/\text{m}^3$)	PM2.5 Max ($\mu\text{g}/\text{m}^3$)	TVOC Median ($\mu\text{g}/\text{m}^3$)	TVOC Max ($\mu\text{g}/\text{m}^3$)	CO2 Median (ppm)	CO2 Max (ppm)
CS1	4	12	200	1000	800	1600
CS2	3	10	100	300	700	1400
CS3	2	6	50	300	650	1200
CS4	3	11	150	800	700	1500
CS6	2	6	75	300	600	1000

Table 5.3 compares indoor air quality metrics, PM2.5, TVOC, and CO₂ across five case studies (CS1–CS4, CS6). CS1 exhibited the highest pollutant concentrations, with a median PM2.5 of 4 $\mu\text{g}/\text{m}^3$ and a maximum of 12 $\mu\text{g}/\text{m}^3$, TVOC peaking at 1000 $\mu\text{g}/\text{m}^3$, and CO₂ reaching 1600 ppm, indicating the highest pollutant load among the homes monitored. CS4 similarly reported elevated VOC levels, with a TVOC maximum of 800 $\mu\text{g}/\text{m}^3$, suggesting high levels of pollutant-generating activity. CS2 showed moderate IAQ conditions, while CS3 and CS6 recorded the lowest concentrations across all three parameters, indicating comparatively better IAQ. These findings support earlier qualitative insights, reinforcing the ways in which differences in occupant activities, ventilation strategies, and system usage influence IAQ performance across households.

CS5 has been excluded from Table 5 because its data were collected in 2021 under a different monitoring timeline and environmental conditions. To ensure consistency and comparability across pollutant levels (PM2.5, TVOC, and CO₂), only case studies conducted within the same monitoring window (2022) were included in this comparative analysis. Nonetheless, CS5 remains part of the qualitative analysis to provide behavioural insight across the broader sample.

Section summary.

The interview findings complement the questionnaire responses by providing deeper insight into how occupants manage indoor air quality through daily routines and personal judgment. While most participants perceived their IAQ as “*very good*,” the interviews revealed behaviours such as frequent cooking, the use of strong cleaning agents, scented products, and

reliance on opening windows, which may contribute to pollutant accumulation or undermine the effectiveness of installed ventilation systems. These insights highlight the complexity of occupant behaviour, showing that past experiences, comfort preferences, safety concerns, and varying levels of awareness often influence decisions. Importantly, they demonstrate that no single solution can address all IAQ challenges; instead, effective strategies must be context-specific, combining user-friendly system design with targeted occupant education to support healthier indoor environments in both mechanically and naturally ventilated homes.

5.2.4 Behavioural Change Experiment – A Mixed-Methods Evaluation of Awareness and Daily Practices.

The primary aim of this experiment was to evaluate whether providing real-time access to IAQ data could influence occupant behaviour and improve air quality outcomes. The intervention involved a live dashboard displaying pollutant levels, notably PM_{2.5}, TVOC, and CO₂, which were monitored using Uhoor Aura sensors. The experiment was conducted in four of the six case study homes: CS1, CS3, CS5, and CS6. These households consented to participate in the study during the final phase of the monitoring period. The experiment centred on a behavioural and educational intervention designed to raise awareness of IAQ. Participants were informed about the health-related thresholds for each pollutant and about how specific household activities, such as cooking, cleaning, or using fragranced products, can affect them. By providing this knowledge alongside real-time visual feedback, the intervention aimed to encourage occupants to make informed decisions that could improve their IAQ.

Before the experiment, a semi-structured interview was conducted to evaluate participants' experiences and their awareness of IAQ. The occupants were also asked to complete a daily diary activity to monitor pollutant concentrations.

The study's key focus was the educational intervention. The aim was to evaluate the impact of educating occupants on real-time data on IAQ parameters and their thresholds. This intervention involved explaining how specific activities, such as cooking, cleaning, or using household products, could affect pollutant levels in their homes. By providing this knowledge, we aimed to enable the occupant to make informed decisions to improve their IAQ. Additionally, by enabling the occupant to access real-time IAQ data via a dashboard, the study sought to determine whether this awareness would lead to changes in their behaviour. For example, would they alter their cooking habits, increase ventilation during high-pollutant

activities, or adopt other practices to improve IAQ? The key aspect of this study was comparing IAQ data before and after access to the dashboard was permitted. This method allowed for a clear assessment of the impact of occupant behaviour on air quality. The comparison was instrumental in understanding whether informed occupants made conscious efforts to improve their IAQ.

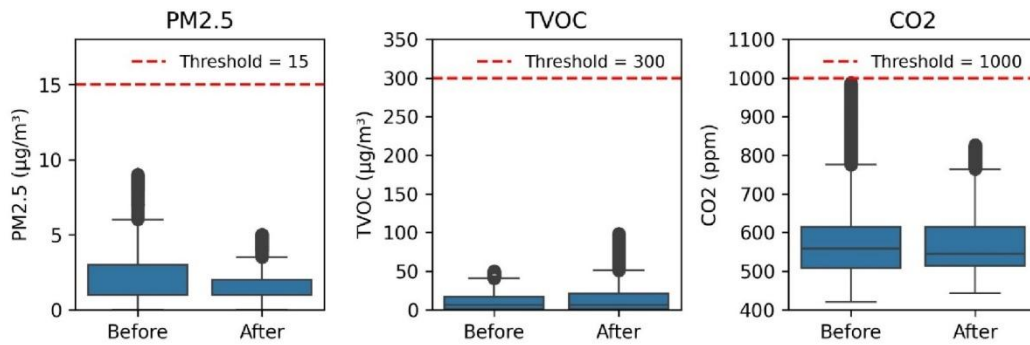
The study analysed whether occupants modified their behaviour in response to the information provided. This included tracking changes in ventilation practices, the use of activities that generate pollutants, and overall awareness of IAQ. This analysis also involved examining specific events, such as cooking sessions, to determine whether there was a noticeable reduction in pollutant peaks.

To increase occupant awareness, the sensor output provides device awareness, enabling the dashboard platform to display air quality information clearly and accessibly, allowing users to understand their environment and respond effectively without feeling overwhelmed ([Gabriel et al., 2024](#)). The uHoo sensor, with its dashboard capability, was utilised in this research. Occupants were granted access to this dashboard, which uses a colour-coded traffic light system to indicate their level of exposure to poor air quality.

The experimental design involved comparing data from two separate phases:

1. *Phase One (before)*: When the occupant had no access to sensor data. In the first phase of this study, we conducted initial monitoring. This involved monitoring the IAQ without the occupants having access to the sensor data. This phase was crucial for establishing a baseline of typical pollutant levels and activities under no intervention or awareness.
2. *Phase Two (after)*: The occupant was provided access to the sensor data dashboard and was educated on pollutant parameters, their threshold, and the correlation between their activities and IAQ. In the second phase, occupants were given access to a user-friendly dashboard that displayed real-time IAQ data via a traffic-light visualisation. Red indicated poor air quality, green indicated good air quality, and amber served as a warning. They were also provided with a simple educational explanation of different pollutants, their safe thresholds, and how various activities, such as cooking and cleaning, affect IAQ.

CS5: Sensor data was compared before and after the occupant gained access to the IAQ dashboard.



Before: 25 – 31 Dec 2021 **vs After:** 1 – 7 Jan 2022 (Two-week experiment).

Figure 5.16: Comparison of one week without and one week with the IAQ sensor dashboard in CS5.

Figure 5.16 illustrates the changes in PM2.5, TVOC, and CO₂ levels in CS5 before and after the occupant gained access to the IAQ dashboard. The data compares two one-week periods: before (December 25–31, 2021), when the occupant had no visibility into indoor air quality data, and after (January 1–7, 2022), when real-time sensor readings became accessible via a live dashboard.

The PM2.5 data show a reduction in both the median concentration and the upper range after accessing the dashboard. The median dropped from approximately 3.5 µg/m³ to about two µg/m³, with fewer extreme values observed. This suggests that the occupant may have responded to the data by modifying behaviours related to particle generation, such as improving ventilation during cooking or reducing the frequency of activities that produce particulates. In contrast, TVOC levels show only a slight reduction. The median remains relatively stable, and although the upper range seems slightly narrower, it suggests that changes in VOC-related activities were limited. This may indicate either a delay in behavioural adaptation or a lack of clarity regarding which actions contribute most to VOC emissions. CO₂ concentrations also show a modest decline in median values, from approximately 600 ppm to just below 550 ppm, along with a reduction in the range of high readings. This indicates an improvement in

ventilation behaviour, potentially due to increased window use or decreased occupancy density during peak times.

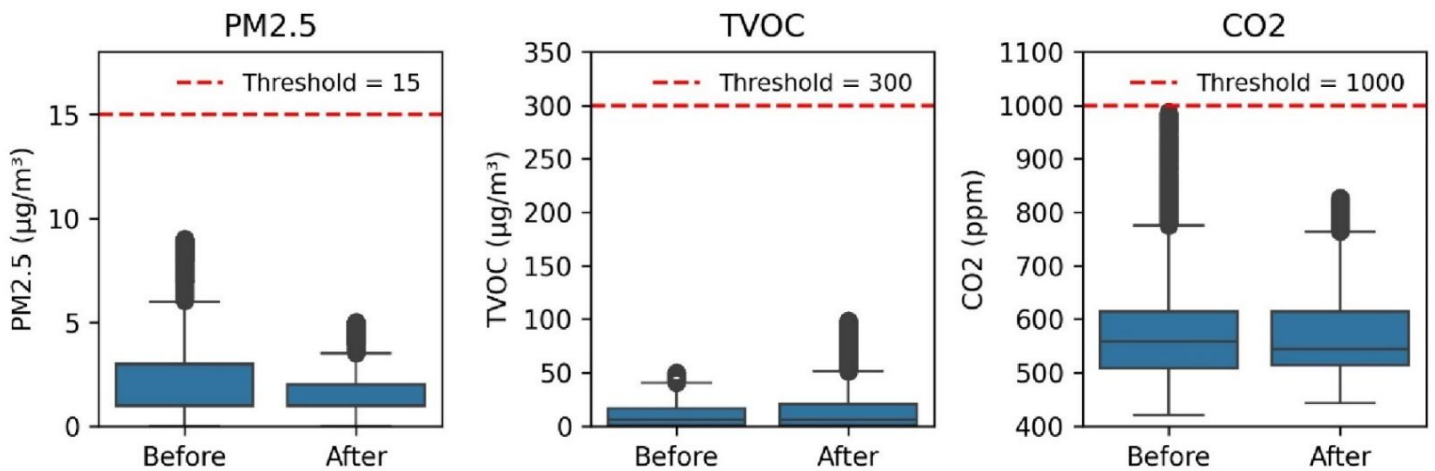


Figure 5. 17: Example of the occupant engagement with IAQ sensor data shared by the occupant.

Figure 5.17 was shared directly by the occupant of CS5 (Tamworth), demonstrating their engagement with the real-time IAQ dashboard. It displays minute-by-minute CO₂ readings recorded in the kitchen on 14 January 2022. At approximately 11:20 AM, the graph indicates a sharp rise in CO₂ concentration, from about 700 ppm to over 860 ppm within 15 minutes. According to the occupant, this spike occurred after they intentionally closed the window in response to outdoor smoke from a fire and poor outdoor air quality. This observation highlights how rapidly IAQ can deteriorate when ventilation is restricted, even over a short period.

The occupant's accompanying comments reflect strong enthusiasm for the data and a growing awareness of IAQ dynamics: *"You have just left our house, and I opened the window for a short period just after you left; there is more toxic air outside than in on this foggy day. I like this. It is interesting."* They further noted how the visual feedback from the dashboard influenced their understanding of indoor conditions: *"One thing I have noticed on the charts is that the hotter I have set the heating, the higher the carbon dioxide levels, which I guess isn't rocket science, I guess, but I never realised until I saw it on the graphs."* These reflections underscore how real-time sensor feedback can prompt greater environmental literacy and behavioural awareness. The figure not only evidences a specific IAQ event but also reinforces the role of occupant-facing tools in promoting more responsive and informed air quality management within homes.

CS6: Sensor data was compared before and after the occupant gained access to the IAQ dashboard.



Before: 24 – 30 April 2022 **vs After:** 25 – 31 May 2022 (Two-week experiment).

Figure 5. 18: Comparison of one week without and one week with the IAQ sensor dashboard in CS6.

Figure 5.18 illustrates the impact of providing real-time IAQ feedback to the occupants of CS6 by comparing pollutant levels (PM2.5, TVOCs, and CO₂) before and after access to a live sensor dashboard. The "before" period spans from April 24 to 30, 2022, and the "after" period covers May 25 to 31, 2022. Each phase represents one week of monitored data, with and without occupant access, respectively.

The box plots reveal that PM2.5 levels before access had higher medians and wider distributions, indicating more frequent and higher spikes in PM2.5. After access, lower median levels and a narrower distribution suggest that occupants may have reduced activities contributing to PM2.5 or improved their ventilation practices. TVOC levels before access had higher median levels and a wider distribution, whereas after access, TVOC levels were slightly higher in both the median and the distribution. Interview responses revealed that the occupant had purchased new furniture, which explained the higher TVOC levels. TVOC levels can be influenced by the age of the home, with newer homes having the highest mean levels, particularly in those where painting has been done, and new furniture has been introduced (McGill et al., 2015), as in this case. Despite these differences, Figure 45 effectively communicates that access to real-time air quality data via the sensor dashboard can influence occupants' behaviour, thereby improving IAQ. This aligns with the idea that awareness and real-time feedback can improve indoor environment management.

Occupant CS6 also stated in the interview that they noted, "*Since using the sensor in my routine for a few weeks now, I've become more mindful of the air quality I'm exposed to. As a result, I've made changes, particularly using the booster of the extract fan during cooking and cleaning and avoiding using scented candles.*" This quote highlights how visualising IAQ in real-time can enhance environmental literacy, raise awareness of indoor habits, and prompt healthier ventilation behaviours.

Before being shown the sensor data, occupants often lacked awareness of how their daily activities influenced IAQ or how poor air quality could impact their health and well-being, highlighting an environmental literacy gap (Wargoeki & Kostyrko, 2022). Other studies have found that raising awareness can effectively encourage behaviour change (Ferguson et al., 2021; Abdel Sater et al., 2024). This research supports these findings, revealing that occupants' awareness of IAQ-related problems increased after they were granted access to the sensors. Only shortly after incorporating device data into their routines did occupants become aware of their activities and behaviour patterns and subsequently change their behaviour to improve their homes' air quality.

In CS1, the occupant initially relied on habitual window opening as the primary means of ventilation, practices shaped by previous housing experiences and a limited understanding of the MVHR system. However, a marked behavioural shift was observed after gaining access to the IAQ dashboard between July 6 and 31, 2022. The occupant stated, "*We realised that the MVHR background ventilation was working by viewing the sensor data, which showed all the pollutant levels green, and it was also educational as we always check when we are cooking or cleaning to check whether it is necessary to open the window or not.*" This new awareness reduced window use, particularly during colder periods, thereby improving energy efficiency. The occupant also began checking pollutant levels on the dashboard to guide decisions about cooking and cleaning, illustrating how real-time visual feedback can encourage greater engagement with building systems and promote more effective IAQ management.

In CS3, access to the dashboard during the same July period enabled the occupant to link specific activities, such as burning traditional incense and scented candles, with spikes in pollutant concentrations. Before this intervention, these products were routinely used for odour control and comfort. After accessing the sensor data, the occupant noted, "*We used to use many candles and traditional oud sticks, particularly at nighttime. We stopped using too much of the traditional and scented candles, as we realised the concentration levels were elevated, and*

after talking to the researcher, decided to minimise using them.” This awareness reduced the use of fragranced products and encouraged the implementation of more effective ventilation strategies during activities that generate pollutants. The case illustrates the potential of data-driven feedback to influence occupant behaviour and reduce unnecessary indoor pollution, reinforcing the value of real-time monitoring as a tool for promoting and educating occupants by presenting real-world data.

These findings demonstrate that increased awareness, supported by real-time feedback, can lead to measurable improvements in IAQ. This supports Ferguson et al. (2021), who highlight the role of feedback in influencing behaviour. The results further indicate that behavioural adaptation is not immediate or consistent, as some pollutant sources, such as VOC emissions from materials, remain less responsive to short-term behavioural changes.

5.2.5 Occupant Daily Diary.

This section involves producing daily diaries for occupants to complete, recording their activities in specific areas, including cooking, cleaning, ventilation, and other relevant behaviours. Occupant diaries were disseminated to occupants, and they were briefed on how to complete the diary (figure 44), which contained detailed questions about:

- Cooking activities
- Ventilation activities (habits)
- Cleaning activities
- Occupant special activities (e.g., Smoking, candle burning, air freshener use, etc.)

The record sheet was condensed to a single A4 page for each measurement day to minimise the burden and encourage participation. This format was designed to capture a comprehensive range of indoor-environment source activities at hourly intervals, including occupants' daily habits and routines. By maintaining detailed records of their time-activity patterns, occupants can document their location and activities at specific times, offering valuable insights into their interactions with the indoor environment.

Occupants could fill out these diaries weekly and submit them via email, providing real-time insights into their behaviours. Alternatively, some occupants completed the provided A4 paper

diaries, which the researcher collected every two weeks. This dual approach was used to accommodate occupant preferences, making it easier to ensure their full participation. This method facilitated comprehensive data collection, enabling a deeper understanding of the impact of increased awareness on IAQ practices.

The primary aim of this daily diary is to complement sensor-monitored data by explaining any unusual spikes or patterns in IAQ measurements and comparing these spikes with recorded activities. For example, an unexpected increase in particulate matter could correlate with vacuuming or the use of an air freshener spray, as noted in the diary. By cross-referencing diary entries with sensor data, researchers could pinpoint when and which specific activities contributed to changes in indoor pollution levels. This detailed behaviour record is essential for understanding the impact of everyday activities on IAQ and for developing effective strategies to improve indoor environments and mitigate the effects of poor air quality on health and well-being. Figure 39.19 presents the daily diary tool used for this study.

		Indoor Environment Source Activities						
House ID		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Activities Tick Box:		Time (e.g. 7 A.M. – 8 A.M.) Week						
Cooking Activities	<input type="checkbox"/> Frying							
	<input type="checkbox"/> Toasting							
	<input type="checkbox"/> Microwave use							
	<input type="checkbox"/> Water boiling, etc.							
	<input type="checkbox"/> Baking							
Total Hours								
Ventilating Activities	<input type="checkbox"/> Window/Door opening							
	<input type="checkbox"/> Switching on the extractor fan							
	<input type="checkbox"/> Other							
Total Hours								
Cleaning Activities	<input type="checkbox"/> Vacuuming							
	<input type="checkbox"/> Sweeping							
	<input type="checkbox"/> Floor Waxing							
	<input type="checkbox"/> Use of Cleaning Products or Furniture Polish							
	<input type="checkbox"/> Other							
Total Hours								
Occupant Special Activities	<input type="checkbox"/> Smoking							
	<input type="checkbox"/> Candle Burning							
	<input type="checkbox"/> Painting							
	<input type="checkbox"/> Spray Air Fresheners							
	<input type="checkbox"/> Electric Air Freshener Diffuser							
<input type="checkbox"/> Other								
Total Hours								

Figure 5. 19: Occupant daily diary logging tool.

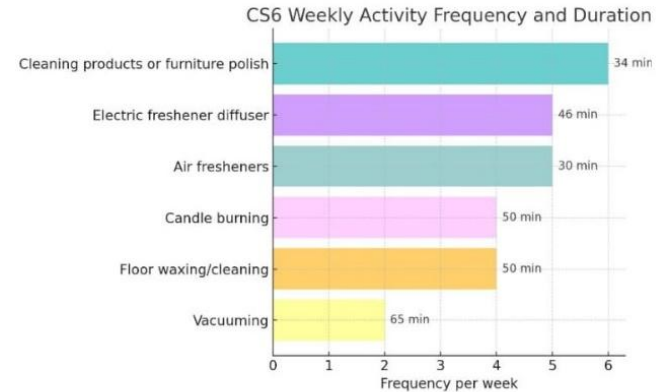
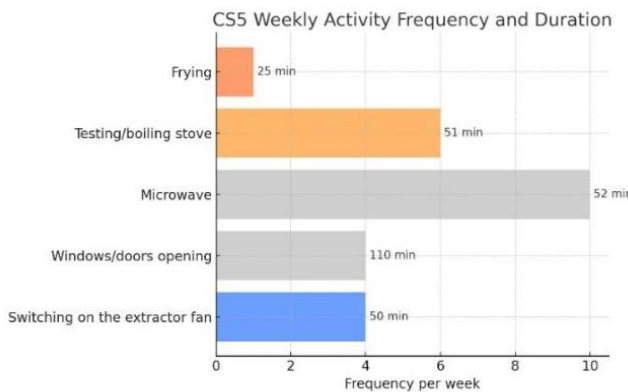
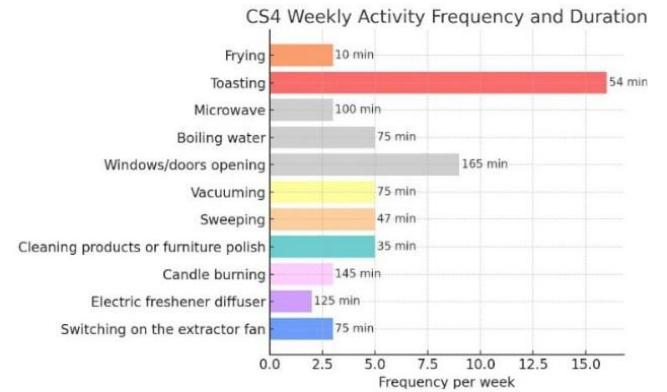
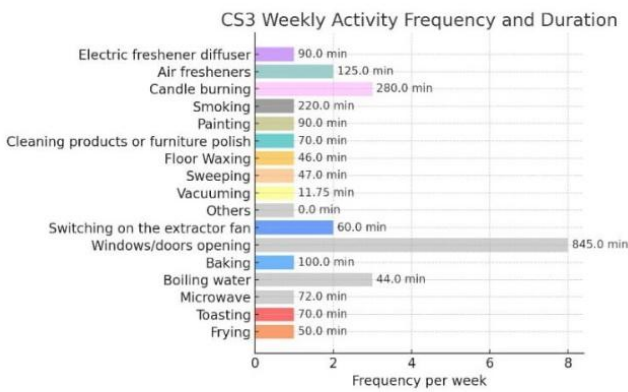
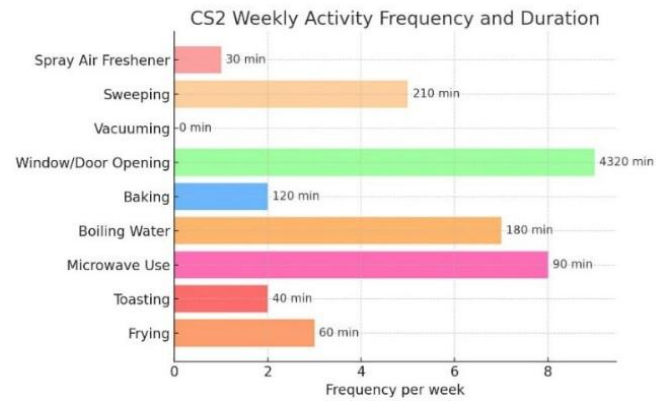
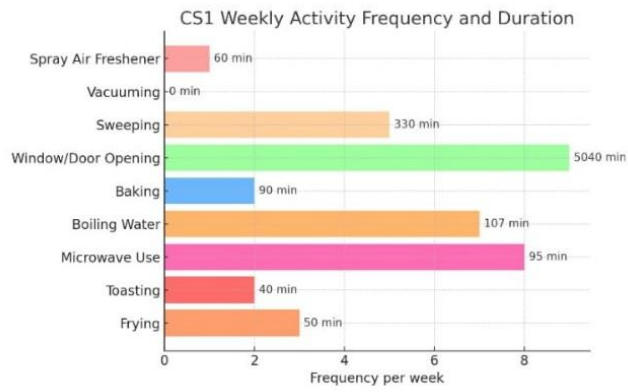


Figure 5.20: Weekly summaries of indoor environmental source activities across all case studies (CS1–CS6).

Figure 5.20 presents the weekly activity patterns logged by occupants in each case study home (CS1–CS6), illustrating the total frequency (number of times per week) and total duration (in minutes) of key indoor activities, including cooking, cleaning, ventilation, and special activities such as the use of air fresheners or scented products. The charts highlight variations in behaviours across households and visually demonstrate the range of activities that contribute to indoor air quality outcomes. This comparative summary offers insights into how specific

routines and occupant choices impact IAQ, highlighting the diversity of household practices in newly constructed homes.

The daily activity diaries for CS1, CS2, and CS3 reveal distinctive patterns in domestic routines and their potential implications for indoor air quality (IAQ). In CS1, boiling water, cooking in the microwave, and sweeping were the most frequently reported activities, with boiling water standing out for both its high frequency and its prolonged weekly duration. Window or door openings were consistently recorded, indicating a strong reliance on natural ventilation strategies, regardless of season or activity. Data from CS1 show that daily cooking and cleaning are integral to household routines, resulting in sustained occupancy-related emissions, while near-continuous window opening reflects an occupant's belief in the necessity of window opening for IAQ control.

For CS2, the occupant reported frequent use of the microwave, boiling water, and sweeping, similar to CS1. However, they also logged regular oven use and more intensive baking sessions. Notably, CS2 demonstrated a higher frequency of overall cooking activities, consistent with interview data indicating multiple daily meal preparations. This high activity rate and persistent window openings suggest a greater potential for pollutant generation, even with regular air exchange. The diary also records less frequent use of extractor fans, which may highlight a gap in the effective use of mechanical ventilation.

CS3 presented a slightly different pattern, with the microwave and sweeping remaining common, but “toasting” emerged as a frequent activity. Opening windows and using extractor fans were less prominent than in CS1 and CS2, suggesting a possible reliance on background mechanical ventilation or limited engagement with natural ventilation. However, the overall time spent on activities was lower, and the frequency of tasks such as boiling water and baking decreased compared to previous cases. These differences suggest that occupant lifestyle, appliance choice, and ventilation habits play a central role in shaping exposure to indoor pollutants, with each case showing unique interaction patterns between behaviour and IAQ management.

For the naturally ventilated homes CS4, CS5, and CS6, the diary data further highlight the diversity of daily behaviours and their potential impact on IAQ. In CS4, toasting and microwave cooking were common, while sweeping and opening windows constituted a significant portion of daily activities. The regular use of natural ventilation is apparent, as is

the integration of cleaning tasks into the weekly routine. The high frequency and duration of window openings demonstrate both a reliance on and an awareness of natural ventilation to reduce the accumulation of indoor pollutants.

CS5 showed slightly lower frequencies for most activities but consistently longer durations for opening windows and doors, indicating intentional, potentially prolonged ventilation. Tasks like cleaning, cooking, toasting, and using the microwave remained important parts of weekly routines. The balance between activity frequency and ventilation duration suggests an occupant strategy focused on diluting potential emissions from daily tasks. This practice aligns with interview findings indicating awareness of the importance of regular ventilation for controlling odours and perceived stuffiness.

In CS6, activities such as toasting, sweeping, and using the microwave occurred most frequently. Sweeping was conducted nearly every day, underscoring a strong emphasis on cleanliness. Opening windows and using the extractor fan were reported for significant durations, indicating proactive ventilation behaviour. These patterns align with an occupant who is both engaged in regular household maintenance and aware of the necessity to balance indoor activities with effective pollutant dilution.

5.2.5.1 Discussion and Analysis.

The analysis was performed after the monitoring period, with occupant diaries collected throughout the period. The primary aim was to identify instances of poor IAQ in the surveyed homes, assess the presence of pollutants in relation to diary-reported activities, and evaluate the correlation between behavioural variables and IAQ measurements. Figures were produced to summarise key observations and findings.

The results from the occupant daily diaries confirm that achieving good IAQ is a complex challenge, influenced by interactions among building design, interior layout, systems, occupant behaviour, and environmental conditions. As shown in Figure 45, daily routines, such as the frequency and duration of cooking, cleaning, and ventilation, as well as the use of air-polluting products, directly affect the indoor environment. A common barrier to maintaining focus on IAQ is the intangible nature of its health benefits and the difficulty in measuring them, as noted by Persily and Emmerich (2012). They observed that IAQ often receives less consideration in

building design paradigms, with attention typically directed towards more measurable or visible issues.

Bone et al. (2010) further highlight that building rating tools tend to prioritise factors such as water and energy use over health-related aspects, making IAQ a less visible priority. Meanwhile, Salthammer (2014) and Persily & Emmerich (2012) emphasise that the complexity of IAQ stems from the diverse range of indoor contaminants and their variability over time, across space, and with individual activities. This makes it challenging to define and assess IAQ performance solely on the basis of contaminant concentrations, given individual susceptibilities and the absence of comprehensive guidelines for most indoor pollutants.

These findings from the activity diaries underscore the need for holistic and behaviourally informed strategies to improve IAQ. They also highlight the importance of educating and engaging occupants, as awareness and targeted feedback, such as the visual data provided in this study, can prompt meaningful behavioural changes that contribute to healthier indoor environments.

Section summary.

The daily diary data, supported by interview responses, illustrate that occupant behaviour plays a pivotal role in maintaining good IAQ in residential settings. In all cases, household routines such as frequent cooking, cleaning, and ventilation strategies directly affect the timing and magnitude of indoor pollution events. The variability observed between homes highlights that there is no universal pattern; instead, individual decisions, habits, and levels of engagement with ventilation systems are the key factors influencing IAQ outcomes.

These findings reveal a clear need for targeted occupant education as a central solution for improving IAQ. Many households rely on habitual behaviours, such as frequently opening windows or selectively using extract fans, often without fully understanding the benefits or limitations of their installed ventilation systems. Educating occupants by raising awareness of pollutant sources, providing practical guidance on adequate ventilation, and leveraging real-time IAQ feedback can empower residents to make informed choices. Such interventions can lead to more consistent and efficient practices, reduce unnecessary energy loss, and promote healthier indoor environments. The evidence from this study emphasises that behaviour

change, supported by clear education and feedback, is essential for achieving and maintaining good IAQ in newly built homes.

5.3 Technology and Systems.

This section presents and discusses the results of interviews with residents of the studied homes, focusing on the design characteristics and occupant interactions associated with the residential technologies implemented in these homes. It examines the effectiveness of different ventilation systems, ranging from MVHR and centralised continuous MEV to decentralised continuous DMEV and natural ventilation, and how this effectiveness is influenced by both their technical specifications and the ways in which residents understand and operate them. The section explores patterns of system use, habitual behaviours such as opening windows and doors, and the challenges associated with usability, technological understanding, and perceived adequacy in managing IAQ. Table 5.4 summarises the ventilation strategies and technologies investigated in the studied homes.

These findings are analysed in relation to both observed occupant behaviour and existing literature to assess how system performance is influenced not only by technical design but also by user interaction.

Table 5. 4: Overview of ventilation systems installed in case study homes.

Location	Birmingham UK			Burton upon Trent	Tamworth	Chelmsford
Cases	CS1	CS2	CS3	CS4	CS5	CS6
Ventilation Type	Mechanical Ventilation with Heat Recovery (MVHR)	Mechanical Ventilation with Heat Recovery (MVHR)	Natural ventilation with decentralised Continuous Mechanical Extract Ventilation (dMEV)	Natural ventilation with decentralised Continuous Mechanical Extract Ventilation (dMEV)	Natural Ventilation	Centralised Continuous Mechanical Extract Ventilation (MEV)

Table 5.4 summarises the ventilation technologies and their specifications across six case study homes, providing context for understanding differences in occupant interaction and usage practices. Cases CS1 and CS2 (Birmingham) are equipped with Mechanical Ventilation with Heat Recovery (MVHR), while CS3 (Birmingham) and CS4 (Burton upon Trent) are naturally ventilated with decentralised Continuous Mechanical Extract Ventilation (dMEV). CS5 (Tamworth) is naturally ventilated with mechanical extractors from the kitchen and wet rooms, and CS6 (Chelmsford) features centralised Continuous Mechanical Extract Ventilation (MEV).

The variety of systems reflects both homes built to the Future Homes Standard (CS1–CS3) and those following the current UK building standard (CS4–CS6).

5.3.1 Ventilation system.

To understand the impact of occupant behaviour on ventilation practices, households completed questionnaires and participated in interviews. The results provide insights into ventilation usage during activities such as cooking and cleaning.

In CS1, the occupant reported relying more on opening windows than on the MVHR system, stating, *"We get used to opening the windows for fresh air from the morning, and some days all day, especially in the summertime."* Their lack of confidence in the MVHR system stemmed from both limited control and understanding, as well as the absence of a boost button, which further reduced its perceived effectiveness. Figure 41 shows the kitchen window habitually left open, thereby compromising the system's heat-recovery efficiency and increasing energy consumption.

The occupant noted that in their previous home, they regularly used the cooker hood during cooking and boosted a fan when showering. In contrast, they expressed a lack of confidence in the new system, stating, *"This gave us no confidence in the system as we did not know how to control the system, and it may take a while to get used to it."* The absence of a boost button in CS1 was clearly an issue for the occupant, alongside their lack of understanding of the system.

