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A review of building technology solutions and their influence on indoor environmental quality in the healthy building movement

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ABSTRACT

The healthy building movement is increasingly recognized for placing occupant health at the forefront, distinguishing it from green and sustainable building concepts, which primarily focus on environmental impact. This review synthesizes existing research on building technology solutions that contribute to the healthy building movement by promoting indoor environmental quality (IEQ) and health in homes, offices, and schools. The objectives were to identify the status of research on building technology solutions in connection to their stated outcomes towards healthy buildings, and to identify key IEQ and health indicators and potential research gaps. Based on a systematic literature review, data from 27 studies, covering 60 building technology solutions applying 39 IEQ and health indicators, were analyzed. The building technology solutions were categorized into seven groups, including HVAC systems, biophilic design, daylighting and lighting, control and automation, façade systems, materials, and miscellaneous aspects. Key findings revealed that IAQ, along with thermal, visual, and acoustical comfort, were mostly objectively evaluated, with particulate matter and volatile organic compounds serving as primary indicators for IAQ. Health indicators were mainly subjectively assessed through surveys. HVAC systems, the most studied category, showed significant improvements in IAQ and thermal comfort. Biophilic design showed positive impacts on mental health. Though many building technology solutions currently are not yet linked to their health effect, the health assessment of those technologies that are part of the literature review generally shows a rather limited interpretation of the meaning of health. Few studies integrated multiple IEQ indicators or assessed long-term impacts, with the connection to health often being implicit, indirect, or absent altogether. There is a need for standardized assessment frameworks and more research for more diverse climates and cultural contexts.

1. Introduction

1.1. Overview of the healthy buildings movement

For millennia, humanity has sought safe and comfortable living environments, from early shelters in caves designed to protect

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against the elements, focusing on safety, to modern structures, where comfort has become the most important requirement. Today, people spend up to 90 % of their time indoors—in homes, workplaces, schools, and other indoor facilities [1]. Buildings influence our emotions, health, and productivity, often in ways we may not consciously recognize. Over the past two decades, global challenges such as climate change, resource depletion, and growing health concerns have led to the development of concepts like green, sustainable, and, more recently, healthy buildings [2–4].

The green building movement emerged in response to the energy crises of the 1970s, with an emphasis on reducing environmental impact through energy efficiency and renewable resources [5]. Various organizations and authorities have since developed green building certification systems [6], such as BREEAM (1990, UK) [7], LEED (1998, US) [8], CASBEE (2001, Japan) [9,10], Green Star (2003, Australia) [11], ESGB (2006, China) [12], AQUA (2007, Brazil) [13], DGNB (2009, Germany) [14] and others worldwide. These systems encourage environmentally sustainable practices in the design, construction, and operation of buildings. Governments incentivized practices like retrofitting buildings for better insulation and integrating energy-efficient measures into building codes. Meanwhile, the broader concept of sustainable development arose, emphasizing the need to balance economic growth with environmental stewardship, as well as social equity [15]. First articulated in the Brundtland Report [16], sustainable development became a global priority. And then it was reinforced by international efforts like the 1992 United Nations Conference on Environment and Development (UNCED) [17].

While green and sustainable buildings addressed environmental concerns, they did not fully consider the health and well-being of occupants. This gap prompted the rise of the healthy building movement, which places occupant health at the center of building design. However, the concept of "healthy buildings" is still evolving, with no universally accepted definition [18]. Initially seen as a response to Sick Building Syndrome (SBS) in the 1990s [19–21], the term has since expanded.

