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Research Article

Evaluating the Impact of Building Materials on Indoor Air Quality: A Critical Analysis

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ABSTRACT

It is known that people generally spend 90% of their time indoors. Therefore, indoor air quality is a major concern for many people. Building materials play an important role in indoor air quality. Therefore, this study evaluates the role of building materials in IAQ by conducting a bibliometric analysis of articles from the Web of Science Core Collection and utilizing VOSviewer software to analyze publications from 2010 to 2023, focusing on the citation, year, country, and keywords co-occurrence. The analysis reveals key trends and gaps in the literature, highlighting the predominance of specific materials and pollutants. It also highlights that variability in building parameters makes attributing pollution sources difficult and underlines the need for context-specific assessments. These findings underscore the critical need to prioritize IAQ in building design and management to ensure safe and healthy indoor environments. This study manifests by methodologically mapping the research landscape on building materials and IAQ, guiding future empirical research.

1. Introduction

We all know that air quality greatly impacts our health and well-being. However, it is known that the building materials used in houses and buildings can also play a role in indoor air quality (IAQ). A successful building design requires a good indoor environment that not only impacts energy consumption but also affects the comfort of the inhabitants. Building environments vary in size, design, and function, influenced by the available building materials, climate, and culture. Building spaces are thermally conditioned to provide indoor and thermal comfort suitable for different weather conditions. The indoor environment is frequently contaminated with dangerous compounds and biological pollution sources, which can cause various health issues. IAQ is influenced by chemical, biological, building materials, furnishing, design, and mechanical systems. Poor IAQ can greatly impact occupant health. Figure 1 illustrates the various sources and types of contaminants (chemical, biological, and physical) that impact users, leading to a range of diseases.

IAQ and the comfort of occupants are closely intertwined. The indoor environmental conditions include four major factors. These are thermal comfort, indoor air quality, visual comfort, and acoustic comfort. Frontczak et al. [2] found that IAQ significantly impacts occupants' satisfaction, with factors such as visual, thermal, acoustic, and indoor air quality contributing to overall satisfaction. Additionally, Astolfi and Pellerey [3] found that satisfaction with indoor environments is related to thermal, acoustic, visual, and air quality conditions.

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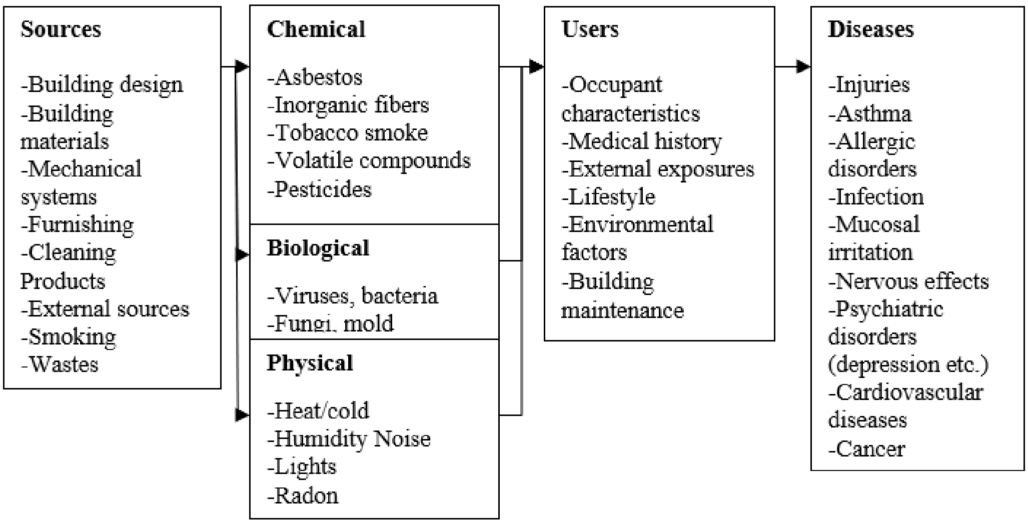

Figure 1. The built environment to health effects pathway [1]

Control of pollutant sources, removing contaminants from the air using effective filters, and dilution ventilation are important techniques for IAQ management. Architects must consider IAQ as a part of human-centered design strategies, requiring adequate ventilation systems, air filtration, humidity regulation, and temperature control [4]. Studies have shown that outdoor/indoor temperature, wind velocity, humidity, ventilation, and occupancy influence IAQ and thermal comfort.

According to the literature, Indoor Air Quality (IAQ) is crucial in minimizing Sick Building Syndrome (SBS) symptoms. IAQ is a significant concern for human health, and many studies have been conducted to address this issue. Numerous studies have focused on indoor air pollutants' sources, concentrations, and health risks, such as VOCs, PM, and biological pollutants (Table 1). Experimental studies, such as those conducted by [5] and [6], have specifically examined the impact of certain pollutants like viruses. Both studies aimed to provide architects with solutions to reduce the risk of disease transmission through effective air disinfection techniques, engineering controls, and design methods.

Related studies, such as Ma et al. [7], investigated the correlations among thermal comfort, IAQ, and human health and well-being factors. The study identified factors like outdoor and indoor temperature, wind velocity, relative humidity, physical features of the room, ventilation, and air exchange rates as contributing to IAQ. To improve IAQ and reduce exposure to pollutants, studies proposed using green materials, plants, and nanomaterials [8-13]. For example, nanomaterials have been recommended to detoxify indoor air using heterogeneous photocatalysis [9]. In another case, houseplants reduced formaldehyde, a poisonous substance, in indoor air environments [13]. Green adhesives from renewable natural resources include tannin and cashew nutshell liquid. With the ability to have low formaldehyde release from wood products, they can hence boost indoor air quality [12].

Moreover, much better regulation is essential, enhancing the IAQ integrity [14]. Various researchers have indicated the importance of controlling of emission of volatile organic compounds (VOCs) due to their toxicity, especially from building material formaldehyde and other toxic substances [15-22].

Megahed et al. [23] studied design strategies in post-pandemic architecture to address IAQ challenges related to COVID-19. Their work aimed to provide architects with solutions to reduce the risk of disease transmission through effective air disinfection techniques, engineering controls, and design methods. Their conceptual model discusses the need for human-centered design through holistic IAQ management strategies like ventilation systems, air filtration, humidity control, and temperature regulation.

