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Comparative Assessment of Insulation Materials for Improving Indoor Air Quality in Building Retrofit

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Abstract

This paper evaluates the impacts of different insulation materials on Indoor Air Quality (IAQ) and occupant health with a focus on the Volatile Organic Compound (VOC) emissions. The main aim is to identify options that minimize exposure rates while improving IAQ and energy in retrofitted buildings. A comprehensive literature review was conducted synthesizing scholarly articles, guidelines from international organizations, and information on pollutants, IAQ standards, and retrofit strategies. The findings show high emission rates for some insulation materials that could negatively affect health. Hemp insulation in contrast was identified as a promising solution exhibiting low VOC emissions compared to other insulation materials. As sustainable construction practices advance, hemp insulation emerges as a viable retrofit strategy for social housing by synergistically addressing performance gaps related to energy conservation, air quality, and thermal comfort. The synthesis of evidence from this paper suggests that, from environmental and public health perspectives, certain insulation materials are preferable for improving IAQ and reducing the risk of exposure to indoor air pollutants in retrofitted buildings.

Keywords

Indoor air quality; VOCs; Insulation materials; Health and wellbeing; Retrofit

1. Introduction

The rapid urbanization of the last century has led to a significant increase in social housing populations in cities worldwide. Poor housing conditions in social housing units are typically associated with increased indoor pollution exposure and consequently detrimental health impacts. Studying Indoor Environmental Quality (IEQ) in these settings is crucial since people living in social housing are typically more sensitive because of their age and/or financial position (Diaz Lozano Patino and Siegel, 2018). This is in part to assess whether these residents are disproportionately exposed to environmental elements that could worsen pre-existing health consequences or cause new ones. Social housing units may experience deteriorating general housing conditions because of factors including building age and poor upkeep (Diaz Lozano Patino and Siegel, 2018). Studies suggest that people from disadvantaged socio-economic backgrounds are exposed to higher concentrations of indoor air pollutants in their homes. Variations in these pollutant exposures are caused by the interaction of physical structures, indoor and outdoor sources, and patterns of household activities (Adamkiewicz, 2013).

The circumstances of the indoor environment have a significant impact on human welfare because most individuals spend 90% of their time indoors, mostly at home or at work (Leech et al., 2012). According to the World Health Organisation (WHO), 3.8 million deaths worldwide are attributed to indoor air pollutants (IAPs) (WHO, 2020). IAPs can be produced by residents' activities including cooking, smoking, and cleaning as well as from furniture and building materials. Particulate Matters (PMs), aerosol, biological pollutants, volatile organic compounds (VOCs), carbon monoxide (CO), and others are among the harmful pollutants found inside buildings (Kumar, 2013). Studies on air quality regulation have started to focus more on indoor settings over the past ten years, reflecting lifestyle changes that are associated with higher levels of urbanization (Tran and Park, 2020). Research has shown that poor IAQ can lead to building-associated illnesses, which can have a detrimental impact on human health (Hromadka et al., 2017), (Koivisto et al., 2019). IAPs, stemming from both indoor and outdoor sources, pose significant threats to public health. Recognizing the urgency of addressing this challenge, the scientific community has advocated for optimized retrofit interventions to curtail the adverse effects of indoor pollutants while improving energy efficiency in buildings.

To this end, this study focuses on a crucial aspect of retrofitting wall insulation. Walls, as integral components of a building's envelope, play a pivotal role in regulating thermal comfort, IAQ, and energy performance in buildings. The research aims to unravel effective measures that not only enhance energy efficiency but also contribute to creating healthier living spaces. Various thermal insulation materials categorized into organic (carbon-containing) and inorganic (mineral-based, lacking carbon-hydrogen bonds) are studied. Each category can be further divided into natural and synthetic insulations, depending on the origin of the raw materials and the processing techniques used. Through a comprehensive review and comparative analysis, the objective is to identify insulation materials that minimize VOC emissions while promoting improved IAQ and energy performance in retrofitted buildings.

2. Research Methodology

This study utilizes a comprehensive literature review approach to examine insulation materials from the perspective of IAQ, energy efficiency, and occupant health. The methodology involves a systematic literature search across multiple scholarly databases like PubMed, Scopus, Google Scholar, and ScienceDirect. Keywords related to "indoor air quality", "volatile organic compounds", "insulation materials", and "building retrofits" were used to retrieve relevant peer-reviewed articles, reports from international organizations like WHO and EPA, standards documents, and other credible sources. The review synthesizes information from this extensive literature on indoor pollutants, IAQ guidelines, retrofit strategies, insulation material properties, and quantification of VOC emissions from different insulations. The primary focus is on three main categories of insulation materials (Figure 1): mineral wool insulation, synthetic insulations (including Expanded Polystyrene (EPS) Foam, Extruded Polystyrene (XPS) Foam, Rigid Urethane Foam (PIR), and Phenolic Foam (PF)), and hemp insulation. These groups correspond to the primary raw material sources: mineral, petroleum, and bio-based, respectively.