For instance, the WELL Building Standard, launched in 2014 [22], introduced a health-first evaluation system, defining a healthy building as "a space that actively promotes and enhances the health and well-being of its occupants through intentional design, operations, and policies. It integrates evidence-based strategies across ten areas, including air quality, water, nourishment, light, movement, thermal comfort, sound, materials, mental health, and community engagement, to create an environment where people can thrive physically, mentally, and socially." Similarly, the Buildings Performance Institute Europe, from 2015 onwards [23], emphasized that a healthy building safeguards mental and physical health, is designed for human needs, and enhances sustainability while enabling transformation through people empowerment and resilience. In 2017, the U.S. Centers for Disease Control (CDC) and U. S. General Services Administration developed Fitwel, which in its latest 2024 version (v3) includes eight scorecards and 140 evidence-based strategies for promoting health within buildings and communities [24]. The Living Building Challenge (LBC), in its latest version 4.1 released in 2024 [25], defines a regenerative approach to building design with seven performance areas or "Petals": place, water, energy, health + happiness, materials, equity, and beauty. It challenges buildings to generate net positive energy, manage water sustainably, and contribute to ecological and community health. Additionally, the Royal Institution of Chartered Surveyors (RICS), in its 2023 practical guide [26], highlights the critical role of integrating health considerations throughout a building's lifecycle—from design and construction to management and maintenance—emphasizing occupant well-being and sustainable value creation. In China, the Architectural Society defined healthy buildings in the standard T/ASC02-2021 (Assessment Standard for Healthy Building) [27], as "a building that, while meeting its functional requirements, provides a healthier environment, facilities, and services to promote the physical health, mental health, and social well-being of its users, thereby achieving enhanced health performance." Other scholars like Bluyssen [28,29], Lin et al. [30], Allen et al. [31], and Sternberg et al. [32,33], etc., have also explored and defined the healthy building, further detailed in the supplementary information.

It is well-acknowledged that "healthy buildings" represent the next generation of green and sustainable buildings [3,31,34]. They integrate environmentally responsible practices with occupant health and performance, addressing indoor environmental quality (IEQ) factors such as air quality, thermal comfort, lighting, and acoustics, and expanding them with topics such as ergonomics, personal controls, and social engagement. This integration aligns with the World Health Organization's holistic definition of health, which includes physical, mental, and social well-being [35].

Public health concerns, energy efficiency goals, and economic imperatives are driving the Healthy Building Movement. Poor IEQ has been linked to rising health conditions [36], and improving IEQ is shown to enhance productivity and cognitive performance [37], which is especially important in workspaces where human capital comprises 90 % of operating costs [38]. Particularly, the COVID-19 pandemic has accelerated the focus on health-first building designs, highlighting the need for better ventilation, filtration, hygiene, and other indoor conditions [31]. In response, regulations and societal expectations have increasingly favored healthier indoor environments, reinforcing the significance of the healthy building movement [23,39,40].

Several European-funded initiatives have been searching to advance healthy indoor environments but also reveal persistent challenges and barriers. For instance, HOPE [41] developed a health optimization protocol for energy-efficient buildings yet found that reducing ventilation can compromise IEQ if not carefully managed. PERFECTION [42] emphasized the fragmentation of regulations across regions and limited stakeholder awareness, hindering user-centric solutions. OFFICAIR [43] highlighted the complex mix of pollutants in modern offices, complicating IAQ assessments. SINPHONIE [44] exposed how older school infrastructures and budgetary restrictions undermine necessary upgrades for healthier learning spaces. SONATA [45] underscored the difficulties of coordinating adaptive technologies and addressing occupant needs in open-plan offices. Meanwhile, the ongoing HBM project [40] noted that weak policy support and financial constraints often delay the integration of technical, medical, and economic perspectives. Collectively, these experiences demonstrate that entrenched economic, regulatory, technological, and behavioral hurdles continue to stall progress, underscoring the need for further research and coordinated policy efforts.

1.2. The role of building technologies in advancing IEQ and health

Building technology solutions play a critical role in creating healthy indoor environments. Innovative building technologies such as advanced ventilation systems, air filtration technologies, biophilic design elements, and smart automation systems, have the potential to enhance IEQ conditions. They may overcome some limitations of traditional construction methods, subsequently improving occupants' health and well-being [46–50].

For example, Fermo et al. (2021) evaluated an air purifier with a water-bath filtration system. Their study demonstrated that the purifier significantly reduced particulate matter (PM) and volatile organic compounds (VOCs) concentrations. This showcased the effectiveness of air filtration technologies in improving indoor air quality (IAQ) outcomes [51]. Li et al. (2023) explored the impact of biophilic design by studying the effects of implanted wood components on the restorative quality of indoor informal learning spaces in colleges. Their research found that spaces with higher wood rates, particularly between 60 and 80 %, significantly improved students' restorative perceptions. Zhang et al. (2020) developed a lighting system with programmable LED luminaires that can vary both illuminance and correlated color temperature (CCT) throughout the day. Their results showed that the dynamic LED lighting system increased afternoon alertness and marginally improved mood [52]. These studies highlight how building technologies can directly affect key IEQ parameters and, by extension, occupant health and well-being.