Building materials can release various pollutants, which can cause indoor air-related health problems [24]. Kozielska et al. [25] monitored indoor pollutants in a residential building in Poland and found that CO_2 concentrations and BTEX were higher in homes with more people and fewer rooms, while NO_2 levels increased during cooking. The highest exposure risks were associated with PM4 (with a diameter of ≤4 μm), which poses significant health risks. Poor ventilation contributed to high pollutant levels.

Riaz et al. [8] explore the impact of microbial colonies in wet and damp indoor environments on human health. The authors discuss Building-associated illness (BRI) and SBS as significant health issues caused by indoor biological pollutants or bioaerosols such as bacteria, fungi, and viruses like coronavirus. They argue for using nanomaterials in heterogeneous photocatalysis for indoor air detoxification. They also stress the importance of cost-effective and safer materials to address indoor air quality and public health issues. Aydoğan et al. argue that biological methods based on plants and their associated microorganisms offer a promising solution to eliminate toxins from indoor environments. They discuss the psychological, physiological, and cognitive benefits of incorporating vegetation into indoor environments and cleaning the air [26].

Radon gas exposure raises lung cancer risk. Community-level data is vital to prioritize testing and remediation, conserve public health resources, and involve building owners [27]. Popa et al. emphasize that because of inadequate ventilation and the widespread use of new building materials that emit organic chemicals, indoor environments risk human discomfort and harm to health. It notes that several VOCs, some of which are known to be hazardous, mutagenic, or carcinogenic, have been found in indoor air [14].

To forecast PM2.5 conditions, Saini et al. suggest an IAQ monitoring system using Internet of Things-based sensors. The Vayuveda system was evaluated using a variety of datasets from both urban and rural areas, and updates were made available to users via an online portal. To establish the optimal model for real-time IAQ assessment, the authors evaluated various approaches at each stage of the development process [28]. When the relationships between PM concentrations are examined, it is emphasized that location affects the results and that a uniform approach cannot effectively combat air pollution [29].

A dangerous pollutant with a large global production and consumption rate, formaldehyde, is discussed by Wang et al. as a source of pollution in Chinese homes. The study aimed to assess home formaldehyde pollution in 11 cities and investigate potential contributing factors. The findings indicate that northern cities, bedrooms, and warm seasons had higher pollution levels [15].

The BTEX group of hazardous organic chemicals, which includes benzene, toluene, ethylbenzene, and xylenes, is the paper's subject by Mokammel et al. The study evaluated the health hazards and factors of BTEX levels in indoor and outdoor air in rural communities in Ardebil, Iran. According to the findings, indoor air contained higher levels of BTEX than outdoor air. According to the report, tobacco smoke was a prominent temporary source of indoor BTEX, and using kerosene fuel for heating systems resulted in higher concentrations of BTEX [10].

Alfuraty discusses using eco-friendly materials in the design of interior decorations. The paper explores the current issues of the decoration materials, the idea, and the value of environmental protection together with the analysis of relevant information on modern green design, providing sustainable development of environmentally friendly material for interior design. The study observes that environmental protection materials help improve IAQ and include outdoor spaces in continuity with indoor spaces [30].

Mareş et al. evaluate the IAQ and energy efficiency of a single-family house in Cluj-Napoca County, Romania. Past research studies have found that with increased energy efficiency, there is reduced IAQ due to more energy efficiency, and there tends to be less natural ventilation. The research also observed that their installation caused a higher IAQ at low energy costs and significant energy savings compared to conventional ventilation [31].

The emissions of VOC and PAHs and their impact on IAQ were studied by Pineiro et al. The study looked at both primary and secondary emissions. The study found that an original coal-tar membrane used to waterproof the terrace was a possible source of contaminants. The article suggested that the contaminated materials should be removed, and ventilation systems should be installed to force the emitted gases from the rest of the contaminated slab outside to remediate the emission problem [16].

Adam et al. researched personal exposure to particulate-bound black carbon (BC) in urban areas of Trivandrum, India. The study aimed to quantify the levels of exposure to BC in a home-based and mobility-based scenario. The study found that BC concentrations were highest during transportation, such as using motorcycles and cars. The inhaled dose of BC was relatively larger in the mobility-based scenario. The study highlights the need to reduce personal exposure to fossil fuel-related particulate emissions in cities for public health reasons [11]. The article highlights the need for better legislation to improve household IAQ. It discusses sources of indoor air pollution, health impacts, and groups affected by COVID-19 and poor IAQ [17].

The emissions of VOCs and SVOCs and the presence of mold were examined by Gallon et al. at various stages of construction. According to the study, the entire implementation process is closely linked to the future indoor air quality of a building. During construction, mold spore measurements can reach high levels. They argue that SVOC and VOC emissions must be regulated due to their toxicity [18].

Alenezi et al.'s study in Kuwait measured the precise concentrations of VOCs and the associated risks in homes near fuel dispensing stations. The study found that BTEX has mutagenic and carcinogenic characteristics, leading to high health risks for the neighboring community [32].

In winter in Xi'an, China, Huang et al. measured harmful VOCs and carbonyls in typical apartments. The study discovered significant indoor levels of formaldehyde, acetone, naphthalene, methylene chloride, and acetaldehyde in Chinese households. According to the study, the main sources of indoor VOCs and carbonyls are household items, smoking, cooking, paints and adhesives, furniture and building materials, and paints and adhesives [33]. Skaar et al. evaluated indoor emissions of toxic substances from products and their impact on human health, which is typically not considered in life cycle assessments (LCAs). They developed a method based on measured emission rates to calculate the impact on human health during the use stage of products that emit VOCs [34].

Building materials are significant sources of VOCs and Formaldehyde, which can pose health risks to occupants. With the increasing use of composite wood products in Korea, efforts are being made to reduce formaldehyde emissions in indoor environments using green adhesives from natural materials [35]. Toxic substances like Formaldehyde and VOCs released from building materials and wood composite products can be the cause of SBS symptoms. The placement of indoor plants in newly built apartment houses in Seoul has been shown to reduce SBS symptoms and ventilation [13].

Fungal metabolites such as beta-D-glucan, mycotoxins, and VOCs that induce ill health in susceptible occupants are strongly associated with indoor humidity and IAQ [19]. The use of composite wood products in indoor environments in Korea has increased, causing problems related to human health due to the emission of toxic substances such as Formaldehyde and VOCs. Green adhesives from natural materials such as tannin and cashew nutshell liquids reduce formaldehyde emissions and improve IAQ [20].

