Proceedings of the Creative Construction Conference (2025)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu & Žiga Turk
https://doi.org/10.22260/CCC2025/0029

ENHANCING OCCUPANT HEALTH THROUGH RESIDENTIAL RETROFITS: A COMPREHENSIVE REVIEW OF INDOOR ENVIRONMENTAL QUALITY

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Abstract

Residential retrofits are central to decarbonisation but risk unintended health impacts via indoor environmental quality (IEQ). This systematic review of 29 studies (2005–2024) employs the IEQ-Compass framework to evaluate retrofits across thermal comfort (THER), indoor air quality (IAQ), lighting (VIS), and acoustics (ACOU). While retrofits significantly reduce energy demand, they introduce critical trade-offs: airtightness traps radon and Volatile Organic Compounds (VOCs), while insulation increases overheating risks for vulnerable groups. Smart technologies, such as Internet of Things (IoT) ventilation and hygrothermal modelling, stabilise humidity (<35% RH) and particulate matter, though regional disparities persist. For instance, passive insulation in rural China mitigates energy poverty-related hypertension, while adaptive solar Heating, Ventilation, and Air Conditioning (HVAC) systems optimise thermal stability (20–25°C) in temperate climates. However, gaps remain in acoustic standards and equitable design, exacerbated by engineering-centric databases underrepresenting health outcomes. The IEQ-Compass's uniform domain weighting overlooks climate-specific priorities, such as shading in tropical zones. Policy recommendations advocate embedding health metrics—IAQ thresholds, overheating resilience—into global building codes to align with Sustainable Development Goals (SDGs). Future research must integrate longitudinal health tracking, occupant behaviour dynamics, and multi-disciplinary approaches to bridge energy efficiency with well-being. By harmonising building science and public health, this review calls for occupant-centric retrofits that prioritise IEQ alongside decarbonisation, ensuring equitable health co-benefits.

Keywords: indoor air quality, health, sustainable materials, retrofit, thermal comfort.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2025.

1. Introduction

Residential retrofits have emerged as an urgent priority in the global effort to mitigate climate change, alleviate energy poverty, and enhance public health within ageing housing stocks. over 25% of energy use in the European Union [1], the residential sector represents a critical frontier for decarbonisation. Retrofitting existing buildings—through measures such as improved insulation, airtightness enhancements, and hybrid renewable energy systems (e.g., photovoltaic-wind integration)—can reduce household energy demand by up to 80% [2, 3]. These interventions align with sustainability targets by curbing greenhouse gas emissions while addressing energy equity, particularly in low-income households vulnerable to fuel poverty [4, 5]. Construction practices play a pivotal role in this transition, offering technical pathways to optimise energy performance and indoor environmental quality (IEQ). However, the systemic focus on energy savings risks overshadowing occupant health outcomes, exemplified by unintended consequences such as overheating and degraded indoor air quality (IAQ) due to insufficient ventilation [6, 7].

Despite the theoretical potential of retrofits to enhance occupant health, the empirical evidence remains fragmented and often contradictory. For instance, while some studies report fewer respiratory ailments post-retrofit [8], others document elevated formaldehyde levels in tightly sealed homes, exacerbating respiratory conditions [7,9]. This lack of a unified understanding is not merely an academic issue; it

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creates a significant barrier for policymakers and practitioners, leading to the implementation of well-intentioned retrofits that may inadvertently trade long-term energy savings for immediate health risks. The core of the problem lies in a persistent disciplinary siloing, where technical building science is divorced from public health outcomes. To address these challenges, this review synthesises interdisciplinary insights, advocating for retrofit frameworks that embed health equity as a core outcome, informed by lessons from both successes and unintended consequences in diverse contexts.

The primary contribution of this review is the systematic application of the IEQ-Compass framework to synthesise a fragmented, interdisciplinary body of research. This approach allows us to move beyond a simple aggregation of findings to instead build a structured understanding of the health-related trade-offs, synergies, and unintended consequences of residential retrofits. By mapping the evidence against the framework's core domains (Thermal Comfort, Indoor Air Quality, Lighting, and Acoustics), this review provides clear, evidence-based insights for policymakers and practitioners, ensuring that future decarbonisation efforts can deliver equitable health co-benefits. The findings aim to inform policymakers and practitioners in prioritising health co-benefits as non-negotiable outcomes in retrofit frameworks, ensuring that decarbonisation efforts equitably enhance human well-being.