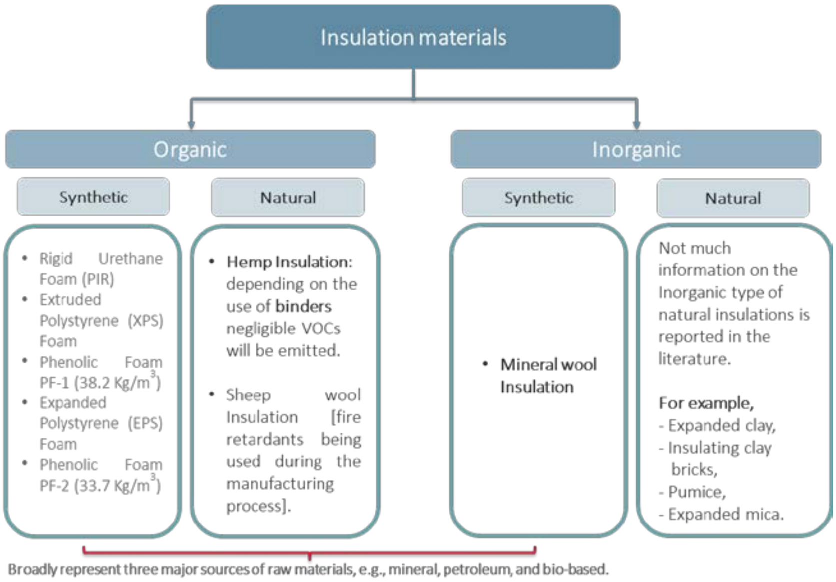

Figure 1: Insulation materials selected for the comparative analysis in the literature.

The review focuses on synthesizing findings on the following key aspects:

- Main pollutants affecting IAQ and their health impacts.
- Existing IAQ guidelines and standards.
- VOC emissions from common insulation materials.
- Properties and performance considerations of various insulation materials.

The following table (Table 1) summarises some of the key references and sources analyzed and synthesized in the literature review, including guidelines from WHO and EPA, journal articles examining VOC emissions from insulation and building materials, and other relevant studies on IAQ factors. The literature review pulls insights from these sources to provide a comprehensive overview of the topic.

Table 1: Key References Reviewed

Reference	Summary
USEPA (2023) Volatile Organic Compound's Impact on Indoor Air Quality	Comprehensive overview from the US EPA on how VOCs emitted from household products, building materials, furniture, etc. can accumulate indoors and degrade air quality, leading to health effects like eye/respiratory irritation, headaches, and elevated cancer risk.
WHO (2021) Global Air Quality Guidelines	Updated WHO guidelines providing the latest targets for maximum annual and short-term exposure levels for key indoor/outdoor pollutants based on extensive reviews of health studies.
Wi et al. (2021) Hazard evaluation of the indoor environment	An experimental study measuring VOC and formaldehyde emissions over 90 days from 5 different insulation materials (XPS, EPS, PIR, phenolic foams) installed in a 20m^2 test chamber simulating unfavorable indoor conditions. Quantified emission rates and concentration profiles over time.
Yang et al. (2020) VOCs in Swiss energy-efficient homes	Field study in Switzerland measuring VOC levels in 169 newly constructed energy-efficient dwellings retrofitted with improved insulation and airtightness. Found elevated terpenes, hexaldehyde, formaldehyde, toluene, and butane likely from insulation, wood products, and human activities.

Yan et al. (2019) Emissions from new furniture	Measured concentrations of key VOCs emitted from new footstool and bedside table furniture products at different loading rates over time using an environmental chamber.
CIBSE TM40 (2020) Indoor Air Quality Guide	UK guide comparing various standards and best practice recommendations for ensuring adequate indoor air quality in buildings through pollutant monitoring and mitigation strategies.

3. Literature review

3.1. Key Indoor Air Pollutants

It has been established that a wide range of indoor air contaminants negatively affect both human health and IAQ (OSHA, 2020). Particulate matter ($PM_{2.5}$, PM_{10}), Nitrogen oxides (NOx), volatile and semi-volatile organic compounds (VOCs), Sulphur Dioxide (SO_2), Ozone (O_3), Carbon monoxide (CO), radon, hazardous metals, and microbes are the principal indoor air pollutants. Table 2 enumerates some prevalent contaminants.