When combined with ventilation, indoor plant placement in newly constructed apartment buildings in Korea was proven to improve the mental and physical health of the occupants. The planting of indoor plants alone proved insufficient to minimize indoor hazardous chemical compounds despite improvements in mental health and some physical parameters [21]. This study used houseplants to examine the signs of SBS in 82 households in a recently constructed apartment building in Korea. The study proved that houseplants positively impacted indoor air quality and formaldehyde levels. Some toxic chemical substances that cause SBS were quantitatively reduced by using houseplants [22].

Table 1. Overview of the past reviews

Ref.	Method	Sources	Pollutants
[8]	Review	TiO_2 nanomaterials-based air filters and building coatings	Bioaerosols
[10]	Experimental	Heating systems, paints, building materials, smoking, cooking appliances, furnishings, and cleaning products	BTEX (benzene, toluene, ethylbenzene, and xylene)
[11]	Experimental	Black carbon	PM, PAHs
[13]	Experimental	For VOCs: paints, varnishes, waxes, conservation materials, solvents of anti-mold agents, and detergents. For benzene: plastics, resins, and detergents For formaldehyde and acetaldehyde: chipboards, various resins, paints, disinfectants For Terpenes: household detergents and perfumes	VOCs
[14]	Experimental	Construction materials	VOCs
[15]	Experimental+ Survey	Household characteristics (building age, distance from a traffic road, residence duration, window glass layers, decoration, furniture, and type of AC)	Formaldehyde
[16]	Experimental +Numerical	Coal-tar membrane for insulation	VOCs, PAHs
[17]	Analytical	-	Biological pollutants: Virus (COVID-19)
[18]	Experimental	Construction material	VOCSs, tVOCs
[19]	Analytical	Building materials (mineral wool, plasterboard, cardboard), cigarette smoke	Fungal metabolites, mycotoxins, and VOCs
[20]	Analytical	The wood-based panel, furniture, engineered flooring, and construction adhesive	Formaldehyde and VOCs
[21]	Experimental	-	Formaldehyde, CO, CO_2
[22]	Experimental+ Survey	-	Toxic chemical
[24]	Experimental	MDF	VOCs, Formaldehyde
[25]	Experimental	For NO_2: gas-fired appliances (stoves, ovens, cookers, and water heaters) For VOCs: (installations, odors, room furnishings, furniture, carpets, electronics, etc.)	CO_2, VOCs, PM, NO_2, and BTEX
[21]	Experimental	-	Formaldehyde, CO, CO_2
[26]	Review	-	-
[27]	Survey	Bedrock-penetrates building foundation and cracks	Radon
[28]	Experimental +IoT	Biomass fuels such as wood, cow dung, and kerosene	PM2.5, PM10, CO_2, CO, NO_2, and tVOC
[30]	Analytical	Surface finishing, furnishing, lighting system, equipment, and electrical devices	-
[31]	Experimental +Numerical	-	Radon
[32]	Experimental	Fuel dispensing station near the residential area	VOCs and BTEXs (benzene, toluene, ethyl benzene and xylenes)
[33]	Experimental	Furniture and building materials, paints and adhesives, household products, smoking, and cooking	Formaldehyde, acetaldehyde acetone, naphthalene, and methylene chloride
[34]	Experimental+ Numerical	Room furnishing	VOCs
[35]	Numerical	Building and furnishing materials (paint, coating, wood-based panels, plywood)	VOCs, Formaldehyde
[36]	Experimental	Floor/wall coverings, furniture, and the use of cleaning products, heating system	VOCs, benzene, ethylbenzene, o-xylene, and formaldehyde
[37]	Analytical	Indoor coal smoke	Formaldehyde
[38]	Experimental	House dust	Macromolecular organic compounds (MOC) and VOCs

Aldehyde compounds are the most common chemical group in the indoor air of atopy patients and control households in Korea. Atopic dermatitis and allergic asthma patients' homes had considerably higher indoor air benzene, ethylbenzene, xylene, styrene, and formaldehyde substances. Higher quantities of formaldehyde and other VOCs were associated with house age, floor or wall coverings, and the type of heating system [36].

The article reviews energy-saving in building and IAQ-related standards in China. It discusses how the two systems of building energy-saving and IAQ-related standards have been established separately. The article also explains the importance of formaldehyde as a pollution index in the IAQ control strategy in China [37]. Molhave et al. describe the composition of floor dust from Danish offices collected and analyzed to be used in an exposure experiment. The study found that the dust contained microorganisms, microfungi, endotoxins, allergens, macro-molecular organic compounds (MOD), and VOCs. The article emphasized that sediments of dirt and dust resulted in airborne dust, which causes exposure and soiling problems [38].

These studies discuss IAQ, focusing on pollutants, ventilation, humidity control, and temperature regulation. Several studies emphasize the correlations between thermal comfort and human health. The use of green materials and houseplants to improve IAQ is also discussed. Common pollutants such as VOCs and Formaldehyde, as well as their potential health risks, are explored in multiple studies. Many studies recommend the adoption of better legislation and building standards to promote and ensure healthy IAQ. Controlling IAQ is crucial for mitigating SBS. Effective ventilation can maintain IAQ below set pollutant limits, but perceptions of air quality and ventilation rates are correlated. Therefore, adequate ventilation should be central to design or remediation efforts.

Although extensive research has investigated the impact of building materials on indoor air quality (IAQ), a gap exists in synthesizing this body of work through bibliometric analysis. This study was necessitated by consolidating and analyzing existing literature to identify common trends, methodologies, and gaps. Using a bibliometric approach using VOSviewer to review articles in the WoSCC systematically, this research provides a data-driven perspective on the impact of building materials on IAQ. Unlike previous reviews that qualitatively discuss the effects of specific materials, our study maps the research landscape quantitatively. It provides insight into the most frequently studied materials, contaminants, and their associated health effects.

2. Methodology/Bibliometric Analysis

This study aimed to conduct a thorough literature review on IAQ in residential buildings by searching for relevant articles on the Web of Science (WoS) using various keywords. All data were obtained from the Web of Science Core Collection between 2010 to 2023. English-only document types were articles, letters, and reviews from the following indexes: SCI-EXPANDED, SSCI, ESCI and A&HCI, CPCI-S. Data from different sources were collected and analyzed. VOSviewer [39] software version 1.6.18 was used to display the literature on indoor air quality and building materials. The relevant publications were selected based on specific criteria such as publication year, language, journal, title, author, institution, keywords, document type, abstract, and citation counts. The data from these publications were entered into the software manually in text format [4].