1.3. Need for a comprehensive review of technology solutions

Despite the growing recognition of the importance of building technologies for health, existing research on building technologies that claim to promote healthy buildings is often fragmented. The existing literature has not yet comprehensively synthesized these solutions within the context of the healthy building movement. Reviews have largely focused on green [5,48,53–57], low-carbon [58,59], and sustainable buildings [4,60–62], but, to the best of our knowledge, there is a limited body of literature review specifically focused on the comprehensive integration of building technologies for healthy buildings.

Some existing reviews touch on aspects related to healthy buildings. For example, Spengler and Chen (2000) provided a detailed review of indoor air quality factors in designing healthy buildings, emphasizing the importance of advanced ventilation design tools and the integration of computational fluid dynamics (CFD) into air quality and risk assessment models [18]. Liu et al. (2023) offered a comprehensive review of healthy building research, constructing a DNA framework that categorizes the characteristics, triggers, guides, and actions necessary for understanding and developing healthy buildings. Their review highlights the need for standardized platforms for healthy building stakeholders and promotes the high-quality development of healthy buildings. However, their focus was more on establishing a framework rather than the technological integration and assessment [30]. Lin et al. (2022) reviewed the research and development of healthy buildings in China, focusing on the key elements of evaluation standards, energy conservation measures, new technology applications, and lessons from the SARS-CoV-2 outbreak. Their work provides valuable insights into the unique challenges and milestones in China's healthy building development but centers primarily on regional aspects and policy recommendations rather than a global perspective on technological integration [3]. Brunsgaard and Fich (2016) emphasized the importance of user interaction with the indoor environment in achieving healthy buildings. They reviewed projects like "The Comfort Houses" and "Home for Life", highlighting the need for user-friendly solutions that align with occupant behavior to ensure the effective operation of building systems. Their study demonstrates that understanding user behavior is crucial for the success of healthy building technologies [63].

These studies, though valuable and related, have their specific objectives and scopes that do not fully address the comprehensive technological integration required for healthy buildings on a broader scale. To address this, it is essential to conduct a systematic review of the current scientific research on building technology solutions aiming to arrive at healthy buildings, particularly in homes, offices, and schools. These three building scenarios are chosen because they represent the primary environments where people spend the majority of their time.

1.4. Research question, objectives, and significance

To address the identified need above, this review aims to answer the following research question: What building technology solutions that promote IEQ and health have been proposed in studies that claim to contribute to the development of the "healthy buildings" concept?

The primary objective of this review is to assess and synthesize existing research published in the scientific literature that assumes health claims related to building technology solutions for healthy buildings, and how they affect IEQ and health in homes, offices, and schools. This involves several key objectives: (1) To identify IEQ indicators used in health claims related to building technology solutions, and how these are assessed in the literature; (2) To analyze the actual outcomes reported, focusing on how building technology solutions impact these IEQ indicators and health; (3) From this analysis, to understand the current research gaps and offer future research directions.

In terms of research significance, this review synthesizes existing research across disciplines such as architecture, environmental science, and public health, providing a comprehensive overview of how building technologies contribute to IEQ and health. By bringing together findings from diverse fields, it aims to bridge gaps in knowledge and offer a holistic perspective on the role of technology in healthy buildings. The findings will be valuable to architects, engineers, facility managers, and policymakers by providing evidence-based recommendations for integrating technologies into health-centered building design and operations.

2. Methods

This systematic scoping review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) extension [64]. The PRISMA checklist was used to improve the transparency of the review process. This section introduces the eligibility assessment for selecting the sample of studies from the initial database of papers.

2.1. Literature search strategy

Related publications were collected from two multidisciplinary scientific databases: Scopus and Web of Science (WoS). Only papers written in English and classified as articles or review articles were included. The initial search was conducted on Feb 6th, 2024 in the title, abstract, or keywords. There were no restrictions based on the year of publication, as the concept of "Healthy Building" has been emerging only since the 1980s.

The search strategy consisted of two categories, connected by the Boolean operator "AND": "Healthy Building" concepts and indoor environmental quality (IEQ) indicators, as illustrated in Fig. 1. The primary reason for appending the word "healthy" to each building type (e.g., "healthy offices," "healthy schools") in our queries was to ensure that occupant health and well-being were explicitly stated as a primary concern in the identified studies. This approach helps filter out articles centered on other building performance or sustainability topics where health is not a direct outcome, aligning our review precisely with the "healthy building" concept.