Table 2: Common air pollutants and their health impacts (Tran and Park, 2020)

Pollutant	Sources	Health Impacts
PM	Outdoor environment, cooking, combustion activities (burning of candles, use of fireplaces, heaters, stoves, fireplaces and chimneys, cigarette smoking), cleaning activities	Pre-mature death in people with heart or lung disease, non-fatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, increased respiratory symptoms
VOCs	Paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry-cleaned clothing, building materials and furnishings	- Eye, nose, and throat irritation - Headaches, loss of coordination and nausea - Damage to liver, kidney, and central nervous system - Some organics can cause cancer
NO_2	Gas-fuelled cooking and heating appliances	- Enhanced asthmatic reactions - Respiratory damage leading to respiratory symptoms
O_3	Outdoor sources, photocopying, air purifying, disinfecting devices	DNA damage, lung damage, asthma, decreased respiratory functions
SO_2	Cooking stoves; fireplaces; outdoor air	- Impairment of respiratory function - Asthma, chronic obstructive pulmonary disease (COPD), and cardiovascular diseases
CO_x	Cooking stoves; tobacco smoking; fireplaces; generators and other gasoline-powered equipment; outdoor air	Fatigue, chest pain, impaired vision, reduced brain function

3.2. IAQ guidelines and standards

Even at low air pollutant concentrations, prolonged exposure to indoor anthropogenic activities can degrade IAQ and pose serious health hazards to people. The scientific community and pertinent organizations have tried to create and implement IAQ standards and recommendations to address these IAQ issues (Tran and Park, 2020). The international community finally succeeded in establishing IAQ standards and guidelines based on an integrated building strategy after much effort (Avgelis and Maggos, 2016). The aim is to eliminate, or at least reduce, potential dangers to human populations because the WHO and USEPA(United States Environmental Protection Agency) state that the purpose of IAQ guidelines is to provide a vital database as a reference for the prevention of detrimental consequences of IAP and preservation of public health (WHO, 2000). The WHO's Air Quality Guidelines (AQG) for a few prevalent contaminants are presented in Table 3 (WHO, 2021). The WHO and USEPA standards often specify the maximum concentration for duration (e.g., one hour, twenty-four hours, or a year).

Table 3: WHO Global Air Quality Guidelines 2021 (WHO, 2021)

Pollutants		**Long-term AQG Level (Annual) (µg/m^3)**	**Short-term AQG Level (24 Hour) (µg/m^3)**
PM	10	15	45
	2.5	5	15
O_3		60	100 (8 hour)
NO_2		10	25
SO_2		-	40
CO		-	4
CO_2		-	1800

IAQ is affected by the concentration of total volatile organic compounds (TVOCs), which are made up of many individual chemical species that come from indoor sources like furniture and building materials. Different international guidelines rely on qualitative ratings of air quality to determine permissible TVOC levels. For instance, the North American LEED (Leadership in Energy and Environmental Design) and RESET (Regenerative, Ecological, Social & Economical Targets) guidelines specify that TVOC concentrations should not exceed 500 µg/m^3 to protect health. On the other hand, more stringent standards enforced by the German Federal Environmental Agency and Chartered Institution of Building Services Engineers (CIBSE) TM40 - 2020 Guide – Indoor air quality comparisons recommend that total VOCs be kept below 300 µg/m^3 to promote better IAQ and reduce exposure. By continuously measuring and reducing indoor TVOC concentrations in comparison to these reference values, indoor environments can effectively reduce the potential health risks associated with indoor air pollutants. Table 4 shows the exposure limits of TVOC set by CIBSE, LEED, RESET, and IAQ Levels by the German Federal Environmental Agency.

Table 4: TVOC concentrations according to various guidelines

TVOC Concentration (µg/m^3)	**Standards for Indoor air quality**	**Sources**
<300	Recommended value	CIBSE TM40 - 2020 Guide – Indoor air quality comparisons (CIBSE TM40, 2020)
<500	TVOC Limit	LEED Green Building Rating System (LEED, 2023)
<500	Acceptable range	RESET Standard for Indoor Air Quality (RESET, 2018)
<300	Target value	IAQ Levels by the German Federal Environmental Agency (German Federal Environmental Agencies, 2007)

The index used by the USEPA for reporting air quality is called the Air Quality Index (AQI) (AirNow, 2023). The amount of air pollution and the corresponding health concerns increase with a higher AQI value. For instance, good air quality is indicated by an AQI value of 50 or less, whereas hazardous air quality is indicated by an AQI value of 300 or higher (AirNow, 2023). An AQI value of 100 for any given pollutant typically denotes a level of ambient air concentration that meets the national ambient air quality standard for public health protection for a given period. Air quality becomes unhealthy when AQI values are above 100, initially for sensitive individuals and later for everyone as the numbers rise (AirNow, 2023). According to most research, $PM_{2.5}$ levels of 12 µg/m^3 or below are thought to be healthy and pose little to no danger of exposure. When the amount rises to 35 µg/m^3 or more in 24 hours, the air is deemed hazardous and might aggravate respiratory conditions like asthma in those who already have them.