2. Methodology

This systematic literature review investigates the relationship between residential retrofits and occupant health outcomes using a structured five-stage process (Table 1). The methodology integrates rigorous search protocols, systematic screening, and an IEQ-compass-framework-based synthesis to ensure reproducibility and alignment with best practices in evidence synthesis.

Table 1. Five-stage literature review process

Stage	Description
1. Scope Definition	Align research objectives with IEQ-Compass framework to target health-retrofit interrelationships
2. Search Strategy	Develop Scopus queries combining retrofit and management keywords via Boolean logic.
3. Screening	Apply inclusion/exclusion criteria through title/abstract screening and full-text review.
4. Data Extraction	Collate study attributes using predefined templates.
5. Synthesis	Classify findings into IEQ-Compass domains (THER, IAQ, ACOU).

The scope definition stage establishes the research boundaries and objectives by aligning the systematic review with the IEQ-Compass framework, a holistic tool for evaluating Indoor Environmental Quality in residential retrofits [10]. The framework prioritizes four IEQ domains critical to occupant health: Thermal Comfort (THER), Indoor Air Quality (IAQ), Lighting (VIS), and Acoustics (ACOU). These domains are contextualised within health-retrofit interrelationships to identify how retrofit interventions (e.g., insulation, ventilation upgrades) influence occupant well-being through measurable IEQ parameters. The scope explicitly excludes occupant behaviour (e.g., window-opening habits) to focus on building design and system performance

The review focused on peer-reviewed journal and conference articles indexed in Elsevier Scopus, selected for its large multidisciplinary coverage with over 90 million records from 7000 publishers in 105 countries. Two keyword clusters guided the search: (1) terms related to residential retrofits (retrofit, houses) and (2) terms linked to management. The search string is TITLE-ABS-KEY (Retrofit AND Houses AND Management).

The search on Scopus yielded 148 results. Following the abstract screening process, 38 papers were selected for full-text examination. This thorough examination excluded a further 18 papers. Consequently, 20 papers were transferred to the synthesis process.

3. Finding

The intersection of building retrofits and occupant health has emerged as a critical area of research, particularly as energy efficiency initiatives often inadvertently impact indoor environmental quality (IEQ).

This systematic review synthesises findings from 29 academic articles using the IEQ-Compass framework—a taxonomy assessing health-related retrofit impacts via THER, IAQ, VIS, ACOU, and other health-related criteria. Through this lens, we evaluate retrofit strategies' efficacy, unintended consequences, and implications for occupant well-being [11, 12].

Table 2. Key findings

Category	Key findings
Thermal (THER)	• Humidity control (RH <35%) prevents mould/respiratory risks • Insulation raises temperatures for vulnerable groups • Smart HVAC reduces overheating but requires shading
IAQ	• Airtightness traps radon/ Volatile Organic Compounds (VOCs) without ventilation • Mandatory IAQ assessments prevent health liabilities • IoT ventilation balances energy/air quality
Lighting (VIS)	• Daylight alignment improves circadian rhythms/sleep • Glare reduction enhances elderly visual safety
Acoustics (ACOU)	• Retrofit glazing lowers noise (12-15 dB), reducing anxiety • Acoustic dampers limit HVAC/ventilation noise

3.1. Thermal Comfort and Occupant Health

The integration of thermal comfort as a core objective in residential retrofits has proven instrumental in mitigating health risks associated with suboptimal indoor climates. The reviewed studies highlight a dual focus: optimising energy efficiency while safeguarding occupant well-being through humidity regulation, targeted insulation, and adaptive technologies.

[11] demonstrated that retrofits prioritising hygrothermal modelling prevent unintended consequences like mould proliferation. By coupling high-efficiency windows with relative humidity (RH) -controlled ventilation, they maintained indoor RH below 35%—a threshold critical for inhibiting mould growth. This approach directly reduces respiratory risks, as mould exposure is linked to asthma and allergies [11]. Similarly, [13] addressed post-retrofit humidity spikes in UK homes using mesoporous silica coatings, which stabilized RH within 30–70%, effectively curbing mould and microbial growth. These interventions exemplify how material science and ventilation strategies converge to protect respiratory health.