In this study, we did not use "building technology" or a direct synonym (e.g., "technological solutions") as a mandatory search term. We acknowledge that building technology interventions can appear under various terminologies (e.g., engineering interventions, passive solutions, HVAC modifications, material innovations, etc.). Restricting the search to the phrase "building technology" might have inadvertently excluded studies that address such interventions under broader or alternative terms. Instead, our search captured the essence of health-focused interventions by combining the concept of "Healthy Building" with the major domains of IEQ, as illustrated in Fig. 1. In the subsequent selection stage (Section 2.2), we specifically confirmed the presence of a proposed or tested building technology solution for each retrieved study using our inclusion criteria. This two-step approach balances thoroughness (via broad search terms) and specificity (via our inclusion requirement for building technologies).

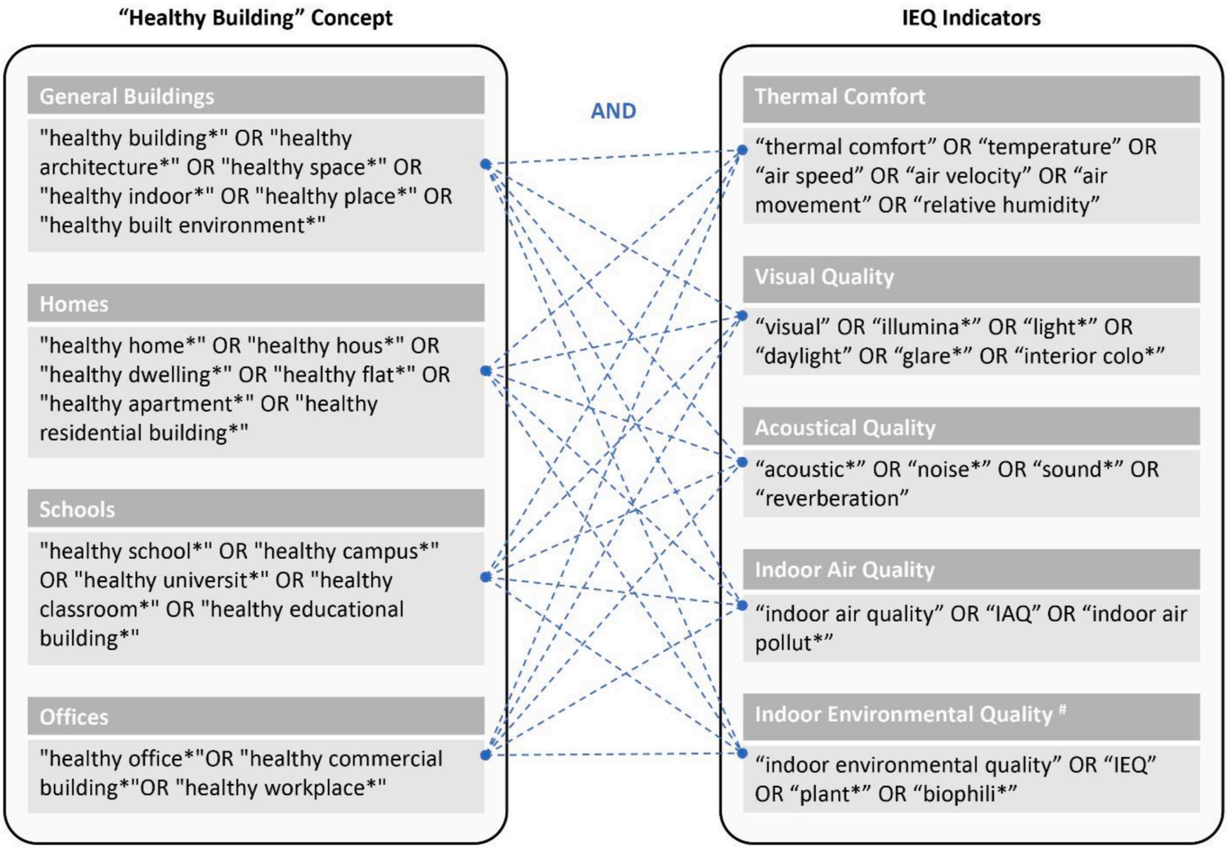

Fig. 1. Search strategy (# Note: the search terms "plant*" and "biophili*" were included in the "indoor environmental quality" category considering their potential contributions to other aspects such as visual quality and indoor air quality; the asterisk * means searching word roots and alternate spellings).