Extended exposure to concentrations higher than 50 µg/m^3 can cause major health problems and early death (Indoor Air Hygiene Institute, 2023). The air quality standards set by EPA for PM_{10} and $PM_{2.5}$ are shown in Table 5 (AirNow, 2023).

Table 5: AQI for PM_{10} and $PM_{2.5}$ (WHO, 2021)

AQI categories	US AQI	US-EPA range (24 hr)	
		PM_{10} (ug/m^3)	$PM_{2.5}$ (ug/m^3)
Good	0-50	0-54	0-12.0
Moderate	51-100	55-154	12.1-35.4
Unhealthy for sensitive individuals	101-150	155-254	35.5-55.4
Unhealthy	151-200	255-354	55.5-150.4
Very unhealthy	201-300	355-424	150.5-250.4
Hazardous	301-500	425-604	250.5-500.4

The WHO has imposed a tougher eight-hour limit than both OSHA and NIOSH, at 100 µg/m³ (0.1 mg/m³) for O_3. The EPA's AQI breakpoints provide an additional lens through which to view ozone. Although we are using these breakpoints for ambient ozone, we can also use them to calculate safe indoor ozone levels (Kaiterra, 2021). Ozone exposure is divided by the EPA into two-time intervals: one hour and eight hours. The following Table 6 lists different ozone concentrations along with how safe they are to be exposed to for eight hours.

Table 6: AQI for Ozone (Kaiterra, 2021)

AQI categories	US AQI	Ozone Level (ppm)
Good	0-50	0.000-0.054
Moderate	51-100	0.055-0.070
Unhealthy for sensitive individuals	101-150	0.071-0.085
Unhealthy	151-200	0.086-0.105
Very unhealthy	201-300	0.106-0.200

As per the current WHO air quality recommendation, an indoor nitrogen dioxide guideline of 200 µg/m^3 for one hour is advised (WHO, 2020). Asthmatics show slight reductions in lung function at roughly twice this level. At this stage, sensitive individuals may already exhibit slight alterations in their airway's reactivity to a range of stimuli. There is no evidence to support an indoor guideline that differs from the ambient guideline from studies on the indoor environment (WHO, 2020). As per the current WHO air quality recommendation, a yearly average indoor nitrogen dioxide guideline of 40 µg/m^3 is advised (WHO, 2020). Table 7 shows the US EPA range for NO_2 and their AQI categories.

Table 7: AQI for NO_2 (WHO, 2020)

AQI categories	US AQI	US-EPA Range for NO2 (ppb) (1 hour)
Good	0-50	0-53
Moderate	51-100	54-100
Unhealthy for sensitive individuals	101-150	101-360
Unhealthy	151-200	361-649
Very unhealthy	201-300	650-1249
Hazardous	301-500	1250-2049

Higher or longer exposure levels have the potential to cause death via airway constriction, but exposures of 50 to 100 ppm may be tolerated for more than 30 to 60 minutes. Because sulfur dioxide is heavier than air, it can cause asphyxiation if it is present in enclosed, poorly ventilated, or low-lying places. The WHO has not identified SO_2 as a pollutant for which specific IAQ guidelines are required, The WHO guidelines are for general air quality (WHO, 2021). There are no established CO standards for indoor air (USEPA, 2023). Any home with a fossil fuel appliance will contain carbon monoxide (CO), also known as "The Silent Killer," a colorless, odorless gas. Even though most poisonings happen in the winter, CO can exist year-round (McAfee, 2021). The following details in Table 8 describe some symptoms that could manifest after one hour of CO exposure:

Table 8: Exposure ranges and health effects of CO (McAfee, 2021)

CO Exposure ranges (ppm)	Health effects
0-9	Typical airborne CO levels; no health danger.
10-29	Long-term exposure issues: persistent issues include headaches and nausea.
30-35	Flu-like symptoms start to appear, notably in young people and the elderly.
36-99	All symptoms are flu-like, including headaches, nausea, lethargy, and exhaustion.
100+	Extreme symptoms, including disorientation and severe headaches; eventually, brain damage, coma, and/or death, particularly at 300–400+ ppm.