In this software, analysis types such as citation analysis, co-citation analysis and bibliographic matching are frequently preferred. In addition to these traditional methods, this study incorporates an approach by analyzing keyword co-occurrences, specifically within word mining, enhancing the understanding of the field's thematic structures and semantic networks. The types of analysis in Table 2 show the types of bibliometric analyses used in this study. In the study conducted with VOSviewer, 4059 publications were found with the keyword "IAQ." In this analysis, the minimum frequency of occurrence of terms was chosen as 10, and there are 50,840 terms in total. 3264 of these terms meet the determined threshold value. As a rule of thumb in analysis, 60% of the terms were selected as the most relevant.

A bibliometric study examined the development of IAQ within scholarly articles and its correlation with environmental factors, reflecting its increasing prominence in academic research. This study utilized a systematic bibliographic review of literature central to the theme, following a structured methodology: (1) establishing search parameters, keywords, and timeframes; (2) utilizing the Web of Science database for data retrieval; (3) refining and adjusting the search criteria; (4) comprehensive exportation of the data; (5) analyzing the gathered data and discussing the findings with five analysis.

Table 2. Types of bibliometric analysis used

Analysis Type	Characteristics Analyzed
Citation	Documents, Sources, Authors, Numbers, Countries
Bibliographic coupling	
Publication numbers (year)	
Publication numbers (country)	
Keyword Co-occurrence	

2.1. Findings

This section details the principal findings from a comprehensive examination of published articles, focusing on the correlation between various building materials and their contributions to IAQ. Advanced bibliometric tools have allowed for a nuanced data analysis, revealing key materials and pollutants that play pivotal roles in indoor air environments. The five analyses, which are citation analysis, publication number according to year and country, bibliographic analysis and keyword co-occurrence analysis methods mentioned above, are examined below.

2.1.1. Citation analysis

Many researchers have made significant contributions to the field of indoor air quality. The analysis from WoSCC highlights the top ten authors with the most citations for their work and the titles of their publications. This comprehensive overview demonstrates the depth of research and the critical insights these scientists provide to understanding and improving indoor air quality.

Table 3. Citation analysis of top ten publications between 2010 to 2023

Ref. No.	Authors	Title	Doc. Type	Total Times Cited
[40]	Liu, C; Hsu, PC; Lee, HW; Ye, M; Zheng, GY; Liu, NA; Li, WY; Cui, Y	Transparent air filter for high-efficiency PM2.5capture	Article	816
[41]	Cao, XD; Dai, XL; Liu, JJ	Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade	Article	805
[42]	Rupp, RF; Vásquez, NG; Lamberts, R	A review of human thermal comfort in the built environment	Review	562
[43]	Sundell, J; Levin, H; Nazaroff, WW; Cain, WS; Fisk, WJ; Grimsrud, DT; Gyntelberg, F; Li, Y; Persily, AK; Pickering, AC; Samet, JM; Spengler, JD; Taylor, ST; Weschler, CJ	Ventilation rates and health: multidisciplinary review of the scientific literature	Article	510
[44]	Sarigiannis, DA; Karakitsios, SP; Gotti, A; Liakos, IL; Katsoyiannis, A	Exposure to major volatile organic compounds and carbonyls in European indoor environments and associated health risk	Review	434
[45]	Schober, W; Szendrei, K; Matzen, W; Osiander-Fuchs, H; Heitmann, D; Schettgen, T; Jörres, RA; Fromme, H	Use of electronic cigarettes (e-cigarettes) impairs indoor air quality and increases FeNO levels of e-cigarette consumers	Article	387
[46]	Schripp, T; Markewitz, D; Uhde, E; Salthammer, T	Does e-cigarette consumption cause passive vaping?	Article	374
[47]	Wolkoff, P	Indoor air humidity, air quality, and health - An overview	Review	366
[48]	Pacheco-Torgal, F; Jalali, S	Earth construction: Lessons from the past for future eco-efficient construction	Review	348
[49]	Vakiloroaya, V; Samali, B; Fakhar, A; Pishghadam, K	A review of different strategies for HVAC energy saving	Review	331

Table 3 below lists these influential authors and their seminal work, demonstrating the scope of the study and the impact of their research on the academic community and beyond. The most cited publication was the most cited publication between 2010 and 2023, with 816 citations. This study is a study on PM2.5, a particularly important air pollutant.

2.1.2. Bibliographic coupling

In this analysis, there are five clusters with ten or more authors. This analysis does not generally represent all 11610 authors who contributed to this topic, but only those who contributed to the central research network. Accordingly, the total power of co-authorship resources with other authors was calculated for one of the 45 authors.

Figure 2 shows a network map visualizing co-author affiliations within 4059 publications with IAQ keyword search. The network map reveals collaborations and relationships among scientists conducting IAQ research. Clusters of different colors represent specific research groups or authors who collaborate extensively. While each link represents at least one joint publication between the two authors, the links' density and thickness indicate this collaboration's frequency and strength.

The strongest connections within this central network of writers are Zhang Yinping, Wei Wenjuan, Li Baizhan, and Pawel Wargocki. Almost all of the strongest links are between the same authors.

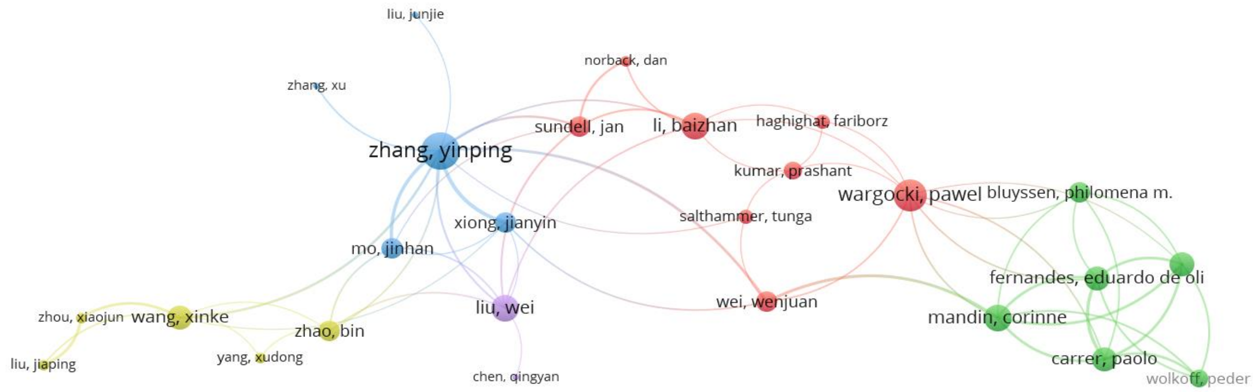

Figure 2. Network map visualization of IAQ keyword search

2.1.3. Year analysis

Figure 3 shows that there has been significant growth in research on indoor air quality over the years, reaching a peak in 2022, the highest number of publications at 1004, between 2010 to 2023.