While the initial search focused on identifying articles related to IEQ and health, the specific selection process, described in Section 2.2, ensured that articles involving "building technology" were included by applying both inclusion and exclusion criteria.

This review focused on three major building types: homes, offices, and schools. The search queries for the "Healthy Building" concept combined the term "healthy" with four sub-categories of locations: general buildings, homes, schools, and offices. For general buildings, the terms used were "building*", "architecture*", "space*", "indoor*", and "built environment*". For homes, the search terms included "home*", "hous*", "dwelling*", "flat*", "apartment*", and "residential building*". For schools, the terms were "school*", "campus*", "university*", "classroom*", and "educational building*". Finally, for offices, the search included "office*", "commercial building*", and "workplace*". This approach ensured a thorough search of health-building-related research.

For the category of IEQ indicators, five sub-categories were included: thermal comfort, visual quality, acoustical quality, indoor air quality, and indoor environmental quality. The search terms for thermal comfort included "thermal comfort", "temperature", "air speed", "air velocity", "air movement", and "relative humidity". For visual quality, the search terms were "visual", "illumina*", "light*", "daylight", "glare*", and "interior colo*". In the acoustical quality category, the terms used were "acoustic", "noise*", "sound*", and "reverberation". For indoor air quality, the search terms included "indoor air quality", "IAQ", and "indoor air pollut*". Finally, for indoor environmental quality, the search terms were "indoor environmental quality", "IEQ", "plant*", and "biophili*".