3.3. Volatile organic compounds (VOCs) exposure in building materials

Hazardous VOCs, like butanol, formaldehyde, and acetone, are present in a lot of household items and can pollute indoor air. It is crucial to understand VOC concentration and units of measurement to protect public health. For instance, common harmful substances include:

- Formaldehyde: Found in pressed wood products and formaldehyde-based resins (such as plywood and fibreboard), which are used to make flooring, paneling, furniture, and other items.
- Acetaldehyde: Found in laminates, cork, foam mattresses, linoleum, and other items; used in the manufacture of polyester resins and basic dyes.
- Phenol: Found in a variety of products, including vinyl flooring and wall coverings.
- BTEX substances: Found in many petroleum products, BTEX comprises benzene, toluene, ethylbenzene, and xylene.
- Glycol ethers: Found in many cleaning supplies, coatings, and solvents.
- Methylene chloride, often used in adhesives.

Within the confines of human indoor environments, furniture assumes a substantial role. Furthermore, one must comprehend both the emissions of building materials and furniture to assess the true amounts of VOCs indoors. Wood-based panel, adhesive, and surface coating materials are the primary components of furniture, and these materials can release a variety of VOCs, such as aldehydes, terpenes, aromatic hydrocarbons, esters, ketones, hydrocarbons, and so on (He, Zhang, & Wei, 2012). The focus of furniture research is on VOCs and the amounts of these emissions (Kang and Liu, 2017). Ho et al. (2011) and Song et al. (2015) identified 39 target VOCs from five widely accessible furniture brands. The findings demonstrated that the VOC contents differed significantly amongst the products. More than 400 different types of VOCs were found in the new dorms that (Pei et al., 2016) evaluated for long-term indoor gas pollution. The dormitories had recently been furnished. According to (Chang et al., 2017), panel furniture was the primary source of TVOC and formaldehyde indoors. Moreover, it has frequently been determined that the benzene series comprises most furniture components (Song et al., 2015). Ultimately, the amount of VOCs released by furniture is mostly determined by the constituent materials used in its manufacture, its kind and age, the production method, and how it is stored, transported, and utilized indoors (Yan et al., 2019).

In a study conducted by (Yan et al., 2019) two different types of furniture (a footstool and a bedside table) had their VOC emissions measured in an environmental chamber at three different loading rates. The most common substances found in the footstool and bedside table were, respectively, n-undecane and styrene. VOC concentrations rose swiftly, peaked in about 1-2 hours, and then declined as emission rates reduced. In a study by (Ho et al., 2011), five furniture samples - a desk chair, bedside table, dining table, sofa, and cabinet were used to quantify the VOC emission rates from common furniture used in homes and businesses during a period of up to 14 days following the two weeks following the furniture's creation. The findings indicated that the predominant components of emissions were toluene and α-pinene, with most VOCs showing comparable declining tendencies with time. If measured in terms of VOCs, the relative ordering of emission rates for each of the five types of furniture remained relatively constant over time: dining table > sofa > desk chair > bedside table > cabinet.

VOCs can be harmful to both human and animal health. Unfortunately, typical household materials such as some paints, air fresheners, and cleaning supplies release them. When paint is applied, VOCs are gradually released over several weeks or months. At least 48 hours following painting, a space may be deemed "high risk" for volatile organic compounds. Precautionary steps ought to be followed for a full 72 hours including staying away from the room and not sleeping in it (Ghobakhloo et al.,2023). The duration of VOC emission following painting is contingent upon several elements, such as the type of paint used, the space in which it is applied, ventilation, the existence of an air purifier, temperature, humidity, and numerous others. Paint-related VOCs do eventually evaporate when the paint dries on the wall, but this process can take some time, with the majority dissipating during the first six months of application (Ghobakhloo et al.,2023).

3.4. Volatile organic compounds emitted by insulation materials

Many common insulation products are used in the construction of off-gas volatile organic compounds (VOCs) into indoor air, degrading air quality and posing health hazards. VOCs are gases containing elements like carbon, oxygen, and nitrogen emitted from solids and liquids. Insulation materials made from plastics, polymers, and some synthetic fibers release VOCs such as formaldehyde, benzene, toluene, xylenes, and styrene during and after installation (Adamová et al.,2020). Exposure to these chemicals can lead to eye, nose, and throat irritation, headaches, breathing difficulties, nausea, kidney and liver damage, and cancer risks. As buildings aim to cut energy use through increased insulation, understanding these unintended emissions consequences is vital.