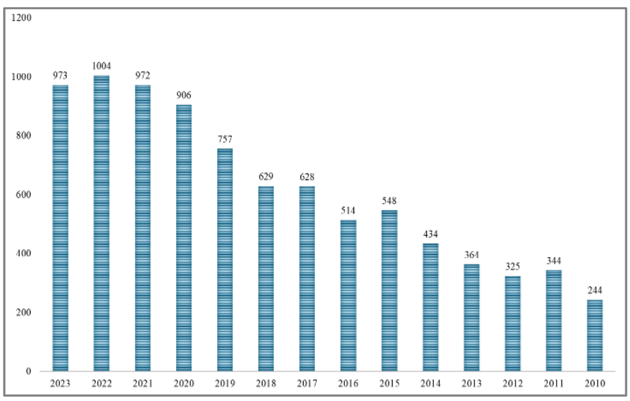

Figure 3. Number of publications related to IAQ between 2010 and 2023

The general trend shows a steady increase in publications, with some fluctuations, since 2010. This trend reflects the increasing awareness and importance of IAQ in recent years.

2.1.4. Country analysis

Figure 4 shows the number of publications on indoor air quality (IAQ) in different countries between 2010 and 2023. The USA is the country with the most publications in the field of indoor air quality, with 1605 publications. China ranks second with 778 publications. South Korea ranks third with 597 publications, while England ranks fourth with 550 publications. It is included in this ranking in Turkiye and ranks twenty-fourth with 133 publications.

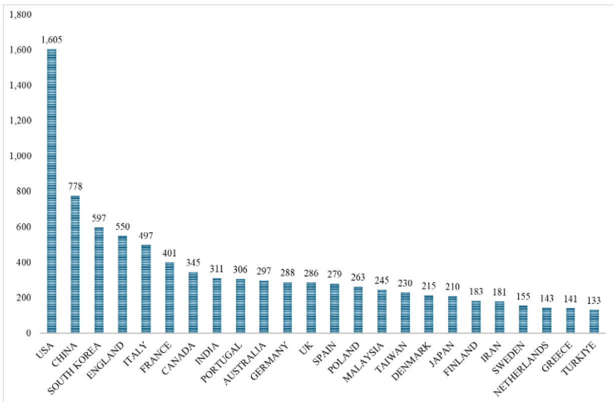

Figure 4. Number of publications on IAQ in different countries between 2010 and 2023

2.1.3. Keyword Co-occurrence

The distribution of the relationships between words or terms in documents based on indoor air quality is determined by keyword co-occurrence analysis. The color distributions on the map show that current and basic publications are clustered separately.

Figure 5 shows the flowchart maps the structured process of bibliometric analysis, which focuses on examining the impact of building materials on indoor air quality (IAQ). The first phase begins with bibliometric analysis, in which a search is performed using specified keywords in the Web of Science database. After the search, the data is downloaded and carefully analyzed.

Three different sets of keywords form the basis of our analysis:
Figure 6a corresponds to articles on "Building Materials OR Construction Materials" and "Indoor Air Quality" OR "IAQ" representing the first broad search. In this figure a network with 4059 references and related with 3264 keywords in WoS.

Figure 6b narrows the scope by focusing on articles covering a more specific subset of the literature, 'Building Materials, Indoor Air Quality and Toxic Chemicals.' A search on WoS for "toxic chemicals" OR "chemicals" added to 'Building Materials and Indoor Air Quality,' resulted in a network with 2160 references and 2256 keywords, as seen in Figure 6b.

Figure 6c represents a further refined search covering "Building Materials OR Construction Materials" and "Indoor Air Quality" OR "IAQ," "Toxic Chemicals" OR "Chemicals," "Residential," and "Health" targeting articles. In addition to the previous keywords, a search for "residential" and "health" produced a network consisting of 34 references and 50 keywords, displayed in Figure 6c.

In Figures 6a, 6b and 6c, the size of the nodes in the graphs represents the frequency of occurrence, with keywords that commonly appear together and are linked by curves. The font size also indicates the prevalence of the keyword [50]. From this analysis, primary concepts like "environment," "health," and "building material" emerged as the most relevant, with secondary concepts closely linked to these primary ideas. These major themes emerge as focal points of research in the collected literature.