CS1-Birmingham



Figure 5. 21: Kitchen window in a partially open position, illustrating occupant ventilation preference during cooking.

The occupants of CS1 habitually keep the kitchen window open all day during the summer and, most of the time, in the winter, believing it provides fresh air. Figure 5.21 illustrates the significant gap that results from leaving the window open for extended periods. This behaviour undermines the efficiency of the MVHR system, resulting in increased energy consumption and higher utility bills. Such observations highlight the need for better occupant education on ventilation systems and the importance of encouraging behavioural change.

Similar issues were observed in CS2, where the occupant also left windows open for most of the day, expressing uncertainty about the MVHR system's functionality and its effectiveness at removing cooking odours. The occupants did not fully understand how the system operated and sometimes felt that it was not effectively extracting odours and pollutants during cooking. As a result, they often reverted to the traditional method of opening the kitchen window. The occupant reported that the windows were open most of the day and closed as the day progressed, typically shut in the evening. In both homes, the boost button wasn't working, which might lead to different outcomes once the boost is installed.

This behaviour is consistent with observations in the CS3 naturally ventilated home, where the pattern of window opening, as a habitual and personal preference, was identical to that in CS1 and CS2. However, CS2 has a point-extraction fan that runs automatically in the kitchen and bathrooms as background ventilation, and it features a humidity sensor that activates when humidity exceeds 60%. On the day of the interview, the fan was found to be off. When asked if they were aware that the fan was off, the occupant replied, *"I didn't know where to turn it on and off and didn't know that it comes on automatically."* We also asked if they knew about the options to boost the fan during cooking and cleaning, and they replied, *"Yes, we pull the cord to boost it."* The system works by either pulling the cord or automatically switching to boost mode if the room's humidity exceeds 60%. This was demonstrated to the occupant, showing that the fan enters boost mode when the humidity threshold is crossed. However, activating the sensor proved difficult because the fan was mounted far from the cooker area, limiting its effectiveness.

The primary observation in CS4 indicated that the occupant recognised the importance of ventilation. They demonstrated this by opening the kitchen window during cooking and cleaning and keeping the kitchen door closed to prevent food odours from spreading throughout the house. However, when asked about the trickle vents, the occupant was unaware of them.

As with CS3, the occupant was unaware of the automated boost fan and background ventilation and relied primarily on opening windows to control the indoor environment.

These observations reveal varying levels of occupant understanding and engagement with ventilation systems across the studied homes. While most occupants recognised the importance of ventilation, they often lacked the knowledge to use mechanical systems effectively. This pattern extended to CS5 and CS6, where similar behaviours were observed, including habitual window opening due to perceived inadequacies in ventilation systems.

5.3.1.1 Challenges with Ventilation Systems.

Recent evidence indicates significant ventilation and IAQ issues in most new homes, primarily due to inefficient ventilation systems (Sharpe et al., 2015; Wargocki, 2013). Studies have linked low ventilation rates with adverse health effects (Wargocki, 2002; McGill et al., 2015). Increasing evidence suggests that these systems are regularly inadequately specified, installed, commissioned, and used (Dimitroulopoulou et al., 2023; Singer et al., 2017), resulting in inadequate ventilation and higher energy consumption (McGill et al., 2015). This aligns with our findings in cases CS1 and CS2, in which the windows were open while the MVHR system was operating in background ventilation mode. This was due to a combination of habit and frustration, as occupants did not believe that the system was effectively extracting food odours during cooking. Additionally, poor maintenance further undermines their effectiveness, thereby degrading IAQ. Some occupants may turn off these systems due to a lack of understanding and concerns about energy efficiency (Mlecnik et al., 2012). Many are unaware of the advantages of mechanical ventilation, leading to systems being switched off or neglected in terms of maintenance (Sharpe et al., 2015).

5.3.1.2 Implications for Residential Ventilation.

The findings suggest that window-opening behaviour is primarily influenced by occupants' habits and personal preferences rather than the form of the building fabric. However, airtight building envelopes may exacerbate this behaviour, particularly during warmer seasons, as occupants seek to compensate for perceived ventilation inadequacies.

Occupant behaviour, driven by habit and a limited understanding of mechanical systems, plays a significant role in ventilation practices. The tendency to rely on window openings rather than

mechanical systems often stems from frustration or a lack of confidence in mechanical systems. This emphasises the importance of occupant education on ventilation technologies, system design and placement, and proper installation and maintenance.

One major challenge is the recent introduction of complex ventilation services in residential buildings, as the UK residential sector still lacks extensive experience in their design, installation, and operation. Ventilation strategies are often poorly integrated with other home features, and spatial constraints can lead to suboptimal positioning of ventilation components. This results in misuse, insufficient maintenance, and ineffective operation, further compounded by system failures or malfunctions. Such issues not only pose risks to IAQ but also undermine energy-efficiency strategies, as occupants open windows, leading to increased heat loss and higher energy consumption.

This research adopts a holistic Pathway Approach to address IAQ and ventilation systems in residential settings. It explores the complexities of ventilation performance, uncovering multiple uncertainties that impact air quality and ventilation strategies. While this study provides a foundational framework, some aspects have been treated superficially due to its limited scope. Future research should incorporate practical considerations and industry feedback to refine and expand upon the findings.

Although energy performance is beyond the scope of this study, the research lays a solid foundation for more focused studies on specific topics identified in this work. By optimising ventilation systems and developing appropriate mitigation strategies, this study aims to improve IAQ in new residential buildings and serve as a stepping stone for further advancements in the field.

5.3.2 Discussion of technology and systems.

Interviews with occupants revealed a consistent lack of awareness of the MVHR system's purpose and operation across all cases. Most occupants did not rely on the MVHR system to meet their fresh-air requirements and were unfamiliar with how it operated. This lack of understanding, compounded by inadequate handovers and guidance, created significant operational challenges.

In some cases, occupants perceived the MVHR system as a source of high electricity bills because it was described as "*always on.*" This lack of understanding regarding the system's

purpose, energy consumption, and operation, compounded by inadequate handovers and poor guidance, led to scepticism and mistrust. Issues such as not knowing whether the system was operational and improper commissioning further discouraged occupants from using it. Some individuals actively closed supply vents or attempted to deactivate the system, negatively impacting IAQ and energy efficiency. For example, in CS2, the absence of a boost button left occupants unable to adjust the system's performance during activities such as cooking, resulting in frustration and diminished trust. The occupants stated, "*The problem is not only that the system boost button was not installed, but also that we can't increase it as we don't understand it fully yet.*" As a result, they relied on natural ventilation through window openings, undermining the MVHR system's efficiency and increasing energy consumption.

In contrast, CS6 faced initial operational difficulties despite having a boost button installed. The occupants believed the extract hood fan and the MVHR system's background ventilation were sufficient to manage pollutants during cooking and cleaning, and rarely used the boost button. However, after being introduced to a sensor dashboard, they observed that PM2.5 and TVOC levels during cooking and cleaning did not dilute as quickly as expected. This insight prompted them to begin using the boost button and open windows to increase pollutant removal. Although this improved the system's effectiveness, it also highlighted a key operational challenge: the need for feedback mechanisms to bridge gaps in occupant understanding and system usability.

Building operations involve a wide range of services, capabilities, procedures, and technologies essential to ensuring buildings perform their intended functions (Gupta & Kapsali, 2015). In residential contexts, these activities include operating and maintaining equipment, systems, and access control, as well as other cleaning and operational practices (Gola et al., 2019). The study revealed that occupants did not always use the provided ventilation technologies as intended. For example, mechanical ventilation and the extract fans were sometimes switched off during cooking. These findings are not unique and have been observed in previous studies (Moreno-Rangel et al., 2023; Wells et al., 2015). Although occupants are expected to receive guidance on operating and maintaining ventilation equipment (HMG, 2010e), this guidance did not always result in the intended operation in these cases.

This raises the question of how to more effectively encourage the intended use of such technologies. Designers and manufacturers often assume that occupants will ventilate when pollution levels rise. However, in some cases, what occupants considered desirable was

technically a pollutant. Occupants typically had limited formal knowledge of indoor pollutant sources and perceived a problem only when pollutants had a strong odour or caused direct, noticeable health effects. This is important because many indoor pollutants are either odourless or pleasantly scented, further complicating the issue. The findings also highlighted considerable variability in ventilation rates due to weather conditions and simple occupant activities, such as cooking style and window use for ventilation. These physical findings further highlight the challenge of designing robust ventilation systems that account for the realities of occupied homes.

As a result, occupants often supplemented or replaced installed ventilation technology with natural ventilation out of habit. When the mechanical ventilation system seems ineffective, occupants may lose trust in the technology. As one occupant from CS2 stated, "*We don't feel that the mechanical ventilation system does anything to dilute the steam and the smell of food while cooking, so we open the windows. We are not sure whether the boost button will help when installed*". This lack of confidence and mistrust was further aggravated by concerns about energy consumption when the window is opened for purge ventilation. It is essential to assess occupant knowledge and the usability of mechanical systems, particularly in new low-energy buildings. In theory, the low-energy concept approach offers a well-established, systematic methodology, supported by scientific literature, for achieving optimal performance, at least in terms of energy. However, this must be considered alongside risk factors, such as occupant understanding, operation, and system performance, as these significantly affect overall outcomes. Furthermore, factors such as indoor pollutant concentrations, room volumes, and weather conditions play crucial roles in determining the resulting quality of the indoor environment, particularly regarding IAQ. Mitigating factors include the presence of adaptive opportunities, such as opening windows, flexible indoor spaces, and control features. Similarly, adequate maintenance of the MVHR system is crucial in ensuring consistent system performance.

The challenges of new technologies for occupants in this study highlight that ventilation solutions must be adaptable to occupant behaviour, easy to operate, energy-efficient, cost-effective, and scalable for mass-market housing. The dichotomy of 'old understanding, new technology' plays a substantial role in the use and performance of MVHR systems. For example, in CS1, multiple engineer call-outs were required due to confusion about how the system operated. This lack of technical advice, combined with a reliance on familiar habits like

opening a window, underscores the need for more adaptive systems that align with user expectations and behaviours.

Considering the existing and expected levels of airtightness and ventilation in new energy-efficient homes, it is essential to incorporate both passive and active design strategies to achieve acceptable IAQ standards and mitigate indoor pollutant concentrations. These strategies should include best practices for controlling pollutant sources within buildings ([Shrubsole et al., 2012](#)) and for improving ventilation, particularly in areas such as kitchens ([Hasselaar, 2009](#)) and bedrooms. To address the challenges highlighted in this study, it is essential to develop ventilation solutions that are both adaptable to occupant behaviour and capable of meeting IAQ standards in a wide range of scenarios. These solutions should prioritise ease of use, integration with occupant habits, and energy efficiency while remaining cost-effective and scalable for mass-market housing.

Ventilation is recognised as an important proactive measure to mitigate poor air quality. Ventilation and IAQ are interconnected variables that must be carefully considered, particularly during the building design stage, to prevent poor IAQ. Inadequately ventilated spaces can create environments conducive to mould growth ([Benton, 2024](#)), a biological agent linked to adverse health effects. Adequate air ventilation in buildings is essential to provide sufficient fresh air for occupants' well-being, dilute and neutralise polluted air, and remove excessive heat and moisture from the space ([Crawley et al., 2008](#)).

The concentration of CO₂ in indoor environments is a key indicator of ventilation rate. CO₂ is produced by human metabolism. A well-ventilated space typically has low CO₂ concentrations, which are influenced by factors such as location, occupancy levels, and time of day ([Franco & Schito, 2020](#)). The ventilation rate is influenced by factors such as prevailing wind conditions, window type, and orientation. Enhancing cross-ventilation in naturally ventilated buildings can be achieved by using openings of varying sizes ([Pourtangestani et al., 2024](#)).

Occupants also faced difficulties with heating system controls, often finding them overly complex and resorting to using the external heater. While this may allow systems to operate efficiently, it unintentionally distances occupants from their environment and reduces engagement. Addressing these challenges requires designing user-friendly and intuitive systems and improving occupant education to bridge the gap between technology and user

needs. Such measures are essential for effective IAQ management and the successful adoption of modern ventilation technologies in residential settings.

Section summary.

This section highlights that adequate ventilation is essential for maintaining good IAQ and supporting occupant health. While mechanical and natural ventilation systems are designed to manage airflow and control indoor pollutants, their success depends on technical performance, occupant understanding and how they operate. The case studies reveal that many residents lacked confidence in, or knowledge of, how to operate their systems, often reverting to habitual practices, such as opening windows, even when this undermined system efficiency.

Key challenges included poor user interfaces, inaccessible controls, and insufficient handover guidance, which limited the effectiveness of ventilation technologies. Features such as boost buttons, humidity sensors, and automated modes must be intuitive and clearly explained to encourage proper use. Educating occupants and designing systems that align with their everyday practices can foster trust, reduce misuse, and improve IAQ outcomes.

These findings reinforce the need for robust system design, proper installation, and occupant-centred approaches. The Pathway Approach acknowledges these realities and supports the development of adaptable, easy-to-use ventilation strategies suited for real-world residential settings. By aligning technology with user behaviour, future homes can achieve improved air quality and energy performance in a scalable and cost-effective way.

This research has presented a holistic Pathway Approach to address IAQ and ventilation systems and strategies in residential settings. The study has covered all relevant aspects affecting ventilation performance, uncovering complexities arising from multiple uncertainties impacting ventilation and air quality. However, it is acknowledged that some subjects are treated only superficially because they require more extensive studies beyond the scope of this research. Many practical considerations have been excluded, with the expectation that they can be incorporated into future versions in response to relevant industry feedback. This study does not consider energy performance. Nevertheless, this research is a first step in the holistic treatment of IAQ and ventilation strategies in new homes. It serves as a stepping stone toward a solid foundation for more focused studies on the specific topics identified in this research,

with the aim of optimising ventilation systems and appropriate mitigation strategies for poor IAQ in new homes.

5.4 Home Development Process Results and Discussion.

This section presents and analyses the results of interviews conducted with home developers, select participants in their supply chain, and relevant professionals in the construction industry. Semi-structured interview responses were coded and categorised using thematic analysis (NVivo 12), thereby enabling identification of key patterns within each participant category. Following Saunders et al. (2019), the objective was to gain an in-depth understanding of decision-making stages in the UK home development process that influence IAQ challenges in new UK homes. Interview topics included government policies and regulations, land acquisition, design and construction practices, environmental factors (e.g., climate change and adaptation), operational use (e.g., occupant awareness and maintenance), planning challenges, and strategies for design and mitigation. Data analysis aligned with the research objectives to identify key elements of the home development process that are crucial to cost-effective IAQ solutions in new homes. The chapter is structured into the following sections:

- Thematic and Conceptual Visualisation
- Decision-Making Processes in New UK Home Development and IAQ
- Discussion of the Results
- Contribution to the Solutions
- Chapter Summary

Thematic analysis identified five core themes: land purchase and strategic planning; design and scheme planning; construction; handover and occupation; and regulation, policies, market dynamics, and the business environment. These themes stem from the thematic analysis in this study, which aims to identify and report patterns within the interview data. The analysis involved a systematic process of coding and categorising data to uncover underlying meanings, concepts, and insights. To illustrate the range and focus of discussions within the interviews, Figure 42 presents a word cloud of the most frequently mentioned terms, visually emphasising the central topics and priorities that emerged from the analysis.

Table 5 5: Interview guide structure and thematic sections.

Land Purchase	Planning & Design	Construction	Technical Department	Marketing & Sales	Operation & maintenance
<ul style="list-style-type: none"> • Land purchase process. • Site selection decision-making process. • Environmental concerns. • Greenfield Brownfield site handling. • Planning authorities. 	<ul style="list-style-type: none"> • Tender & Procurement process. • Policy & Regulation Integration. • Certification systems for sustainable design principles. • Covid-19's Effects. • Decisions concerning scheme orientation. • IAQ assessment and knowledge among professionals. 	<ul style="list-style-type: none"> • On-site inspection processes. • IAQ mitigation and adaptation strategy. • Engaging occupants. • Capacity to implement ventilation strategies. • Specifying building materials. • Quality control standards. 	<ul style="list-style-type: none"> • Future trends. • Housing typologies. • Home performance measurements. 	<ul style="list-style-type: none"> • After-sales care process. • Customer satisfaction & complaints. • Customer expectations & perceptions. 	<ul style="list-style-type: none"> • Commissioning of systems. • Home induction processes. • Previous issues regarding IAQ. • Liability procedures. • Soft-landing procedures. • Post-occupancy evaluation procedures.

The interview guide, shown in Table 5.5, provided a framework to investigate how IAQ considerations are incorporated (or overlooked) at each stage, from initial site selection to the ongoing operation and maintenance of new homes. This thematic approach ensured that a wide range of industry perspectives were captured, thereby supporting a comprehensive analysis of the barriers, opportunities, and practices that influence IAQ throughout the home development process.

Semi-structured interviews were conducted with housing developers, manufacturers, and building professionals to gather their insights into the decision-making stages of the UK home development process and the direct and indirect impacts of these stages on IAQ. The interview topics were designed to investigate various aspects of decision-making, including environmental considerations during land acquisition, compliance with policies and regulations, design decisions, material specifications, relevant tests and assessments, skills, capacity, and availability, performance gaps, and end-user education. These topics required iterative engagement with different industry stakeholders, achieved through purposive sampling focused on specialist knowledge and willingness to participate (Campbell et al., 2020).

The research was supported by a steering group consisting of representatives from industry partners, who are partial sponsors of the PhD research, and a steering group was formed to collaborate on this research. In addition, facilitated interviews across the sector. This steering group provided regular updates, typically monthly. They also provided a valuable platform for establishing connections with multiple housing developers and their associated supply chain companies through purposive sampling. Purposive sampling is a non-probability sampling

method in which researchers select participants based on specific criteria, such as expertise in the research area and willingness to participate. The interviewees included technical directors at different housing developers, environmental consulting firms, and other senior professionals from different supply chain companies. Table 12 summarises the interviews (in section 4.6), detailing the timing, method, and participants to maintain confidentiality and comply with ethical standards. Companies are identified using special characters, with only their type being disclosed.

The interviewees were engaged through semi-structured interviews. The interview guide was organised into the following sections outlined in Table 5: Land acquisition, planning and design, construction, technical department, marketing and sales, and operation and maintenance. This structure aligned with the typical stages of the RIBA process in UK home development. Each section of the semi-structured interview included a set of questions developed from concepts identified in the literature review, recent policy and regulatory changes, industry practices, and other areas of interest to the researcher. A pilot test was conducted with a fellow researcher to ensure the clarity, coherence, and language of the questions while also probing subjects and concepts.

The main semi-structured interview guide is attached in Appendix 2 of this document, titled “Interview Guide for Housing Developers.” Due to its semi-structured nature, there was flexibility to explore additional issues based on the responses. This provided flexibility in obtaining answers to company-specific questions. The standard interview guide was also customised to suit different companies based on their specialisations. Manufacturers were primarily questioned about their products and their integration into the home development process, whereas other professionals were asked specific questions about their practices and typical involvement in the process. These interviews were conducted between March 2021 and October 2021 with 15 UK-based companies directly involved in delivering homes. All interviews were conducted online via Microsoft Teams, except for one, and each session lasted approximately an hour. Interviews continued until data saturation was presumed to have been reached. With the participant’s permission, all interviews were recorded and securely stored for analysis.

5.4.1.1 Land Purchase Strategic Planning.

This section addresses land acquisition and strategic planning. It investigates how decisions regarding environmental assessments, such as location, proximity to outdoor pollution, land

contamination, and noise, can affect IAQ. All home developers reported having strategic and immediate land-purchasing departments. Strategic land is a land bank that may not become viable for tens of years but provides the company with an opportunity to enter the market by purchasing land at a low price, requiring long-term investments for potential future development, often in developing areas. Immediate land purchases are for more imminent use, typically in familiar places with identified sales opportunities.

Each site acquisition involves environmental awareness, with critical factors at the site level, including location and technical constraints such as ground conditions and infrastructure. At this stage, business considerations balance land costs against the type and quantity of houses, and determine their sales value using marketing strategies and previous sales data. The timing and frequency of environmental assessments, including noise and biodiversity evaluations, vary across developers. Home Developer (HD4) stated, "Now it is involved earlier *because it's mostly legislation driven.*" He highlighted the need for improvement beyond mere compliance. Another developer emphasised the importance of addressing environmental issues right from the inception of the development, as these factors significantly impact the viability and constraints of the site. (HD3) mentioned that "*Environmental issues are considered at the outset, as these will affect the viability of the site and site constraints. We conduct early Desktop reviews of the site to gather as much information as possible and assess this risk.*"

Interview data indicate that decisions about environmental assessments, such as noise assessments, can significantly affect the risk of poor IAQ. R14, the founder of a Building Physics Consultancy, stated, "*My instinct is that there are sites that are too noisy to build homes on. It just isn't a good site for a home. That is too noisy. I don't think living in a place where you can't open the windows is humane.*" When asked about the limitations of poor air quality mitigation strategies, she emphasised the importance of noise reports. She added, "*The other big problem comes in when it's a noisy site, and you've got an acoustic report that says it's really noisy, it's on a main road, we're recommending that you don't rely on openable windows to prevent poor IAQ. At that point, it all gets really hard.*" The frequency and consistency of environmental reports on noise pollution vary among developers, but the interviews reveal a need for improvement.

5.4.1.2 Design and Scheme Planning.

During the design phase, the interviewees indicated that decisions regarding scheme orientation and building design are affected by a gap that impacts IAQ. R6 revealed that, "*When we design*

a building, we do it site-specific; we consider both opportunities and constraints. I think up there with the hierarchy of things, it's all about factors like views, noise and of course, those, yeah, natural light, get a lot of natural light in there. I think those things are always considered more than air quality". A senior Technical Coordinator for HD1 explains that while specific requirements exist for other aspects of scheme design, such as distances between houses, rear garden lengths, and defensible space, *"there are no strict rules governing orientation"*. He further notes that orientation is not typically given extensive consideration. Additionally, the respondent (R4), a sales director from a major ventilation manufacturer in the UK, adds, *"I'm not sure that it would yet occur to specifiers that orientation and positioning on the plot would impact building services further down the design process."*

Furthermore, the interviews reveal that ventilation is often overlooked as a critical aspect of IAQ. R6, an architect with considerable experience serving as an Associate Director, expressed that *"while ventilation is acknowledged, its importance may not receive the emphasis it truly deserves"*. R8 pointed out that *"ventilation is always considered at the final stage of the design process"* and is often treated in isolation, lacking a holistic integration into the overall design considerations.

The interview highlighted that building material specifications can also affect IEQ. R3 stated, *"Not only do issues arise with the specifications and proper installation of building materials, but also ventilation fails to synchronise with insulation installation; together, these factors lead to a problem"*. R8 added that *"the one thing I've had on a couple of things where we think there's been an issue was installing carpets that are too thick so that they've blocked the air gap underneath the doors to bathrooms, so they don't get cross ventilation"*.

The interview results reveal that ventilation is not a high priority in the design stage. R6, a seasoned architect and an Associate Director, stated, *"I think it is a consideration, but probably not as much, not as much as it should be."* R4, a sales director at a major UK ventilation systems manufacturer, echoed this sentiment, stating that *"ventilation is always considered last"* and that ventilation decisions are *"an isolated decision."*

In the design stage, the interviews also highlight that gaps in scheme-oriented decision-making can affect IAQ. Explaining the complexity of scheme orientation, HD4 from Housing Developer 3 stated that it involves *"a dichotomy argument of wanting as much daylight through*

windows but not as much heat in summer". A Senior Technical Coordinator for Housing Developer 1 states that there are specific requirements on other factors of scheme design, such as distance between houses, rear garden lengths and defensible space, "but there are no hard rules on orientation." He further added "most of the time in terms of orientation, you know, we don't really think about that too much." R4, a sales director of a major UK ventilation manufacturer added "I'm not sure that it would yet occur to specifiers that orientation and positioning on the plot would impact building services further down the design process."

The planning stage involves obtaining detailed planning permission approvals, typically outsourced to architects and planning consultants. This is an extensive process that encompasses developing a site plan and negotiating with local authority development planners. All the interviewees expressed frustration with the planning process, using phrases such as *"expensive and time-consuming"* and *"absolute nightmare"*. One of the interviewees described the planning process as *"a combination of political dynamics and the scientific elements involved in the planning process"*. R6, a designer manager, explained how delayed planning approvals created on-site challenges, as certain building materials specified in the planning application were unavailable due to these delays. This highlights the challenges of implementing necessary changes to align with the initial design intent once planning approvals are obtained. This is something that many home developers may be reluctant to undertake; as R23 expressed, *"Once you obtain planning approvals, then this just adds an extra layer of complexity"*.

The interviews show that material specifications can also affect IAQ. R8 mentioned this when talking about carpet thickness. He stated, *"The one thing I've had on a couple of things where we think there's been an issue was installing too thick carpets so that they've blocked the air gap underneath the doors to bathrooms, so they don't get cross ventilation. One thing to note is the thickness of the floor compared to the gap underneath the door. Because obviously, you probably get the bathroom doors shut for a majority of the time, isn't it?"*

All respondents expressed frustrations with the planning process, using terms like *"absolute nightmare"*, *"it's the worst I've known it"*, *"protracted"*, and *"expensive."* One respondent described the planning process as *"a mixture of politics and planning as a science."* Planning influences IAQ in homes when other factors, such as material availability and supply, are taken into account. R8, a design manager, described how late approvals led to on-site challenges when certain building materials specified in the planning application were unavailable due to

approval delays. These included specific bricks and windows with a g-value of 0.35, specified for building airtightness reasons. This also reveals that, once planning approvals are obtained, introducing changes that may be necessary to improve IAQ beyond non-material amendments (NMAs) is something many home developers might not want to subject themselves to. As R7 stated, *"If you've already got planning, then that's just an extra layer of complexity."*

The interviews revealed that the timing of introducing critical MEP (Mechanical, Electrical, and Plumbing) supply chain companies and consultants into the home development process, as well as their inclusion in planning and design, are important factors in IAQ. The respondents of this research include representatives from an aircrete, insulation, and MEP manufacturer and supplier, as well as various energy and sustainability consultants. When asked at what point they are introduced into home developments, they mostly agreed that it is not early enough. R5, an Energy Consultant, said, *"It's probably RIBA stage three or four"* R10, a Building Physics Consultant, reports that *"It varies quite a lot right from early doors and Stage 1-2 through to probably too late when we're in stage, three, four, and it's a bit too late to make a difference, you know, post planning..."* R4, an MEP manufacturer, when asked how often they are engaged early on in a project, said, *"I'd say less, not massively."* He added that in most situations, it is the Architect or the M&E engineer who requests their most suitable product, one that ticks several boxes without engaging them in the design process. He stated, *"We are treated more as a supplier...like here is the sort of lane.... tell us which products you offer, which tick these boxes."*

5.4.1.3 Construction.

The interviews indicated that the availability of skills could be an issue during construction, with implications for the successful implementation of new ventilation and building systems that affect IAQ. HD3, when asked about the availability of skilled workers, said, *"We do up to a point. I think as the zero-carbon agenda comes forward, we won't have enough."* Similarly, HD2 expressed doubts about the ability to deploy new systems widely without facing workforce challenges: *"I would doubt we could roll out these new systems through our build without workforce challenges."* In addition to labour concerns, most interviewees emphasised persistent issues with quality control and inspections. Most interviewees noted additional problems with the construction method, highlighting the importance of quality control and inspections in workmanship. *"The main barriers are probably cultural. You know, you're trying to change the company and people from doing things the same way they've been doing them for so many years. The second is just logistics; we have a lot of sites, so it's about getting the*

right product in the right location. The next one is skills; you need the right people to put in this stuff correctly and at the right quality. The final point is that many of these new products and technologies fail to obtain the necessary regulatory approvals, and they often lack their own due diligence. So, we find that we have to do a lot of due diligence on a lot of these systems before we can apply them" (HD1). Additionally, RS10 highlighted that "You know, evidencing the installation of products correctly as to the manufacturers' guarantees and warranties... there's not enough of it. Greatly.... You know, building control can only do so much, you know". These challenges can directly impact IAQ, as improper installation, insufficient commissioning, or inadequate quality oversight can lead to underperforming ventilation, unintended air leakage, or the accumulation of indoor pollutants, ultimately undermining the intended benefits of advanced building systems in delivering healthy, energy-efficient indoor environments.

5.4.1.4 Handover and Occupation.

The interviews reveal that failing to properly educate home occupants about the use of home systems can lead to poor indoor environmental quality. When talking about MVHR systems, R10 mentions, *"I think there's a lot of Education around MVHR needed because I think still it's the case that a lot of them don't work very well and people don't understand how they're supposed to work and don't understand when their filters need changing or how to change them."* R9, a Building Control Agent further explains *"what you'll never regulate for you is that you walk away from a building on a Monday by Friday the first tenant might have moved in, had the windows changed, all the trickle vents altered, blocked the air vents because there's a draft and might have disabled the fans because they don't like the noise. Then, very quickly, you end up with a building that is nothing like it was designed to perform, as sometimes education will help, and sometimes people don't care. So, we design, oversee the construction, and sign off on a building that is compliant, but ultimately, the use will affect the quality of air."*

Most new home occupants receive a Home User Guide (HUG) or a handover pack. However, its effectiveness is being questioned. R8 explains, *"They'll look at it, make sure it's been signed, put it in the drawer and never read it."* He adds, *"Obviously, then you've got the first wave of residents coming in, you'd hope there would be some kind of handover pack with our user guides in and things like that to explain to the resident what the unit does and everything, but you know, in reality, they are just going to put that in a drawer and forget about."*

The interviews also suggest that the lack of a direct relationship between occupants and the MEP suppliers and installers involved in building their homes influences their interactions with the heating and cooling systems and, thus, their indoor thermal comfort. R4, an MEP manufacturer, explains that due to this lack of direct contact, *"there will be plenty of homes where the resident, the end user, won't know what is installed in their house, what it is, where it is."* Respondent 9 further adds that, currently, in most developments in which they are involved, their *"expertise, if it was ever on-site, is almost gone at the point the occupant takes ownership."*

5.4.1.5 Regulation & Policies.

Throughout the home development process, one theme that consistently emerges in all stages is the role of government policy and regulation. When asked why IAQ concerns are rising on the agenda for home developers, HD3 of Housing Developer 3 states, *"It is becoming more legislation-driven."* HD1 of Housing Developer 1 added, *"We're a heavily regulated industry, rightly so, and a lot of the stuff that we need to do is in response to the regulations."*

Respondent 15, an Energy Consultant, explained how policy and regulation affect the delivery of products and services in the UK housing market: *"It has to be led by proper legislation; it has to be built into Part L. When you give people the option, it comes down to pennies, and if it's going to cost the developer another pound to build, they're not going to do it unless they are forced to. I think that's the real problem with the building industry. Unless they have to do it, they won't."*

However, R3 described what he felt was a political unwillingness to take significant action and stated that regulation was not keeping up with sentiment. He added, *"We're talking about, you know, sustainability, about embodied energy. These are things that are beyond regulation. Regulations are, they're old news, really."*

5.4.1.6 Market Dynamics and Business Environment.

Market dynamics and business environment-related matters are other factors that consistently influence the home development process. Respondents repeatedly mentioned that the competitive nature of the housing market is a barrier to implementing effective strategies to improve IAQ in UK homes. Statements such as *"cost comes into play always"*, *"It's a competitive market"*, *"Some clients are just about money"*, and *"We live in a commercial world"*, among others, reflect this challenge. This competitive pressure may explain why IAQ is often not prioritised. As Respondent 10 explained, *"It's normally considered a little bit too*

late..... after it's already set, then you've got someone around the table goes, 'right, so how are we going to prevent poor air quality?', " R11 added, "air tightness was talked about quite a bit; IAQ has not been considered to the same extent in the market." R4, the MEP manufacturer, added, "Ventilation was sort of the forgotten part of any sort of element of the build." R11 elaborated, "You know, the attitude we get to the major house builders is literally, 'Can we build the same house at 20% improved specification for the same money?" When asked about potential barriers, R11 further explained, "It's really cost concerns, you know, the nature of our industry is, it's all about value engineering or cost-cutting. We can do calculations properly and provide the correct materials on the site, but people take shortcuts if it's out of their budget. That's the biggest barrier to providing really good performance on site."

HD1 from Housing Developer 1 explained the business environment of the home development process: "Because we have a housing shortage in the UK, the main concerns are going to be location and price. Almost everything else is secondary to those concerns." He further explained, "The housing market, in my view, isn't something that customers drive. It's something that, because of the supply issues, if you build something, it's going to sell," R5 added, "People don't have another choice, and if it's not done in the first place, then people might just go around and buy it." R3 further elaborated, "The nature of the construction sector in the UK is that we do not build our own homes. Most people do not have a say in the types or performance of the homes they will live in. People buy because of location and price, you know."

Section summary.