Controlled lab analysis has allowed the quantification of VOC emission rates from various insulation materials over time. In a study conducted by (Wi et al., 2021) on a 20 m^2 test bed, five different types of insulation materials were developed, and the pollutants' concentrations were tracked over time. Five different types of building insulation were chosen to serve as the test groups: two types of PF insulation, one type of XPS, one type of EPS, and one type of PIR. Through the simulation of unfavorable climatic circumstances, this study attempted to analyze rather clear changes in IAQ. The MOLIT's health-friendly housing guidelines state that indoor building finishing materials, like flooring and wallpaper, have TVOC emissions of no more than 0.10 mg/m^2 and HCHO emissions of no more than 0.015 mg/m^2 (Wi et al., 2021). The MOE has issued the IAQ management legislation enforcement regulations, which include emission restrictions for building materials. Specifically, the TVOC emission limit for flooring materials and wallpapers is 4.0 mg/m^2, while the HCHO emission limit is 0.02 mg/m^2. The Korea Air Cleaning Association (KACA) has devised a collective certification system for healthy building materials. The best rating for TVOCs and HCHO is less than 0.10 mg/m^2 and 0.008 mg/m^2, respectively (Wi et al., 2021). Table 9 displays the TVOC emission data from (Wi et al., 2021) utilizing the 20 L small chamber. Based on the insulation, the largest TVOC emissions were for PF-2 at 0.1727 mg/m^2 -h, and for EPS at 0.1216 mg/m^2 -h. The emissions from PF-2 and EPS were less than those required by the emission regulations of building materials for flooring and wallpaper in IAQ management (MOE). They did, however, surpass the healthy building certification requirements (KACA) and the health-friendly housing construction standards (MOLIT) (Wi et al., 2021). Table 10 shows the properties of mineral and bio-based thermal insulations. Among them, Hemp insulation is the one with no known pollution and has no known detrimental effects on health. Hemp insulation materials (HIMs) have gained attention for their environmental benefits (Martínez et al., 2022). A study explored the feasibility of large-scale hemp cultivation in Canada and the suitability of HIMs for residential buildings (Liu et al., 2023). It is argued that full substitution using 5% hemp fiber insulation (HF) and 95% hempcrete (HC) can mitigate 101% of greenhouse gas emissions caused by existing mainstream insulation materials (MIMs), contributing to a 7.38% reduction in emissions and aiming for net-zero emissions by 2050 (Liu et al., 2023). Additionally, hemp-based materials offer lower embodied carbon compared to fossil fuel-based alternatives (Martínez et al., 2022). Case studies have demonstrated the effectiveness of hemp insulation in real-world applications such as historic building retrofits (Johansson et al., 2018; International Hemp Building Association, n.d.).

Table 9: VOC Emissions from Insulation Materials and Associated Health Hazards (Wi et al., 2021)

Insulation Material	VOCs Emitted	Emission Levels (mg/m^2-h)	TVOC (mg/m^2-h)	TVOC Emission Duration (0-90 days)
Extruded Polystyrene (XPS) Foam (34.7 Kg/m^3)	Toluene	0.0036	0.021	Persist at lower levels for months after installation
	Ethylbenzene	0.0013		
	Xylene	0.0006		
	Styrene	0.0098		
Expanded Polystyrene (EPS) Foam (35.7 Kg/m^3)	Toluene	0.0104	0.1216	Reaches its maximum on the 14th day and gradually decreases and achieves a safe level only after 90 days
	Ethylbenzene	0.0163		
	Xylene	0.0047		
	Styrene	0.0687		
Rigid Urethane Foam (PIR) (36.8 Kg/m^3)	Formaldehyde	0.0013	0.0068	Persist at lower levels with slight variations on the 14th and 28th day for months after installation
Phenolic Foam PF-1 (38.2 Kg/m^3)	Formaldehyde	0.0039	0.0241	Persist at lower levels for months after installation
	Toluene	0.0024		
Phenolic Foam PF-2 (33.7 Kg/m^3)	Toluene	0.0016	0.1727	Gradual increase in emission until the 14th day and then decreases and persists above safe level throughout 90 days.