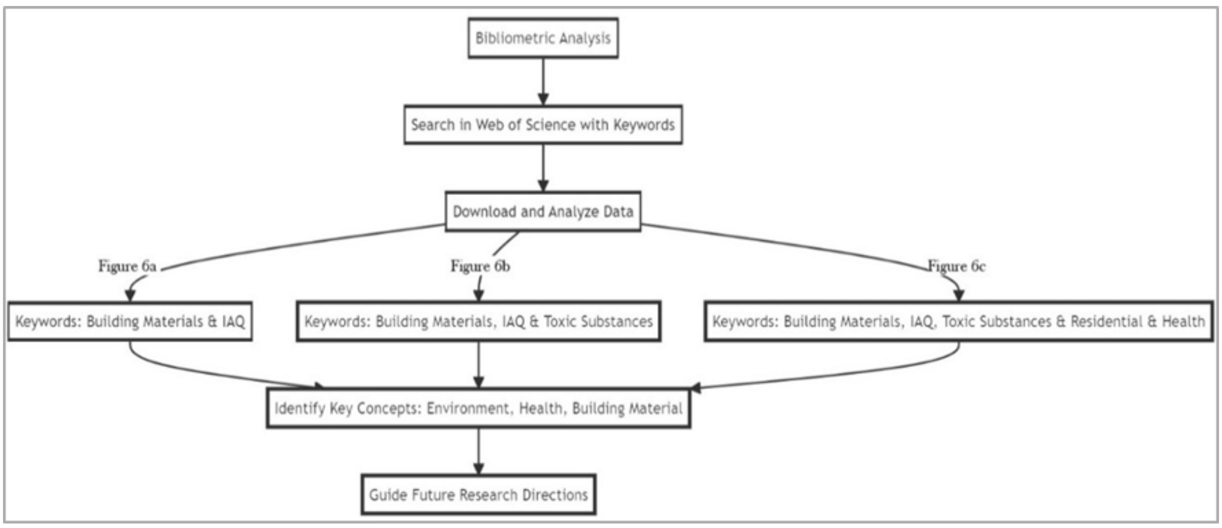

Figure 5. Flowchart of the Bibliometric Analysis

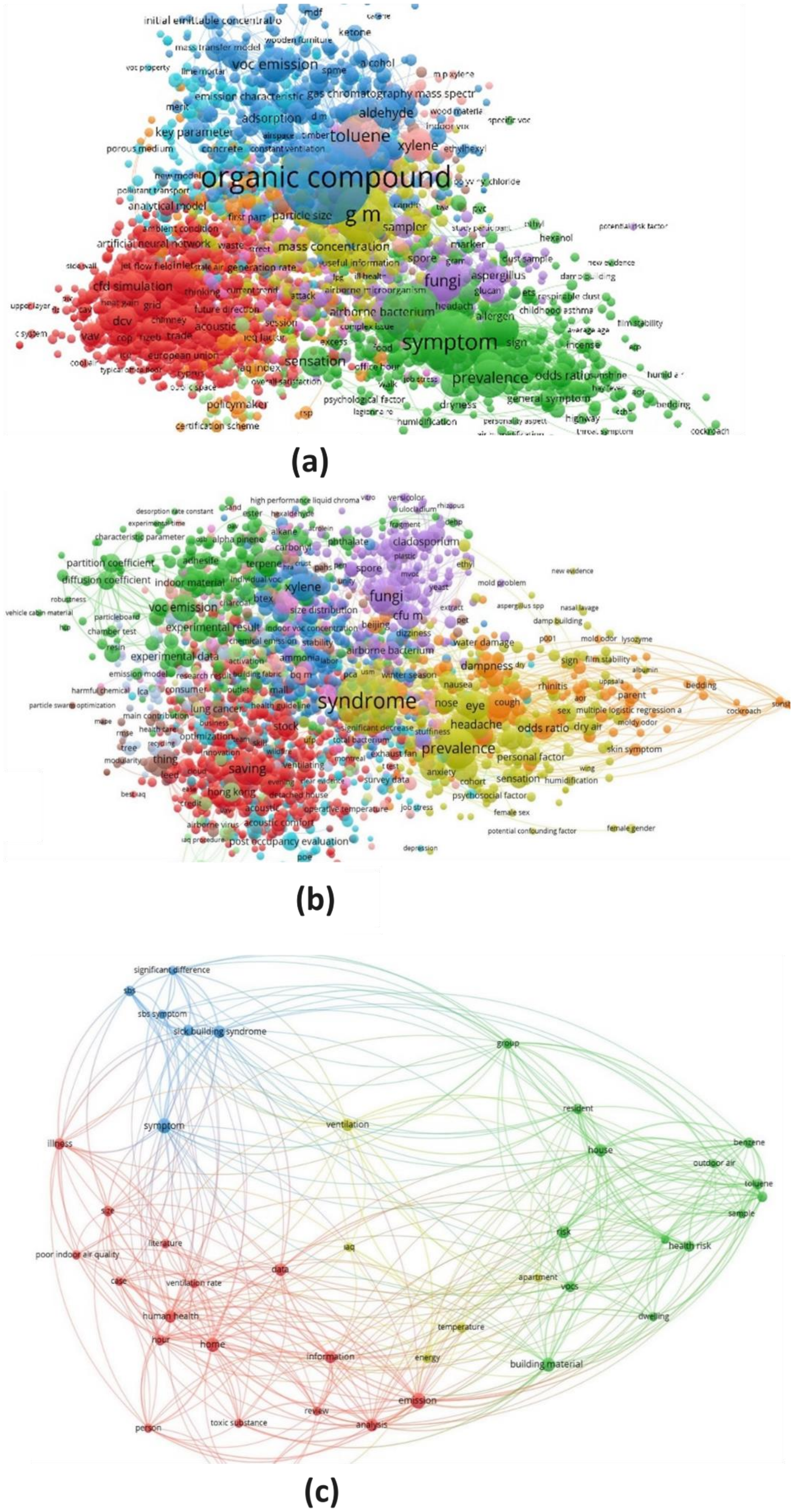

Figure 6. (a) Building materials and IAQ keyword co-occurrence analysis network visualization, (b) toxic substances keyword co-occurrence analysis network visualization, (c) Network visualization based on

analysis of the co-occurrence of the keywords building materials, IAQ, toxic substances, residential, and health

This bibliometric analysis helps understand IAQ's complex dynamics better and guides future research directions by highlighting under-researched areas and emerging trends. This article, therefore, contributes to the field by providing a comprehensive, methodologically novel approach to assessing the role of building materials in influencing indoor air environments. This study has some inherent limitations that should be considered. First is the database. The analysis is limited to articles from the WoSCC. Studies published in languages other than English or journals not indexed by this database are not included in this analysis. The second is time. The study examines the literature of a specific period (2010-2023). This provides insights into the latest trends. And keywords the results obtained from this bibliometric analysis are based on the assumed relevance and accuracy of the data of the resulting keywords. Thus, the selected keywords reflect trends and patterns in the academic literature.

Figure 7. Word cloud of the keywords in the selected papers

The bibliometric analysis conducted here focused on the effects of building materials on indoor air quality and the most common and mentioned pollutants, and in particular, studies in the literature examined the prevalence of total volatile organic compounds (TVOCs) and formaldehyde (CH_2O). Textometric analysis of the last 34 sampled articles reveals keywords repeated at least five times [51-52]. The word 'IAQ' was the most frequently used keyword 19 times. The word 'VOC' was the most frequently used keyword 12 times. This figure is graphically organized according to their frequency (Figure 7) in a word cloud obtained from an online word cloud generator – the size of each word is related to the frequency of its appearance. This analysis prominence of terms like "pollutants," "IAQ," "health," and "building material" visually conveys the focal points of the literature on IAQ.

Analysis of scientific articles in the WoSCC, dating from 2010 to 2023, has led to some relevant discoveries outlined below:

Building Material Emissions: The literature reviewed consistently reported that various building materials are significant sources of indoor air pollutants. TVOC and formaldehyde emissions, particularly from materials such as paints, adhesives, and insulation materials, are of great concern due to their prevalence and impact on IAQ.