Home Development Stages	Land Purchase and Strategic Planning	Design and Scheme Planning	Construction	Handover and Occupation
RIBA Stages	0 - 2	3 - 4	5	6 - 7
Overarching Principles	<p>Inadequate environmental considerations regarding:</p> <ul style="list-style-type: none"> • Ecology • Geotechnical surveys • Air pollution • Flooding • Noise 	<p>Gaps in scheme orientation decisions.</p> <p>Ventilation as an isolated decision.</p> <p>Material specification</p> <ul style="list-style-type: none"> • high VOC levels • non durability and high replacement ratio <p>Late approvals:</p> <ul style="list-style-type: none"> • Material unavailability • Redesign beyond NMAs. <p>Late involvement of MEP subcontractors, suppliers and energy consultants.</p>	<p>Workmanship and skills issues.</p> <p>Inadequate inspections and Quality control.</p>	<p>Inadequate testing and commissioning.</p> <p>Ineffective occupant education.</p> <ul style="list-style-type: none"> • An occupant lifestyle that strains the home. <p>Lack of access to MEP subcontractors who installed systems.</p>
	←		<p>Policy and regulations.</p> <p>Economy and Market dynamics</p>	→

Figure 5. 23: Key decision-making points impacting IAQ throughout UK home development stages, based on the interview results.

Figure 5.23 presents a stage-by-stage overview of the main decision points and barriers impacting IAQ throughout the home development process, as identified through interviews. Organised according to RIBA project stages, the figure emphasises how factors such as inadequate early environmental assessment, gaps in scheme orientation, late involvement of MEP specialists, workmanship and quality control issues, and insufficient occupant education can each pose risks to IAQ. Fundamental principles, including policy, regulation, and market dynamics, influence decisions and challenges at every stage, highlighting the importance of integrating IAQ considerations throughout the development process.

Stakeholder Involvement in Home Development Process

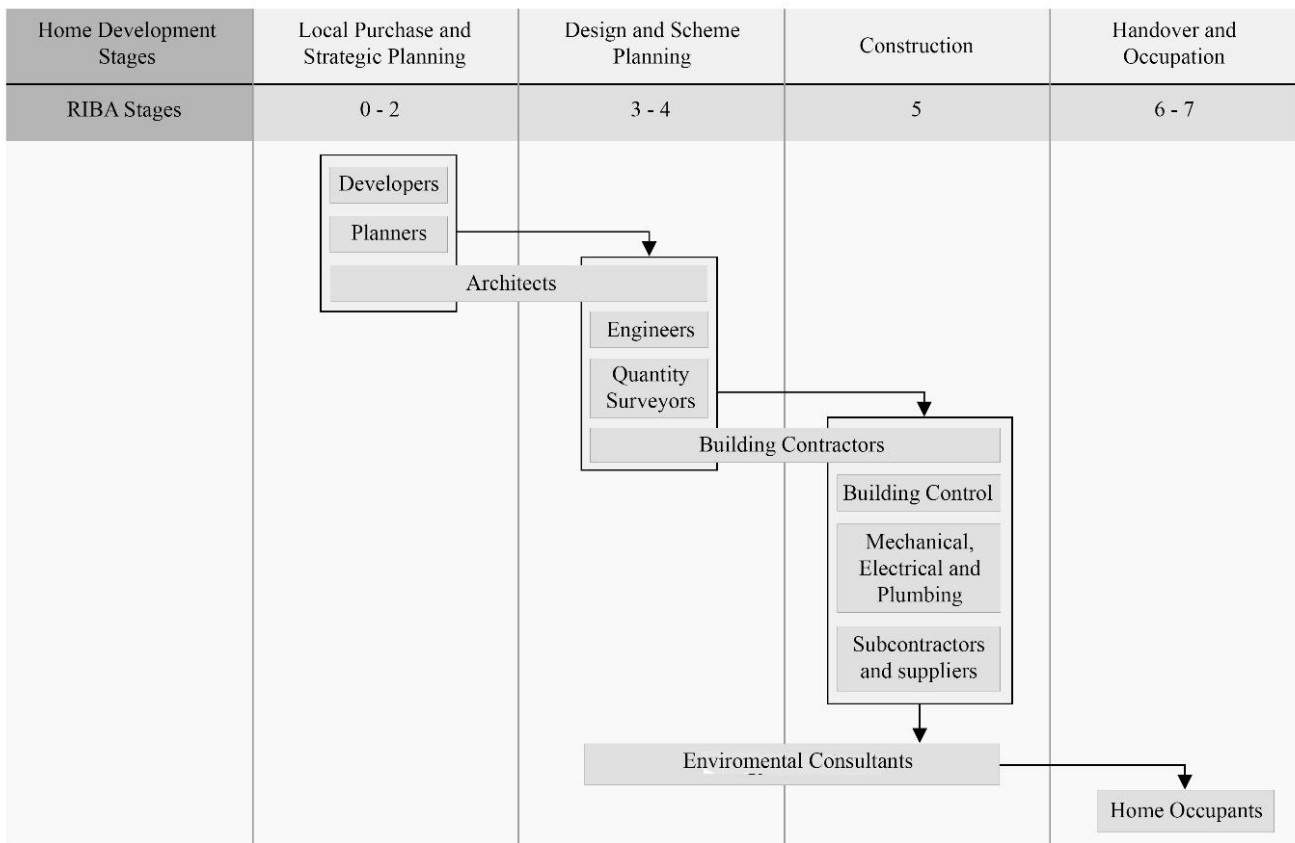


Figure 5. 24: Stages of stakeholder involvement in the home development process.

Figure 5.24 shows the various stages of stakeholder involvement in the home development process, highlighting the typical participation of developers, planners, architects, engineers, contractors, building control officials, MEP specialists, environmental consultants, and home occupants. The diagram shows that many technical specialists, such as environmental consultants and MEP contractors, are often engaged relatively late in the process, which can limit the opportunity to address IAQ comprehensively from the beginning. Figure 45 illustrates the complex, multi-actor nature of home development, emphasising the importance of timely, coordinated collaboration in creating healthy indoor environments.

Together, these figures demonstrate that improving IAQ in new homes requires both technical solutions and earlier, more integrated stakeholder involvement and process coordination across all stages of home development.

5.4.2 Discussion of the research findings.

This section synthesises the findings across all pathways, integrating empirical results with the existing body of knowledge to offer a comprehensive interpretation of IAQ in new residential homes.

This research aimed to improve IAQ in mass-market housing by investigating the pathways and a wide range of contributory factors essential for achieving successful IAQ. The results demonstrated that achieving good IAQ is a multifaceted challenge, requiring a comprehensive, holistic approach that considers the interplay among building materials, interior layout, occupants, and environmental conditions. Identifying the exact causes of inadequate air quality was often challenging, as these could stem from the materials introduced into the building, their integration, or overall occupant behaviour and activities.

Understanding the complex interactions and causalities among the factors that deliver good IAQ was seen as a key requirement for negotiating a successful Pathway. This pathway to developing an effective IAQ strategy must be embedded within the housing delivery process, and occupant behaviour, building usage patterns, and interactions with ventilation systems must be considered. Current solutions tend to focus on technological and regulatory aspects, but the critical issues of occupant knowledge and behaviour, as well as decision-making in the development process, are equally important. The Pathway approach, discussed in more detail in the following chapter, acknowledges these complex interactions. It realises that professionals with limited knowledge must make compromises, that there are alternative solutions, and that occupants must be part of the solution, particularly where they can mitigate poor conditions. Incorporating IAQ monitoring in all new homes and providing feedback to occupants can guide occupants' lifestyle adjustments and inform designers and developers on how to improve IAQ effectively.

From the analysis of the whole period and the weekly period for the houses, no significant differences were identified between houses with different ventilation systems or airtightness levels. Variations were primarily attributed to differences in occupancy and cooking patterns, corroborated by the exposure limit study, which found that better insulation and airtightness did not significantly alter exposure to indoor pollutants. However, homes equipped with MVHR systems showed a more rapid decline in pollutant levels (Van Rooyen & Sharpe, 2024). This finding underscores that cooking patterns and behaviours influence IAQ (Wargocki, 2013).

In the unoccupied analysis, pollutant levels remained below exposure limits and were generally close to zero, except for occasional peaks associated with construction activities. This indicates that building materials have a negligible impact on IAQ in the homes studied. This is consistent with previous research, which suggests that the influence of building materials on indoor pollutants is minimal compared to occupant activities ([Weschler, 2015](#); [McGill et al., 2017](#)).

CO₂, PM_{2.5}, and TVOC levels did not exhibit a consistent trend across the houses, primarily due to variations in cooking methods and devices. Traditional ovens, air fryers, and toasters were commonly used, with culturally influenced cooking practices and ingredients contributing to pollutant levels ([Korsavi et al., 2020](#)). Cooking activities significantly increased TVOC and PM_{2.5} levels, with pollutant concentrations spiking during cooking and then quickly decaying. This rapid decay is likely due to effective ventilation practices, including opening windows and doors ([Sharpe et al., 2015](#)).

The influence of MVHR systems on CO₂ levels was not clearly detectable; however, they maintained adequate environmental conditions, except during cooking activities. The absence of a boost facility in some MVHR systems meant they provided only continuous background ventilation, which was insufficient to prevent high peaks in CO₂ and PM_{2.5} during cooking. However, they facilitated faster pollutant decay post-activity ([Howieson et al., 2013](#)).

Cooking and internal air movement experiments indicated that high pollutant levels in the kitchen did not significantly spread to other parts of the house, such as the living room. This was due to the enclosed kitchen design, which separates the kitchen from the main living area by doors. Some small spikes in living room pollutant levels were correlated with higher kitchen pollutant levels, possibly because occupants kept doors open during the day. However, there was no substantive movement of pollutants between the kitchen and the living area, even with the doors open ([Nasir & Colbeck, 2013](#)).

Interviews revealed a lack of understanding among residents regarding their mechanical ventilation systems, particularly about airflow requirements for optimal system performance. Homes were handed over without floor coverings, except in kitchens and bathrooms. Many households installed laminate flooring in living areas and corridors, covering the recommended 10mm gap under kitchen and bathroom doors. This lack of internal airflow was evident in the data: pollutants such as CO₂ did not decay overnight when internal doors were closed; instead,

they decreased only when internal doors and windows were opened again in the morning (Derbez et al., 2014).

These findings highlight the critical role of occupant education and engagement. Similar to Sharpe et al. (2015) and Fernández-Agüera et al. (2019), this study found that even well-designed ventilation systems can be implemented ineffectively due to improper operation or a lack of understanding.

Overall, the proposed Pathway Approach highlights the importance of incorporating IAQ considerations at every stage of the housing delivery process. This includes ensuring that both designers and occupants are informed and equipped to maintain healthy indoor environments, and that IAQ is not considered in isolation but as part of an integrated strategy for improving it through informed building design, effective use of technology, and enhanced occupant engagement. This research contributes new insights into the management of IAQ in residential buildings, emphasising that sustained improvements in occupant health and well-being require a coordinated, holistic approach throughout the entire home development and occupation cycle.

5.4.3 Chapter Conclusion.

This chapter has explored the complex factors that affect IAQ in newly built UK homes, using quantitative sensor data, qualitative interviews, and a thematic analysis of the home development process. The findings confirm that good IAQ depends on a complex interplay between building design, ventilation technology, construction quality, occupant behaviour, and external regulatory and market influences.

The quantitative analysis showed that pollutant levels, particularly PM_{2.5}, TVOCs, and CO₂ are most heavily influenced by everyday household activities, specifically cooking and ventilation habits, rather than solely by the type of ventilation system or airtightness. Although mechanical ventilation systems, such as MVHR, can promote faster pollutant reduction, their effectiveness depends heavily on proper use and maintenance, which in turn require occupant understanding and engagement. The daily diary and interview results confirmed that knowledge gaps, habitual behaviours, lifestyle, and usability problems often reduce the performance of even advanced ventilation systems.

The home development process analysis revealed that IAQ is often viewed as a separate issue, with key decisions, such as ventilation strategy, material choice, and stakeholder involvement,

typically made too late for integrated solutions. Regulations and market pressures often prioritise cost and compliance over occupant health, while handover and occupant education remain weak points in the delivery of healthy indoor environments.

Overall, this chapter emphasises that good IAQ require more than technological fixes or stricter regulations. A holistic, integrated strategy is needed, one that aligns design, construction, education, and ongoing engagement across all the stages of the home development process. The Pathway Approach, developed in response to these findings, provides a systems-based framework to address these challenges by promoting the early integration of IAQ considerations, enhancing stakeholder coordination, and actively involving occupants in IAQ management. The following chapter examines this approach in detail and provides practical recommendations for creating healthier indoor environments in future UK homes.

Chapter 6. Developing Pathways Approach to IAQ Improvement.

Introduction.

Achieving good IAQ in new homes has proven to be a complex, multifaceted challenge, as demonstrated by this research. Analysis in the previous chapter shows that IAQ outcomes result from the dynamic interplay between building design and materials, occupant behaviour, ventilation systems, and the broader home development process. Moreover, solutions for achieving good IAQ cannot be universal or purely technical, particularly when applied to mass-market housing. Instead, the interactions among these factors, especially the knowledge, practices, and decisions of occupants, developers and building professionals, most often determine IAQ in practice.

The results further reveal that pollutant levels are influenced by daily household activities, such as cooking and cleaning, as well as choices regarding ventilation and building design. Moreover, opportunities for IAQ improvement emerge not only during the planning and construction, but also through ongoing support for occupant engagement and behavioural change. These insights underscore the need for an integrated framework that considers IAQ holistically across all phases of the housing delivery process. The Pathways Approach presented in this chapter is directly derived from the synthesis of empirical findings discussed in Chapter 5, translating observed interactions between building, technology, and occupant behaviour into a structured and scalable framework for IAQ improvement.

This chapter introduces the Pathways Approach, a framework synthesised from the findings in this thesis. The Pathways Approach recognises the interconnectedness of technical, behavioural, and organisational factors, offering a means to identify, prioritise, and adapt IAQ strategies to the specific context of each stage of the home development process. By outlining the structure and rationale of this approach, the chapter lays the foundation for more effective, context-aware IAQ improvement in the residential sector, establishing a basis for translating empirical findings into a structured, evidence-based framework and practical strategies tailored to the complexities of new housing delivery.

6.1 Key Findings Informing the Pathways Approach.

This section outlines the main findings from the previous chapters, integrating research results with relevant literature. Three pathways have been identified from the qualitative and quantitative data analysed from a home development perspective, which inform the proposed framework. The pathways are: site (context), building (design and technology), occupation (occupant behaviour and maintenance).

These pathways represent distinct yet interconnected areas, each offering opportunities for intervention to enhance IAQ. The Pathways Approach proposed in this thesis refers to a framework developed from analysing how these pathways interact and where targeted actions can be most effective. The relationship between the pathways and the framework is as follows: the pathways define the main influence areas within the housing development process, and the framework systematically organises and integrates solutions across these areas to deliver practical, scalable IAQ improvement strategies for new homes.

The following subsections explain how building context and design, occupant behaviour, technology and systems, and the home development process each contribute to the proposed framework.

6.1.1 Home Development Process.

A key insight from this study is that the home development process, influenced by planning, procurement, and stakeholder priorities, often determines whether or not IAQ is effectively addressed in new housing. As highlighted in Section 5.4.1, interviews with developers and procurement professionals showed that IAQ considerations are seldom a factor in early-stage decision-making. For example, a development manager explained, “*Our focus is still largely on compliance and cost; indoor air quality is rarely discussed in early design meetings unless there’s a specific client request.*” This observation aligns with findings in the literature (Poorisat et al., 2024; Stevenson, 2018) that identify a persistent gap between regulatory compliance and occupant health outcomes. The tendency to overlook IAQ early in the process can result in missed opportunities to incorporate effective solutions before construction begins.

Further, the research identified several process-related barriers to IAQ integration that arise during project delivery. As discussed in Section 4.4.2, many interviewees described how value engineering, tight procurement schedules, and late-stage contractor involvement often lead to cost-driven decisions that can undermine previously identified IAQ objectives. For example,

one procurement officer stated, “*If IAQ isn’t in the spec, it’s the first thing to get squeezed out if budgets are tight.*” There were also concerns about fragmentation among design, construction, and handover teams, which can lead to poor information transfer regarding IAQ measures and system operational requirements.

Despite these challenges, the study also found emerging opportunities for more holistic approaches to IAQ through collaborative working practices. Some developers reported that early contractor involvement, client education, and joint design workshops were effective in raising awareness of IAQ risks and embedding better solutions. As shown in Section 5.4.3, interview participants in such collaborative initiatives reported more successful outcomes, both in terms of system performance and occupant satisfaction. These results support calls in the literature (Moreno-Rangel et al., 2020) for a shift from minimum compliance to performance-driven delivery models in housing, in which IAQ is championed by all stakeholders throughout the home development process rather than treated as an afterthought.

6.1.2 Pathway 1: Site (Contextual Solution).

Site-specific factors are crucial in determining IAQ outcomes in new housing developments. Interview evidence from this study shows that proximity to outdoor pollution sources, such as busy roads, industrial facilities, or areas with poor ambient air quality, consistently concerns both developers and consultants. These findings echo Warren Andersen et al. (2018), who suggest that urban context and proximity to pollution sources are among the key factors affecting IAQ in homes. Similarly, Pagani et al. (2023) emphasise the importance of spatiotemporal analysis for evaluating environmental health risks associated with housing location and highlight the need for early-stage contextual site assessments.

Regulatory guidance underlines these concerns. Section 2 of Approved Document F (HM Government, 2021, p. 16) states that “*buildings located near significant local pollution sources should be designed to minimise the intake of external air pollutants.*” However, the real-world application of such guidance is often constrained by site-specific conditions. For example, the interview data reveal that commercial pressures and the scarcity of available land frequently result in the development of sites with suboptimal environmental conditions. One Technical and Innovation Director (HD4) described this dilemma as a “*trade-off between plot yield and environmental quality,*” sometimes resulting in developments that “*bake in*” IAQ risks from the outset. Other studies also emphasise the importance of site-based environmental risk

assessment, noting that land-use planning and early-stage decision-making have long-lasting effects on air quality in new residential developments (Shrubsole et al., 2019; Ige-Elegbede et al., 2020).

Moreover, interviewees frequently emphasised that contextual factors, such as noise and air pollution, directly influence natural ventilation strategies, particularly window-opening behaviour, a point supported by previous research (Shrubsole et al., 2019; Dimitroulopoulou et al., 2023). As one architect and consultant (R7) observed, “There are sites that are too noisy to build homes on. It just isn’t a good site for a home. That is too noisy. I don’t think living in a place where you can’t open the windows is humane.” This sentiment is supported by research findings, which emphasise that noise restrictions can fundamentally deter occupant-led ventilation and, consequently, IAQ improvement (Willand et al., 2015; Baker & Steemers, 2014).

The tension between environmental risk and commercial imperatives was further described by the Technical and Innovation Director (HD4), who stated, *“Our focus is still largely on compliance and cost; indoor air quality is rarely discussed in early design meetings unless there’s a specific client request.”* HD2 from Midland Heart, the quality and construction manager, explained, *“Site context assessments covering air quality, noise, and ecology are often conducted only as a planning requirement, not as a basis for optimising IAQ.”* Consistent with this evidence, the Head of Group Technical HD3 participant described the enduring industry dilemma: *“There’s always a trade-off between plot yield and environmental quality.”* Sometimes, this results in developments that introduce risks to IAQ from the earliest stages.

These findings show that context-specific IAQ risks are often identified but are not consistently addressed during land selection or early project planning. Instead, as noted in broader research (Shrubsole et al., 2019), mitigation is usually attempted at later design or construction stages, thereby limiting effectiveness and increasing costs. The evidence from this research reinforces the need for robust, site-specific IAQ strategies proactively tailored to each development’s unique environmental risks, planning constraints, and commercial realities. Embedding such a strategy at the earliest project stages is critical to delivering effective, scalable IAQ improvements across the housing sector, as outlined in the proposed Pathways Approach framework.

In summary, the findings from this research, drawing on baseline monitoring and professional interviews, highlight the following points:

- Baseline monitoring in unoccupied homes showed relatively stable IAQ levels, with little variation, serving as a benchmark for comparison with occupied homes.
- Occupied homes showed higher and more varied pollutant levels, highlighting how site context combined with occupant activity influences IAQ outcomes.
- Site location and surrounding environment (e.g., proximity to traffic or external pollution sources) contributed to indoor pollutant infiltration.
- Building orientation and internal layout influenced airflow and pollutant distribution, affecting how pollutants accumulated or dispersed in different rooms.
- Interview with developers and construction professionals revealed that IAQ is rarely considered during the planning or site selection stages, with decisions more often based on land availability, value, and regulatory compliance.

6.1.3 Pathway 2: Building (Design & Technology).

The design, internal layout, and technological features of a building are crucial factors affecting IAQ outcomes, pollutant sources, airflow patterns, and subsequent interventions. As outlined in Section 5.2.1, experimental data from unoccupied homes showed that indoor pollutant levels remained stable in the absence of occupant activities and were primarily driven by emissions from building materials and external sources. This finding emphasises the importance of selecting appropriate materials and considering environmental context at the design stage.

Further experiments conducted in occupied homes examined pollutant migration following activities such as cooking, and the results were analysed in detail. The data analysis revealed that when the kitchen door was kept closed during and after cooking, pollutants generated in the kitchen were largely contained and did not migrate into adjacent living areas. This observation indicates that using enclosed kitchens, or at least closing kitchen doors during pollution-generating activities, could be an effective strategy to reduce exposure elsewhere in the home. These findings align with the broader literature, emphasising the importance of internal layout and the management of pollutant pathways for effective IAQ improvements (Few et al., 2024; Shrubsole et al., 2019).

The research findings also reveal that ventilation design, system selection, and installation quality play decisive roles in achieving intended IAQ outcomes. Several building professionals interviewed for this study expressed concern that, despite the acknowledged significance of ventilation, its importance is often underestimated or considered only at later stages of the

design process. As one architect (R6, Associate Director, HGP Architects) stated, “*while ventilation is acknowledged, its importance may not receive the emphasis it truly deserves.*” Another respondent (R8, Design Manager, Tricas Construction Ltd) observed that “*ventilation is always considered at the final stage of the design process and is often treated in isolation, lacking holistic integration into broader design considerations.*” These practitioner insights are echoed by Shrubsole et al. (2019) and Guyot et al. (2018), who argue that the effectiveness of mechanical and natural ventilation in practice is frequently compromised by fragmented design and inadequate commissioning.

Industry guidance and research reinforce the need to embed IAQ objectives from the earliest design stages. A well-conceived building design should enable, rather than constrain, occupant-driven ventilation and support passive strategies such as stack and cross ventilation (Gupta & Gregg, 2016). Prioritising a fabric-first approach, optimising the building envelope before relying on mechanical solutions, is widely regarded as a best practice for both energy performance and indoor environmental quality (Willand et al., 2015). This approach, supported by these research results, reduces reliance on complex systems and mitigates the risk of performance gaps between intended and actual outcomes (Guyot et al., 2018).

Another insight from this research concerns the unintended consequences of late-stage modifications or value engineering. For example, installing laminate flooring in kitchens was found to close under-door gaps, undermining the effectiveness of intended cross-ventilation routes. This phenomenon, also observed by Few et al. (2024), highlights the importance of quality control and stakeholder coordination from design through to construction and fit-out.

Crucially, the research reveals that occupant proficiency in effectively understanding and operating installed ventilation systems is a key factor affecting IAQ outcomes. The research findings indicate that many occupants found system controls confusing or unintuitive, often resulting in inconsistent or ineffective use of the equipment. Interview respondents highlighted these challenges: for example, CS1 described the MVHR unit control interface as “*complicated and unclear,*” while an occupant in CS2 stated, “*nobody clearly really explained how to use it, so we just open windows instead.*” These findings are consistent with previous research (Dimitroulopoulou, 2012; Patlakas et al., 2021), which reports that inadequate user guidance and poor system commissioning often result in insufficient system operation and limited IAQ improvement. The importance of providing not only technical ventilation solutions but also thorough end-user education during commissioning and ongoing post-occupancy support is

thus highlighted. Hamilton et al. (2015) similarly advocate for robust user education and continuous engagement to maximise the performance of residential ventilation systems. Ultimately, the success of technological interventions relies not only on the systems themselves but also on the clarity, accessibility, and usability of their controls, as well as the extent to which occupants are educated and empowered to operate them confidently in their daily routines.

Overall, the evidence shows that early, integrated, and context-aware building design, including internal layout, material selection, and ventilation strategies, is crucial for achieving good IAQ outcomes in new homes. Failing to address these aspects systematically not only increases the risk of poor IAQ but can also result in costly and less effective remedial measures later in the construction process. These findings reinforce the importance of building and design decisions within the Pathways Approach framework for scalable IAQ improvement.

The results of this section can be summarised as follows:

- Baseline monitoring in unoccupied homes revealed low and stable IAQ levels, establishing a benchmark for comparison with occupied homes.
- Cooking experiments showed that closing kitchen doors during and after cooking reduced pollutant spread into adjacent living areas.
- Ventilation was often considered at a late stage in the design process, limiting its integration into broader IAQ strategies.
- Interviews with professionals revealed that ventilation is undervalued and often treated only for compliance rather than as a design focus.
- Late-stage modifications, such as installing laminate flooring that blocked under-door gaps, disrupted planned airflow routes and reduced ventilation effectiveness.
- Many occupants found ventilation controls confusing and unclear, with some defaulting to window opening instead of using the installed ventilation systems.

6.1.4 Pathway 3: Occupation (Behaviour & Maintenance).

Occupant behaviour and routine maintenance are key factors affecting IAQ outcomes in new homes, as demonstrated in Section 5.3. Daily activities such as cooking, cleaning, and opening windows directly and indirectly influence indoor pollutant levels, including PM_{2.5}, TVOCs, and CO₂. Data from behavioural change experiments conducted as part of this research demonstrated that occupants' awareness and responsiveness are vital for improving IAQ. When

provided with real-time feedback via sensor dashboards, households adjusted their behaviour and ventilation routines, resulting in tangible reductions in pollutant levels. These findings support previous studies (Fernández-Agüera et al., 2019), which have found that accessible information and targeted education encourage behaviour change, making this one of the most practical and cost-effective methods to enhance IAQ.

Interviews with occupants further supported these findings. Several occupants stated that receiving feedback on the impact of their activities increased their motivation to adopt healthier practices, such as opening windows and regularly checking the ventilation system's maintenance. One participant from CS3 explained, “*I didn't realise how quickly cooking would affect the readings, but now I open the window or use the extractor more often.*” Others highlighted challenges: “*We get used to our routines, so reminders from the app helped us make small changes*”, CS4. These real-world experiences align with the literature, highlighting the importance of feedback mechanisms and user engagement in improving IAQ (Wong-Parodi et al., 2018; Shrubsole et al., 2019).

Moreover, the interview data revealed that the effectiveness of technological solutions, such as MVHR systems, depended not only on design and commissioning but also on occupants' understanding of how to operate them. Several occupants reported that maintenance tasks were often neglected or not carried out at all due to a lack of knowledge about what to do, echoing findings from Sharpe et al. (2015) and Hamilton et al. (2015), who highlight the importance of clear instructions and ongoing support for system users.

In some cases, confusion about control interfaces or uncertainty regarding when and how to perform maintenance led to inefficient operation of installed systems, thereby compromising IAQ outcomes. As one occupant commented, “*The system is great in theory, but if you don't know what to do, you just open a window*”, CS2. The literature supports these observations for simple user interfaces to encourage effective occupant interaction with ventilation systems (Patlakas et al., 2021; Guyot et al., 2018).

Overall, the evidence shows that occupant behaviour and maintenance are not just passive outcomes of building design but active elements in improving IAQ. Ongoing education, engagement, and support mechanisms, such as real-time feedback, user-friendly information, and accessible maintenance guidance, are essential for encouraging households to make decisions that improve air quality. Including these behavioural and maintenance aspects during

handover and post-occupancy is crucial for achieving scalable IAQ improvements across the residential sector, as outlined in the proposed Pathways Approach framework.

The results of this section can be summarised as follows:

- Daily activities such as cooking, cleaning, and opening windows directly and indirectly influenced IAQ outcomes, affecting PM_{2.5}, TVOCs, and CO₂ levels.
- Behavioural change experiments showed that when provided with real-time sensor feedback, households adjusted their routines (e.g., opening windows, using extractors), resulting in measurable reductions in pollutant levels.
- Interviews with occupants revealed that feedback motivated some households to adopt healthier practices more consistently than others, demonstrating differences in how occupants responded to the information.
- The effectiveness of MVHR systems relied not only on design and commissioning but also on occupants' knowledge and ability to operate them efficiently.
- Maintenance tasks were often neglected or poorly understood, with several occupants lacking knowledge of what was required, leading to inefficient system operation.
- Evidence shows that behaviour and maintenance are key factors in IAQ improvement, needing continuous education, feedback systems, and easy-to-use guidance to maintain long-term results.

6.1.5 The Process of Pathways.

The Pathways Approach, developed in this research, conceptualises IAQ improvement through a series of distinct yet interconnected “pathways.” Each pathway represents a vital domain within the home development process where IAQ challenges typically emerge and where targeted solutions can be most effective. These pathways, Site (Pathway 1), Building/Design & Technology (Pathway 2), and Occupation/Behaviour & Maintenance (Pathway 3), reflect the empirical findings from the previous chapters, demonstrating that IAQ outcomes are shaped by multiple, interrelated factors rather than isolated components.

While poor IAQ often results from a complex interplay between pathways, analysing each pathway separately provides clarity for practical intervention without overwhelming the broader system. This approach enables targeted actions while recognising the dynamic interdependencies among pathways. Early decisions regarding site selection and environmental

analysis (Pathway 1) establish the foundation for subsequent design and system choices (Pathway 2), which then influence how effectively occupants can maintain healthy indoor environments through their behaviours and routines (Pathway 3). Choices made at one stage often constrain or enable options at later stages, highlighting the need for holistic consideration throughout the home development process.

The order in which pathways are addressed can greatly affect the overall success of IAQ strategies. As shown in Figure 45.1, these pathways are connected within the broader timeline of home development, from strategic planning and land acquisition through design and construction, to handover and occupation. Focusing only on IAQ at one stage risks overlooking the interconnected factors that influence real-world outcomes; therefore, a systems-based, integrated approach is crucial for achieving good IAQ.

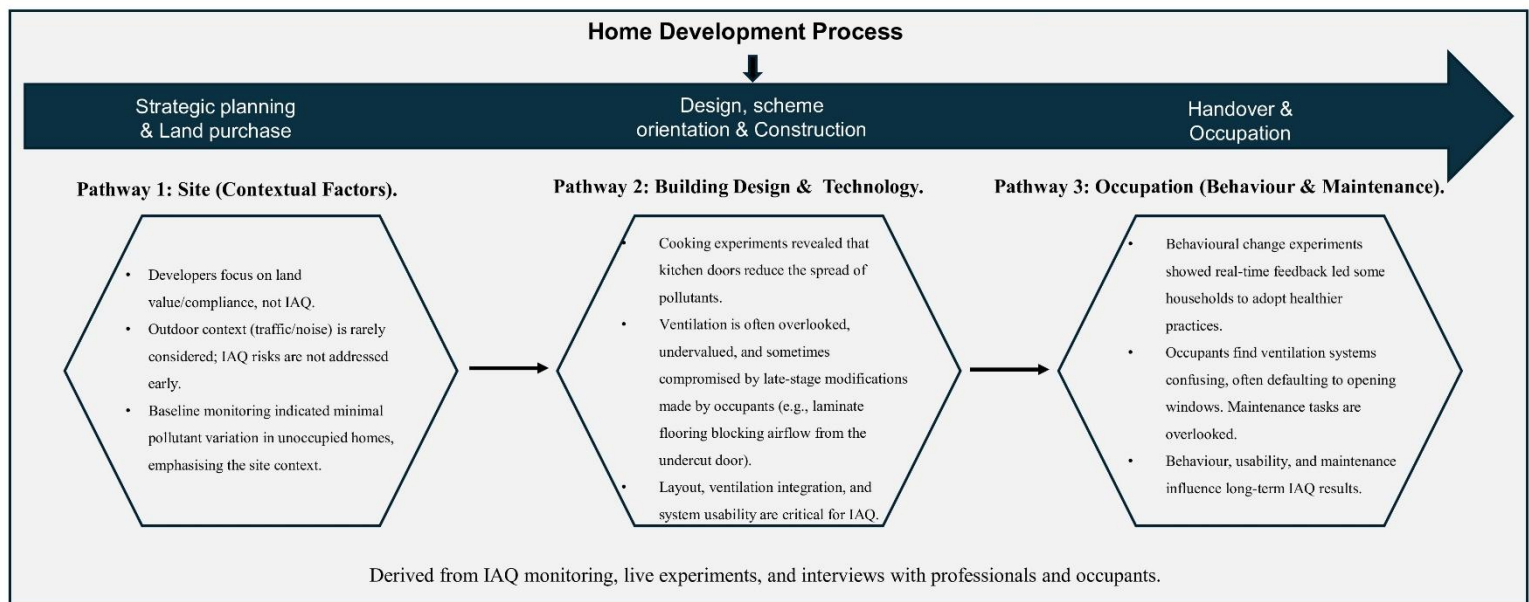


Figure 6. 1: Integration of the Pathways Approach within the home development process.