Table 10: Thermal Insulation Properties (Latif, 2020)

Type of insulation	Constituents and Manufacturing	Pollution	Health Impacts
Mineral Wool Insulation	Naturally occurring rocks like basalt or diabase are essential components of rock wool insulation. Blast furnace slugs or iron ore are used to make slag wool insulating materials.	There will probably be emissions during the curing process if formaldehyde has been used as a binder. The insulation can release any leftover formaldehyde following the curing procedure.	Mineral wool insulation is categorized by the International Agency for Research on Cancer (IARC) as "B, possibly carcinogenic to humans." The insulating fibers of mineral wool also irritate the skin and eyes. Upper respiratory tract infections can also be brought on by mineral wool insulation exposure.
Hemp Insulation	Bast fibers make up most of the hemp insulation—typically more than 60%—and are both renewable and	No known pollution	Hemp insulation has no known detrimental effects on health. The high moisture buffer capacity of the insulations allows

	biodegradable. It is possible to combine hemp fibers with other fibers, like cotton, wood, etc.		for the stabilization of internal relative humidity, which can improve the quality of the surrounding air.
Sheep Wool Insulation	Between 75 and 90 percent of pre-consumer sheep wool waste from other sectors is used to make sheep wool insulation. Sometimes virgin wool is used straight away. As binding agents recycled adhesive binder (about 5%), synthetic binder, or natural latex milk are utilized. Boric salts, urea derivatives, or borax (sodium salt) are added to the fabric to increase fire resistance and prevent moth infestation.	If the insulation burns, sulfur compounds may be liberated from the keratin, giving sheep's wool a foul smell.	Sheep wool's hygroscopic qualities allow it to buffer moisture and maintain a constant relative humidity within. Sheep wool's high moisture and gas adsorption ability allows it to also adsorb volatile organic compounds (VOCs) like formaldehyde. Sheep wool dust can irritate eyes and respiratory tracts if inhaled.

3.5. Air tightness, infiltration, and energy performance gap

Air leakage, defined as the normal unintended movement of air into and out of buildings, is an important contributor to building energy loads that is often overlooked (Chan and Joh, 2013). The leakage rate is measured in air changes per hour (AC/H), which quantifies the rate of replacement of internal air with external air. Temperature differences between indoor and outdoor environments, as well as wind pressures on the building envelope, can increase air leakage rates considerably. A simulation analysis of a wide range of residential and commercial building types by Chan et al. (2013) demonstrated the major impact that air leakage can have on energy consumption. By reducing leakage through cost-effective measures such as applying sealants, installing weatherstripping around windows/doors, adding storm windows, or replacing worn-out components, the study found heating and cooling energy use could be lowered by 5-40% (Chan et al.,2013). The large range represents differences in building construction and leakiness levels.

It is commonly observed that retrofitted buildings do not achieve the estimated energy savings that were computed to guide the design phase or to get energy performance certification (Sunikka-Blank and Galvin, 2012) (van den Brom et al., 2017). The "energy performance gap" refers to the discrepancy between the projected (or simulated) and measured (or actual) post-retrofit energy performance of buildings. Most studies assess the energy performance in terms of the building's annual energy demand for heating and/or cooling (de Wilde, 2014). There are signs that dwellings refurbished using the aforementioned weatherisation procedures tend to deteriorate IEQ and contribute to ill health (Bone et al., 2010) (Richardson and Eick, 2006), as well as may lead to energy performance gap resulting in missed governmental targets, increased energy bills, and longer investment pay-back timelines (Anastasios and Itard, 2018) (Majcen, 2016). According to the European Commission's policy report from 2016, a lack of information and statistics on IEQ in energy-efficient homes may jeopardize inhabitants' health and comfort (Kephalopoulos et al., 2016).

Controlling airtightness, together with thermal insulation of the building envelope and its windows, has been identified as a critical method for achieving energy savings in buildings. This is because space heating accounts for more than half of all carbon emissions in the residential sector. As a result, buildings that allow air seeping and/or heat loss are likely to spend more on heating (Pan, 2010). Weatherization and restoration programs that are heavily focused on lowering permeability and boosting thermal insulation to save energy can introduce some dangerous factors to the inhabitants' health (Ortiz et al., 2020). Internal and surface condensation, moisture surplus or dampness, pollutant buildup owing to limited ventilation, radon concerns, and overheating may come from adding internal thermal insulation and increasing building airtightness (Ortiz et al., 2020). These IEQ problems also become more severe when the mechanical ventilation systems are not correctly planned, installed, maintained, or operated (Ortiz et al., 2020).

When sealing the home for energy savings, the indoor chemistry of the residence can have a severe impact on the health of the occupants (Weschler, 2011). Indoor contaminants can become more frequent in an airtight home, in addition to undesired emissions from the insulation components used (Marlow et al., 2012). In France, for example, a comparison of the IAQ of energy-efficient houses to conventional structures revealed greater concentrations of terpenes and hex aldehyde, probably due to wood or wood-based goods and human activities (Derbez et al., 2018). Thermal retrofit of dwellings and the absence of appropriate ventilation systems are associated with elevated levels of formaldehyde, toluene, and butane indoors (Yang et al., 2020).