Health and Exposure Considerations: The relationship between exposure to indoor air pollutants from building materials and health outcomes is an issue addressed in all studies. Articles have highlighted the importance of IAQ management in residential environments, focusing on how pollutants such as formaldehyde and VOCs can affect health.

Emerging Trends: Incorporating new methodologies, such as in-home measurements and detection, to enable home testing of pollutants such as formaldehyde, CO_2, VOCs, etc., indicates a trend toward more accessible and user-friendly IAQ monitoring techniques.

Legal and Regulatory Insights: The articles reviewed call for improved regulatory standards and legislation to reduce the impact of indoor pollutants. Some studies include using green-certified materials and improved building practices for a healthier indoor environment.

These findings highlight the impact of building materials, construction practices, and IAQ, affecting health, environmental policy, and material use. According to this analysis, it has been observed that some pollutants and several factors directly affect IAQ. These can be grouped under 3 main headings according to the literature review.

Chemical pollutants

These substances are released into the air from various sources, including household and industrial chemicals. Some of the most common chemical pollutants that affect IAQ include cigarette smoke, VOCs found in interior paints and varnishes, chemicals used in cleaning products and furniture, and scented products such as incense and deodorizers [53]. VOC concentration in indoor environments can increase due to ventilation in areas with high traffic [54]. Studies have found that bedrooms have the highest levels of TVOCs compared to other areas, such as kitchens, living rooms, and workplaces, with emissions from furniture and carpeting being possible contributors [55].

Biological pollutants
These living organisms can be found in the air and can cause allergic reactions, infections, and other health concerns. For instance, ultrafine particles were significant risk factors for dermal symptoms [56]. The most common biological pollutants that affect IAQ are mold, fungi and bacteria, pet dander and soil, pollen, and other allergens.

Environmental factors
The quality of air indoors can be affected by environmental factors. Air pollution from external sources can significantly impact indoor air quality. Polluted outdoor air will create indoor air pollution. Therefore, the IAQ affects the indoor environment, location, climate, temperature, and light. High temperatures cause mold and bacteria to grow, while low light levels create a suitable environment for them to thrive and multiply. Also, low humidity can cause respiratory problems, while high humidity can encourage mold growth and other biological contaminants.
It is known that people, in general, spend 90% of their time indoors. This is why the IAQ is a major concern for many people. Building materials can adversely affect indoor air quality by releasing VOCs and Formaldehyde, which can cause respiratory irritation and trigger allergic reactions in some people. According to an article published by Artiola et al., all respiratory symptoms, such as coughing and throat irritation, are responsible for all VOC cases released by paint, carpet, furniture, insulation, and similar building materials [57]. VOC release can damage the respiratory system and affect immunity, leading to chronic diseases such as asthma or allergies later in life.

Improving IAQ is important in creating a safe and healthy living space. It is necessary to know how the building materials used in the construction of buildings affect health and the precautions and requirements to be taken in this regard.

2.2. IAQ requirements

Ensuring that the quality of IEQ is good for the occupants' overall mental and physical well-being is crucial. Achieving this involves considering factors such as IAQ, lighting, acoustics, and thermal comfort. National and international organizations have established building standards, regulations, and guidelines to promote good IAQ and thermal comfort. These standards ensure that occupants of indoor environments are healthy and comfortable.

Indoor air that is of low quality can have negative effects on both health and comfort. It can also have a detrimental impact on performance in a variety of settings, from offices to schools and healthcare facilities. Global guidelines and standards exist for indoor air pollutants. Various studies have been conducted on the IAQ, following the regulations and standards of different countries. Information regarding the distribution of global deaths caused by indoor and outdoor air pollution, and annual CO_2 emissions can be found in Table 4. The table also provides data on the relative percentage contribution of publications in Indoor Air Quality for various countries.

Most deaths per 100,000 people are due to indoor air pollution in India and China. India and China are the two countries that have the highest fatalities resulting from outdoor air pollution. Türkiye, South Korea, and Greece follow these countries. This information is based on statistics from 1990 to 2019. The United States contributed the most publications regarding IAQ, followed by China, the United Kingdom, Italy, South Korea, Canada, and India, according to a keyword search of the literature databases. The Scopus literature database identified 16.245 papers between 2010 and 2023 when the term "indoor air quality" was used in a search. Looking at the table , the highest contribution was made by the United States, 14.66%, and China, 13.14%, while the United Kingdom, South Korea, Italy, and Canada followed with 5.31%, 4.28%, respectively, 4.27%, and 3.19%.

Table 4. Compared mortality due to indoor/outdoor air pollution, annual tons of CO_2, and contributions to the overall number of IAQ publications for the respective countries [58]

Country	**Share of deaths from indoor/outdoor air pollution (per 100,000) in 1990**		**Share of deaths from indoor/outdoor air pollution (per 100,000) in 2019**		**Annual CO_2 emissions tonnes**		**Contributions to the total amount of publications IAQ**	**National/ International bodies involved in setting air quality guidelines and standards**		
Country	Indoor	Outdoor	Indoor	Outdoor	Start in 1860	End in 2021	%	2010-2023	%	Standards
Australia	0.76	12.42	0.03	4.06	509,296 t	391,187,420 t	669,637	409	2.52	NHMRC
Belgium	0.29	45.21	0.02	13.8	16,458,689 t	95,722,280 t	1,425	161	0.99	AIVC, SHC
Canada	0.28	18.52	0.01	5.35	458,000 t	545,634,500 t	15,587.75	519	3.19	Health
China	195.56	77.15	20.73	81.28		11,472,369,000t	9.84 b.t.	2135	13.14	AIVC,
Denmark	0.17	44.26	0.02	10.7	784,096 t	29,576,956 t	25,577	314	1.93	DICL
France	0.25	26.85	0.02	8.73	41,241,984 t	305,963,700 t	14,994	454	2.79	ANSES,

2.3. International standards for IAQ

There are different standards for IAQ across the world, with some countries having national regulations or international standards and others having their own guidelines. The WHO and the EPA guidelines are generally followed in the European Community. IAQ is a major concern for many governments and health organizations due to its impact on human health, and the European Union has encouraged its members to act against air pollution. National organizations and the WHO have set standards and guidelines to reduce the air pollutants people are exposed to. Table 5 summarizes the indoor air contaminant standards and guidelines set by different international organizations. CO_2 concentration is a crucial aspect of IAQ and is often used to indicate air exchange rates and whether fresh air is being provided sufficiently. Various organizations suggest different CO_2 concentration limit values, with ASHRAE and OSHA recommending no more than 700-1000 ppm above outdoor concentrations, the EPA suggesting 800 ppm, and WHO and CIBSE suggesting 1000 ppm.