Figure 6.1 integrates results from IAQ monitoring, live experiments, interviews with developers, building professionals, and occupants, and design diaries. It demonstrates how Pathway 1 (Site), Pathway 2 (Building: Design & Technology), and Pathway 3 (Occupation: Behaviour & Maintenance) interact throughout the overall development timeline, highlighting the interdependencies that influence real-world IAQ outcomes. It emphasises that these pathways are not isolated silos but are deeply interconnected elements within the broader timeline of home development. Early-stage decisions, such as those related to site context or material specifications, often have lasting impacts on both the technical effectiveness of

installed building systems and the behaviours of future occupants. In contrast, interventions focused solely on a single pathway may fail to address the complex, cross-cutting interactions that ultimately influence IAQ in practice. Therefore, a holistic, integrated approach that spans the entire process from planning to post-occupancy is essential for effective IAQ improvement.

The rationale behind this multi-pathway perspective sets the stage for the next section, which introduces the Proposed Framework for Scalable and Adaptable IAQ Solutions. This framework builds on lessons learned from analysing these pathways, offering a structured approach to IAQ improvement that is both context-sensitive and practical.

6.2 Proposed Framework for Scalable and Adaptable IAQ Solutions.

Introduction

This section expands on the findings and analysis presented in the previous section, which examined the home development process, the factors influencing IAQ, and the limitations of current IAQ approaches in new UK homes. Key limitations identified include insufficient consideration of environmental context in site selection, lack of integration of ventilation and material choices during design, and inconsistent occupant engagement post-handover. Real-time IAQ monitoring and the interviews revealed that pollutant levels were most influenced by site-specific factors, building design, and daily occupant practices, confirming that the interplay of technical, contextual, and behavioural patterns shapes IAQ outcomes. The framework presented in this chapter is derived from the analytical interpretation of combined quantitative and qualitative data discussed in Chapter 5.

The research also found that current IAQ solutions often prioritise regulatory compliance and cost over comprehensive IAQ improvement, and that late-stage value engineering can undermine earlier IAQ intentions. Many occupants reported confusion about system controls and a lack of clear guidance, which limited the effectiveness of the installed technologies. These findings highlight the need for a more integrated, adaptable approach to address IAQ at multiple stages of the home development process.

The section is organised as follows: it begins with a synthesis of the key research findings that inform the framework, followed by a detailed outline of the Pathways Approach. The

subsequent discussion explains its practical implementation, including how the framework aligns with established development processes (such as the RIBA Plan of Work) and how it can be applied through scenario-based examples. Figure 46.2 presents the visual summary of the framework, highlighting the integration of solutions and feedback mechanisms across the different stages and pathways of the home development process. In doing so, this section addresses the critical need for holistic, evidence-based, and context-dependent strategies to improve IAQ, demonstrating both the rationale for the proposed Pathways Approach and its application.

Proposed Pathway Approach Framework for IAQ Improvement in New UK Homes.

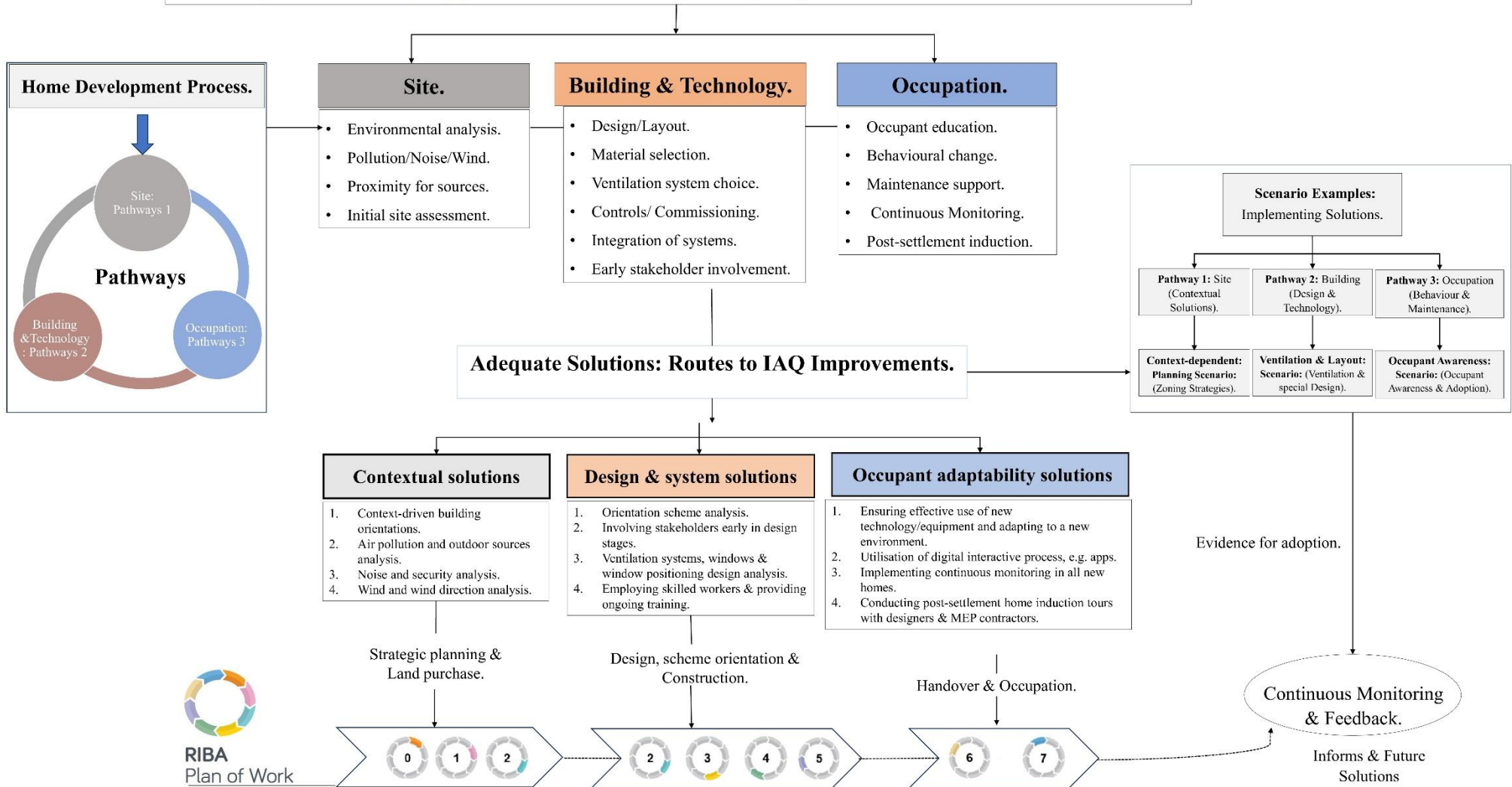


Figure 6. 2: Proposed Pathways framework for improving IAQ in new UK homes.

Figure 6.2 synthesises the Pathways Approach into a holistic framework for IAQ improvement, structured around three interconnected pathways: Site (Contextual Factors), Building Design & Technology, and Occupation (Behaviour & Maintenance). Each pathway is positioned within the broader home development process and is mapped against the RIBA Plan of Work stages, illustrating how IAQ considerations can be integrated from strategic planning and land acquisition (Stages 0–1) through design and construction (Stages 2–5) to handover and occupation (Stages 6–7).

The top row presents the three pathways and their core components (e.g., environmental analysis, ventilation system choice, occupant education). The middle section shows how these pathways lead to adequate solutions (contextual, design/system, and occupant adaptability), while the bottom row directly links these solutions to corresponding RIBA stages, illustrating their sequential implementation.

On the right-hand side, the framework includes scenario examples (context-dependent, ventilation & layout, and occupant awareness) that demonstrate its practical application. Arrows trace the flow from pathways to solutions and scenarios, highlighting the adaptability of the framework across different contexts.

The feedback loop is included to represent ongoing monitoring and evaluation of IAQ through sensor data and occupant feedback. This illustrates how post-occupancy insights can inform future decisions and support continuous improvement across development stages.

To further clarify how the Pathways Approach Framework operates, the following discussion explains how the three pathways function and interact to influence IAQ outcomes throughout the housing delivery process.

The operation of the pathways can be understood as a sequence of interacting decisions and responses across the housing system. For example, design and construction decisions (e.g., airtightness levels, ventilation strategy, and material selection) establish baseline conditions for pollutant generation and removal. These conditions are then influenced by occupant activities such as cooking, cleaning, and window operation, which introduce and modify pollutant levels in real time. The effectiveness of technological systems (e.g., mechanical ventilation) depends not only on their specification but also on how they are used and maintained by occupants. As a result, IAQ outcomes emerge from the interaction between design intent, system

performance, and occupant behaviour. When these pathways are integrated, pollutant concentrations increase, leading to poor IAQ. Conversely, coordinated decision-making across pathways enables effective mitigation, reducing exposure and supporting improved IAQ and health outcomes. This demonstrates that IAQ is not determined by a single pathway but results from the integrated interaction of decisions across interconnected pathways.

The Pathways Approach Framework is the primary contribution of this research, conceptualising IAQ as the outcome of multiple interconnected decisions made throughout the housing delivery and occupancy process, rather than as a single technical performance metric or a post-occupancy problem. The framework is structured around three main and interconnected pathways: (1) site and contextual conditions, (2) building design and technologies, and (3) occupation and use. Each pathway represents a critical domain in which decisions directly or indirectly affect IAQ outcomes.

The site and contextual pathway involve planning-stage factors such as environmental conditions, proximity to pollution, site orientation, and external constraints. These set baseline conditions that influence pollutant ingress and ventilation effectiveness, meaning IAQ risks can be introduced or mitigated early in development. The building design and technology pathway covers spatial layout, materials, ventilation strategies, and system integration, all of which influence the generation, distribution, and removal of indoor pollutants. It emphasises translating design intent into technical performance, with particular attention to commissioning and usability. The occupation pathway represents how buildings are used in practice, including occupant behaviour, system interaction, maintenance practices, and levels of awareness. This pathway acknowledges that IAQ performance is not fixed at handover but continues to evolve through everyday activities such as cooking, cleaning, and ventilation use. Occupants, therefore, play an active role in shaping IAQ outcomes.

These pathways illustrate how IAQ risks and opportunities emerge at various stages and through different actors. They do not operate independently. Rather, they interact dynamically, with decisions in one pathway influencing conditions in others. For example, design choices influence system usability, which subsequently affects occupant behaviour, while site conditions may limit both design options and ventilation strategies. IAQ outcomes are therefore understood to result from these interdependencies.

The framework translates these interactions into ‘adequate solutions’, representing intervention points across the pathways. These are categorised into contextual solutions, design and system

solutions, and occupant adaptability solutions. This categorisation reflects the need for interventions that are not only technically effective but also cost-efficient, scalable, and responsive to context-specific conditions. A key strength of the framework is its alignment with the RIBA Plan of Work, which connects IAQ decision-making to stages already familiar to the industry, from strategic planning through to occupation. This enhances the practical applicability of the framework as a decision-support tool rather than solely an academic model.

The framework also incorporates continuous monitoring and feedback, recognising IAQ as a dynamic performance challenge. This enables post-occupancy learning to inform future projects, rather than treating IAQ as a one-off compliance check, and supports both feedback and feedforward improvement across development stages.

The novelty of the framework lies not only in identifying multiple factors affecting IAQ, but also in demonstrating how these factors are interconnected and how interventions can be introduced earlier and more systematically across the home development process. It shifts the focus from isolated technical solutions to holistic, system-based interventions introduced at appropriate stages.

Finally, the framework is supported by scenario-based applications that illustrate how different solution pathways can be implemented in practice depending on specific site, design, and occupancy conditions. These scenarios demonstrate the framework's flexibility and its potential to facilitate real-world IAQ improvements in new UK homes.

6.2.1 Integrating the Pathways Approach in line with the RIBA Plan of Work for IAQ Solutions.

The proposed framework developed in this thesis translates research findings into a practical solution for new homes by aligning the Pathways Approach with the key stages of the RIBA Plan of Work. In practice, challenges and solutions for IAQ span multiple areas, site, building, technology/systems, and occupant behaviour, and often do not fit within a single stage of home delivery or occupation. Therefore, the framework is designed to ensure that IAQ remains a continuous, interconnected priority throughout the home development process. This process comprises four primary stages: Land Purchase and Strategic Planning (RIBA 0–1), Design and Scheme Planning (RIBA 2–4), Construction (RIBA 5), and Handover and Occupation (RIBA 6–7). Specific solutions for context, design/system, and occupant adaptability are proposed at each stage, drawing directly on the qualitative and quantitative findings of this research. In

doing so, the framework links research evidence with practical application, ensuring that IAQ considerations are consistently addressed and integrated throughout the lifecycle of new homes.

6.2.1.1 Land Purchase and Strategic Planning (RIBA Stages 0–1).

Research findings from housing development professionals revealed that early-stage decisions about site location, environmental risks, and land constraints often determine IAQ outcomes, sometimes “baking in” risks that are difficult to mitigate later. To address this, the framework supports a comprehensive environmental assessment as the basis for subsequent IAQ strategies. This includes air pollution and noise assessments, analysis of prevailing winds, and collaboration with environmental health consultants from the beginning. As the literature emphasises (Ige-Elegbede et al., 2020; Willand et al., 2015), transdisciplinary dialogue at this stage is essential to overcome siloed decision-making and to establish IAQ as a key criterion for site selection and strategic planning. Some contextual solutions (e.g., buffer zones, orientation decisions) are identified here, but their effectiveness relies on implementation throughout the design and construction phases.

6.2.1.2 Design and Scheme Planning (RIBA Stages 2–4).

Decisions made during design and scheme planning stages directly impact airflow, pollutant accumulation, and overall IAQ outcomes. Research findings from this thesis (see Section 5.2.1) demonstrated that key factors such as house orientation, layout, window positioning, and the specification of ventilation systems and building materials are essential for managing pollutant ingress and removal (Stamp et al., 2021; Nazaroff, 2013). Interview evidence indicated that IAQ and ventilation considerations are often introduced too late in the process or addressed in isolation rather than as part of a holistic strategy. To address this, the framework recommends that IAQ solutions be integrated from the outset of design and informed by collaborative engagement among architects, ventilation engineers, and suppliers. Decisions should be based on thorough scheme orientation analysis, the selection of low-emission materials, and context-responsive ventilation design. Incorporating systems thinking at this stage enables the identification of leverage points at which interventions can be most effective (Reynolds, 2013).

It is also vital that design decisions account for the future adaptability of homes and for occupants' ongoing involvement in maintaining IAQ (Gunay et al., 2023; Stevenson, 2018). This holistic, iterative approach ensures that solutions remain appropriate for diverse developments

and evolving occupancy patterns. In line with the research findings, design optimisation should begin with passive measures that are less energy- and carbon-intensive before considering mechanical interventions, such as the fabric-first approach (Willand et al., 2015). Passive ventilation strategies such as stack and cross ventilation, and efficient window design, should be prioritised, with decisions justified by the orientation, geographical location, and specific house type. Aesthetic design variations and some degree of occupant control are recommended to support both technical performance and end-user satisfaction.

6.2.1.3 Construction (RIBA Stage 5).

Evidence from both monitoring and industry interviews in this research highlighted performance gaps caused by installation errors, value engineering, and inadequate commissioning (see Section 5.4.2). The installation, commissioning, and maintenance of building systems, especially ventilation, are critical for bridging the gap between design intent and realised performance (Abdul-Wahab et al., 2015). Performance gaps are frequently observed between predicted and real-world IAQ outcomes due to inconsistent installation and poor quality control (Guyot et al., 2017; Shrubsole et al., 2018). To mitigate these, the framework emphasises quality assurance and rigorous commissioning of IAQ-related systems, with a focus on ventilation and pollutant control.

This requires training for installers, thorough documentation, and ongoing collaboration with manufacturers. This includes employing skilled labour, conducting rigorous commissioning and inspections, and documenting the process to ensure accountability. Training for contractors and installers is essential, as is collaboration with manufacturers for ongoing support. Avoiding cost-cutting measures that compromise IAQ should be a priority, with evidence-based decision-making guiding all modifications and value-engineering efforts. Quality control also requires accounting for future maintenance needs, linking to occupant engagement and education during handover (Guyot et al., 2017; Shrubsole et al., 2018).

6.2.1.4 Handover and Occupation (RIBA Stages 6–7).

The occupation phase is where IAQ outcomes are ultimately achieved and maintained. Post-occupancy monitoring and resident interviews showed that air quality depends on occupants' understanding, daily behaviours, and ability to operate building systems effectively (see Section 4.3). The framework recommends thorough occupant induction, including clear user

guides, digital tools, and ongoing support to ensure that intended solutions are maintained in practice. Continuous feedback mechanisms (e.g., sensor dashboards) encourage occupants to adapt their routines based on real-time IAQ data (Gupta & Chandiwala, 2010; Hamilton et al., 2015), thereby increasing long-term success.

Educational resources such as induction tours and home user guides (HUG) further support occupant understanding and engagement. Continuous monitoring, possibly using IoT and sensor platforms, facilitates a feedback loop that encourages occupants to take responsibility for air quality and supports long-term adaptation. Maintaining relationships between occupants, developers, and suppliers is also important to ensure that support and updates remain available as needs change over time. Occupant behaviour patterns, lifestyle choices, perceptions of IAQ, and interactions with building systems and ventilation strategies are vital for maintaining good IAQ (Delzende et al., 2017). Solutions initiated early in the process (e.g., user-friendly, easily maintainable systems, accessible controls) become critical during occupation, demonstrating the value of transversal, integrated planning throughout development.

Summary.

By mapping the Pathways Approach with both the home development stages and the RIBA Plan of Work, this framework provides a traceable, holistic model for scalable IAQ improvement. It ensures that site, design, construction, and occupancy considerations are systematically aligned with established industry procedures while rooted in the realities of housing delivery. Importantly, the framework acknowledges that interventions are often transversal, emerging at one stage but only effective when continued through subsequent phases, and realised through feedback and adaptation in use. This systems-based perspective is vital for developers, policymakers, and practitioners aiming to deliver healthy, adaptable homes at scale.

6.2.2 Scenarios for Pathway Implementations

Introduction.

Managing IAQ in residential settings is a complex challenge that requires a comprehensive, adaptable approach. The Pathways Approach developed in this research offers a holistic framework that integrates building design, technical systems, occupant behaviours, and

environmental factors to improve IAQ in specific contexts, thereby ensuring enhanced IAQ across various stages of the home development process. While the previous chapters focused on research findings and the analysis of selected case studies, this section moves beyond theory to demonstrate how these insights can be applied in practice through scenario-based examples.

The scenarios presented here do not directly replicate the case studies but are based on the key patterns, behaviours, and intervention points identified throughout the research. Each scenario addresses potential interventions for IAQ improvement, site context, systems and design, and occupant adaptability, corresponding to the three core pathways in the Adequate Solution framework (see Figure 46). By presenting scenarios along these pathways, the research not only demonstrates the framework's practical implementation but also highlights the dynamic interconnections that underpin effective IAQ solutions.

Each scenario is explicitly linked to specific research findings:

- The *site contextual scenario* draws on evidence demonstrating how site location and environmental factors influence IAQ risks, highlighting the importance of early-stage analysis for developers.
- The *ventilation and interior layout scenario* is based on observed patterns of pollutant migration and system usability, emphasising the need for design decisions and technology interaction that support healthy indoor environments.
- The *behavioural change scenario* derived from the experimental and interview data shows that targeted education might encourage occupants to adopt practices that improve IAQ.

By linking each scenario in the research findings, this section demonstrates the traceability between evidence and practical intervention, directly addressing the need for holistic, context-dependent, and adaptable solutions. The scenarios collectively bridge theory and practice, providing actionable guidance for developers, practitioners, and occupants committed to improving IAQ in mass-market housing.

6.2.2.1 Scenario 1: Context-Dependent Solutions

This scenario provides a practical example of how the Pathways Approach can be implemented in a real-world development setting. The example of a new 300-home residential development demonstrates how site-specific factors identified in the research can guide the implementation

of customised IAQ strategies at scale. The scenario goes beyond generic recommendations by demonstrating how the framework enables developers and practitioners to adapt solutions to local risks and opportunities, thereby ensuring effective, scalable improvements in IAQ.

Scenario Description and Application:

In a new development of 300 homes, the proximity of houses to a main road results in varying levels of exposure to traffic-related air pollutants and noise. To address these site-specific challenges, the development is divided into three zones, each with a tailored IAQ strategy based on risk:

- ***Zone 1 (the first 100 homes closest to the main road):*** Homes in this zone are most exposed to traffic-related pollutants, including PM, NO₂, vehicle emissions, and elevated noise levels. Based on research findings on contextual and design pathway interventions, these homes would benefit from mechanical ventilation systems with high-efficiency particulate air (HEPA) filters to reduce the ingress of outdoor pollutants. Air intakes should be positioned away from the road, and in-home air purifiers are recommended. This zoning aligns with the framework's emphasis on addressing site context (Pathway 1) in early planning and integrating design and system solutions (Pathway 2).
- ***Zone 2 (The middle 100 homes):*** Located further from the road, these homes face moderate pollution risks. A hybrid approach is employed, combining mechanical and natural ventilation. Research supports optimising window positioning and size to enhance airflow while reducing pollutant entry. Green infrastructure, such as vegetative buffers or hedgerows, can further filter air before it enters the homes. Smart ventilation systems that adjust in response to real-time air quality data provide a balanced approach to improving IAQ and conserving energy. This highlights the Pathways Approach's ability to tailor solutions for intermediate-risk zones through integrated design, systems, and landscape strategies.
- ***Zone 3 (the most distant 100 homes in the development, furthest from the road):*** The homes furthest from the main road experience the lowest levels of direct traffic pollution but may still face residual risks, particularly during certain wind conditions.

In this zone, the strategy emphasises natural ventilation, with larger operable windows and ventilated facades to promote cross-ventilation. The presence of green spaces helps to create a microclimate that further enhances IAQ. These homes can also benefit from occupant education on optimal window use and maintenance (Pathway 3: Occupation/Behaviour), which aligns with the framework's call for adaptability and ongoing engagement.

By applying the Pathways Approach in this scenario, the framework is operationalised through zoning and tailored interventions, demonstrating proactive management of IAQ risks rather than reactive responses. Early-stage site analysis and strategic planning (Pathway 1) inform design and technology choices (Pathway 2), which are further reinforced by occupant education and behaviour support (Pathway 3). This integrative, evidence-based approach ensures that IAQ improvements are embedded throughout the home development process, with each solution supporting the others in practice.

6.2.2.2 Scenario 2: Ventilation and Interior Layout.

This scenario demonstrates how the proposed Pathways Approach facilitates the practical integration of design and technology interventions to control the migration of indoor pollutants. Drawing on research findings from both monitored case studies and occupant feedback, it shows how interior and ventilation system choices, when considered together, can be used to achieve good IAQ across various home types. Case study analysis and monitoring revealed that the layout of homes, particularly kitchens, and the positioning of doors, windows, and ventilation systems influence pollutant movement. Direct observations in the studied homes demonstrated how design features (such as door undercuts or open-plan versus closed-plan kitchens) can either help improve or worsen IAQ.

Scenario Description and Application:

In designing new homes, developers often face a choice between open-plan and closed kitchen layouts. Findings from this thesis indicate that closed kitchens are generally more effective at containing cooking-related pollutants. In contrast, open-plan layouts may allow pollutants to disperse throughout the home, especially without targeted ventilation strategies. Although a direct comparative analysis between open and closed kitchens was not conducted, case study observations suggest that home zoning and the presence of physical barriers (e.g., doors)

significantly influence pollutant migration. The following approaches are recommended to apply these findings in practice.

- *Pollutant Movement Control through Design*: Pollutants generated during cooking, cleaning, or other household activities have the potential to migrate throughout the rest of the house, impacting IAQ in rooms where occupants spend the most time. This risk is amplified by inadequate ventilation. By designing the airflow paths throughout the home, including the strategic positioning of doors, vents, windows, and exhaust fans, developers can guide pollutants towards extraction points and away from occupied spaces. The scenario also draws on research findings that effective IAQ improvement requires combining passive design (layout, barriers, and natural ventilation) with active systems (mechanical extraction, smart controls). Incorporating smart ventilation that responds to pollutant spikes and encourages occupants to close doors or use exhaust fans during cooking or cleaning can further improve IAQ.

By applying the Pathways Approach to interior layout and ventilation system design, this scenario emphasises the importance of considering both building-level decisions (Pathway 2). The interventions described are based directly on observed pollutant migration patterns in the research, highlighting that measurable improvements in IAQ are best achieved when interior layout and technology are coordinated.

6.2.2.3 Scenario 3: Occupant Awareness and Behavioural Change.

This scenario reflects experimental and interview data from the thesis, which showed that increasing occupant awareness and providing real-time feedback on IAQ are among the most effective strategies for encouraging behaviour change. When occupants have access to clear information about indoor pollutant levels and the impact of their daily activities, they are much more likely to adopt healthier routines. The provision of real-time IAQ data (via apps or dashboards) led to changes in window-opening behaviour, filter maintenance, and reduced activities that generate pollutants.

Scenario Description and Application:

This scenario focuses on practical methods to increase occupant awareness and promote sustained behavioural change as key strategies for improving IAQ. Building on the research findings (see Chapter 4, Section 5.3.4), the study suggests that all new homes should be

equipped with IAQ sensors and user-friendly dashboards, ensuring that occupants receive regular, practical, and easy-to-understand information about air quality in their homes. The feedback system is designed to accommodate different home-ownership models.

- *Private owners:* Receive detailed maintenance reminders, best-practice guides, and performance feedback on the use of installed systems.
- *Socially rented homes:* Feature simplified guidance, clear visual direct reporting for maintenance issues, and targeted education for both residents and housing managers. Additionally, residents and housing managers should be provided with targeted education and support, recognising different levels of prior knowledge and engagement.

These actions are linked to the research findings: in the case studies, increased feedback and targeted awareness campaigns encouraged occupants to understand and maintain the IAQ of their homes (See Section 5.3.4). This scenario highlights the importance of integrating the occupant/behaviour pathway (Pathway 3) with technological solutions (Pathway 2), ensuring that occupants are integral to IAQ-improving solutions.

Overall, these scenarios support the key findings of this research by demonstrating how the Pathways Approach can be adapted to address specific challenges in the real-world delivery of new housing. Each scenario is built on empirical evidence from case studies and experiments, ensuring traceability and relevance. By providing examples of practical applications across diverse site contexts, systems, and occupant behaviours, this section offers developers actionable, research-backed strategies to achieve cost-effective, scalable IAQ solutions.

6.3 Chapter Summary.

This chapter has introduced the Pathways Approach as a proposed framework for improving IAQ in new homes. Based on evidence from case studies, literature, and empirical research, the framework combines the key pathway levels: Site, Building, Design & Technology/Systems, Occupation, within the broader Home Development Process. This framework addresses the complexity and variability of IAQ challenges in homes. The chapter demonstrated how scalable, adaptable, and practical solutions can be developed by aligning contextual analysis, design integration, system optimisation, and occupant adaptability at each stage of the housing delivery process. Practical implementation was illustrated through scenario-based examples linking research findings to real-world applications, ensuring relevance and traceability.

The Pathways Approach offers developers, practitioners, and occupants evidence-based strategies to enhance IAQ and encourages integrating IAQ considerations throughout the planning, design, construction, and occupancy of residential settings. The next chapter will summarise the overall research, highlight the key contributions of this study, and conclude the thesis.

Chapter 7. Conclusions and Recommendations.

Introduction.

This chapter consolidates the key findings of this research, which adopts a holistic approach to addressing IAQ in new UK homes. Central to the study is the Pathways Approach, which conceptualises IAQ management through three main pathways: Building, Technology/Systems, and Occupation, each integrated within the broader context of the home development process. The research recognises the home development process not as a separate pathway but as the overarching context in which these pathways interact, influencing IAQ outcomes at every stage, from strategic planning to post-occupancy. This chapter consolidates the research findings, connecting the initial research problem and objectives outlined in Chapter 1 with the empirical evidence and framework established in Chapters 5 and 6, thereby illustrating a clear evidence trail from problem identification to solution development.

The research employs multiple methods, including interviews with developers and industry professionals; real-time IAQ monitoring in both occupied and unoccupied homes; targeted experiments (e.g., cooking-related pollution); and daily activity diaries and occupant surveys. Baseline IAQ data from unoccupied homes further supported the findings.

Through this approach, the study has developed a comprehensive framework, the Pathways Approach, that integrates technical, behavioural, and organisational factors to deliver scalable, adaptable solutions for IAQ improvement. This chapter synthesises the main research findings, evaluates the achievement of research objectives, and outlines the implications for practice and policy. It also discusses limitations, proposes areas for future research, and reflects on the research process. The chapter is structured as follows: achievement of research objectives; main conclusions; research contributions; recommendations; dissemination; limitations; future research directions; reflections on the research journey; and a chapter summary.

7.1 Key findings in achieving the research aim and objectives.

The main aim, objectives, and questions of this thesis were outlined in Section 1.3 (Chapter 1). The main aim was to identify and assess the key pathways contributing to poor IAQ in new homes, and to develop cost-effective, scalable strategies to improve IAQ and minimise health

risks. To achieve this, the research was guided by five objectives and two central research questions, which were addressed using a mixed-methods approach, as described in Chapter 3.

Each objective and question was addressed through a combination of literature review, empirical measurement, stakeholder engagement, and the development of an integrative framework. The table below summarises how each objective was achieved, the methods used, and the chapters where supporting evidence can be found.

Table 7 1: Mapping of research aims, objectives, and questions against thesis findings.

Research Aim	Research Objectives	Method of Achievement	Chapter Presented
This research aims to improve indoor air quality by investigating pathways across building design, technologies, occupant behaviours and the home development process, in order to develop cost-effective strategies and minimise health risks.	1. To review and synthesise the multiple factors affecting IAQ in homes.	Comprehensive literature review of IAQ determinants, health impacts, regulatory context, and systems thinking; synthesis of current knowledge.	Chapter 2, Chapter 4
	2. To measure IAQ in practice under different house types and occupant activities to determine how poor IAQ arises in real-world scenarios.	Real-time IAQ monitoring in both occupied and unoccupied homes, utilising sensor data for comparison across dwelling types and daily activity logs.	Chapter 4, Chapter 5
	3. To assess occupants' understanding of how their behaviour patterns and lifestyle choices influence IAQ.	Surveys, semi-structured interviews, and behavioural experiments (e.g., cooking episodes); analysis of daily diaries and occupant feedback.	Chapter 4 (Section 4.3), Chapter 5
	4. To examine decision-making processes in the home development process that affect IAQ and identify opportunities for more effective interventions.	Qualitative interviews were conducted with home developers, industry professionals, and supply chain members, and the data were analysed thematically to identify barriers and opportunities.	Chapter 4 (Section 4.2), Chapter 5
	5. To propose an evidence-based framework and practical recommendations to guide designers, developers, and occupants in adopting best practices and increasing IAQ awareness.	Development and presentation of the Pathways Approach and Adequate Solution Framework; validation through practical scenario application.	Chapter 5, Chapter 6
Research Question	Addressing the Research Questions		
<ul style="list-style-type: none"> How do decision-making processes across various stages of the home development process influence IAQ, and what opportunity exists to integrate IAQ considerations from land acquisition to occupancy? 	This was achieved by mapping the home development process, identifying critical intervention points (Chapters 4 and 5), and exploring stakeholder perspectives. The Pathways Approach demonstrates how decisions at each stage, from strategic planning to occupancy, influence IAQ outcomes, emphasising the importance of integrating IAQ measures early.		

- How can a holistic and systemic approach to managing IAQ be implemented to address the complex and interconnected factors influencing it, avoiding unintended consequences of isolated interventions?

The thesis developed a holistic, systems-based framework (the Pathways Approach) that synthesises findings from empirical research, case studies, and industry engagement. By integrating the pathways of Building, Technology/Systems, and Occupation within the Home Development Process, the research highlights the need for coordinated, adaptable solutions. These solutions were demonstrated through real-world scenario applications (Chapter 5).

As shown in Table 7.1, the research systematically addressed each objective and both research questions through a practice-oriented methodology. The following sections of this chapter explain the implications, synthesis, and practical contributions of these findings.

7.2 Key Findings in Relation to Research Questions.

The two research questions that guided the study were:

1. How do decision-making processes across various stages of the home development process influence IAQ, and what opportunity exists to integrate IAQ considerations from land acquisition to occupancy?
2. How can a holistic and systemic approach to managing IAQ be implemented to address the complex and interconnected factors influencing it, avoiding unintended consequences of isolated interventions?

7.2.1 RQ1.

How do decision-making processes across various stages of the home development process influence IAQ, and what opportunity exists to integrate IAQ considerations from land acquisition to occupancy?

The findings revealed that IAQ was rarely prioritised at the beginning of development. Discussions around land acquisition, planning, and scheme orientation were dominated by commercial pressures, land availability, and compliance with planning requirements, with limited attention given to site-specific air quality or environmental risks.