Advanced IoT systems have emerged as vital tools for real-time thermal management. [14] deployed a solar-powered HVAC system with AWS cloud integration, maintaining indoor temperatures at 20–25°C year-round. This stability is crucial for residents with cardiovascular conditions, as extreme temperatures exacerbate health risks. Borkowski's (2024) low-cost IoT sensors provided actionable data on overheating, enabling pre-emptive adjustments to avoid heat-related hospitalisations—a critical intervention as climate change intensifies heatwave frequency.

[16] identified retrofit-induced overheating in UK social housing, where insulation improvements raised summer temperatures by 3–5°C. Their solution—integrating shading and cross-ventilation—lowered indoor temperatures during heatwaves, directly reducing heatstroke risks. This approach highlights the importance of holistic design; without such measures, energy efficiency gains could paradoxically harm occupant health.

3.2. Indoor Air Quality: Mitigating Hidden Hazards in Retrofitted Homes

Residential retrofits aimed at energy efficiency often inadvertently compromise IAQ, introducing health risks from pollutants such as mould spores, volatile organic compounds, and radon. The reviewed studies highlight the critical role of IAQ monitoring, ventilation strategies, and retrofit design in safeguarding occupant health, offering actionable insights to balance energy savings with air quality preservation.

Excessive indoor humidity is a pervasive issue in retrofitted homes, fostering mould growth linked to respiratory illnesses. Tariku et al. (2014) demonstrated that integrating hygrothermal modelling with mechanical ventilation—such as Relative Humidity Controlled Ventilation (RHCV)—effectively maintained indoor relative humidity (RH) below 35%, a threshold critical for inhibiting mould proliferation.

Similarly, [13] tested mesoporous silica coatings in UK retrofits, which stabilised RH within 30–70%, reducing mould-related health risks by 65% compared to non-buffered systems. These findings underscore the necessity of dynamic humidity management in retrofits to prevent asthma exacerbations and allergic reactions.

Retrofits that enhance airtightness often trap airborne pollutants, necessitating vigilant monitoring. [17] deployed a custom ICA system in 100 Romanian retrofits, revealing alarmingly high formaldehyde (95% exceeding safe limits) and radon levels (52% surpassing 300 Bq/m^3). Their real-time CO_2 and radon tracking highlighted the consequences of inadequate ventilation, directly linking poor IAQ to increased cancer risks. [18] further identified 21% higher radon concentrations in retrofitted French homes, emphasising the carcinogenic dangers of neglecting post-retrofit ventilation upgrades. Such studies advocate for mandatory IAQ assessments alongside energy audits to mitigate long-term health liabilities.

Emerging IoT technologies enable proactive pollutant control. [12] integrated smart thermostats with ultrafine particle sensors in a Net-Zero Energy House, demonstrating that automated HVAC adjustments during cooking reduced Ultrafine Particle exposure by 29 $\mu g/m^3$. This framework, leveraging real-time data on appliance use and airflow, lowered cardiovascular and respiratory disease risks by optimising ventilation cycles without compromising energy efficiency. Similarly, [19] operationalised CO_2 thresholds (<1000 ppm) in subtropical retrofits, using an Information and Control System (ICS) to validate air exchange rates, thereby minimizing drowsiness and cognitive impairment linked to poor ventilation.

The interplay between insulation and airflow is pivotal. [20] contrasted natural ventilation with Heat Recovery Ventilation (HRV) in Dutch retrofits, finding HRV reduced heating demand by 60% while maintaining safe CO_2 levels. In contrast, [21] prioritised architectural redesigns—such as wind deflectors and atriums—to enhance natural ventilation in Tianjin homes, cutting VOCs by 40% without mechanical systems. These approaches emphasise context-specific solutions: HRV for cold climates and passive designs for temperate regions, both mitigating sick building syndrome risks.

3.3. Lighting: Enhancing Health through Daylight and Visual Comfort

Lighting in retrofitted homes is not merely a functional necessity but a critical determinant of occupant health, influencing circadian rhythms, cognitive function, and psychological well-being. The reviewed studies underscore the transformative role of daylight optimisation and tailored artificial lighting in mitigating health risks associated with poorly lit environments.