4. Discussion

In the realm of energy-efficient retrofit strategies, thermal comfort, and IAQ, insulation plays a pivotal role. The extensive literature review on IAPs, air quality guidelines, and VOC emissions from insulation materials underscores the critical importance of holistic approaches to building design, construction, and renovation. The multifaceted nature of the indoor environment, encompassing factors such as air pollutants and insulation choices necessitates a nuanced understanding for creating sustainable and healthy living spaces. The diversity of IAPs, ranging from PMs to different gases, VOCs, microbiological organisms, etc. signifies the complexity of maintaining optimal IAQ. Both outdoor and indoor sources contribute to a spectrum of contaminants, emphasizing the need for comprehensive mitigation strategies. IAQ standards and guidelines, as established by reputable organizations like WHO and USEPA, play a pivotal role in shaping building practices. Adherence to these standards is crucial for safeguarding public health and preventing the detrimental consequences of indoor air pollution (IAP).

One of the critical considerations in retrofit strategies is the impact of insulation materials on IAQ. The literature highlights that many common insulation products emit high levels of VOCs that can adversely affect health. In contrast, Hemp insulation demonstrates negligible VOC emissions, compared to other materials like Extruded Polystyrene (XPS) Foam, Expanded Polystyrene (EPS) Foam, Rigid Urethane Foam (PIR), and Phenolic Foam (PF-2). Moreover, compared to insulation materials based on minerals or petrochemicals, hemp insulation may require less energy during manufacture and result in reduced emissions. This aligns with the broader goal of creating energy-efficient buildings while minimizing the environmental impact. Insulation materials must not only be environmentally friendly but also effective in enhancing thermal comfort.

The results of this study provide significant insights into the role of various insulation materials in enhancing building performance while supporting sustainable development. The findings demonstrate that hemp-based insulation materials not only offer comparable thermal, mechanical, and acoustic properties to conventional materials but also present distinct advantages in terms of sustainability and environmental impact. The significance of these findings lies in their potential to promote the adoption of bio-based insulation materials, contributing to the reduction of the construction sector's carbon footprint. By highlighting the efficiency and benefits of hemp insulation, this study advocates for a shift towards more sustainable building practices. This aligns with global sustainability goals, such as reducing greenhouse gas emissions and promoting the use of renewable resources. The use of hemp insulation can significantly reduce reliance on petroleum-based materials, thus mitigating their environmental impact.

However, several barriers exist that could hinder the widespread adoption of hemp insulation. These include higher initial costs, lack of awareness among stakeholders, and limited availability of materials. Addressing these barriers requires concerted efforts from policymakers, industry stakeholders, and researchers to promote sustainable materials through incentives, education, and research investments. Future research should therefore focus on developing cost-effective production methods for hemp insulation and exploring its long-term performance in diverse climatic conditions. Additionally, studies should investigate the lifecycle analysis of hemp insulation to provide a comprehensive understanding of its environmental impact from production to disposal. Furthermore, using sustainable materials can enhance IAQ, contributing to better health outcomes for building occupants.

Hemp insulation, and similar insulation materials, could therefore be a viable alternative to traditional insulation materials to simultaneously improve energy performance while mitigating risks of poor IAQ in buildings. By addressing the barriers to its adoption and highlighting its benefits, this research contributes to the broader discourse on sustainable development in the construction industry. Future work should aim to further validate these findings and explore innovative solutions to promote the use of sustainable insulation materials.

5. Conclusion

The comparative analysis of insulation materials reveals a spectrum of considerations. Traditional materials such as XPS and EPS, while effective in thermal insulation, are associated with environmental concerns and potential VOC emissions. Retrofitting, a key strategy for enhancing energy efficiency and addressing IAQ issues in existing buildings, involves the integration of advanced technologies and methodologies. It is a dynamic field that requires careful consideration of multiple variables. The concept of the "performance gap" in retrofitting indicates challenges in achieving projected energy savings. To have a more comprehensive approach to building retrofit, the “unintended” effects of poor retrofit strategies on IAQ should be added to the performance gap subject. The complex interactions between retrofit measures, occupant behavior, and long-term building performance underscore the need for ongoing research and refinement of strategies. As sustainable building practices gain prominence, there is a concurrent need for standards and certifications that reflect the broader goals of environmental conservation and occupant health. In conclusion, the synthesis of findings from this study points towards a future where building practices seamlessly integrate environmental sustainability and occupant health considerations. Further research is required to assess the combined effects of building design, construction methods/materials, occupant behavior, and outdoor air quality on IAQ and their effects on occupant health and comfort.

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Ethics approval

The authors have received ethics approval from the ethics committee of the University of East London, for the interviews and surveys that were conducted by the authors.

Conflict of interest

The authors declare that there is no competing interest.

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