As a result, ventilation design and IAQ-related measures were typically deferred until late in the process, often in isolation. Collaboration with MEP specialists and ventilation manufacturers was also delayed until RIBA Stages 3-4, limiting opportunities to effectively integrate IAQ into the overall design intent. Construction practices further affected IAQ outcomes. Commissioning of ventilation systems and quality-control checks were inconsistent,

and handovers often left occupants without clear instructions for operating the system. These gaps led to performance shortfalls and undermined the intended systems outcomes, reflecting broader concerns about the performance gap in housing delivery.

Despite these challenges, opportunities were identified across the process. Developers and construction professionals acknowledged that IAQ could be systematically embedded by integrating environmental assessments (noise, air quality, site context) during planning, engaging ventilation specialists earlier in the design process, and improving commissioning and handover protocols. These leverage points, identified through this research, demonstrate that IAQ integration is achievable if incorporated at key decision stages, rather than retrofitted as an afterthought.

7.1.2 RQ2.

How can a holistic, systemic approach to managing IAQ be implemented to address the complex, interconnected factors that influence it while avoiding the unintended consequences of isolated interventions?

The results revealed that IAQ in new homes arises from a systemic interplay of site context, building design, technologies, and occupant behaviour, rather than from isolated factors. Monitoring in unoccupied homes revealed a low baseline for pollutant levels. However, occupation introduced pollutant spikes from everyday activities, such as cooking, cleaning, and the use of consumer products. These patterns underline that IAQ cannot be fully understood or improved without considering occupant behaviour and lifestyle.

Ventilation systems had the potential to mitigate poor IAQ and reduce pollutant spikes, but were undermined by usability problems and inconsistent occupant engagement. Many residents defaulted to opening windows, which sometimes diluted pollutants but also introduced outdoor pollution and energy losses. Feedback interventions identified opportunities for behavioural change, as some occupants adjusted their routines when provided with real-time IAQ data. This highlights the value of combining behavioural measures with technical solutions.

The findings highlighted that isolated interventions, whether improving building envelopes, installing mechanical systems, or promoting behaviour change, are not enough on their own. Instead, IAQ requires coordination throughout the entire home development process, aligning planning and scheme orientation, building design, ventilation systems, commissioning, and

occupant education. This reinforces the need for a pathways approach, in which design, technology, development practices, and occupant behaviour are viewed as interconnected elements of IAQ improvement.

7.3 Research Overall Contribution.

This thesis makes an original contribution to knowledge by reframing IAQ in new UK homes as the result of interconnected decisions involving building design, technologies and systems, occupant behaviour, and the home development process. Its novelty lies not only in identifying these factors but also in demonstrating how they interact in real residential settings and translating these interactions into a Pathways Approach that supports practical decision-making. Empirically, the research contributes evidence from monitored occupied and unoccupied homes, supported by interviews, diaries, and targeted experiments. Conceptually, it promotes a systems-based framework that considers IAQ as a cross-stage housing-delivery issue rather than purely a technical or post-occupancy problem. Practically, the findings are relevant to developers, designers, contractors, housing providers, and policymakers, as they highlight where IAQ can be addressed more effectively across planning, design, construction, handover, and use. The potential benefits include earlier, more integrated IAQ decision-making, improved alignment between health and energy objectives, better system usability and occupant support, and more scalable strategies to reduce pollutant exposure in mass-market housing.

The following sections explain how these contributions are achieved across the identified pathways and are supported by the empirical findings of this research. Addressing IAQ is not solely a technical matter but also a socio-environmental problem, requiring a comprehensive, integrated approach that transcends traditional disciplinary boundaries. Unlike previous work that isolates particular components or focuses on post-occupancy technical fixes, this research integrates IAQ improvement into the housing delivery process. In doing so, it highlights the need for systemic integration, demonstrating that effective solutions must account for the complex interdependencies of design decisions, system capabilities, and user practices.

The building and design pathway established that decisions regarding airtightness, spatial layout, and material selection are fundamental in shaping home pollutant dynamics. While improved airtightness offers energy efficiency benefits, it also increases reliance on mechanical

ventilation to maintain adequate IAQ (Janda & Topouzi, 2015). Monitoring during the unoccupied phase revealed that emissions from construction materials had a minimal impact on IAQ compared with daily occupant activities, echoing Dimitroulopoulou's (2012) findings. Experimental evidence from occupied homes further noted the importance of closed kitchen layouts in limiting pollutant migration, reinforcing conclusions drawn by Xiang et al. (2021) and Weschler (2015). These findings underline the limitations of one-size-fits-all solutions and emphasise the need for contextually responsive IAQ strategies (Rojas et al., 2024).

The research's technology/systems pathway identified persistent challenges in installation quality, system usability, and real-world performance, with a particular focus on MVHR systems. Notably, the study identified frequent installation flaws, such as missing boost controls, often resulting from subcontractor errors and inadequate oversight. Similar problems have been observed in other UK studies (McGill et al., 2017; Kang et al., 2022), resulting in suboptimal system operation and unintended occupant behaviours, such as running the MVHR with windows open. The research results indicated that occupants frequently found ventilation interfaces confusing, leading many to default to opening windows, thereby undermining energy-efficiency and IAQ goals. This echoes another study that emphasised how regulatory assumptions about occupant behaviour do not always hold in practice, highlighting the gap between intended use and real-world operation (McGill et al., 2015). It also highlighted the persistence of habitual behaviour, such as routinely opening windows, even in homes with advanced ventilation systems, a clear indicator of the importance of effective handover, accessible user guides, and occupant education (Sharpe et al., 2015).

The occupation pathway revealed that everyday household activities, including cooking, cleaning, and using consumer products, were the primary drivers of pollutant spikes. Behavioural change experiments indicated that real-time feedback encouraged some households to adopt healthier practices, demonstrating the importance of feedback mechanisms and ongoing engagement. At the same time, the findings reveal that education and support are not always effective, with varying uptake across households. This highlights the need for tailored approaches that consider diverse occupant preferences and lifestyles.

At the home development process level, the research identified systemic barriers rooted in the sequential, cost-driven, and regulatory-focused nature of UK homebuilding. IAQ was often overlooked during land acquisition, early design, and construction, resulting in missed opportunities for integration and persistent performance gaps. This finding aligns with

Sterman's (2002) call for system-wide, coordinated interventions and highlights the need for collaborative, cross-disciplinary decision-making that extends beyond minimum compliance. It reflects a persistent tension between commercial imperatives and environmental health and underscores the need for cross-disciplinary collaboration and earlier integration of IAQ considerations.

The Pathways Approach Framework presented in this research is, therefore, a key contribution. It serves both as a conceptual lens for understanding IAQ as the outcome of interconnected pathways and as a structured approach to support decision-making. It maps IAQ throughout the RIBA Plan of Work and demonstrates it through scenario-based applications. By connecting empirical evidence from monitoring, live experiments, and interviews with both industry professionals and occupants, the framework demonstrates how context-specific, technical, and behavioural factors intersect to influence IAQ outcomes. It further shows how these factors can be addressed systematically through adequate, adaptable solutions that can be scaled and potentially applied across mass-market housing delivery.

In summary, this research contributes to both theory and practice by:

- Establishing the Pathways Approach as a novel, system-based framework that defines IAQ as a result of interconnected decisions involving building design, technologies and systems, occupant behaviour, and the home development process.
- Providing real-world evidence from monitored unoccupied and occupied homes, demonstrating how pollutant behaviour varies between baseline conditions and daily use, and how IAQ is influenced by occupant activities and system interactions.
- Identifies and explains the performance gap between design intent and actual IAQ outcomes, linking this to system usability, commissioning quality, and behavioural adaptation.
- Demonstrates the role of occupant behaviour and feedback mechanisms in shaping IAQ outcomes, emphasising the importance of usability, education, and engagement alongside technical solutions.
- Provides a scalable and adaptable decision-support approach for housing developers, designers, contractors, housing providers, and policymakers, supporting improved IAQ management, reduced pollutant exposure, and better alignment between health and energy objectives in mass-market housing.

Collectively, these contributions demonstrate that IAQ in new homes cannot be addressed with isolated interventions; it requires an integrated approach that aligns decisions across all stages of the housing delivery process. This holistic approach improves the theoretical understanding of IAQ as a complex system. It provides practical guidance for developers, policymakers, and researchers, supporting the creation of healthier, adaptable homes at scale. Overall, this research advances understanding of IAQ by moving beyond single-perspective solutions and offering a holistic, practical, and scalable approach to improving IAQ in new UK homes.

7.4 Recommendations & Implications.

To achieve the aim of this research, the proposed Pathway Approach requires a comprehensive, holistic strategy to improve IAQ within the UK home development process, considering the interplay among building design, technologies and systems, occupants, and environmental conditions. This proposed Pathway Approach framework recognises that solutions for managing IAQ cannot be standardised and must be tailored to specific applications. The purpose of this research is to provide scalable, adaptable solutions that address specific IAQ challenges and demonstrate their capacity to adapt to changing conditions. The outcomes are ‘adequate solutions,’ which, although not optimisable, resolve specific issues and, importantly, present how these solutions can be adapted for evolving circumstances. These recommendations are summarised below:

1. Early Environmental Analysis:

- Conduct comprehensive environmental assessments during the land acquisition and strategic planning stages, focusing on air pollution sources, noise levels, and site orientation to optimise natural ventilation.
- Integrate IAQ-focused strategies into broader planning frameworks to address site-specific challenges.

2. Design and Scheme Planning:

- Ensure IAQ is a central consideration during the design stage by conducting:
 - Orientation Analysis: Optimise the site layout to minimise pollutant ingress and maximise ventilation potential.
 - Ventilation and Window Design Optimisation: Develop solutions tailored to the building’s airtightness while balancing energy efficiency and IAQ.

- Collaborative approach and participatory design: Involve all relevant stakeholders early in the process to integrate IAQ considerations into decision-making, ensuring feasibility and considering site-specific factors.
- Building design with people in mind.
- Focus on interior layout, particularly in spaces like kitchens, to mitigate pollutant movements.
 - Some kitchens in the studied homes lacked extractor hoods and instead relied on MVHR outlets or mechanical extract fans. While these systems facilitated rapid decay of pollutants, they were insufficient to prevent high peak concentrations of particulates and VOCs during cooking. With the increasing use of modern cooking appliances such as air fryers and microwaves, traditional extractor hoods may also be less effective in mitigating pollutants.
 - Enclosed kitchens in the study were effective at limiting pollutant migration to other living areas. However, the increasing prevalence of open-plan layouts, in which kitchens are integrated with dining and living spaces, presents significant IAQ challenges. While open-plan designs align with contemporary preferences for maximising space and fostering connectivity, they increase occupant exposure to pollutants generated by the kitchen. Consequently, open-plan designs should be reconsidered, particularly in contexts where controlling pollutant migration is critical for maintaining IAQ.

3. Construction and Implementation:

- Ensure that designed solutions are implemented accurately by:
 - Engaging skilled labour trained in IAQ-focused systems, such as MVHR.
 - Conducting thorough quality control and system testing to ensure ventilation systems meet performance standards.
 - Avoid unplanned cost-cutting measures that compromise IAQ strategies.
 - Communication design team and subcontractors.

4. Post-Construction and Occupation:

- Promote occupant education through comprehensive induction programs, including:
 - Interactive home tours.
 - User-friendly guides for ventilation systems.
 - Digital support tools, such as mobile apps, can provide ongoing assistance.
- Establish channels for ongoing monitoring and feedback to refine IAQ strategies based on occupant experiences and environmental changes.
- Explore pilot studies in diverse locations to assess IAQ challenges under varying external conditions, such as noise, security, and outdoor air pollution.
- Handover best timing.

In conclusion, the recommendations align with the Pathway Approach by addressing IAQ challenges at every stage of home development, from early environmental analysis to post-occupancy monitoring. These recommendations are designed to be scalable and adaptable, offering solutions for both broad home development processes and individual homes. By embedding IAQ considerations into the home development process, this approach ensures sustainable improvements in IAQ, with long-term benefits for occupant health and well-being. The integration of IAQ management strategies into the design, construction, and occupancy phases is crucial for maintaining occupant health and well-being.

7.5 Main Conclusion.

IAQ is a critical determinant of occupant health and well-being (NICE, 2020b), particularly because people spend most of their time indoors (Ferguson et al., 2021; Kornartit et al., 2010). Poor IAQ, resulting from a buildup of pollutants such as CO₂, PM_{2.5}, and VOCs, can have significant health implications. While ventilation is a key mechanism for diluting indoor pollutants (RCP, 2016), it is only one aspect of a complex system influenced by building design, occupant behaviour, and environmental conditions. Balancing ventilation needs with energy efficiency requirements poses a challenge, particularly as tighter building envelopes reduce infiltration while demanding effective ventilation strategies (ZCH, 2016; CIBSE, 2015). This is critical, given global commitments to reduce CO₂ emissions through agreements such as the Paris Accord (UNFCCC, 2015).

By assessing IAQ in real-world settings, this research revealed that traditional design and assessment methods, which rely on synthetic occupant profiles, often fail to accurately predict the extent of air quality challenges. Monitoring real houses with actual occupants highlighted significant discrepancies between design expectations and operational outcomes. Occupants generally had limited formal knowledge of indoor pollutant sources and tended to recognise issues only when pollutants produced unpleasant odours or caused noticeable health effects. This is particularly concerning, as many indoor pollutants are either odourless or have a pleasant scent. These findings underscore the need for occupant-centred strategies that account for variability in behaviours, such as cooking practices, window use, and ventilation system operation.

The research also highlights the need for a holistic Pathway Approach to IAQ management that addresses its multifaceted nature by integrating building design, technological systems, occupant practices, and the housing delivery process. The research identified that only cost-effective mitigation strategies have the potential for widespread adoption by home builders and integration across the home development sector. Practical and scalable solutions were validated, emphasising strategies that not only address immediate causes of poor air quality but also promote long-term success. These findings informed the development of a proposed pathway approach framework designed to embed IAQ considerations into every stage of the home development process, from land acquisition to post-occupancy use.

The results demonstrate that IAQ interventions must account for the interconnectedness of technical systems, environmental conditions, and occupant behaviour to avoid unintended consequences. For instance, habits such as opening windows while operating MVHR systems highlight the need for improved system usability and occupant education. Educating residents about their role in maintaining IAQ and providing tools for continuous monitoring can empower them to make informed decisions, thereby enhancing air quality while supporting energy-efficiency goals. This research has provided critical insights into the limitations of current IAQ practices and offers a pathway for improved air-quality management in mass-market housing. By aligning technical solutions with occupant needs and addressing IAQ holistically, this study contributes to a deeper understanding of IAQ dynamics in new UK homes. The proposed scalability framework ensures that solutions are adaptable, cost-effective, and capable of addressing long-term challenges, driving improvements across the housing development sector.

In conclusion, this thesis highlights the importance of integrating IAQ considerations into all stages of the home development process. By adopting a systemic pathway approach, stakeholders, including developers, designers, and policymakers, can create healthier living environments while addressing the interconnected challenges of building design, occupant behaviour, and technological systems. This work lays the foundation for future research, further refinement of IAQ management strategies, and broader implementation of scalable solutions in the UK housing sector.

7.6 Main Limitations of the Study.

This research set out to offer a practice-based solution for IAQ in new UK homes; several limitations should be recognised. These stem mainly from constraints inherent in monitoring occupied homes, the characteristics of the case study sample, and the realities of conducting research in real-world development environments.

All case study homes were located in England and were primarily constructed of traditional brick. While this reflects a significant portion of the UK mass-market sector, it does not represent the full range of construction methods, such as modular or timber-frame homes, nor does it account for regional differences across Wales, Scotland, or Northern Ireland. The professional stakeholders involved were predominantly from the English volume-building sector, with perspectives from local authorities, housing associations, and owner-builders not directly included. These factors limit the wider applicability of the findings.

COVID-19 restrictions further affected the study, particularly by reducing in-person interaction and limiting the ability to implement extensive behavioural change interventions. Although participant willingness was generally high, national lockdowns sometimes limited follow-up visits and equipment troubleshooting, affecting data completeness and the scope of intervention research.

A further limitation concerns the reliance on participant-reported information, such as daily diaries and interviews. While these data offer valuable insights into occupant behaviour and perceptions, they are subject to recall bias, subjectivity, and incomplete reporting. Therefore, it is impossible to establish definitive causal links between specific behaviours and measured IAQ outcomes based solely on these sources.

Overall, the findings and recommendations should be interpreted as indicative rather than conclusive, given the realities of conducting applied research in real-world settings. Future work would benefit from wider geographic and construction-type coverage, larger and more diverse samples, and improved capacity for long-term, in-depth behavioural intervention studies.

7.7 Future Research.

Building on the study's findings and limitations, several directions for future research are proposed to enhance understanding and the practical management of indoor IAQ in UK homes.

Future work should expand the scope of monitored homes to include a wider range of construction types and geographic areas across the UK, including Wales, Scotland, and Northern Ireland. Incorporating modular, timber-frame, and other emerging construction methods will help determine whether the pathways and interventions identified here are applicable across different building contexts and regulatory environments.

Increasing the sample size and diversity in terms of homes and participant demographics would enable more analysis of IAQ outcomes and generalise the findings. Studies focusing on specific household types, occupancy patterns, or at-risk groups (such as vulnerable occupants or homes in areas with higher pollution) could also help clarify the pathways that influence IAQ. Overcoming practical constraints faced in this research will also be important. Developing longer-term, in-depth behavioural intervention studies, possibly using advanced sensor networks, real-time feedback tools, and more structured occupant engagement, would enable assessment of how behavioural change strategies can enhance IAQ over time in real-world conditions.

There remains a need for research into how IAQ management integrates with other housing priorities, such as energy efficiency, decarbonisation, and occupant comfort. Performing life-cycle assessments and cost–benefit analyses of IAQ improvement measures, especially those proposed in the Pathway Approach, would offer valuable guidance to developers, policymakers, and practitioners who must weigh health, performance, and affordability.

Finally, developing and deploying digital tools, such as user-friendly dashboards or mobile applications, would help both occupants and professionals monitor, interpret, and act on IAQ data. Expanding stakeholder engagement to include local authorities, housing associations, owner-builders, and supply chain members will also be crucial for refining and scaling up the

solutions proposed in this research. By exploring these areas, future research can further develop scalable, adaptable, and context-sensitive strategies for IAQ management in the UK housing sector.

7.8 Final Research Journey Note.

A researcher's personal background, professional experience, and evolving perspective inevitably influence the direction, methodology, and outcomes of academic inquiry. In this section, I reflect on my research journey and how my background, previous experience, and interactions with industry and occupants have contributed to this thesis on IAQ in new UK homes.

My initial motivation for pursuing this research stemmed from a long-standing interest in the built environment, particularly building design, and a growing awareness of the relationships among climate change, sustainability, and health. With prior industry experience, I was particularly drawn to this project because it allowed direct collaboration with practitioners and, more importantly, provided an opportunity to observe firsthand how design choices, construction practices, and cultural expectations influence IAQ. These experiences sparked my curiosity about how IAQ is managed or, at times, overlooked in new housing, especially as homes become more airtight and technologically complex.

From the outset, I recognised that this research offered an opportunity to address a timely, real-world challenge at the intersection of housing, health, and technology. Early meetings with my supervisory team and collaboration with industry partners, including leading UK home developers, provided a clear understanding of the project's practical relevance and highlighted the challenges currently facing the UK housing sector.

The timing of my research coincided with the COVID-19 pandemic, which introduced both limitations and unexpected opportunities. While the literature review and conceptual work proceeded remotely, access to homes for sensor deployment and face-to-face engagement with occupants was repeatedly postponed. Like many others, I adapted by shifting interviews with developers, supply chain professionals, and building professionals online and by reconsidering data collection and research planning to accommodate new constraints. At the same time, the pandemic increased awareness of indoor environments, highlighting the importance of IAQ as more people spent extended periods at home.

As restrictions eased, the research progressed to the case study phase and successfully implemented live IAQ monitoring in six newly built homes. Practical challenges emerged, including determining suitable sensor placement, liaising with households, and addressing technical issues such as connectivity and device reliability, all of which highlighted the realities and complexities of real-world research. Engaging with occupants through interviews, daily dairies, and experiments not only enhanced the research data but also added a vital human perspective, revealing how habits, knowledge gaps, and lifestyle choices interact with buildings to influence IAQ. Regular meetings with industry partners ensured that the work remained focused on both practical needs and ethical standards. These engagements highlighted the importance of delivering findings that could inform both policy and practice, while also revealing the challenge of balancing academic precision with commercial and real-world sensitivities.

One of the most rewarding aspects of the research was the opportunity to engage directly with home occupants and industry professionals. These exchanges contributed to the dataset and deepened my understanding of how everyday practices and user knowledge influence the operation and effectiveness of IAQ management. Capturing this diversity of experience required continual reflection and adaptability, particularly in maintaining objectivity and rigour. Looking back, this research journey has involved methodological adaptation, learning and collaboration across professional and disciplinary boundaries. While there were inevitable limitations, including delays, sample size constraints, and the challenges of keeping participants engaged, the experience highlighted the value of flexibility, openness, and participatory methods in academic research. Most importantly, it reinforced the need for holistic, practical, and occupant-centred approaches for improving IAQ in the UK housing sector.

In conclusion, this thesis not only addresses an urgent public health concern but also reflects a personal and professional journey of growth as a researcher. It integrates practice-based insights and academic investigation to support healthier homes through integrated, evidence-based IAQ management.

Chapter 8 References.

- Abdel Sater, R., Perona, M., Huillery, E. & Chevallier, C. (2024). 'The power of personalised feedback: Evidence from an indoor air quality experiment', *Behavioural Public Policy*, pp. 1–38.
- Ahmed Abdul-Wahab, S., En, S.C.F., Elkamel, A., Ahmadi, L. & Yetilmezsoy, K. (2015). 'A review of standards and guidelines set by international bodies for the parameters of Indoor Air Quality', *Atmospheric Pollution Research*, 6(5), pp. 751–767.
- Aberdeen, T. (2013). Yin, R. K. (2009). Case study research: Design and methods (4th ed.). Thousand Oaks, CA: Sage. *The Canadian Journal of Action Research*, 14(1), pp. 69–71.
- Abrams, E.M. (2020). 'Cleaning products and asthma risk: A potentially important public health concern', *Canadian Medical Association Journal*, 192(7).
- Adams, D., Leishman, C. and Moore, C. (2009). Why not build faster? Explaining the speed at which British housebuilders develop new homes for owner-occupation, *Town Planning Review*, 80(3), pp. 291–314.
- Adetuyi, A., Adebowale, A., Olamide, O., Uche-Ugwu, C. M. & Borode, D. (2024). 'Housing crisis in England: A comparative policy paper on the Ministry of Housing, Communities and Local Government (MHCLG)', *WSEAS TRANSACTIONS ON BUSINESS AND ECONOMICS*, 21, pp. 1055–1063.
- Agarwal, N., Meena, C. S., Raj, B. P., Saini, L., Kumar, A., Gopalakrishnan, N., Kumar, A., Balam, N., Alam, T., Kapoor, N., Aggarwal, V. (2021). 'Indoor air quality improvement in COVID-19 pandemic: Review', *Sustainable Cities and Society*, 70, p. 102942.
- Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M. and Elsarrag, E. (2016). 'Occupant productivity and office indoor environment quality: A review of the literature', *Building and Environment*, 105, pp. 369–389.

- Alapieti, T., Pasanen, P., Salonen, H., Lappalainen, S. and Kähkönen, E. (2020). The influence of wooden interior materials on indoor environment: A Review, *European Journal of Wood and Wood Products*, 78(4), pp. 617–634.
- Allen, J.G. and Ibrahim, A.M. (2021). ‘Indoor air changes and potential implications for SARS-COV-2 transmission’, *JAMA*, 325(20), p. 2112.
- Amaratunga, D., Baldry, D., Sarshar, M., & Newton, R. (2002). ‘Quantitative and qualitative research in the built environment: Application of “Mixed” research approach’, *Work Study*, 51(1), pp. 17–31.
- Anderson, L.G. (2015). ‘Effects of using renewable fuels on vehicle emissions’, *Renewable and Sustainable Energy Reviews*, 47, pp. 162–172.
- Amaratunga, D., Baldry, D., Sarshar, M. and Newton, R. (2015). ‘Cost-effective technologies to control indoor air quality and comfort in energy efficient building retrofitting’, *Environmental Engineering and Management Journal*, 14(7), pp. 1487–1494.
- Arundel, A.V., Sterling, E.M., Biggin, J.H. and Sterling, T.D. (1986). ‘Indirect health effects of relative humidity in indoor environments’, *Environmental Health Perspectives*, 65, p. 351.
- ASHRAE (2016). Ventilation for Acceptable Indoor Air Quality, *Standards 62.1 & 62.2*. Available at: <https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2>. (Accessed: 09 February 2023).
- ASHRAE (2022a). ANSI/ASHRAE Standard 62.1-2022, Ventilation and Acceptable Indoor Air Quality. *Peachtree Corners, GA: ASHRAE*.
- Asikainen, A., Carrer, P., Kephelopoulos, S., de Oliveira Fernandes, E., Wargocki, P., Hänninen, O. (2016). Reducing the Burden of Disease from Residential Indoor Air Exposures in Europe (HEALTHVENT Project). *Environmental Health*, 15(S1).
- ATTMA (2016). *Air Tightness Testing and Measurement Association. Go to the main NBS website*. Available at:

<https://www.thenbs.com/PublicationIndex/documents?Pub=ATTMA>. (Accessed: 20 April 2024).

- Averchenkova, A., Fankhauser, S. and Finnegan, J.J. (2020). 'The impact of strategic climate legislation: Evidence from expert interviews on the UK climate change act', *Climate Policy*, 21(2), pp. 251–263.
- Baeza Romero, M.T., Dudzinska, M.R., Amouei Torkmahalleh, M., Barros, N., Coggins, A.M., Gazioglu Ruzgar, D., Kildsgaard, I., Naseri, M., Rong, L., Saffell, J., Scutaru, A.M., & Staszowska, A. (2022). 'A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants', *Indoor Air*, 32(11).
- Baker, N. and Steemers, K. (2014). Daylight design of buildings. *A Handbook for Architects and Engineers*. Routledge.
- Balmes, J.R. (2019) 'Household air pollution from domestic combustion of solid fuels and Health', *Journal of Allergy and Clinical Immunology*, 143(6), pp. 1979–1987.
- Baxter, L.K., Clougherty, J.E., Laden, F., & Levy, J.I. (2006). Predictors of concentrations of nitrogen dioxide, fine particulate matter, and particle constituents inside lower socioeconomic status urban homes, *Journal of Exposure Science & Environmental Epidemiology*, 17(5), pp. 433–444.
- Baxter, P. and Jack, S. (2015). 'Qualitative case study methodology: Study Design and implementation for novice researchers', *The Qualitative Report*, 13(4). Pp. 544-559.
- Bédard, A., Varraso, R., Sanchez, M., Rava, M., Januel, E., Torrent, M., Kauffmann, F. and Le Moual, N. (2014). 'Cleaning sprays, household help and asthma among elderly women', *Respiratory Medicine*, 108(1), pp. 171–180.
- Bekö, G., Morrison, G.C., Weschler, C.J., Koch, H.M., Salthammer, T., Schripp, T., Dameris, M., Skov, H., Frederiksen, M., Gunnarsen, L., Clausen, P.A., Hänninen, O., Jantunen, M. and Mandin, C. (2020). The indoor chemical human emissions and reactivity (ICHEAR) project: Overview of experimental methodology and preliminary results, *Indoor Air*, 30(6), pp. 1213–1228.

- Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I., Salamone, F., Scamoni, F. and Scrosati, C. (2019). 'A review of performance of Zero Energy Buildings and Energy Efficiency Solutions', *Journal of Building Engineering*, 25, p. 100772.
- Benton, E. (2024). 'Damp and mould, the big picture. How do we tackle the damp and mould crisis in social Housing: Lessons from the UK', *Frontiers in Environmental Health*, 3.
- Berardi, U. (2017). 'A cross-country comparison of the building energy consumption and its trends', *Resources, Conservation and Recycling*, 123, pp. 230–241.
- Berglund, B., Brunekreef, B., Knöppel, H., Lindvall, T., Maroni, M., Mølhave, L. and Skov, P. (1992). 'Effects of indoor air pollution on human health', *Indoor Air*, 2(1), pp. 2–25.
- Bhagat, R.K., Davies Wykes, M.S., Dalziel, S.B. and Linden, P.F. (2020). Effects of ventilation on the indoor spread of COVID-19, *Journal of Fluid Mechanics*, 903.
- Biesta, G. (2010). 'Pragmatism and the philosophical foundations of mixed methods research', *SAGE Handbook of Mixed Methods in Behavioural Research*, (2nd ed., pp. 95–118). Stage.
- Bingham, A.J., Mitchell, R. and Carter, D.S. (2024). 'Understanding and applying theoretical and conceptual frameworks', *A Practical Guide to Theoretical Frameworks for Social Science Research*, pp. 14–25.
- Black, D., Pilkington, P., Williams, B., Ige, J., Prestwood, E., Hunt, A., Eaton, E., Scally, G. (2021). 'Overcoming systemic barriers preventing healthy urban development in the UK: Main findings from interviewing senior decision-makers during a 3-year planetary health pilot', *Journal of Urban Health*, 98(3), pp. 415–427.
- Bluyssen, P.M. (2013). 'What do we need to be able to (re)design healthy and comfortable indoor environments?', *Intelligent Buildings International*, 6(2), pp. 69–92.
- Bone, A. *et al.* (2010). 'Will drivers for Home Energy Efficiency Harm Occupant Health?', *Perspectives in Public Health*, 130(5), pp. 233–238.

- Boogaard, H., Hoek, G., Knol, A., de Hartog, J., Slottje, P., Ayres, J. G., Borm, P., Brunekreef, B., Donaldson, K., Forastiere, F., Holgate, S., Kreyling, W. G., Nemery, B., Pekkanen, J., Wichmann, E., van der Sluijs, J., Stone, V., Wichmann, E., & van der Sluijs, J. (2009). Concentration response functions for ultrafine particles and all-cause mortality and hospital admissions: Results of a European expert panel elicitation. *Epidemiology*, 20.
- Boogaard, H. *et al.* (2022). ‘Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis’, *Environment International*, 164, p. 107262.
- Braun, V. and Clarke, V. (2006). ‘Using thematic analysis in psychology’, *Qualitative Research in Psychology*, 3(2), pp. 77–101.
- Brook, R.D. *et al.* (2010). ‘Particulate matter air pollution and cardiovascular disease’, *Circulation*, 121(21), pp. 2331–2378.
- Brown, S.K. (1999). ‘Occurrence of volatile organic compounds in indoor air’, *Organic Indoor Air Pollutants*, pp. 170–184.
- Brown, S.K., Sim, M.R., Abramson, M.J. & Gray, C.N. (1994). ‘Concentrations of volatile organic compounds in indoor air - A Review’, *Indoor Air*, 4(2), pp. 123–134.
- Bruce, N., Pope, D., Rehfuess, E., Balakrishnan, K., Adair-Rohani, H. & Dora, C. (2015). ‘Who Indoor Air Quality Guidelines on household fuel combustion: Strategy implications of new evidence on interventions and exposure–risk functions’, *Atmospheric Environment*, 106, pp. 451–457.
- Buonanno, G., Morawska, L. and Stabile, L. (2009). ‘Particle emission factors during cooking activities’, *Atmospheric Environment*, 43(20), pp. 3235–3242.
- Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D. & Walker, K. (2020). ‘Purposive sampling: Complex or simple? Research case examples’, *Journal of Research in Nursing*, 25(8), pp. 652–661.

- Cao, G., Awbi, H., Yao, R., Fan, Y., Sirén, K., Kosonen, R. & Zhang, J.J. (2014). ‘A review of the performance of different ventilation and airflow distribution systems in buildings’, *Building and Environment*, 73, pp. 171–186.
- Caracci, E., Canale, L., Buonanno, G., Stabile, L. (2022). Effectiveness of eco-feedback in improving the indoor air quality in residential buildings: Mitigation of the exposure to airborne particles, *Building and Environment*, 226, p. 109706.
- Caron, F., Guichard, R., Robert, L., Verrièle, M. & Thevenet, F. (2020). ‘Behaviour of individual vocs in Indoor Environments: How ventilation affects emission from materials’, *Atmospheric Environment*, 243, p. 117713.
- Carrasco, S. and Egbelakin, T. (2023). ‘Adaptive Mixed Methods Research for evaluating community resilience and the built environment’, *Mixed Methods Research Design for the Built Environment*, pp. 233–250.
- Carrié, F.R., Olson, C. and Nelson, G. (2021). ‘Building air-tightness measurement uncertainty due to steady stack effect’, *Energy and Buildings*, 237, p. 110807.
- Carroll, E., Carroll, N., Dalton, N., Dardis, F., & Downing, S. (2018). ‘831 Communicating Workplace Health & Wellbeing in the Health Service Executive (HSE)’, *Communications in Occupational Health*. EH40/2005. HSE.
- Carslaw, N. and Shaw, D. (2022). ‘Modification of cleaning product formulations could improve indoor air quality’, *Indoor Air*, 32(3).
- Carslaw, N., Aghaji, J., Shaw, D., Dillon, T. J., Kumar, A., Shaw, M. D., Carslaw, D., Lewis, A., Lee, J. D., Hamilton, J. F., Budisulistiorini, S. H., West, S. E., Edwards, P., McEachan, R., Wood, C. & Yang, T. (2025). ‘The ingenious project: Towards understanding air pollution in homes’, *Environmental Science: Processes & Impacts*, 27(2), pp. 355–372.
- Chaloulakou, A., Mavroidis, I. and Gavriil, I. (2008). Compliance with the annual NO₂ Air Quality Standard in Athens. Required NO_x levels and expected health implications, *Atmospheric Environment*, 42(3), pp. 454–465.