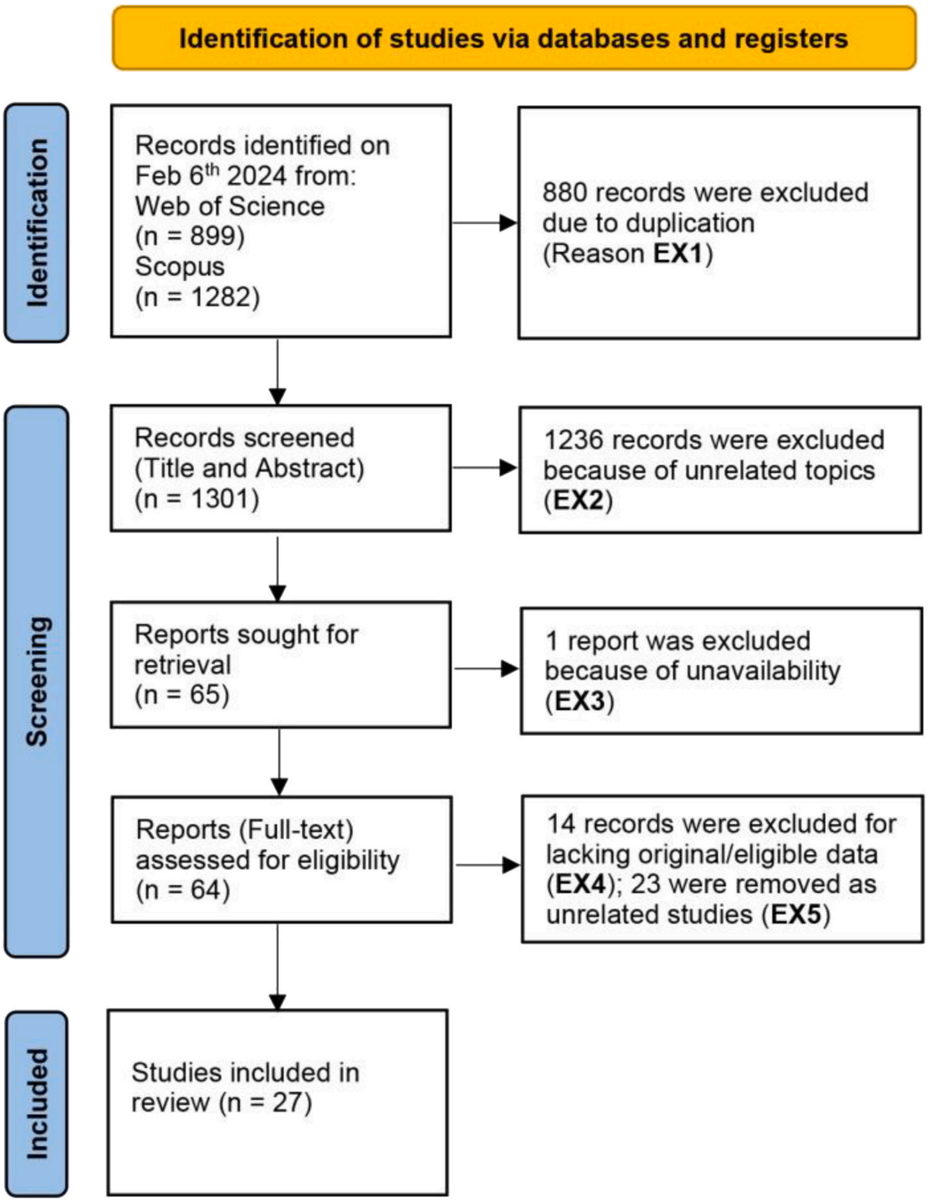

Fig. 2. Study selection process.

These search terms were confirmed with panel experts from the Healthy Building Movement (HBM) project [40], as well as referenced against other literature [65,66]. Additionally, two points need to be clarified. Firstly, in the category of “indoor air quality”, specific parameters such as CO_2, particulate matter (PM), volatile organic compounds (VOCs), etc., were not included. This is because the range of indoor pollutants is vast, and it was not feasible to list every individual pollutant. Instead, broader terms like "indoor air pollut*" were used to capture the general concept of indoor air contaminants. Secondly, the search terms “plant*” and “biophili*” were included in the “indoor environmental quality” category considering their potential contributions to other aspects such as visual quality and indoor air quality. In addition, the assumption was made that, for example, personal control options for the IEQ were captured by the “indoor environmental quality”/“IEQ” statements and/or the thermal comfort, indoor air quality, visual quality, and acoustical quality statements. The specific search terms in each sub-category can be found in Fig. 1.

2.2. Study selection

Following the initial search described in Section 2.1, 899 results were identified in the WoS database and 1282 results in the Scopus database. To refine the selection of papers, both inclusion and exclusion (EX) criteria were established. The selection process is illustrated in Fig. 2.

Firstly, duplicate records across the databases were removed before the title-abstract screening. This process (**EX1**) eliminated 880 papers, resulting in a total of 1301 records.

Secondly, the titles and abstracts of the remaining 1301 articles were reviewed, applying the following inclusion criteria:

(1) The study must have proposed one or more building technologies or specific solutions, whether active or passive. Notably, this condition was verified qualitatively by reviewing each article identifying whether a distinct intervention—such as a ventilation strategy, filtration system, façade design, lighting approach, or material innovation—was introduced, assessed, or validated. We did not require the phrase “building technology” to appear verbatim; rather, we looked for tangible design or operational measures aligned with advancing healthy buildings.
(2) These solutions may be applicable in the design, construction, operation, or maintenance stages.
(3) The study must have validated or verified the proposed solutions using one of the IEQ performance indicators (objective or subjective), which are covered in Fig. 1.
(4) The study may use field/laboratory experiments or simulations to test the proposed solutions.

The exclusion criteria (**EX2**) based on titles and abstracts were:

(1) Papers are not aligned with the topics specified in the inclusion criteria.
(2) Studies focused on the urban scale, community scale, regional planning, or broader environmental issues such as climate change, air pollution, or public health interventions, rather than the indoor built environment.
(3) Studies focused solely on health-related topics such as body development, nutrition, mental health, or medical conditions (e.g., symptoms, diseases, or chronic illnesses), without a direct connection to the indoor built environment. This includes studies that mention the indoor environment but focus on unrelated aspects such as steel structures, construction materials, architectural design aesthetics, management, behavior (such as ‘sleep behavior,’ ‘dietary behavior,’ or ‘physical activity’—without verifying or measuring any building technological intervention), or building codes, without engaging with both core concepts, namely, indoor environmental quality (IEQ) and the healthy building concept.

Applying these criteria, 1236 records were excluded, leaving 65 articles for further review.