Natural light exposure is pivotal for regulating circadian rhythms, which govern sleep-wake cycles and hormonal balance. In retrofitted homes, strategies such as daylighting optimisation through architectural redesign—demonstrated in [21]—significantly improve occupants' exposure to natural light. Their Tianjin case study revealed that integrating atriums and light-enhancing architectural forms increased daylight factors by 35%, reducing reliance on artificial lighting while aligning occupants' circadian cycles with natural daylight patterns. This alignment is linked to improved sleep quality and reduced instances of seasonal affective disorder, particularly in elderly populations [22].

Inadequate lighting strains visual perception, leading to eye fatigue and headaches. [22] employed Fuzzy Analytic Hierarchy Process (FAHP) to evaluate luminous environments in rural Chinese homes, identifying glare reduction and uniform illumination as priorities for elderly residents. Post-retrofit improvements, including strategically placed windows and anti-glare films, minimised visual discomfort and enhanced reading and mobility for ageing occupants, directly reducing fall risks and promoting independence.

3.4. Acoustics: Mitigating Noise for Cognitive and Psychological Well-being

Acoustic comfort in retrofitted residences plays a pivotal role in safeguarding occupant health, influencing sleep quality, stress levels, and cognitive performance. Post-retrofit environments often face unintended noise amplification due to increased airtightness, necessitating targeted interventions. [23] demonstrated the critical link between mechanical noise and occupant well-being in high-rise condominiums. Retrofitting measures, such as vibration isolation mounts for pumps and elastomer pads for pipes, reduced structure-borne noise transmission by dampening resonant frequencies. Subjective assessments post-intervention revealed reduced sleep disruption—a key factor in preventing stress-related conditions like hypertension.

Efforts to balance energy efficiency with acoustic resilience remain critical. For instance, [18] identified retrofits that inadvertently increased radon concentrations but noted that mechanical ventilation systems, while essential for IAQ, required acoustic dampers to prevent introducing outdoor traffic noise. This dual focus underscores the necessity of holistic retrofit frameworks that prioritize both silence and safety. Collectively, these studies illustrate that acoustic retrofits transcend mere noise control—they are vital public health interventions. By mitigating auditory stressors, such strategies foster environments conducive to mental clarity, emotional stability, and restorative sleep, particularly in vulnerable populations. Future designs must integrate material acoustics and spatial configurations to harmonise energy goals with the auditory well-being of occupants.

4. Future directions

Research on residential retrofits and occupant health has advanced, but key areas need further investigation to optimise health outcomes, ensure equity, and enhance building performance resilience. Future work should prioritise integrated approaches that bridge simulation, monitoring, occupant behaviour, and policy.

Focus areas include refining predictive models for thermal comfort, particularly concerning moisture and overheating, and understanding pollutant dynamics for IAQ, with specific attention to radon and ultrafine particles. Longitudinal monitoring across different seasons is crucial to understand variations in indoor air pollutants. Additionally, assessing the impact of different ventilation pathways and the compatibility of systems like Heat Recovery Ventilation (HRV) is vital.

The call for wider interdisciplinary investigation suggests incorporating dedicated research on optimising daylighting, artificial lighting quality, noise mitigation, and acoustic privacy within integrated retrofit strategies. Addressing these gaps will help develop holistic retrofit strategies that balance energy efficiency with occupant well-being.

5. Conclusion

Residential retrofits have shown the capability in improving occupant health alongside decarbonisation. By employing the IEQ-Compass framework, this review describes energy-efficient retrofits risk unintended health trade-offs, notably pollutant entrapment (e.g., radon, formaldehyde) and overheating in vulnerable groups. Mitigation strategies, such as humidity-controlled ventilation, IoT-driven HVAC balancing thermal stability, require regional adaptation. Despite improving daylight-linked circadian rhythms and reducing noise, research gaps persist in acoustic standards and equitable design. Policymakers can integrate IAQ thresholds and overheating resilience into building codes to align with SDGs. Future research should prioritise longitudinal health impacts and occupant behaviour dynamics via multidisciplinary methodologies, ensuring retrofits deliver equitable, health-centric outcomes.

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