- Chan, W., Kim, Y., Less, B., Singer, B. C., & Walker, I. S. (2019). *Ventilation and indoor air quality in new California homes with gas appliances and mechanical ventilation*.
- Chapman, S.J. (2017). 'Review of *discovering statistics using IBM SPSS Statistics, 4th edition*', *Journal of Political Science Education*, 14(1), pp. 145–147.
- Chatzidiakou, L., Krause, A., Popoola, O. A. M., Di Antonio, A., Kellaway, M., Han, Y., Squires, F. A., Wang, T., Zhang, H., Wang, Q., Fan, Y., Chen, S., Hu, M., Quint, J. K., Barratt, B., Kelly, F. J., Zhu, T. & Jones, R. L. (2019) 'Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments', *Atmospheric Measurement Techniques*, 12(8), pp. 4643–4657.
- Chen, T.-M., Kuschner, W.G., Gokhale, J. & Shofer, S. (2007). 'Outdoor Air Pollution: Nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects', *The American Journal of the Medical Sciences*, 333(4), pp. 249–256.
- Chen, Y., Du, W., Shen, G., Zhuo, S., Zhu, X., Shen, H., Huang, Y., Su, S., Lin, N., Pei, L., Zheng, X., Wu, J., Duan, Y., Wang, X., Liu, W., Wong, M. & Tao, S. (2016). 'Household air pollution and personal exposure to nitrated and oxygenated polycyclic aromatics (PAHs) in rural households: Influence of household cooking energies, *Indoor Air*, 27(1), pp. 169–178.
- Cheng, C.H., Chow, C.L. and Chow, W.K. (2020). 'Trajectories of large respiratory droplets in indoor environment: A simplified approach', *Building and Environment*, 183, p. 107196.
- Chi, C., Chen, W., Guo, M., Weng, M., Yan, G., & Shen, X. (2016). 'Law and features of TVOC and formaldehyde pollution in urban indoor air', *Atmospheric Environment*, 132, pp. 85–90.
- Chin, J.-Y., Godwin, C., Parker, E., Robins, T., Lewis, T., Harbin, P., & Batterman, S. (2014). Levels and sources of volatile organic compounds in homes of children with asthma, *Indoor Air*, 24(4), pp. 403–415.

- CIBSE (2015). *Guide to environmental design (2015, updated 2021)*, CIBSE. Available at: <https://www.cibse.org/knowledge-research/knowledge-portal/guide-a-environmental-design-2015>. (Accessed: 12 June 2023).
- CIBSE (2020). *TM40 Health and Wellbeing in Building Services (2020)*. *Chartered Institution of Building Services Engineers*. Available at: <https://www.cibse.org/knowledge-research/knowledge-portal/technical-memorandum-40-health-and-wellbeing-in-building-services/>. (Accessed: 16 April 2023).
- Cincinelli, A. and Martellini, T. (2017). ‘Indoor Air Quality and Health’, *International Journal of Environmental Research and Public Health*, 14(11), p. 1286.
- Clark, V. L. P., Creswell, J. W., Green, D. O., & Shope, R. J. (2008). Mixing quantitative and qualitative approaches: An introduction to emergent mixed methods research. In S. N. Hesse-Biber & P. Leavy (Eds.), *Handbook of emergent methods* (pp. 363–387). The Guilford Press.
- Collis, J. and Hussey, R. (2014). ‘Dealing with practical issues’, *Business Research*, pp. 21–41.
- COMEAP. (2018). *The Effects of Long-Term Exposure to Ambient Air Pollution on Cardiovascular Morbidity: Mechanistic Evidence*. *Committee on the Medical Effects of Air Pollutants*.
- Committee, R.P. (2024). *The volatile organic compounds in paints, varnishes and Vehicle Refinishing Products Regulations 2012: Post-implementation review - RPC opinion (green-rated)*, GOV.UK. Available at: <https://www.gov.uk/government/publications/the-volatile-organic-compounds-in-paints-varnishes-and-vehicle-refinishing-products-regulations-2012-pir-rpc-opinion-green-rated>. (Accessed: 24 August 2024).
- Corbin, J. and Strauss, A. (2008). *Basics of Qualitative Research (3rd ed.): Techniques and procedures for developing grounded theory*. *Sage Publications*.

- Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). 'Contrasting the capabilities of Building Energy Performance Simulation Programs', *Building and Environment*, 43(4), pp. 661–673.
- Crawley, J., Wingfield, J. and Elwell, C. (2018). 'The relationship between air-tightness and ventilation in new UK dwellings', *Building Services Engineering Research and Technology*, 40(3), pp. 274–289.
- Creswell, J. W. (2014). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches* (4th ed.). Thousand Oaks, CA: Sage.
- Creswell, J., Poth, C.N. and Rawlins, P. (2023). 'Mapping design trends and evolving directions using the SAGE handbook of mixed methods research design', *The Sage Handbook of Mixed Methods Research Design*, pp. 527–537.
- Dainty, A. (2008). Methodological Pluralism in Construction Management Research. *Advanced Research Methods in the Built Environment*, 1, 1-13.
- Davies, M. and Oreszczyn, T. (2012). 'The unintended consequences of decarbonising the built environment: A UK case study', *Energy and Buildings*, 46, pp. 80–85.
- Davies, M.G. (2003). 'The CIBSE guide expression for Ventilation Exchange', *Building Services Engineering Research and Technology*, 24(1), pp. 55–60.
- Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B., Hoffert, M. I., Ingersoll, E., Jaramillo, P., Lackner, K. S., Mach, K. J., Mastrandrea, M., Ogden, J., Peterson, P. F., Sanchez, D. L., Sperling, D., Stagner, J., Trancik, J. E., Yang, C.-J. & Caldeira, K. (2018). 'Net-zero emissions energy systems', *Science*, 360(6396).
- Dawadi, P.N., Cook, D.J. and Schmitter-Edgecombe, M. (2016). 'Modelling patterns of activities using activity curves', *Pervasive and Mobile Computing*, 28, pp. 51–68.
- DECC (2014). 'UK Department of Energy and Climate Change announces bold “community energy strategy”', *Renewable Energy Focus*, 15(1), p. 9.

- DEFRA (2023). Air Quality Strategy 2023., *Home- Defra, UK*. Available at: <https://uk-air.defra.gov.uk/>. (Accessed: 05 April 2024).
- Delzendeh, E., Wu, S., Lee, A. & Zhou, Y. (2017). ‘The impact of occupants’ behaviours on Building Energy Analysis: A Research Review’, *Renewable and Sustainable Energy Reviews*, 80, pp. 1061–1071.
- Deng, Z., Dong, B., Guo, X. & Zhang, J. (2024). Impact of indoor air quality and multi-domain factors on human productivity and physiological responses: A comprehensive review. *Indoor Air*, 2024(1).
- Denscombe, M. (2008). ‘Communities of Practice’, *Journal of Mixed Methods Research*, 2(3), pp. 270–283.
- Department for Environment, F.& R.A. (2022). *The Air Quality Strategy for England, Scotland, Wales and Northern Ireland: Volume 1, GOV.UK*. Available at: <https://www.gov.uk/government/publications/the-air-quality-strategy-for-england-scotland-wales-and-northern-ireland-volume-1>. (Accessed: 29 January 2024).
- Derbez, M., Cochet, V., Berthineau, B., Riberon, J., Lethrosne, M., Pignon, C., Wyart, G., & Kirchner, S. (2014). ‘Indoor air quality and comfort in seven newly built, energy-efficient houses in France’, *Building and Environment*, 72, pp. 173–187.
- Derbez, M., Wyart, G., Le Ponner, E., Ramalho, O., Ribéron, J. & Mandin, C. (2017). ‘Indoor air quality in energy-efficient dwellings: Levels and sources of pollutants’, *Indoor Air*, 28(2), pp. 318–338.
- Derudi, M., Derudi, M., Gelosa, S., Sliepcevich, A., Cattaneo, A., Rota, R., Cavallo, D., & Nano, G. (2012). ‘Emissions of air pollutants from scented candles burning in a test chamber’, *Atmospheric Environment*, 55, pp. 257–262.
- Diapouli, E., Chaloulakou, A. and Spyrellis, N. (2007). ‘Indoor and outdoor particulate matter concentrations at schools in the Athens Area’, *Indoor and Built Environment*, 16(1), pp. 55–61.

- Dimitroulopoulou, C. (2012). 'Ventilation in European dwellings: A Review', *Building and Environment*, 47, pp. 109–125.
- Dimitroulopoulou, C., Lucica, E., Johnson, A., Ashmore, M.R., Sakellaris, I., Stranger, M., & Goelen, E. (2015). 'EPHECT I: European Household Survey on domestic use of consumer products and development of worst-case scenarios for daily use', *Science of The Total Environment*, 536, pp. 880–889.
- Dimitroulopoulou, C., Ashmore, M.R. and Terry, A.C. (2017). 'Use of population exposure frequency distributions to simulate effects of policy interventions on no two exposures', *Atmospheric Environment*, 150, pp. 1–14.
- Dimitroulopoulou, S., Dudzińska, M. R., Gunnarsen, L., Hägerhed, L., Maula, H., Singh, R., Toyinbo, O., & Haverinen-Shaughnessy, U. (2023). 'Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort', *Environment International*, 178, p. 108127.
- Du, W. and Wang, G. (2020). 'Indoor air pollution was non-negligible during COVID-19 lockdown', *Aerosol and Air Quality Research*, 20(9), pp. 1851–1855.
- Easterby-Smith, M., Thorpe, R., & Jackson, P. R. (2012). *Management Research* (4th ed.). Sage Publications.
- EEA (2013). *The European Environment: State and Outlook 2015 - synthesis report*. Available at: <https://wedocs.unep.org/handle/20.500.11822/9417>. (Accessed: 05 December 2023).
- EEA (2020). *Air Quality in Europe - 2020 report*, *European Environment Agency's home page*. Available at: <https://www.eea.europa.eu/publications/air-quality-in-europe-2020-report> (Accessed: 05 March 2024).
- Elo, S. and Kyngäs, H. (2008). 'The qualitative content analysis process', *Journal of Advanced Nursing*, 62(1), pp. 107–115.
- Emmerechts, J., Jacobs, L. and F., M. (2011). 'Air pollution and cardiovascular disease', *The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources*.

- EnviroVent Ltd (2021). Approved document F: New ventilation rules 2022 in England.
EnviroVent Ltd. Available at: <https://www.envirovent.com/blog/changes-to-approved-document-f-new-ventilation-rules-2022-england/> (Accessed: 21 April 2023).
- EPA (2014). Indoor Air Quality (IAQ), *United States Environmental Protection Agency*.
- EPA (2020a). Indoor Air Quality (IAQ). Introduction to Indoor Air Quality. Available at: EPA site: <https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality>.
[Accessed 04 March 2022].
- EPA. (2014). The US Environmental Protection Agency Website: Exposure to Radon Causes Lung Cancer in Non-smokers and Smokers Alike. [Online] Available at: <https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality> [Accessed 10 May 2021].
- EPA. (2016). *What is Indoor Air Quality?* The US Environmental Protection Agency. Definition of Green Building. [Online] Available at: <https://www.epa.gov/indoor-air-quality-iaq/inside-story-guide-indoor-air-quality> [Accessed: 01 October 2021].
- EPA. (2017). The US Environmental Protection Agency: An Introduction to Indoor Air Quality. [Online] Available at: <https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality> [Accessed 24 November 2020].
- Esplugues, A., Ballester, F., Estarlich, M., Llop, S., Fuentes, V., Mantilla, E. & Iñiguez, C. (2010). 'Indoor and outdoor concentrations and determinants of NO₂ in a cohort of 1-year-old children in Valencia, Spain', *Indoor Air*, 20(3), pp. 213–223.
- Even, M., Girard, M., Rich, A., Hutzler, C. & Luch, A. (2019). 'Emissions of VOCs from polymer-based consumer products: From emission data of real samples to the assessment of inhalation exposure', *Frontiers in Public Health*, 7.
- Fabi, V., Andersen, R.V., Corgnati, S.P. & Olesen, B.W. (2012). 'Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models', *Building and Environment*, 58, pp. 188–198.
- Fabian, M.P., Stout, N.K., Adamkiewicz, G., Geggel, A., Ren, C., Sandel, M. & Levy, J.I. (2012). 'The effects of indoor environmental exposures on paediatric asthma: A discrete event simulation model', *Environmental Health*, 11(1).

- Fabian, P., Adamkiewicz, G. and Levy, J.I. (2011). ‘Simulating indoor concentrations of NO₂ and PM_{2.5} in multifamily housing for use in health-based intervention modelling’, *Indoor Air*, 22(1), pp. 12–23.
- Fang, L., Clausen, G. and Fanger, P.O. (1998). ‘Impact of temperature and humidity on the perception of indoor air quality’, *Indoor Air*, 8(2), pp. 80–90.
- Farmer, D.K. and Vance, M.E. (2019). ‘Indoor air: Sources, chemistry and health effects’, *Environmental Science: Processes & Impacts*, 21(8), pp. 1227–1228.
- Feijó-Muñoz, J., González-Lezcano, R.A., Poza-Casado, I., Padilla-Marcos, M.Á. & Meiss, A. (2019). ‘Airtightness of residential buildings in the Continental area of Spain’, *Building and Environment*, 148, pp. 299–308.
- Ferdyn-Grygierek, J. and Grygierek, K. (2024). ‘Ventilation methods for improving the indoor air quality and energy efficiency of multifamily buildings in Central Europe’, *Energies*, 17(9), p. 2232.
- Ferguson, L., Taylor, J., Zhou, K., Shrubsole, C., Symonds, P., Davies, M. & Dimitroulopoulou, S. (2021). ‘Systemic inequalities in Indoor Air Pollution Exposure in London, UK’, *Buildings and Cities*, 2(1), p. 425.
- Fernández-Agüera, J., Domínguez-Amarillo, S., Alonso, C. & 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*, 199, pp. 102–114.
- Few, J., Shipworth, M. and Elwell, C. (2024). ‘Ventilation regulations and occupant practices: Undetectable pollution and invisible extraction’, *Buildings & Cities*, 5(1).
- Fichthorn, K.A. (1997). ‘Principles of adsorption and reaction on solid surfaces. Richard I. Masel’, *Journal of Catalysis*, 170(1), pp. 214–215.
- Fisk, W.J. (2018). ‘How home ventilation rates affect health: A literature review’, *Indoor Air*, 28(4), pp. 473–487.
- Fisk, W.J., Faulkner, D., Palonen, J. & Seppänen, O. (2002). ‘Performance and costs of Particle Air Filtration Technologies’, *Indoor Air*, 12(4), pp. 223–234.

- Fisk, W.J., Lei-Gomez, Q. and Mendell, M.J. (2007). 'Meta-analyses of the associations of respiratory health effects with dampness and mould in homes', *Indoor Air*, 17(4), pp. 284–296.
- Fleisch, A.F., Rokoff, L.B., Garshick, E., Grady, S.T., Chipman, J.W., Baker, E.R., Koutrakis, P., & Karagas, M.R. (2019). 'Residential Wood stove use and indoor exposure to PM2.5 and its components in northern New England', *Journal of Exposure Science & Environmental Epidemiology*, 30(2), pp. 350–361.
- Flyvbjerg, B. (2006). 'Five misunderstandings about case-study research', *Qualitative Inquiry*, 12(2), pp. 219–245.
- Forrester, J.W. (1971). 'Counterintuitive behaviour of Social Systems', *Technology*, VOL. 73, No. 3, pp. 52–68.
- Fossey, E., Harvey, C., McDermott, F. & Davidson, L. (2002). 'Understanding and evaluating qualitative research', *Australian & New Zealand Journal of Psychiatry*, 36(6), pp. 717–732.
- Franco, A. and Schito, E. (2020). 'Definition of optimal ventilation rates for balancing comfort and energy use in indoor spaces using CO2 Concentration Data', *Buildings*, 10(8), p. 135.
- Frank, L.D., Schmid, T.L., Sallis, J.F., Chapman, J. & Saelens, B.E. (2005). 'Linking objectively measured physical activity with objectively measured urban form', *American Journal of Preventive Medicine*, 28(2), pp. 117–125.
- Frega, R. (2020). 'Replies to critics, European Journal of Pragmatism and American Philosophy', *European Journal of Pragmatism and American Philosophy*, XII(1).
- Gabriel, M.F., Marques, G., Filipe, D., Felgueiras, F., Cardoso, P.J., Azeredo, J., Kazdaridis, G., Symeonidis, P., Keranidis, S., Conradie, P., Azevedo, I., & Anagnostopoulos, F. (2024). 'Implementation of an IOT architecture for promoting healthy air quality in 84 homes of families with children', *Building and Environment*, 266, p. 112040.

- Gallon, V., Le Cann, P., Sanchez, M., Dematteo, C., & Le Bot, B. (2020). 'Emissions of VOCs, SVOCs, and mould during the construction process: Contribution to indoor air quality and future occupants' exposure', *Indoor Air*, 30(4), pp. 691–710.
- Garrett, M.H., Abramson, J. M., Hooper, M. B., Rayment, R. P., Strasser, P. R., & Hooper, A. M. (1998). 'Indoor environmental risk factors for respiratory health in children', *Indoor Air*, 8(4), pp. 236–243.
- Ghobakhloo, S., Khoshakhlagh, A. H., Morais, S. and Mazaheri Tehrani, A. (2023). Exposure to volatile organic compounds in paint production plants: Levels and potential human health risks, *Toxics*, 11(2), p. 111.
- Gibbs, G.R. (2018). Analysing qualitative data. *Explorations with NVivo*. Open University Press.
- Gilbey, S.E., Reid, M. C., Huxley, R. R., Soares, J. M., Zhao, Y., & Rumchev, K. (2019). 'Associations between sub-clinical markers of cardiometabolic risk and exposure to residential indoor air pollutants in healthy adults in Perth, Western Australia: A study protocol', *International Journal of Environmental Research and Public Health*, 16(19), p. 3548.
- Ginestet, S., Aschan-Leygonie, C., Bayeux, T. & Keirsbulck, M. (2020). Mould in indoor environments: The role of heating, ventilation and fuel poverty. A French perspective', *Building and Environment*, 169, p. 106577.
- Glaser, B.G. and Strauss, A.L. (2017). 'The discovery of grounded theory', *The Discovery of Grounded Theory*, pp. 1–18.
- Gligorovski, S. and Abbatt, J.P. (2018). 'An indoor chemical cocktail', *Science*, 359(6376), pp. 632–633.
- GLOBALABC (2018). '2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector.' Global Alliance for Buildings and Construction. <https://globalabc.org/resources/publications/2018-global-status-report>

- Gola, M., Settimo, G. and Capolongo, S. (2019). 'Chemical pollution in healing spaces: The decalogue of the best practices for adequate indoor air quality in inpatient rooms', *International Journal of Environmental Research and Public Health*, 16(22), p. 4388.
- Goodman, C. and Davies, S.L. (2011). 'Good practice outside the Care Homes', *Mental Health and Care Homes*, pp. 297–311.
- Guarnieri, M. and Balmes, J.R. (2014). 'Outdoor Air Pollution and asthma', *The Lancet*, 383(9928), pp. 1581–1592.
- Gunay, B., Hobson, B. W., Ouf, M., Nagy, Z. & Miller, C. (2023). 'Design of sequences of operation for occupant-centric controls', *Occupant-Centric Simulation-Aided Building Design*, pp. 235–256.
- Waragocki, R. and Chandiwala, S. (2010). 'Understanding occupants: Feedback techniques for large-scale low-carbon domestic refurbishments', *Building Research & Information*, 38(5), pp. 530–548.
- Gupta, R. and Kapsali, M. (2015). 'Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK', *Advances in Building Energy Research*, 10(1), pp. 46–68.
- Gupta, R., Kapsali, M. and Howard, A. (2018). 'Evaluating the influence of building fabric, services and occupant-related factors on the actual performance of low-energy social housing dwellings in the UK', *Energy and Buildings*, 174, pp. 548–562.
- Gustafsson, J. (2017). *Single Case Studies vs. Multiple Case Studies: A Comparative Study*. Academy of Business, Engineering and Science, Halmstad University.
- Guyot, G., Melois, A., Bernard, A.-M., Coeudevez, C.-S., Déoux, S., Berlin, S., Parent, E., Huet, A., Berthault, S., Jobert, R. & Labaume, D. (2017). 'Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes', *International Journal of Ventilation*, 17(3), pp. 187–195.

- Guyot, G., Sherman, M.H. and Walker, I.S. (2018). ‘Smart ventilation energy and indoor air quality performance in residential buildings: A Review’, *Energy and Buildings*, 165, pp. 416–430.
- Hamilton, I., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., Davies, M. & Wilkinson, P. (2015). ‘Health effects of Home Energy Efficiency Interventions in England: A modelling study’, *BMJ Open*, 5(4).
- Hankey, S. and Marshall, J.D. (2017). ‘Urban form, air pollution, and health’, *Current Environmental Health Reports*, 4(4), pp. 491–503.
- Hansen, D.L. (2018). ‘Building Design and Air Quality’, *Indoor Air Quality Issues*, pp. 23–34.
- Harrison, R.M. (2021). *Understanding our environment: An introduction to environmental chemistry and pollution* (3rd ed). *Roy M. Harrison, Ed.* Cambridge: Royal Society of Chemistry.
- Hasselaar, E. (2009). ‘Health issues and the building stock’, *Building Research & Information*, 37(5–6), pp. 669–678.
- Hauke, J. and Kossowski, T. (2011) ‘Comparison of values of Pearson’s and Spearman’s correlation coefficients on the same sets of data’, *QUAGEO*, 30(2), pp. 87–93.
- HBF (2024). *The economic footprint of house building in England and Wales*, Lichfield & Home Builders Federation.
- Heffernan, E., Pan, W., Liang, X. & de Wilde, P. (2015). ‘Zero carbon homes: Perceptions from the UK construction industry’, *Energy Policy*, 79, pp. 23–36.
- Hernandez, G., Wallis, S. L., Graves, I., Narain, S., Birchmore, R. & Berry, T.-A. (2020). The effect of ventilation on volatile organic compounds produced by new furnishings in residential buildings. *Atmospheric Environment: X*, 6, p. 100069.
- HM Government (2010). *Building regulations 2010: Approved documents F ventilation (2010 edition incorporating 2010 and 2013 amendments) (for use in England) (superseded)*, London: TSO. Available at:

<https://www.thenbs.com/PublicationIndex/documents/details?Pub=NBS&DocId=31292>

1. (Accessed: 12 May 2023).

HM Government (2013). Part C - Site preparation and resistance to contaminants and moisture, Approved Document C - Part C - Site preparation and resistance to contaminants and moisture - *Planning Portal*. Available at:

<https://www.planningportal.co.uk/applications/building-control-applications/building-control/approved-documents/part-c-site-preparation-and-resistance-to-contaminants-and-moisture/approved-document-c/> (Accessed: 11 May 2022).

HM Government. (2021). Approved document F: Ventilation, volume 1: Dwellings (2021 edition): *Approved document F, GOV.UK*. Available at:

<https://www.gov.uk/government/publications/ventilation-approved-document-f>.

(Accessed: 12 February 2023).

Hoffmann, B., Boogaard, H., de Nazelle, A., Andersen, Z. J., Abramson, M., Brauer, M., Brunekreef, B., Forastiere, F., Huang, W., Kan, H., Kaufman, J. D., Katsouyanni, K., Krzyzanowski, M., Kuenzli, N., Laden, F., Nieuwenhuijsen, M., Mustapha, A., Powell, P., Rice, M., Roca-Barceló, A., Roscoe, C. J., Soares, A., Straif, K. & Thurston, G. (2021). ‘Who air quality guidelines 2021—aiming for Healthier Air for all: A joint statement by Medical, Public Health, scientific societies and patient representative organisations’, *International Journal of Public Health*, 66.

Holden, K. A., Lee, A. R., Hawcutt, D. B., & Sinha, I. P. (2023). The impact of poor housing and indoor air quality on respiratory health in children, *Breathe*, 19(2), p. 230058.

Holgate, S.T. (2017). “‘Every Breath We Take: The Lifelong Impact of Air Pollution’ – A Call for Action’, *Clinical Medicine*, 17(1), pp. 8–12.

Holsteijn, Ir.R., Li, Ir. W., Valk, Ir. H., & Kornaat, Ing. W. (2016). Improving the energy and IAQ performance of ventilation systems in Dutch dwellings. *International Journal of Ventilation*, 14(4), pp. 363–370.

Hong, T., Taylor-Lange, S.C., D’Oca, S., Yan, D. & Corgnati, S.P. (2016). ‘Advances in research and applications of energy-related occupant behaviour in buildings’, *Energy and Buildings*, 116, pp. 694–702.

- Hopke, P.K., Dai, Q.-L., Li, L. & Feng, Y. (2020). ‘Global Review of recent source apportionments for Airborne Particulate Matter’, *Science of the Total Environment*, 740, p. 140091.
- Hormigos-Jimenez, S., Padilla-Marcos, A. M., Meiss, A., Gonzalez-Lezcano, A. R., & Feijó-Muñoz, J. A. (2017). ‘Ventilation rate determination method for residential buildings according to TVOC emissions from building materials’, *Building and Environment*, 123, pp. 555–563.
- Horvat, T., Pehnc, G. and Jakovljević, I. (2025). ‘Volatile organic compounds in indoor air: Sampling, determination, sources, health risk, and regulatory insights’, *Toxics*, 13(5), p. 344.
- Howieson, S. (2017). ‘The Great Scottish Housing Disaster: The Impacts of feudalism, modernism, energy efficiency and vapour barriers on indoor air quality, asthma and public health’, *Sustainability*, 10(1), p. 18.
- Howieson, S., Sharpe, T. and Farren, P. (2013). ‘Building-tight ventilate-right? How are new air-tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology*, 35(5), pp. 475–487.
- Huang, F., Pan, B., Wu, J., Chen, E., & Chen, L. (2017). ‘Relationship between exposure to PM_{2.5} and lung cancer incidence and mortality: A meta-analysis’, *Oncotarget*, 8(26), pp. 43322–43331.
- Hussein, T., Glytsos, T., Ondráček, J., Dohanyosová, P., Ždímal, V., Hämeri, K., Lazaridis, M., Šmolík, J. & Kulmala, M. (2006). ‘Particle size characterisation and emission rates during indoor activities in a House’, *Atmospheric Environment*, 40(23), pp. 4285–4307.
- IAQM (2021). *IAQM - Indoor Air Quality Guidance: Assessment, monitoring, modelling and mitigation*, Air Quality Hub. *Institute of Air Quality Management*. Available at: <https://www.airqualityhub.co.uk/external-link/iaqm-indoor-air-quality-guidance-assessment-monitoring-modelling-and-mitigation/>. (Accessed: 14 August 2023).
- IARC (2006). *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Formaldehyde, 2-butoxyethanol and 1-tert-butoxypropan-2-ol*, National Centre for

Biotechnology Information. Vol. 88. Lyon: International Agency for Research on Cancer. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK326468/>. (Accessed: 19 February 2024).

IEA & OECD (2019). Energy Policies of IEA Countries: United Kingdom 2019. *Energy Policies of IEA Countries*.

Ige-Elegbede, J., Pilkington, P., Orme, J., Williams, B., Prestwood, E., Black, D. & Carmichael, L. (2020). 'Designing healthier neighbourhoods: A systematic review of the impact of the neighbourhood design on Health and Wellbeing', *Cities & Health*, 6(5), pp. 1004–1019.

IOM (Institute of Medicine) (2011). Climate Change, the Indoor Environment, and Health. *Washington, DC*: National Academies Press.

Ison, R. (2017). *Systems practice: How to Act in a Climate-Change World*. Springer.

Jacobs, D.E., Wilson, J., Dixon, S.L., Smith, J. & Evens, A. (2009). 'The relationship of Housing and Population Health: A 30-year retrospective analysis', *Environmental Health Perspectives*, 117(4), pp. 597–604.

Jacobs, D.E., Brown, M.J., Baeder, A., Scalia Sucusky, M., Margolis, S., Hershovitz, J., Kolb, L., & Morley, R.L. (2010). 'A systematic review of housing interventions and health', *Journal of Public Health Management and Practice*, 16(5).

Jacobs, D.E., Kelly, T. and Sobolewski, J. (2007). 'Linking public health, housing, and indoor environmental policy: Successes and challenges at local and federal agencies in the United States', *Environmental Health Perspectives*, 115(6), pp. 976–982.

Janda, K.B. and Topouzi, M. (2015). 'Telling tales: Using stories to remake energy policy', *Building Research & Information*, 43(4), pp. 516–533.

Jones, E.R., Cedeño Laurent, J.G., Young, A.S., MacNaughton, P., Coull, B.A., Spengler, J.D., & Allen, J.G. (2021). The effects of ventilation and filtration on indoor PM2.5 in office buildings in four countries, *Building and Environment*, 200, p. 107975.

- Juhásová Šenitková, I. (2016). 'Indoor air quality in building design', *MATEC Web of Conferences*, 93, p. 03001.
- Kampa, M. and Castanas, E. (2008). 'Human health effects of Air Pollution', *Environmental Pollution*, 151(2), pp. 362–367.
- Kang, I. *et al.* (2022). 'Indoor air quality impacts of residential mechanical ventilation system retrofits in existing homes in Chicago, IL', *Science of The Total Environment*, 804, p. 150129.
- Kearney, J., Wallace, L., MacNeill, M., Héroux, M.-E., Kindzierski, W. & Wheeler, A. (2014) 'Residential infiltration of fine and ultrafine particles in Edmonton', *Atmospheric Environment*, 94, pp. 793–805.
- Kelly, F.J. and Fussell, J.C. (2019). 'Improving Indoor Air Quality, health and performance within environments where people live, travel, learn and work', *Atmospheric Environment*, 200, pp. 90–109.
- Kim, K., Lee, S., Choi, Y. & Kim, D. (2022). 'Emissions of fungal volatile organic compounds in residential environments and temporal emission patterns: Implications for sampling methods', *International Journal of Environmental Research and Public Health*, 19(19), p. 12601.
- Kim, K.-H., Jahan, S.A. and Kabir, E. (2011). 'A review of diseases associated with household air pollution due to the use of biomass fuels', *Journal of Hazardous Materials*, 192(2), pp. 425–431.
- Kim, S. and Li, M. (2020). 'Awareness, understanding, and action: A conceptual framework of user experiences and expectations about indoor air quality visualisations', *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12.
- Kloster, S., Kirkegaard, A. M., Davidsen, M., Christensen, A. I., Nielsen, N. S., Gunnarsen, L. & Ersbøll, A. K. (2022). Patterns of perceived indoor environment in Danish homes. *International Journal of Environmental Research and Public Health*, 19(18), p. 11498.

- Korsavi, S.S., Montazami, A. and Mumovic, D. (2020). 'Indoor Air Quality (IAQ) in naturally ventilated primary schools in the UK: Occupant-related factors', *Building and Environment*, 180, p. 106992.
- Kruza, M. and Carslaw, N. (2019). 'How do breathing and skin emissions impact indoor air chemistry?', *Indoor Air*, 29(3), pp. 369–379.
- Kruza, M., Shaw, D., Shaw, J., & Carslaw, N. (2021). 'Towards improved models for Indoor Air Chemistry: A Monte Carlo Simulation Study', *Atmospheric Environment*, 262, p. 118625.
- Kubba, S. (2017). 'Green Design and building economics', *Handbook of Green Building Design and Construction*, pp. 573–619.
- Kumar, P., Hama, S., Abbass, R.A., Nogueira, T., Brand, V.S., Wu, H., Abulude, F.O., Adelodun, A.A., Anand, P., Andrade, M.F., Apondo, W., Asfaw, A., Aziz, K.H., Cao, S., El-Gendy, A., Indu, G., Kehbila, A.G., Ketznel, M., Khare, M., Kota, S.H., Mamo, T., Manyozo, S., Martinez, J., McNabola, A., Morawska, L., Mustafa, F., Muula, A.S., Nahian, S., Nardocci, A.C., Nelson, W., Ngowi, A.V., Njoroge, G., Olaya, Y., Omer, K., Osano, P., Pavel, M.R.S., Salam, A., Santos, E.L.C., Sitati, C. & Nagendra, S.M.S. (2022). 'In-kitchen aerosol exposure in twelve cities across the Globe', *Environment International*, 162, p. 107155.
- Kuo, H.-W. and Shen, H.-Y. (2010). 'Indoor and outdoor PM_{2.5} and PM₁₀ concentrations in the air during a dust storm', *Building and Environment*, 45(3), pp. 610–614.
- Kureshi, R.R., Thakker, D., Mishra, B.K. & Ahmed, B. (2021). 'Use case of building an indoor air quality monitoring system', *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)*, pp. 747–752.
- Langer, S. and Bekö, G. (2013). 'Indoor air quality in the Swedish housing stock and its dependence on building characteristics', *Building and Environment*, 69, pp. 44–54.
- Langer, S., Fredricsson, M., Weschler, C.J., Bekö, G., Strandberg, B., Remberger, M., Toftum, J. & Clausen, G. (2016). 'Organophosphate esters in dust samples collected from Danish homes and daycare centres', *Chemosphere*, 154, pp. 559–566.