Thirdly, the full texts of the remaining 65 articles were downloaded and reviewed, applying additional exclusion criteria:

(1) The study cannot be retrieved (**EX3**).
(2) The study is a review article lacking relevant data, or the articles referenced do not specifically address the "healthy building concept" as outlined in the search strategy (**EX4**).
(3) The study is not primarily focused on specific building technologies, instead emphasizing areas such as characterization or diagnosis of current indoor environments, energy consumption, occupants’ behavioral adjustments, building assessment systems, theoretical models, conceptual frameworks, expert opinions, policy discussions, or general sustainability practices. Additionally, studies proposing building technologies without validation through IEQ indicators, or those lacking empirical evidence, were excluded (**EX5**).

Ultimately, 27 articles met all eligibility requirements and were included in this review.

2.3. Data synthesis and analysis strategy

A data collection sheet was developed to extract information from the 27 papers. Information was extracted from each included paper on (1) building technologies (i.e., general classification of the technology, specific solutions, and their definitions); (2) IEQ performance indicators that were objectively or subjectively measured in the study (categorized as thermal, visual, acoustical, and IAQ aspects); (3) other indicators (i.e., specific health outcomes or physiological or psychological indicators, energy and others); (4) study methodologies, including the type of study (field experiment, laboratory experiment, or simulation), duration, sample size (number of human subjects and buildings involved in both reference and experimental groups, if applicable), geographic location of the studies, comparisons made within the studies, and statistical analysis; and (5) key findings.

A second data collection sheet was specifically designed to compile detailed quantitative data related to specific IEQ and health-