Table 5. WHO and some national agencies stipulate the primary IAQ standards and guidelines

Organization	Reference
American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE Standard-55)	[59]
Chartered Institution of Building Services Engineers (CIBSE)	[60]
Occupational Safety and Health Administration (OSHA)	[61]
US Environmental Protection Agency (EPA)	[62]
World Health Organization (WHO)	[63]

2.4. Strategies to improve indoor air quality

Ensuring good IAQ is crucial for maintaining good health and well-being. As most individuals spend around 90% of their lives indoors, it is important to prioritize indoor air quality. Therefore, you should be aware of the dangers indoors. As can be seen in the literature review above, building materials have a great impact on IAQ's various pollutants and VOCs. Improving IAQ is important in creating a safe and healthy living space. Construction, rebuilding, remodeling, extensions, collapse, infrastructure maintenance, and other activities generate 10 billion tons of waste products annually [64]. As these materials enter our air, their use adversely affects IAQ.

Understanding the different building materials and how they affect IAQ is key to maintaining a healthy environment. IAQ can be adversely affected by the presence of various building materials. For example, wood is a common building material that releases PM over time. Building materials such as concrete, mortar, and stone emit particles over time. Certain building materials and chemicals can contribute to indoor air contamination, worsened by increased building airtightness. Petroleum distillates and VOCs are a particular concern as they continue to emit toxins after installation [65].

Strategies to improve indoor air quality include:
Using ventilation and air filtration systems: A well-ventilated home or office can help minimize air pollutants. Using proper ventilation, fresh outdoor air can be circulated throughout the building. Air filtration systems can also help remove dust, pollen, and other airborne contaminants. In addition, more advanced innovative products can be used. Using decentralized ventilation systems [66] instead of central ventilation systems is a good choice both in terms of energy saving and improving indoor air quality.

Banning the smoking of any tobacco product: Cigarette smoke contains various toxic chemicals that can harm smokers and non-smokers. Banning smoking in homes, workplaces, and public places can reduce the risk of respiratory and other health problems from second-hand smoke.

Using low-emission materials in product selection: When choosing products for our homes or workplaces, it is essential to consider the impact of chemical emissions. Furniture, wall paint, flooring, etc., materials may contain chemicals that may cause eye and respiratory tract irritation. Studies have shown that some of the tested furniture has a high emission rate. It has been determined that some furniture used indoors can cause high concentrations of formaldehyde. Therefore, by choosing materials with low emissions, we can reduce the risk of indoor air pollution [67].

Regular maintenance of building damage: Proper maintenance of buildings can help prevent mold and fungus growth. Structural damage can create leaks and dampness, providing a breeding ground for bacteria, mold, or other harmful substances. Repairing any damage to the structure can prevent the increase of indoor pollutants.
Using natural cleaning products: Many traditional cleaning products contain toxic chemicals that can cause skin and respiratory irritation and allergies. Natural cleaning products can be used as a good alternative for cleaning while affecting health less negatively [68].

Controlling the humidity level: High humidity levels can cause respiratory problems and allergic reactions. To prevent these problems, the growth of algae, mold and harmful mites can be prevented by preventing the increase in indoor humidity of houses and workplaces, especially in the bathroom and kitchen [34].

Providing natural light: While natural light positively affects people, especially psychologically, it is also important for health. Good lighting can reduce the risk of indoor air pollution and improve indoor conditions.

Using plants: Plants are natural air filters that add a decorative touch while removing toxins. We can improve IAQ and support a healthy environment by including plants in our living and working spaces [25].

3. Conclusion

IAQ has gained significant attention in the past few years due to various factors, such as the COVID-19 outbreak and increased awareness of the health hazards linked with inadequate IAQ. The need of the hour is to have efficient and effective solutions to improve IAQ to mitigate its associated health risks. That is why researchers and developers are working on several solutions. These include technologies such as ventilation systems, air cleaners, etc. In addition, various international organizations are developing guidelines and standards to meet the requirement.

The extensive bibliometric analysis in this study has examined indoor air pollutants and their health effects, as well as current standards and guidelines, and the studies in the literature and related keywords have been analyzed with VOSviewer with citation, bibliographic coupling, publication numbers (year), publication numbers (country) and keyword co-occurrence analysis. According to these network visualizations that have been made, documents, sources, authors, numbers and countries with the keyword of building materials, which are especially related to the main issues such as health, emissions, viruses, and bacteria. The studies generally focus on parameters such as Formaldehyde, PM, volatile compounds, CO_2, and CO. It has been emphasized that allergic reactions and respiratory problems are seen due to these pollutants.

This study also emphasizes the necessity of considering furnishings and construction materials as potential sources of indoor air pollution. Additionally, since the parameters differ in each situation, it is impossible to identify the sources of pollution that are liable for every building. Every study needs to be judged on its terms, considering its environment. IAQ must be prioritized as a fundamental building design and management component to guarantee everyone a secure and healthy indoor environment.

Considering the shortcomings illuminated by this comprehensive literature analysis study, future research efforts should focus on this topic:

Development of Low Emission Building Materials: Research of new building materials that significantly reduce or eliminate the emission of harmful pollutants and the necessity of green-certified interior materials.

Health Effect Studies: Conduct comprehensive studies to understand the health effects of continuous exposure to various IAQ pollutants, especially in different climatic situations.

Technology-Assisted IAQ Monitoring: Development of real-time IAQ monitoring technologies to provide immediate and accurate assessments.

Holistic IAQ Management Models: Creating models that integrate IAQ management with sustainable building practices, considering emerging phenomena such as climate change and urbanization.

Policy Development and Regulatory Frameworks: Development of comprehensive policies and regulatory frameworks that can govern the selection, use and disposal of construction materials about IAQ.

Harmonization of Global IAQ Standards: Considering the inequality in IAQ standards in different countries, achieving a global consensus by researching harmonizing international IAQ guidelines.

Article Information Form

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The author of the paper declares that it complies with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that do not make any falsification of the data collected. In addition, the author declares that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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