- Langer, S., Ramalho, O., Le Ponner, E., Derbez, M., Kirchner, S. & Mandin, C. (2017). 'Perceived indoor air quality and its relationship to air pollutants in French dwellings', *Indoor Air*, 27(6), pp. 1168–1176.
- Langley, A. and Abdallah, C. (2011). 'Templates and turns in qualitative studies of strategy and Management', *Research Methodology in Strategy and Management*, pp. 201–235.
- Lavigne, E., Burnett, R.T. and Weichenthal, S. (2018). 'Association of short-term exposure to fine particulate air pollution and mortality: Effect modification by oxidant gases', *Scientific Reports*, 8(1).
- Leaman, A., Stevenson, F. and Bordass, B. (2010). 'Building Evaluation: Practice and principles', *Building Research & Information*, 38(5), pp. 564–577.
- Lee, D.-H. and Chung, J.-D. (2011). 'Relevance between total volatile organic compound (TVOC) exposure level and environmental diseases within residential environments', *Korean Journal of Environmental Health Sciences*, 37(3), pp. 193–200.
- Lee, H.-J., Ruppert, K.C. and Porter, W.A. (2008). 'Energy Efficient Homes: Indoor Air Quality and Energy', *EDIS*, 2008(5).
- Less, B., Mullen, N., Singer, B., & Walker, I. (2015a). 'Indoor air quality in 24 California residences designed as high-performance homes', *Science and Technology for the Built Environment*, 21(1), pp. 14–24.
- Letwin, O. (2018). Independent Review of Build out, Final report, Minister of Housing, Communities and Local Government, London
- Leung, D.Y. (2015). 'Outdoor-indoor air pollution in urban environment: Challenges and opportunity', *Frontiers in Environmental Science*, 2.
- Levitt, D. and McCafferty, J. (2018). *The Housing Design Handbook*, Routledge.
- Li, D. and Suh, S. (2019). 'Health Risks of Chemicals in Consumer Products: A Review', *Environment International*, 123, pp. 580–587.

- Lim, A.-Y., Yoon, M., Kim, E.-H., Kim, H.-A., Lee, M.J. & Cheong, H.-K. (2021). Effects of mechanical ventilation on indoor air quality and occupant health status in energy-efficient homes: A longitudinal field study. *Science of the Total Environment*, 785, p. 147324.
- Liu, N. Bu, Z., Liu, W., Kan, H., Zhao, Z., Deng, F., Huang, C., Zhao, B., Zeng, X., Sun, Y., Qian, H., Mo, J., Sun, C., Guo, J., Zheng, X., Weschler, B. L., & Zhang, Y. (2022) 'Health effects of exposure to indoor volatile organic compounds from 1980 to 2017: A systematic review and meta-analysis', *Indoor Air*, 32(5).
- Logue, J.M., McKone, T.E., Sherman, M.H. & Singer, B.C. (2011). 'Hazard assessment of chemical air contaminants measured in residences', *Indoor Air*, 21(2), pp. 92–109.
- Logue, J.M., Price, P.N., Sherman, M.H. & Singer, B.C. (2012). 'A method to estimate the chronic health impact of air pollutants in U.S. residences', *Environmental Health Perspectives*, 120(2), pp. 216–222.
- Long, C.M., Suh, H.H. and Koutrakis, P. (2000). 'Characterisation of indoor particle sources using continuous mass and size monitors', *Journal of the Air & Waste Management Association*, 50(7), pp. 1236–1250.
- Louise Barriball, K. and While, A. (1994). 'Collecting data using a semi-structured interview: A discussion paper', *Journal of Advanced Nursing*, 19(2), pp. 328–335.
- Lowe, R., Chiu, L.F. and Oreszczyn, T. (2017a). 'Socio-Technical Case Study Method in building performance evaluation', *Building Research & Information*, 46(5), pp. 469–484.
- Lu, J. and Yao, L. (2023). 'Observational evidence for detrimental impact of inhaled ozone on human respiratory system', *BMC Public Health*, 23(1).
- Lukso, D., Guidotti, L. T., Franklin, E. D., & Burt, A. (2014). 'Indoor environmental and air quality characteristics, building-related health symptoms, and worker productivity in a federal government building complex', *Archives of Environmental & Occupational Health*, 71(2), pp. 85–101.

- Lunden, M.M., Delp, W.W. and Singer, B.C. (2014). 'Capture efficiency of cooking-related fine and ultrafine particles by residential exhaust hoods', *Indoor Air*, 25(1), pp. 45–58.
- Macmillan, A., Davies, M., Shrubsole, C., Luxford, N., May, N., Chiu, L. F., Trutnevyte, E., Bobrova, Y. & Chalabi, Z. (2016). 'Integrated decision-making about housing, Energy and Well-being: A qualitative system dynamics model', *Environmental Health*, 15(S1).
- Madureira, J., Paciência, I., Rufo, J. P., Ramos, E., Barros, H., Teixeira, J. P., & Fernandes, E. de O. (2015) 'Indoor air quality in schools and its relationship with children's respiratory symptoms', *Atmospheric Environment*, 118, pp. 145–156.
- Maesano, C.N., Caillaud, D., Youssouf, H., Banerjee, S., Prud'Homme, J., Audi, C., Horo, K., Toloba, Y., Ramousse, O., & Annesi-Maesano, I. (2019). 'Indoor exposure to particulate matter and volatile organic compounds in dwellings and workplaces and Respiratory Health in French farmers', *Multidisciplinary Respiratory Medicine*, 14(1).
- 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 structures', *International Journal of Environmental Research and Public Health*, 18(6), p. 3276.
- Manousakas, M.I., Florou, K. and Pandis, S.N. (2020). 'Source apportionment of Fine Organic and inorganic atmospheric aerosol in an urban background area in Greece', *Atmosphere*, 11(4), p. 330.
- Markowicz, P. and Larsson, L. (2014). 'Influence of relative humidity on VOC concentrations in indoor air', *Environmental Science and Pollution Research*, 22(8), pp. 5772–5779.
- Marr, D., Mason, M., Mosley, R. & Liu, X. (2012). 'The influence of opening windows and doors on the natural ventilation rate of a residential building', *HVAC & R Research*, 18(1–2), pp. 195–203.
- Marshall, J. (2011). 'Organisational change: Evaluating systems thinking in the UK housing sector, a work in progress', *Systems Thinking: From Heresy to Practice*, pp. 108–131.

- Martins, N.R. and Carrilho da Graça, G. (2018). 'Impact of PM2.5 in Indoor Urban Environments: A Review', *Sustainable Cities and Society*, 42, pp. 259–275.
- Massey, D., Kulshrestha, A., Masih, J., & Taneja, A. (2012). 'Seasonal trends of PM10, PM5.0, PM2.5 & PM1.0 in indoor and outdoor environments of residential homes located in north-central India', *Building and Environment*, 47, pp. 223–231.
- Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., & Oikonomou, E. (2012). 'Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings', *Building and Environment*, 55, pp. 117–130.
- Maxwell, J.A. (2022). 'Interactive approaches to qualitative research design', *The SAGE Handbook of Qualitative Research Design*, pp. 41–54.
- Maynard, R.L. (2019). Health Effects of Indoor Air Pollution. *Indoor Air Pollution*, pp. 196–218.
- McDonald, B.C. *et al.* (2018). 'Volatile chemical products emerging as largest petrochemical source of Urban Organic Emissions', *Science*, 359(6377), pp. 760–764.
- McGill, G., Oyedele, L., Keeffe, G., & Keig, P. (2014). 'Indoor air quality and the suitability of mechanical ventilation with heat recovery (MVHR) systems in energy efficient social housing projects: Perceptions of UK building professionals', *International Journal of Sustainable Building Technology and Urban Development*, 5(4), pp. 240–249.
- McGill, G., Sharpe, T., Oyedele, L., Keeffe, G., & McAllister, K. (2017). 'An investigation of indoor air quality in UK Passivhaus dwellings', *Smart Innovation, Systems and Technologies*, pp. 245–268.
- McGill, G., Oyedele, L.O. and Keeffe, G. (2015). 'Indoor air-quality investigation in code for Sustainable Homes and Passivhaus dwellings', *World Journal of Science, Technology and Sustainable Development*, 12(1), pp. 39–60.
- Meadow, J.F., Altrichter, A.E., Kembel, S.W., Kline, J., Mhuireach, G., Moriyama, M., Northcutt, D., O'Connor, T.K., Womack, A.M., Brown, G.Z., Green, J.L., & Bohannon,

- B.J.M. (2013). 'Indoor airborne bacterial communities are influenced by ventilation, occupancy, and Outdoor Air Source', *Indoor Air*, 24(1), pp. 41–48.
- Mendell, M.J. (2007). 'Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: A Review', *Indoor Air*, 17(4), pp. 259–277.
- Merriam, S. B., & Tisdell, E. J. (2016). *Qualitative Research: A Guide to Design and Implementation* (4th ed.). *San Francisco, CA: Jossey-Bass*.
- Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). *Sage Publications, Inc*.
- Mingers, J. (2001). 'Combining IS research methods: Towards a pluralist methodology', *Information Systems Research*, 12(3), pp. 240–259.
- Ministry of Housing, C. and L.G. (2022). *Ventilation: Approved document F, GOV.UK*. Available at: <https://www.gov.uk/government/publications/ventilation-approved-document-f>. (Accessed: 20 July 2023).
- Ministry of Housing, C. and L.G. (2023). *Conservation of fuel and power: Approved document L, GOV.UK*. Available at: <https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l>. (Accessed: 28 May 2024).
- Ministry of Housing, C.& L.G. (2021). *The Future Homes Standard: Changes to Part L and Part F of the building regulations for new dwellings, GOV.UK*. Available at: <https://www.gov.uk/government/consultations/the-future-homes-standard-changes-to-part-l-and-part-f-of-the-building-regulations-for-new-dwellings>. (Accessed: 10 April 2022).
- Ministry of Housing, C.& L.G. (2021). *The Future Homes Standard: Changes to Part L and Part F of the Building Regulations for new dwellings. GOV.UK*. Available at: <https://www.gov.uk/government/consultations/the-future-homes-standard-changes-to-part-l-and-part-f-of-the-building-regulations-for-new-dwellings> (Accessed: 25 July 2025).

- Missia, D.A., Demetriou, E., Michael, N., Tolis, E.I., & Bartzis, J.G. (2010). 'Indoor exposure from building materials: A field study', *Atmospheric Environment*, 44(35), pp. 4388–4395.
- Mitchell, A. (2018). A Review of Mixed Methods, Pragmatism and Abduction Techniques. *The Electronic Journal of Business Research Methods*, 16. Pp. 103-116.
- Mlecnik, E., Schütze, T., Jansen, S.J.T., De Vries, G., Visscher, H.J., & van Hal, A. (2012). 'End-user experiences in nearly zero-energy houses', *Energy and Buildings*, 49, pp. 471–478.
- Morantes, G., Jones, B., Molina, C., & Sherman, M. H. (2023). 'Harm from residential indoor air contaminants', *Environmental Science & Technology*, 58(1), pp. 242–257.
- Morawska, L. and Huang, W. (2022). 'WHO health guidelines for indoor air quality and national recommendations/standards', *Handbook of Indoor Air Quality*, pp. 1491–1510.
- Moreno-Rangel, A., Sharpe, T., McGill, G., & Musau, F. (2020). 'Indoor air quality in passivhaus dwellings: A literature review', *International Journal of Environmental Research and Public Health*, 17(13), p. 4749.
- Moreno-Rangel, A., Sharpe, T., McGill, G., & Musau, F. (2023). 'Indoor air quality and thermal environment assessment of Scottish homes with different building fabrics', *Buildings*, 13(6), p. 1518.
- Morgan, D.L. (2007). 'Paradigms lost and Pragmatism regained', *Journal of Mixed Methods Research*, 1(1), pp. 48–76.
- Morgan, D.L. (2014). 'Pragmatism as a paradigm for Social Research', *Qualitative Inquiry*, 20(8), pp. 1045–1053.
- Morrison, G.C. and Nazaroff, W.W. (2002). 'Ozone interactions with carpet: secondary emissions of aldehydes', *Environmental Science & Technology*, 36(10), pp. 2185–2192.
- Morse, J.M., Barrett, M., Mayan, M., Olson, K., & Spiers, J. (2002). 'Verification strategies for establishing reliability and validity in qualitative research', *International Journal of Qualitative Methods*, 1(2), pp. 13–22.

- Moschetti, R. and Carlucci, S. (2016). ‘The impact of design ventilation rates on the indoor air quality in residential buildings: An Italian case study’, *Indoor and Built Environment*, 26(10), pp. 1397–1419.
- Mullen, N., Li, J. and Singer, B. (2013). Participant-Assisted Data Collection Methods in the California Healthy Homes. *Indoor Air Quality Study of 2011-13*.
- Mulliner, E., Riley, M. and Maliene, V. (2020). ‘Older people’s preferences for housing and environment characteristics’, *Sustainability*, 12(14), p. 5723.
- Mumtaz, R., Zaidi, S. M. H., Shakir, M. Z., Shafi, U., Malik, M. M., Haque, A., Mumtaz, S., & Zaidi, S. A. R. (2021). ‘Internet of Things (IOT) based indoor air quality sensing and predictive analytics, a COVID-19 perspective’, *Electronics*, 10(2), p. 184.
- Nakayama, Y. *et al.* (2019). Prevalence and risk factors of pre-sick building syndrome: Characteristics of indoor environmental and individual factors, *Environmental Health and Preventive Medicine*, 24(1).
- Naldzhiev, D., Mumovic, D. and Strlic, M. (2020). ‘Polyurethane insulation and household products – A systematic review of their impact on indoor environmental quality’, *Building and Environment*, 169, p. 106559.
- Nasir, Z.A. and Colbeck, I. (2013). ‘Particulate pollution in different housing types in a UK suburban location’, *Science of the Total Environment*, 445–446, pp. 165–176.
- Nassikas, N.J., McCormack, M.C., Ewart, G., Balmes, J.R., Bond, T.C., Brigham, E., Cromar, K., Goldstein, A.H., Hicks, A., Hopke, P.K., Meyer, B., Nazaroff, W.W., Paulin, L.M., Rice, M.B., Thurston, G.D., Turpin, B.J., Vance, M.E., Weschler, C.J., Zhang, J., & Kipen, H.M. (2024). Indoor Air Sources of Outdoor Air Pollution: Health Consequences, Policy, and Recommendations: An Official American Thoracic Society Workshop Report. *Annals of the American Thoracic Society*, 21(3), pp. 365–376.
- Nau, D. (1995). Mixing methodologies: Can bimodal research be a viable post-positivist tool? *The Qualitative Report. Health Services Research*, 30(2), 46–53.

- Nazaroff, W.W. and Weschler, C.J. (2020). ‘Indoor acids and bases’, *Indoor Air*, 30(4), pp. 559–644.
- Newsham, G.R. *et al.* (2013). Do “green” buildings have better indoor environments? new evidence’, *Building Research & Information*, 41(4), pp. 415–434.
- Ng, L. *et al.* (2017). ‘Evaluating indoor air quality and energy impacts of ventilation in a net-zero energy house using a coupled model’, *Science and Technology for the Built Environment*, 24(2), pp. 124–134.
- NHBC, F. (2023). Indoor air quality in highly energy-efficient homes - *A Review. Report NF90, Guidance and Challenges. NHBC Foundation*. Available at: <https://www.nhbcfoundation.org/wp-content/uploads/2016/05/NF18-Indoor-air-quality-in-highly-energy-efficient-homes.pdf>. (Accessed: 14 May 2024).
- NICE (2017). *Indoor Air Quality at Home*, National Institute for Health and Care Excellence. NG149. Available at: <https://www.nice.org.uk/guidance/ng149>. (Accessed: 20 May 2023).
- NICE (2020). Indoor air quality at home. *National Institute for Health and Care Excellence*. Available at: <https://www.nice.org.uk/guidance/ng149>. (Accessed: 17 May 2023).
- Nowell, L.S., Norris, J.M., White, D.E., & Moules, N.J. (2017). ‘Thematic analysis’, *International Journal of Qualitative Methods*, 16(1).
- OECD (2016). *The Economic Consequences of Outdoor Air Pollution*. Paris: <https://doi.org/10.1787/9789264257474-en>.
- Olsen, J.H., Jensen, S.P., Hink, M., Faurbo, K., Breum, N.O., & Jensen, O.M. (1984). ‘Occupational formaldehyde exposure and increased nasal cancer risk in man’, *International Journal of Cancer*, 34(5), pp. 639–644.
- Oreszczyn, T. and Lowe, R. (2010). ‘Challenges for energy and buildings research: Objectives, methods and funding mechanisms’, *Building Research & Information*, 38(1), pp. 107–122.

- Orme, M. (2001). 'Estimates of the energy impact of ventilation and associated financial expenditures', *Energy and Buildings*, 33(3), pp. 199–205.
- Paciência, I., Madureira, J., Rufo, J., Moreira, A., & Fernandes, E. de O. (2016). 'A systematic review of evidence and implications of spatial and seasonal variations of volatile organic compounds (VOC) in indoor human environments', *Journal of Toxicology and Environmental Health, Part B*, 19(2), pp. 47–64.
- Pagani, A., Christie, D., Bourdon, V., Wall Gago, C., Joost, S., Licina, D., Lerch, M., Rozenblat, C., Guessous, I., & Viganò, P. (2023). 'Housing, street and health: A new systemic research framework', *Buildings and Cities*, 4(1), pp. 629–649.
- Paone, A. and Bacher, J.-P. (2018). 'The impact of building occupant behaviour on energy efficiency and methods to influence it: A review of the state of the art', *Energies*, 11(4), p. 953.
- Parida, S.K., Dash, S., Patel, S., & Mishra, B.K. (2006). 'Adsorption of organic molecules on silica surface', *Advances in Colloid and Interface Science*, 121(1–3), pp. 77–110.
- Pathirage, C. P., Amaratunga, Dilanthi and Haigh, Richard (2008). The role of philosophical context in the development of theory: Towards methodological pluralism. *The Built and Human Environment Review*, 1 (1).
- Patlakas, P., Musso, M. and Larkham, P. (2021). 'A digital curation model for post-occupancy Evaluation Data', *Architectural Engineering and Design Management*, 18(2), pp. 128–148.
- Patton, M.Q. (2022). Impact-driven qualitative research and evaluation. *The SAGE Handbook of Qualitative Research Design*, pp. 1165–1180.
- Persily, A. (2015). 'Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62', *Building and Environment*, 91, pp. 61–69.
- Persily, A. (2022). 'Evaluating ventilation performance', *Handbook of Indoor Air Quality*, pp. 1675–1713.

- Persily, A. and de Jonge, L. (2017). 'Carbon dioxide generation rates for building occupants', *Indoor Air*, 27(5), pp. 868–879.
- Persily, A.K. and Emmerich, S.J. (2012). 'Indoor air quality in sustainable, energy-efficient buildings', *HVAC & R Research*, 18(1–2), pp. 4–20.
- Petrou, G., Hutchinson, E., Mavrogianni, A., Milner, J., Macintyre, H., Phalkey, R., Hsu, S.-C., Symonds, P., Davies, M., & Wilkinson, P. (2022). 'Home Energy Efficiency Under Net Zero: Time to monitor UK Indoor Air', *BMJ*.
- PHE (Public Health England). (2019). Indoor Air Quality Guidelines for Selected Volatile Organic Compounds (VOCs) in the UK. [www.gov.uk/phe](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831319/VO_statement_Final_12092019_CS_1_.pdf). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831319/VO_statement_Final_12092019_CS_1_.pdf. (Accessed: 19 March 2023).
- Philip, L.J. (1998). 'Combining quantitative and qualitative approaches to social research in human geography, an impossible mixture?', *Environment and Planning A: Economy and Space*, 30(2), pp. 261–276.
- Pitarma, R., Marques, G. and Ferreira, B.R. (2016). 'Monitoring Indoor air quality for enhanced Occupational Health', *Journal of Medical Systems*, 41(2).
- Poorisat, T., Aigwi, I.E., Doan, D.T., & Ghaffarian-Hoseini, A. (2024). 'Unlocking the potentials of sustainable building designs and practices: A systematic review', *Building and Environment*, 266, p. 112069.
- Potera, C. (2011). 'Climate change impacts indoor environment', *Environmental Health Perspectives*, 119(9).
- Pourtangestani, M., Izadyar, N., Jamei, E., & Vrcelj, Z. (2024). 'Linking occupant behaviour and window design through post-occupancy evaluation: Enhancing natural ventilation and indoor air quality', *Buildings*, 14(6), p. 1638.
- Prüss-Ustün, A., Wolf, J., Corvalán, C., Neville, T., Bos, R., & Neira, M. (2016). 'Diseases due to unhealthy environments: An updated estimate of the global burden of disease

attributable to environmental determinants of health’, *Journal of Public Health*, 39(3), pp. 464–475.

Rajagopalan, S., Brauer, M., Bhatnagar, A., Bhatt, D.L., Brook, J.R., Huang, W., Münzel, T., Newby, D., Siegel, J., Brook, R.D., Balme, J.R., Burroughs-Peña, M.S., Fuks, K.B., Jones, M.R., & Mittleman, M.A. (2020). Personal-level protective actions against Particulate Matter Air Pollution Exposure: A Scientific Statement from the American Heart Association, *Circulation*, 142(23).

Rashid, M. and Zimring, C. (2008).. ‘A review of the empirical literature on the relationships between indoor environment and stress in health care and office settings’, *Environment and Behaviour*, 40(2), pp. 151–190.

Raunemaa, T., Kulmala, M., Saari, H., & Olin, M. (1989). ‘Indoor Air Aerosol Model: Transport indoors and deposition of fine and coarse particles’, *Aerosol Science and Technology*, 11(1), pp. 11–25.

RCP (2016). Every breath we take: The lifelong impact of air pollution. Royal College of Physicians.

RCP (2019). Driving improvement in air quality, Royal College of Physicians.

Regulations (2020). The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020, *Legislation.gov.uk*. Available at: <https://www.legislation.gov.uk/ukxi/2020/1095/contents/made>. (Accessed: 08 May 2023).

Reinhart, C.F. and Cerezo Davila, C. (2016). ‘Urban Building Energy Modelling – a review of a nascent field’, *Building and Environment*, 97, pp. 196–202.
<https://doi.org/10.1016/j.buildenv.2015.12.001>.

RIBA (2020). *Royal Institute of British Architects (2020). RIBA Plan of Work 2020 overview. - references - scientific research publishing*. Available at: <https://www.scirp.org/reference/referencespapers?referenceid=3152384>. (Accessed: 04 January 2024).

- Richter, M., Horn, W., Juritsch, E., Klinge, A., Radeljic, L., & Jann, O. (2021). ‘Natural building materials for interior fitting and refurbishment—what about indoor emissions?’, *Materials*, 14(1), p. 234.
- Robson, C. (2011). *Real World Research* (3rd ed.). Wiley.
- Rode, C., Abadie, M., Qin, M., Grunewald, J., Kolarik, J., & Laverge, J. (2019). Key findings of IEA EBC Annexe 68 - indoor air quality design and control in low energy residential buildings, *IOP Conference Series: Materials Science and Engineering*, 609(3), p. 032057.
- Rohr, A.C. (2013). ‘The health significance of gas- and particle-phase terpene oxidation products: A Review’, *Environment International*, 60, pp. 145–162.
- Romagnoli, P., Balducci, C., Perilli, M., Gherardi, M., Gordiani, A., Gariazzo, C., Gatto, M.P., & Cecinato, A. (2014). ‘Indoor pahs at schools, homes and offices in Rome, Italy’, *Atmospheric Environment*, 92, pp. 51–59.
- Rouquerol, J., Rouquerol, F., Llewellyn, P., Maurin, G., & Sing, K.S.W. (2014). ‘Introduction’, *Adsorption by Powders and Porous Solids*, pp. 1–24.
- Roussel, S., Reboux, G., Bellanger, A.-P., Sornin, S., Grenouillet, F., Dalphin, J.-C., Piarroux, R., & Millon, L. (2008). ‘Characteristics of dwellings contaminated by moulds’, *Journal of Environmental Monitoring*, 10(6), p. 724.
- Royal College of Physicians. (2016). Royal College of Paediatrics and Child Health (RCPCH). Every breath we take: the lifelong impact of air pollution.
- Ruiz-Jimenez, J., Heiskanen, I., Tanskanen, V., Hartonen, K., & Riekkola, M.-L. (2022). Analysis of indoor air emissions: From building materials to biogenic and anthropogenic activities, *Journal of Chromatography Open*, 2, p. 100041.
- Reynolds, M. (2013). ‘Managing systemic risk using systems thinking in practice’, *AWE Procedia Advances in Applied Sciences, 1st Global Conference on Environmental Studies*, 1, pp. 217–224.

- Rojas, G., Fletcher, M., Johnston, D., & Siddall, M. (2024). 'A review of the indoor air quality in residential passive house dwellings', *Energy and Buildings*, 306, p. 113883.
- Salthammer, T. (2013). 'Formaldehyde in the ambient atmosphere: From an indoor pollutant to an outdoor pollutant?', *Angewandte Chemie International Edition*, 52(12), pp. 3320–3327.
- Salthammer, T. (2014). 'Very volatile organic compounds: An understudied class of Indoor Air Pollutants', *Indoor Air*, 26(1), pp. 25–38.
- Salthammer, T. (2019). 'Formaldehyde sources, formaldehyde concentrations and air exchange rates in European housings', *Building and Environment*, 150, pp. 219–232.
- Salthammer, T., Schieweck, A., Gu, J.W., Ameri, S., & Uhde, E. (2018). 'Future trends in ambient air pollution and climate in Germany: implications for the indoor environment', *Building and Environment*, 143, pp. 661–670.
- Salthammer, T., Mentese, S. and Marutzky, R. (2010). 'Formaldehyde in the indoor environment', *Chemical Reviews*, 110(4), pp. 2536–2572.
- Samet, J.M., Marbury, M.C. and Spengler, J.D. (1988). Health effects and sources of indoor air pollution. Part II', *American Review of Respiratory Disease*, 137(1), pp. 221–242.
- Saunders, M., Lewis, P. and Thornhill, A. (2009) *Research Methods for Business Students*. Pearson, New York.
- Saunders, M., Lewis, P., & Thornhill (2016a). *Research Methods for Business Students* (7th ed.). Edinburgh Gate: Pearson Education Limited.
- Saunders, M., Lewis, P., & Thornhill, A. (2007). *Research Methods for Business Students* (4th ed.). Pearson Education Limited.
- Schieweck, A., Uhde, E., Salthammer, T., Salthammer, L. C., Morawska, L., Mazaheri, M., & Kumar, P. (2018). 'Smart homes and the control of Indoor Air Quality', *Renewable and Sustainable Energy Reviews*, 94, pp. 705–718.

- Schwarz, N. (1999). 'Self-reports: How the questions shape the answers.', *American Psychologist*, 54(2), pp. 93–105.
- Schweizer, C., Edwards, R.D., Bayer-Oglesby, L., Gauderman, W.J., Ilacqua, V., Jantunen, M.J., Lai, H.K., Nieuwenhuijsen, M., & Künzli, N. (2006). 'Indoor time–microenvironment–activity patterns in seven regions of Europe', *Journal of Exposure Science & Environmental Epidemiology*, 17(2), pp. 170–181.
- Sekaran, U. (2003). *Research Methods for Business: A Skill-Building Approach*, (4th Edition). *John Wiley & Sons, New York*.
- Sharpe, R., Osborne, N., Paterson, C., Taylor, T., Fleming, L., & Morris, G. (2020). 'Housing, indoor air pollution, and health in high-income countries', *Oxford Research Encyclopaedia of Environmental Science*.
- Sharpe, R.A., Thornton, C.R., Tyrrell, J., Nikolaou, V., & Osborne, N.J. (2015). 'Variable risk of atopic disease due to indoor fungal exposure in NHANES 2005–2006', *Clinical & Experimental Allergy*, 45(10), pp. 1566–1578.
- Sharpe, T., Farren, P., Howieson, S., Tuohy, P., & McQuillan, J. (2015). 'Occupant interactions and effectiveness of natural ventilation strategies in contemporary new housing in Scotland, UK', *International Journal of Environmental Research and Public Health*, 12(7), pp. 8480–8497.
- Sharpe, T., Morgan, C. and Shearer, D. (2015). 'Towards low carbon homes – measured performance of four passivhaus projects in Scotland', *Proceedings of the EuroSun 2014 Conference*, pp. 1–10.
- Sharpe, T.R., Porteous, C.D.A., Foster, J., & Shearer, D. (2014). 'An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland', *Indoor and Built Environment*, 23(3), pp. 393–416.
- Sheng, Z. (2024). 'Systems and complicated systems', *International Series in Operations Research & Management Science*, pp. 11–21.

- Shibeika, A. and Oliveira, S. (2024). 'Environmental analysis in UK modern methods of construction (MMC) housing: Insights from early-stage architectural design process', *Archnet-IJAR: International Journal of Architectural Research* [Preprint].
- Shrubsole, C., Ridley, I., Biddulph, P., Milner, J., Vardoulakis, S., Ucci, M., Wilkinson, P., Chalabi, Z., & Davies, M. (2012). 'Indoor PM2.5 exposure in London's domestic stock: Modelling current and future exposures following energy efficient refurbishment', *Atmospheric Environment*, 62, pp. 336–343.
- Shrubsole, C., Macmillan, A., Davies, M., & May, N. (2014). '100 unintended consequences of policies to improve the energy efficiency of the UK Housing Stock', *Indoor and Built Environment*, 23(3), pp. 340–352.
- Shrubsole, C., Hamilton, I.G., Zimmermann, N., Papachristos, G., Broyd, T., Burman, E., Mumović, D., Zhu, Y., Lin, B., & Davies, M. (2018). 'Bridging the gap: The need for a systems thinking approach in understanding and addressing Energy and environmental performance in buildings', *Indoor and Built Environment*, 28(1), pp. 100–117.
- Shrubsole, C., Dimitroulopoulou, S., Foxall, K., Gadeberg, B., & Doutsis, A. (2019). 'IAQ guidelines for selected Volatile Organic Compounds (VOCs) in the UK', *Building and Environment*, 165, p. 106382.
- Simpson, K., Janda, K.B. and Owen, A. (2020). 'Preparing "middle actors" to deliver zero-carbon building transitions', *Buildings and Cities*, 1(1), p. 610.
- Singer, B.C., Pass, R.Z., Delp, W.W., Lorenzetti, D.M., & Maddalena, R.L. (2017). 'Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes', *Building and Environment*, 122, pp. 215–229.
- Singer, B.C., Chan, W.R., Kim, Y.-S., Offermann, F.J., & Walker, I.S. (2020). 'Indoor air quality in California homes with code-required mechanical ventilation', *Indoor Air*, 30(5), pp. 885–899.
- Spengler, J.D. and Chen, Q. (2000). "Indoor air quality factors in designing a healthy building," *Annual Review of Energy and the Environment*, 25, pp.567-600.

- Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumović, D., & Davies, M. (2021). 'Seasonal variations and the influence of ventilation rates on IAQ: A case study of five low-energy London apartments', *Indoor and Built Environment*, 31(3), pp. 607–623.
- Stazi, F., Naspi, F. and D'Orazio, M. (2017). 'A literature review on driving factors and contextual events influencing occupants' behaviours in buildings', *Building and Environment*, 118, pp. 40–66.
- Steinemann, A., Wargocki, P. and Rismanchi, B. (2017). 'Ten questions concerning green buildings and Indoor Air Quality', *Building and Environment*, 112, pp. 351–358.
- Sterman, J.D. (2002). 'All models are wrong: Reflections on becoming a systems scientist', *System Dynamics Review*, 18(4), pp. 501–531.
- Stevenson, F. (2018). 'Embedding Building Performance Evaluation in UK architectural practice and beyond', *Building Research & Information*, 47(3), pp. 305–317.
- Stratton, J. and Singer, B. (2014). Addressing Kitchen Contaminants for Healthy, Low-Energy Homes. *Lawrence Berkeley National Laboratory Report*, LBNL-6527E.
- Ström, J.G.V., Guo, Y., Yao, Y., & Suuberg, E.M. (2019). 'Factors affecting temporal variations in vapour intrusion-induced indoor air contaminant concentrations', *Building and Environment*, 161, p. 106196.
- Suihko, M.-L., Priha, O., Alakomi, H.-L., Thompson, P., Mälärstig, B., Stott, R., & Richardson, M. (2009). 'Detection and molecular characterisation of Filamentous Actinobacteria and thermophilic actinomycetes present in water-damaged building materials', *Indoor Air*, 19(3), pp. 268–277.
- Sun, L. and Wallace, L.A. (2021). 'Residential cooking and use of kitchen ventilation: The impact on exposure', *Journal of the Air & Waste Management Association*, 71(7), pp. 830–843.
- Sundell, J. (2004). 'On the history of Indoor Air Quality and health', *Indoor Air*, 14(s7), pp. 51–58.

- Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T., & Weschler, C.J. (2011). 'Ventilation rates and Health: Multidisciplinary Review of the scientific literature', *Indoor Air*, 21(3), pp. 191–204.
- Swift, A. (2022). 'Being creative with resources in Qualitative Research', *The SAGE Handbook of Qualitative Research Design*, pp. 290–306.
- Swope, C.B. and Hernández, D. (2019). 'Housing as a determinant of health equity: A conceptual model', *Social Science & Medicine*, 243, p. 112571.
- Szigeti, T., Dunster, C., Cattaneo, A., Cavallo, D., Spinazzè, A., Saraga, D.E., Sakellaris, I.A., de Kluizenaar, Y., Cornelissen, E.J.M., Hänninen, O., Peltonen, M., Calzolari, G., Lucarelli, F., Mandin, C., Bartzis, J.G., Záray, G., & Kelly, F.J. (2016a). 'Oxidative potential and chemical composition of PM_{2.5} in office buildings across Europe – the OFFICAIR study', *Environment International*, 92–93, pp. 324–333.
- Takigawa, T., Wang, B.L., Sakano, N., Wang, D.H., Ogino, K., & Kishi, R. (2009). 'A longitudinal study of environmental risk factors for subjective symptoms associated with sick building syndrome in New Dwellings', *Science of the Total Environment*, 407(19), pp. 5223–5228.
- Tang, M., Zhu, N., Kinney, K. & Novoselac, A. (2019). 'Transport of indoor aerosols to hidden interior spaces', *Aerosol Science and Technology*, 54(1), pp. 94–110.
- Tang, R. and Pfrang, C. (2023). 'Indoor particulate matter (PM) from cooking in UK students' Studio Flats and Associated Intervention Strategies: Evaluation of cooking methods, PM concentrations and personal exposures using low-cost sensors', *Environmental Science: Atmospheres*, 3(3), pp. 537–551.
- Tang, R., Sahu, R., Su, Y., Milsom, A., Mishra, A., Berkemeier, T., & Pfrang, C. (2024). Impact of cooking methods on indoor air quality: A Comparative Study of Particulate matter (PM) and Volatile Organic Compound (VOC) emissions, *Indoor Air*, 2024(1).

- Tang, X., Misztal, P.K., Nazaroff, W.W. & Goldstein, A.H. (2016). 'Volatile organic compound emissions from humans indoors', *Environmental Science & Technology*, 50(23), pp. 12686–12694.
- Taylor, J., Shrubsole, C., Davies, M., Biddulph, P., Das, P., Hamilton, I., Vardoulakis, S., Mavrogianni, A., Jones, B., & Oikonomou, E.(2014). 'The modifying effect of the building envelope on population exposure to PM2.5 from outdoor sources', *Indoor Air*, 24(6), pp. 639–651.
- Tham, K.W. (2016). 'Indoor air quality and its effects on humans, a review of challenges and developments in the last 30 years', *Energy and Buildings*, 130, pp. 637–650.
- Thatcher, T. (1995). 'Deposition, resuspension, and penetration of particles within a residence', *Atmospheric Environment*, 29(13), pp. 1487–1497.
- Thomas, G. (2011) 'A typology for the case study in Social Science following a review of definition, discourse, and Structure', *Qualitative Inquiry*, 17(6), pp. 511–521.
- Thompson, J.E. (2018). 'Airborne particulate matter', *Journal of Occupational & Environmental Medicine*, 60(5), pp. 392–423.
- Tichenor, B.A., Sparks, L.A., White, J.B., & Jackson, M.D. (1990). 'Evaluating sources of Indoor Air Pollution', *Journal of the Air & Waste Management Association*, 40(4), pp. 487–492.
- Tichenor, B.A., Guo, Z., Dunn, J.E., Sparks, L.E., & Mason, M.A. (1991). 'The interaction of vapour phase organic compounds with indoor sinks', *Indoor Air*, 1(1), pp. 23–35.
- Trochim, W. M. K. (2006). The Qualitative Debate. Research Methods Knowledge Base. <http://www.socialresearchmethods.net/kb/qualmeth.php>.
- Tsoulou, I., Senick, J., Mainelis, G., & Kim, S. (2021). 'Residential indoor air quality interventions through a social-ecological systems lens: A systematic review', *Indoor Air*, 31(4), pp. 958–976.

- Uhde, E. and Salthammer, T. (2007). ‘Impact of reaction products from building materials and furnishings on indoor air quality—a review of recent advances in indoor chemistry’, *Atmospheric Environment*, 41(15), pp. 3111–3128.
- UK Government (2021). Air Quality Library - Defra, UK. *GOV.UK*. Available at: https://uk-air.defra.gov.uk/library/reports?report_id=1021. (Accessed: 19 February 2023).
- UK Government (2023). AWAAB’s law, *National Housing Federation*. Available at: <https://www.housing.org.uk/resources/awaabs-law/>. (Accessed: 24 July 2024).
- UK Parliament (2023). Clean Air (Human Rights) bill - parliamentary bills - *UK parliament*, *Bill (Ella’s Law)*. Available at: <https://bills.parliament.uk/bills/3998>. (Accessed: 26 September 2024).
- Van der Waldt, G. (2020). ‘Constructing conceptual frameworks in Social Science Research’, *The Journal for Transdisciplinary Research in Southern Africa*, 16(1).
- Van Rooyen, C. and Sharpe, T. (2024). ‘Ventilation provision and use in homes in Great Britain: A national survey’, *Building and Environment*, 257, p. 111528.
- Varaden, D., Barratt, B., Dallman, M.J., Skillern, A., Elmi, M.S., Green, D.C., Tremper, A.H., Hedges, M., Hicks, W., Priestman, M., Barron, L.P., Fitzgerald, S.P., Walder, H.M., Wright, S.L., Mudway, I.S., Fisher, M.C., Hemmings, S.J., Poortinga, W., Tiroto, F., Beevers, S., Walton, H., Vu, T., Katsouyanni, K., Evangelopoulos, D., Young, G., Wood, D., Griffiths, C. & Kelly, F.J. (2025). West London Healthy Home and Environment (Well Home) study: Protocol for community-based research investigating exposures across the indoor-outdoor air pollution continuum in urban communities. *International Journal of Environmental Research and Public Health*, 22(2), p. 249.
- Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K.M., Taylor, J., Myers, I., Heaviside, C., Mavrogianni, A., Shrubsole, C., Chalabi, Z., Davies, M., & Wilkinson, P. (2015). ‘Impact of climate change on the domestic indoor environment and associated health risks in the UK’, *Environment International*, 85, pp. 299–313.

- Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Sleenwenhoek, A., Galea, K.S., Dixon, K., & Crawford, J.O. (2020). 'Indoor exposure to selected air pollutants in the home environment: A systematic review', *International Journal of Environmental Research and Public Health*, 17(23), p. 8972.
- Verrielle, M., Schoemaeker, C., Hanoune, B., Leclerc, N., Germain, S., Gaudion, V., & Locoge, N. (2015). 'The mermaid study: Indoor and outdoor average pollutant concentrations in 10 low-energy school buildings in France', *Indoor Air*, 26(5), pp. 702–713.
- Wallace, L. (1996). 'Indoor particles: A Review', *Journal of the Air & Waste Management Association*, 46(2), pp. 98–126.
- Wallner, P., Munoz, U., Tappler, P., Wanka, A., Kundi, M., Shelton, J.F., & Hutter, H.-P. (2015). 'Indoor environmental quality in mechanically ventilated, energy-efficient buildings vs. conventional buildings', *International Journal of Environmental Research and Public Health*, 12(11), pp. 14132–14147.
- Wang, C. and Waring, M.S. (2014). 'Secondary organic aerosol formation initiated from reactions between ozone and surface-sorbed squalene', *Atmospheric Environment*, 84, pp. 222–229.
- Wang, H., Zhang, R., Kong, H., Wang, K., Sun, L., Yu, X., Zhao, J., Xiong, J., Tran, P. T. M., & Balasubramanian, R. (2024). 'Long-term emission characteristics of VOCs from Building Materials', *Journal of Hazardous Materials*, 480, p. 136337.
- Wang, P., Liu, S., Liu, J., Wang, J., & Li, J. (2022). 'Size-resolved splashed cooking oil droplets from 1 to 1000 μm on surfaces: The impact of Residential Range Hoods', *Building and Environment*, 210, p. 108705.
- Wang, S., Yan, Y., Gao, X., Zhang, H., Cui, Y., He, Q., Wang, Y., & Wang, X. (2022). Emission characteristics and health risks of Volatile Organic Compounds (VOCs) measured in a typical recycled rubber plant in China. *International Journal of Environmental Research and Public Health*, 19(14), p. 8753.

- Wang, S., Ang, H.M. and Tade, M.O. (2007). ‘Volatile organic compounds in indoor environment and photocatalytic oxidation: State of the art’, *Environment International*, 33(5), pp. 694–705.
- Wang, Y., Hopke, P.K., Xia, X., Rattigan, O.V., Chalupa, D.C., & Utell, M.J. (2012). ‘Source apportionment of airborne particulate matter using inorganic and organic species as Tracers’, *Atmospheric Environment*, 55, pp. 525–532.
- Wang, Y., Tahmasebi, F., Cooper, E., Stamp, S., Chalabi, Z., Burman, E., & Mumović, D. (2022). Exploring the relationship between window operation behaviour and thermal and air quality factors: A case study of UK residential buildings, *Journal of Building Engineering*, 48, p. 103997.
- Wargocki, P. (2013). ‘The effects of ventilation in homes on health’, *International Journal of Ventilation*, 12(2), pp. 101–118.
- Wargocki, P. and Kostyrko, K. (2022). ‘Measurements of perceived indoor air quality’, *Handbook of Indoor Air Quality*, pp. 609–643.
- Waring, M.S. and Siegel, J.A. (2010). ‘The effect of an ion generator on indoor air quality in a residential room’, *Indoor Air*, 21(4), pp. 267–276.
- Warren Andersen, S., Blot, W.J., Shu, X-O., Sonderman, J.S., Steinwandel, M., Hargreaves, M.K., & Zheng, W. (2018). ‘Associations between neighbourhood environment, health behaviours, and mortality’, *American Journal of Preventive Medicine*, 54(1), pp. 87–95.
- Wei, W., Zhang, Y., Xiong, J., & Li, M. (2012). ‘A standard reference for chamber testing of material VOC emissions: Design principle and performance’, *Atmospheric Environment*, 47, pp. 381–388.
- Wei, W., Little, J.C., Ramalho, O., & Mandin, C. (2022). Predicting chemical emissions from household cleaning and personal care products: A Review, *Building and Environment*, 207, p. 108483.

- Wei, W., Ramalho, O. and Mandin, C. (2015) 'Indoor air quality requirements in Green Building Certifications', *Building and Environment*, 92, pp. 10–19.
- Wells, E.M., Bergés, M., Metcalf, M., Kinsella, A., Foreman, K., Dearborn, D.G., & Greenberg, S. (2015). 'Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations', *Building and Environment*, 93, pp. 331–338.
- Weschler, C.J. (2004a). 'Chemical reactions among indoor pollutants: What we've learned in the New Millennium', *Indoor Air*, 14(s7), pp. 184–194.
- Weschler, C.J. (2006). 'Ozone's impact on public health: Contributions from indoor exposures to ozone and products of ozone-initiated chemistry', *Environmental Health Perspectives*, 114(10), pp. 1489–1496.
- Weschler, C.J. (2009). 'Changes in indoor pollutants since the 1950s', *Atmospheric Environment*, 43(1), pp. 153–169.
- Weschler, C.J. (2011). 'Chemistry in Indoor Environments: 20 years of research', *Indoor Air*, 21(3), pp. 205–218.
- Weschler, C.J. (2015). 'Roles of the human occupant in indoor chemistry', *Indoor Air*, 26(1), pp. 6–24.
- Weschler, C.J. and Carslaw, N. (2018). 'Indoor Chemistry', *Environmental Science & Technology*, 52(5), pp. 2419–2428.
- Weschler, C.J. and Nazaroff, W.W. (2008). 'Semi volatile organic compounds in indoor environments', *Atmospheric Environment*, 42(40), pp. 9018–9040.
- Weschler, C.J. and Nazaroff, W.W. (2010). 'SVOC partitioning between the gas phase and settled dust indoors', *Atmospheric Environment*, 44(30), pp. 3609–3620.
- Weschler, C.J. and Shields, H.C. (1997). 'Potential reactions among indoor pollutants', *Atmospheric Environment*, 31(21), pp. 3487–3495.

- WESCHLER, C.J. and SHIELDS, H.C. (2000). ‘The influence of ventilation on reactions among indoor pollutants: Modelling and experimental observations’, *Indoor Air*, 10(2), pp. 92–100.
- WHO (2021). WHO Global Air Quality Guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulphur dioxide and carbon monoxide, *World Health Organisation*. Available at: <https://www.who.int/publications/i/item/9789240034228>. (Accessed: 20 May 2023).
- WHO (2022). Ambient (Outdoor) Air Pollution. *World Health Organisation*. Available at: [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health). (Accessed: 02 June 2024).
- WHO. (2010). WHO Guidelines for Indoor Air Quality: Selected Pollutants. World Health Organisation, Copenhagen. Available online at: <https://apps.who.int/iris/handle/10665/260127>. [Accessed at: 15 November 2021].
- Wieser, A.A., Scherz, M., Passer, A., & Kreiner, H. (2021). ‘Challenges of a healthy built environment: Air pollution in the construction industry’, *Sustainability*, 13(18), p. 10469.
- Wilkinson, S., Dixon, T., Sayce, S., & Miller, N. (2018). ‘Sustainable real estate’, *Routledge Handbook of Sustainable Real Estate*, pp. 395–409.
- Willand, N., Ridley, I. and Maller, C. (2015). Towards explaining the health impacts of residential energy efficiency interventions – a realist review. Part 1: Pathways’, *Social Science & Medicine*, 133, pp. 191–201.
- Willers, S.M., Eriksson, C., Gidhagen, L., Nilsson, M.E., Pershagen, G., & Bellander, T. (2013). ‘Fine and coarse particulate air pollution in relation to respiratory health in Sweden’, *European Respiratory Journal*, 42(4), pp. 924–934.
- Wolkoff, P. (1995). ‘Volatile organic compounds sources, measurements, emissions, and the impact on indoor air quality’, *Indoor Air*, 5(S3), pp. 5–73.

- Wolkoff, P. (2018). 'Indoor air humidity, air quality, and health – an overview', *International Journal of Hygiene and Environmental Health*, 221(3), pp. 376–390.
- Wolkoff, P. and Nielsen, G.D. (2001). 'Organic compounds in indoor air—their relevance for perceived indoor air quality?', *Atmospheric Environment*, 35(26), pp. 4407–4417.
- Wong-Parodi, G., Dias, M.B. and Taylor, M. (2018). 'Effect of using an indoor air quality sensor on perceptions of and behaviours toward air pollution (Pittsburgh Empowerment Library Study): Online Survey and interviews', *JMIR mHealth and unhealth*, 6(3).
- Woolley, T. (2024). 'Emissions from building materials and health impacts', *Building Materials, Health and Indoor Air Quality*, pp. 53–74.
- Wu, T., Tasoglou, A., Wagner, D.N., Jiang, J., Huber, H.J., Stevens, P.S., Jung, N., & Boor, B.E. (2024). Modern buildings act as a dynamic source and sink for Urban Air Pollutants, *Cell Reports Sustainability*, 1(5), p. 100103.
- Wu, X. (May)., Fan, Z.T., Zhu, X., Jung, K.H., Ohman-Strickland, P., Weisel, C.P., & Liroy, P.J. (2012). Exposures to volatile organic compounds (VOCs) and Associated Health Risks of socio-economically disadvantaged population in a 'Hot Spot' in Camden, New Jersey, *Atmospheric Environment*, 57, pp. 72–79.
- Xiang, J., Hao, J., Austin, E., Shirai, J., & Seto, E. (2021). Characterisation of cooking-related ultrafine particles in a US residence and impacts of various intervention strategies, *Science of the Total Environment*, 798, p. 149236.
- Xu, J., Zhang, J.S., Liu, X., & Gao, Z. (2012). Determination of partition and diffusion coefficients of formaldehyde in selected building materials and impact of relative humidity, *Journal of the Air & Waste Management Association*, 62(6), pp. 671–679.
- Xue, J., Cai, H., Li, W., Pei, Y., Guan, H., Guo, Z., Wu, C., Qu, C., Li, W., & Liu, J. (2023). 'Emissions of VOCs and SVOCs from Polyvinyl Chloride Building Materials: Contribution to indoor odour and inhalation health risks', *Building and Environment*, 229, p. 109958.

- Yang, S., Goyette Pernot, J., Hager Jörin, C., Niculita-Hirzel, H., Perret, V., & Licina, D. (2020) 'Energy, indoor air quality, occupant behaviour, self-reported symptoms and satisfaction in energy-efficient dwellings in Switzerland', *Building and Environment*, 171, p. 106618.
- Younes, C., Shdid, C.A. and Bitsuamlak, G. (2011). 'Air infiltration through building envelopes: A Review', *Journal of Building Physics*, 35(3), pp. 267–302.
- Yu, C. and Crump, D. (1998). 'A review of the emission of VOCs from polymeric materials used in buildings', *Building and Environment*, 33(6), pp. 357–374.
- Yu, C. and Crump, D. (2011). 'Standards for evaluating indoor air', *Indoor and Built Environment*, 20(4), pp. 389–392.
- Yu, C.W.F. and Crump, D.R. (1999). 'Review: Testing for formaldehyde emission from wood-based products - A Review', *Indoor and Built Environment*, 8(5), pp. 280–286.
- Yvonne Feilzer, M. (2009). 'Doing mixed methods research pragmatically: Implications for the rediscovery of pragmatism as a research paradigm', *Journal of Mixed Methods Research*, 4(1), pp. 6–16.
- Zenissa, R., Syafei, A.D., Surahman, U., Sembiring, A.C., Pradana, A.W., Ciptaningayu, T., Ahmad, I.S., Assomadi, A.F., Boedisantoso, R., & Hermana, J. (2020). The effect of ventilation and cooking activities on indoor fine particulates in apartments.' *Civil and Environmental Engineering*, 16(2), pp. 238–248.
- Zero Carbon Hub/NHBC Foundation (2013). Mechanical ventilation with heat recovery in new homes, London: *NHBC Foundation*. Available at: <https://www.nhbc.co.uk/foundation/mechanical-ventilation-with-heat-recovery-in-new-homes>. (Accessed: 05 November 2023).
- Zhang, Q., Gangupomu, R.H., Ramirez, D., & Zhu, Y. (2010) 'Measurement of ultrafine particles and other air pollutants emitted by cooking activities', *International Journal of Environmental Research and Public Health*, 7(4), pp. 1744–1759.

Zukowska, D., Rojas, G., Burman, E., Guyot, G., Bocanegra-Yanez, M. D. C., Laverge, J., Cao, G., & Kolarik, J. (2020). Ventilation in low energy residences: A survey on code requirements, implementation barriers and operational challenges from seven European countries, *International Journal of Ventilation*, 20(2), pp. 83–102.

Appendices.



APPENDIX A: Research Ethics Approval

Faculty of Computing, Engineering & the Built Environment Research Office Millennium Point, Curzon Street
Birmingham
B4 7XG

BCU_ethics@bcu.ac.uk

19/Jan/2021

Dr Monica Mateo Garcia
monica.mateogarcia@bcu.a
c.uk

Dear Monica,

Re: Mateo Garcia /#7942 /sub3 /R(B) /2020 /Dec /CEBE FAEC - Indoor Air Quality and Overheating in new build residential

Thank you for your application and documentation regarding the above activity. I am pleased to take the Chair's Action and approve this activity.

Provided that you are granted Permission of Access by relevant parties (meeting requirements as laid out by them), you may begin your activity.

I can also confirm that any person participating in the project is covered under the University's insurance arrangements.

Please note that ethics approval only covers your activity as it has been detailed in your ethics application. If you wish to make any changes to the activity, then you must submit an Amendment application for approval of the proposed changes.

Examples of changes include (but are not limited to) adding a new study site, a new method of participant recruitment, a new method of data collection, and/or a change of Project Lead.

Please also note that the Computing, Engineering, and Built Environment Faculty Academic Ethics Committee should be notified of any serious adverse effects arising as a result of this activity.

If, for any reason, the Committee feels that the activity is no longer ethically sound, it reserves the right to withdraw its approval. In the unlikely event of issues arising which would lead to this, you will be consulted.

Keep a copy of this letter along with the corresponding application for your records as evidence of approval.

If you have any queries, please contact BCU_ethics@bcu.ac.uk

I wish you every success with your activity.

Yours sincerely,

Professor Sharon Cox

On behalf of the Computing, Engineering, and the Built Environment Faculty Academic Ethics Committee

APPENDIX B: Home Occupant Information Leaflet and Consent Form

Indoor Air Quality and Thermal Comfort in new build residential developments in the UK March 2022

The aim of the project is to propose cost-effective, scalable construction solutions and strategies that take into account human behaviours with the potential to improve the indoor environmental quality (IEQ) of new houses. The research will seek to analyse the factors that affect users' comfort and well-being in indoor environments, enabling residential dwellings to be improved not only in terms of energy savings but also in providing healthy environments. Participants in this project will need to reside in the UK and have their homes built according to the 2013 Building Regulations so that their homes meet the description intended for the research sample. The occupants' views on their experience related to indoor air quality and thermal comfort in their home will be valuable to our research.

When consent is obtained, participants should expect to be engaged throughout 2022. This will involve monitoring occupant houses for indoor air quality parameters from February (As soon as practically possible) to the end of September 2022 for Phase 2. Sensor installation should take around one hour to prepare, position, and set up the sensors. During the monitoring period, occupants should expect to be engaged through the following means:

1. A one-time home specification questionnaire at the onset (Usually done on the day of installing sensors)
2. A daily occupant diary for the first 12 weeks regarding home activities that affect Indoor Air Quality. This can be done remotely through email in two-week intervals.
3. A Thermal Comfort Questionnaire is to be filled out once a month from May to September. This will also be done remotely through email.

All this will be done in adherence to all health guidelines and at the convenience of participants' schedules without affecting their routines.

Engaging in this research will help improve the indoor environmental quality of homes and, consequently, the health and well-being of their occupants. This research will help assess policies and standards that can bring about positive change in the field of Indoor Environmental Quality, and hopefully lead the way to a confident Net Zero Carbon 2050 UK.

Private information, such as names, addresses, and house numbers, will not be required. All the data collected will be anonymised and handled with strict levels of confidentiality. In the event that photographs or videos need to be captured, they will be taken in a manner that ensures locations and individuals remain unidentifiable. Any captured data will be in strict compliance with the Data Protection Act of 1998. All data will be stored in a secure, university cloud-based storage system for a maximum of five years, with access granted only to verified university researchers. All participants have the right to informed consent, the right to withdraw from the study at any stage of data collection (without prejudice), and the right to anonymity and data protection.

Please read the following and indicate your consent by ticking in the boxes below.

I have read and understood the information leaflet	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
I have had the opportunity to ask questions	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
I understand that participation is entirely voluntary	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>

I agree to take part:

By allowing my house to be monitored	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
By Filling in a Questionnaire Survey	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
By allowing unidentifiable photographs of my house to be photographed	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>

I understand that I have the right to withdraw at any stage of the study without prejudice.

YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
-----	--------------------------	----	--------------------------

(Withdrawal at any point of data collection is possible. In case of this, all the data collected up to the point of withdrawal, will be discarded)

I understand my right to anonymity/confidentiality	YES	<input type="checkbox"/>	NO	<input type="checkbox"/>
----------------------------------------------------	-----	--------------------------	----	--------------------------

Name..... Signature.....

In case of any questions or concerns about the study, please contact:

Callistus Gero

PhD Researcher

Birmingham City University

Callistus.Gero@mail.bcu.ac.uk

Mohamed Barre

PhD Researcher

Birmingham City University

Mohamed.barre@bcu.ac.uk

Birmingham City University

Research Ethics Committee

bcu_ethics@bcu.ac.uk

APPENDIX C: Interview Guide for Housing Developers

Indoor Air Quality and Overheating Research Home Development Process

Land Purchase

- What are your sources of information on potential land purchases? ·
- Briefly describe the site selection decision-making process. What would make you look at different strategies in relation to selecting sites? Have you tried doing things differently before? If yes, what was the result? And why do you think that your strategy produces a better value?
- Which site selection criteria do you follow? In terms of Location, area, Surroundings, green areas, and communities? How long does the whole process take? ·
- At what point do environmental concerns come into the land Purchase stage?
- How do you handle Greenfield/Brownfield sites?
- How difficult or easy is it to work with the respective Planning authorities at this stage?

Planning and Design

- Can you briefly describe the Tender & Procurement process? ·
- What is your average planning time frame from instruction to approval?
- Do you implement the National Planning Policy framework? If so, how?
- Which local authorities do you get involved with at this stage?
- Apart from the NPPF, what other planning regulatory document do you use in the planning stage of your projects?
- Are you participating in the Planning White Paper consultation for 2020?
- For your developments in London, do you follow the London Plan to actively assess overheating risks and reduce reliance on air conditioning systems?
- What drives design decision-making? ·
- Can you describe how BFL12 points inform your design process?
- What is your building design approach in terms of the environment and occupants' quality of life?
- Do you have certification systems for sustainable design principles? ·
- Have you had some projects where design modifications have been done? What were the reasons behind the changes? ·
- How is the current COVID-19 situation affecting the design of your future houses?
- New changes to Part L and F regulations are due to be introduced. How will that be integrated into your projects? (Timeframes & Processes). ·
- Once a site has been identified and purchased for construction, how are decisions concerning scheme orientation made? Which parties are involved?
- What are your views on the current change in Planning processes recently introduced by the government?
- Briefly describe how you specify materials and products, such as complying with regulations, manufacturing guidance, low levels of emissions, etc.
- What is the source control strategy in relation to the selection of low-emission building materials? · What are the best practice procedures? ·

Construction

- Can you briefly describe the on-site inspection process, with attention to monitoring the insulation installation stage?
- Do you have a pollutant source management plan during construction?
- In the case of overheating mitigation, what strategies does your company use? (Passive or Active measures) Any examples of this? Do these decisions affect the sale value of the house? Do you engage occupants when making these kinds of decisions? If so, how?
- What are your construction standards in relation to sustainability and passive houses? ·
- Do you have enough capacity (in terms of skilled personnel) to implement potential HVAC strategies? ·

- Do you employ a collaborative approach when tackling the quality control of indoor environments throughout the construction phase? ·
- What intervention procedures and proactive measures do you have in place throughout the construction phase?
- What are the barriers faced when sourcing building materials? ·
- How do you assess the quality of workmanship to achieve your company standard? ·
- Do you have metrics on previously completed projects? For instance, the overall project time frame. Also, at completion, how close were these metrics to the initial projections? What was the degree of variance?

Technical Department

- What future trends is your R&D division working towards? ·
- What role do your innovations and technologies play in building future homes?
- What are the main barriers when implementing new technology or methods?
- Are your houses naturally ventilated, mechanically ventilated or mixed? (If a mixture, in what proportions?) And how are decisions regarding these systems made? ·
- Do you routinely evaluate the performance of newly occupied properties? If yes, what is included in the evaluations? ·
- Do you consider the use of more conventional heating and ventilation systems? What are the barriers to implementing those techniques?
- Do you carry out overheating assessments and indoor air quality-related tests (Modelling, SAP)? And at what point in the construction process are these carried out? ·
- Which instrument and/or software (Dynamic Simulation Models) or tools do you use, and why? ·
- For overheating purposes, what assessment criteria, if any, do you follow? (TM59, TM52, CIBSE guide A, PHPP, PHE, WHO, HQM) ·
- Which criteria do you use to select sample properties within a flat or a scheme for an assessment?

Marketing and Sales

- How do you handle your company's public image throughout the entire process from land purchase through to after-sales? ·
- What is your after-sales care process?
- Do you have data on customer satisfaction and complaints in relation to the indoor environment?
- What are customer expectations and perceptions of a healthy home? ·
- Apart from economics, what other factors are customers looking for when buying a home, i.e., environment, green area, neighbourhood, etc.?
- If some properties are not sold according to your expected timeframe, what happens to the unsold properties?

Operation and Maintenance

- Do current building user guides help occupants understand and operate the building efficiently in line with the original design intent? ·
- What factors do you consider when installing HVAC systems (i.e. location of the outdoor air intake, any contaminant sources nearby, etc.) ·
- Do you have operating instructions, maintenance and calibration records for components of any mechanical ventilation used in your buildings? ·
- Are there any previous investigations regarding environmental issues or overheating complaints, and do you have their results? ·
- Is there any dedicated customer care following the occupation of your houses?
- Will the new occupants receive training for the liability periods, and if there is a defect, to whom will they report?
- Can you briefly describe the steps of soft-landing procedures?
- What post-occupancy evaluation procedures do you follow?
- Do you undertake commissioning for the systems you install in your houses?
- Do you have a list of locations where indoor quality complaints have been reported in the first year of occupancy?
- Have you faced situations where significant changes (micro or major) were made following complaints after houses were occupied? Addition of rooms, change of fabric elements, etc.?

APPENDIX D: Occupant Daily Diary

Name: _____ Title: _____ Tel. No: _____

Location: _____ Date _____ Doc. No: _____

Please record each time you carry out an activity that you perceive affects Indoor Air Quality (IAQ) in the home on the form below.

It is essential that you record the time and duration as accurately as possible because that will help identify activities (e.g., cooking, cleaning, window, door opening, etc.) that may be associated with increased indoor pollutants. Also, record the ventilation patterns (e.g., opening windows & doors, switching on the extract fan, etc.). Any other observations that you think may help identify the cause of poor IAQ should be noted in the “Comments” column.

This activity log has seven rows for seven days of monitoring, and once every two weeks, the activity log will be replaced with new logs. This process is repeated for the duration of the monitoring period. Feel free to attach additional pages for each activity if you need more space to record your comments. **Fill in the time and duration in the boxes provided.**

		Indoor Environment Source Activities						
House ID		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Activities Tick Box:		Time (e.g. 7 A.M. – 8 A.M.) Week						
Cooking Activities	<input type="checkbox"/> Frying							
	<input type="checkbox"/> Toasting							
	<input type="checkbox"/> Microwave use							
	<input type="checkbox"/> Water boiling, etc.							
	<input type="checkbox"/> Baking							
Total Hours								
Ventilating Activities	<input type="checkbox"/> Window/Door opening							
	<input type="checkbox"/> Switching on the extractor fan							
	<input type="checkbox"/> Other							
Total Hours								
Cleaning Activities	<input type="checkbox"/> Vacuuming							
	<input type="checkbox"/> Sweeping							
	<input type="checkbox"/> Floor Waxing							
	<input type="checkbox"/> Use of Cleaning Products or Furniture Polish							
	<input type="checkbox"/> Other							
Total Hours								
Occupant Special Activities	<input type="checkbox"/> Smoking							
	<input type="checkbox"/> Candle Burning							
	<input type="checkbox"/> Painting							
	<input type="checkbox"/> Spray Air Fresheners							
	<input type="checkbox"/> Electric Air Freshener Diffuser							
Total Hours								

APPENDIX E: Occupant's IAQ Perceptions Questionnaire.

Open-ended questions:

1. How do you feel about the air quality in your home?
2. How important do you consider IAQ in preventing mould and condensation?
3. How do you cook in this house at the moment?
4. How often do you clean your house, and what cleaning products do you use?
5. Do you use scented candles/air fresheners at all? Why?
6. Is there any part of your home you suspect has IAQ problems?

Closed questions:

7. Even if you don't have a specific problem with IAQ in your property, how would you rate the quality of the air you breathe inside your home? **(Only tick one answer)**

Very good	<input type="checkbox"/>
Good	<input type="checkbox"/>
Natural	<input type="checkbox"/>
poor	<input type="checkbox"/>
Very poor	<input type="checkbox"/>

8. What are the main reasons for opening windows in your home? **(Please tick all that apply).**

To get rid of moisture/damp	<input type="checkbox"/>
To get rid of smells	<input type="checkbox"/>
Too warm	<input type="checkbox"/>
For fresh air/to air, the room	<input type="checkbox"/>
It helps me sleep better.	<input type="checkbox"/>
Other (Please specify)	<input type="checkbox"/>

9. What factors stop you from opening the windows in your home? **(Please tick all that apply).**

Noise	<input type="checkbox"/>
Security	<input type="checkbox"/>
Pollution	<input type="checkbox"/>
Don't feel the need to	<input type="checkbox"/>
Heat loss	<input type="checkbox"/>
Can't reach/ get to them	<input type="checkbox"/>
Other (Please specify)	<input type="checkbox"/>

10. How would you like to operate the windows when cooking/cleaning the kitchen/living area? **(Only tick one answer.)**

Close the window completely.	<input type="checkbox"/>
Open the window with a slight gap.	<input type="checkbox"/>
Open the window with a big gap.	<input type="checkbox"/>