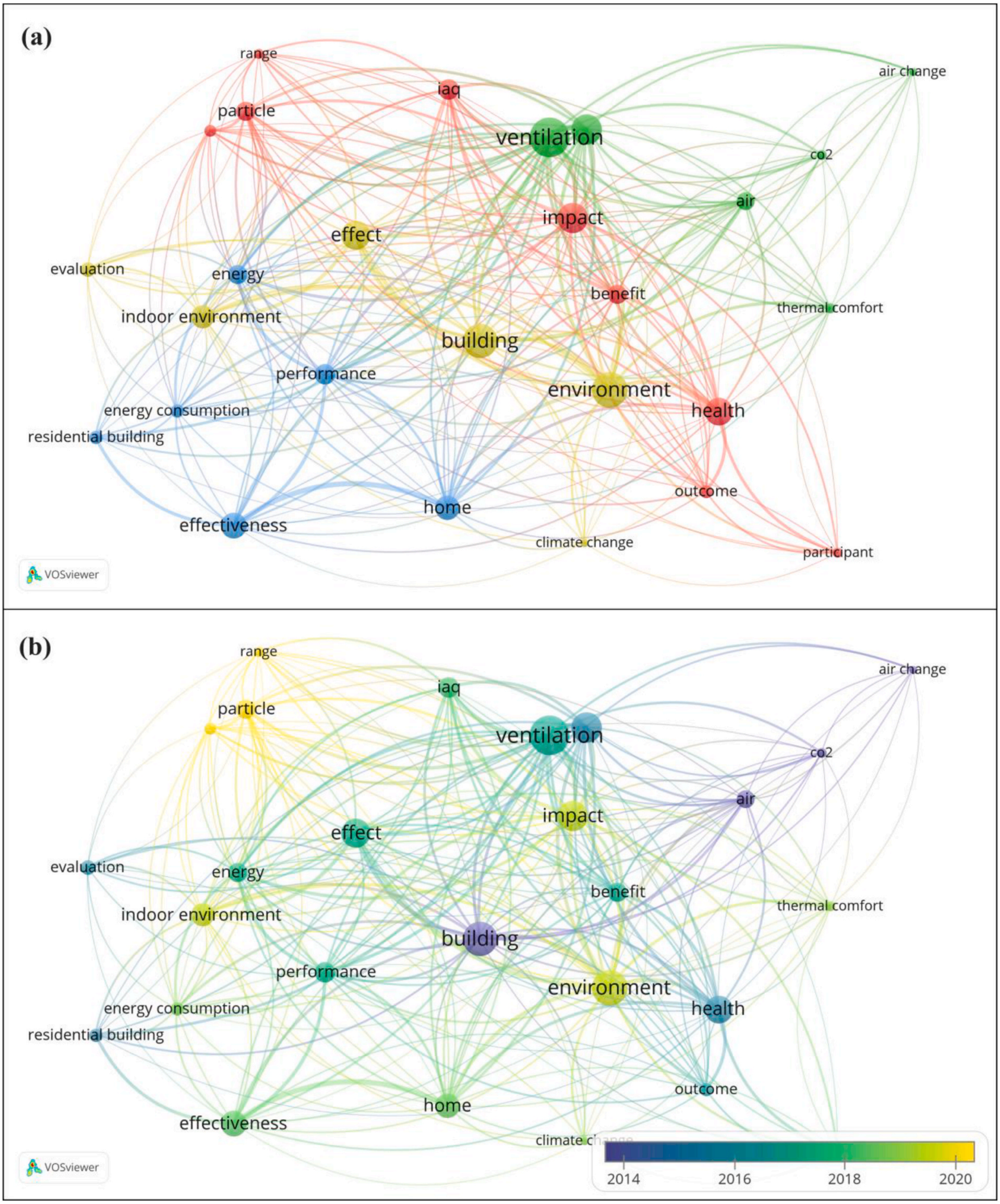

Fig. 3. Clusters of the reviewed articles based on the co-occurrence of the keywords, colored according to (a) topical clustering and (b) year of publication.

related outcomes observed before and after interventions. This sheet included four parts: (1) the building technology solutions that were implemented (referred to as interventions), along with any comparison or baseline solutions used before the interventions (pre-intervention conditions); (2) the measurement or simulation methods and the duration used to obtain IEQ and health-related outcomes; (3) any reported percent or absolute changes in these outcomes; and (4) the statistical significance of the observed changes, including the direction of change (i.e., whether the intervention resulted in an improvement, worsening, or no significant change).

In cases where percent or absolute changes were not explicitly provided in the reviewed studies, these values were calculated using the pre- and post-intervention data. Percent changes were calculated relative to pre-intervention conditions (i.e., %-change intervention I = $(I_{post}-I_{pre})/I_{pre}$x100 %). For example, if the concentration of $PM_{2.5}$ was measured at 50 μg/m^3 before the intervention and dropped to 15 μg/m^3 after the intervention, and no reference or comparison group was available, the percent change was calculated as −70 %. In this scenario, the direction of change would be categorized as "better" to reflect an improvement. It is important to note that negative percent changes (e.g., reductions in pollutant concentrations) cannot be lower than −100 %, as this would represent the complete elimination of the pollutant or negative outcome. Conversely, for cases where IEQ parameters or positive health outcomes improved after an intervention, the percent change could exceed 100 %. This occurs when the post-intervention value is more than double the pre-intervention value. For instance, if light illuminance increased from 100 lux to 300 lux, the percent change would be 200 %. However, the authors also acknowledge that a large percent change (e.g., over 100 %) might occur in cases where the initial values (I_{pre}) are very low, such as low contaminant concentrations or a small prevalence of a health condition. While the percent change may appear large, it may not necessarily have significant medical or practical implications due to the minimal baseline level. Also, large percent changes can more often occur with certain indicators such as viable fungi and bacterial spore counts, allergen levels, particle removal rates, and SF_6 concentrations. One typical example is the air exchange rate, which is frequently used as an indicator in several studies. When the air exchange rate increases from less than one to more than two, this often results in a percent change exceeding 100 %. However, our method accounts for this by accurately recording (available in the supporting information) and carefully interpreting these values within the context of the baseline and post-intervention levels. This approach allows for flexibility in analyzing complex datasets while ensuring that all relevant outcomes are presented transparently for further reader review.

Additionally, it is important to note that for certain parameters, such as temperature, absolute differences were used rather than percent changes. This decision was made because temperature changes are more meaningfully interpreted in terms of degrees rather than percentages.

Subjective outcomes were also analyzed, such as health condition reports based on a five-point frequency scale (ranging from 5: all of the time, to 1: none of the time), percentages of affirmative answers to specific health complaints, or the percentage of subjects experiencing health issues. While subjective indicators may sometimes show smaller absolute changes, the relative percent changes can vary widely, especially when baseline values are low.

In summary, due to the high diversity in building technologies, outcome indicators, study methods, building types, and subjects, formal statistical meta-analyses were not deemed suitable. Instead, the interpretation of outcomes was more based on qualitative trends observed across studies. The data synthesis and analysis strategy employed in this review is designed to integrate a wide range of outcomes from diverse studies, offering an overview of how various building technology interventions influence IEQ conditions and health-related outcomes. The use of standard measures, namely, percent changes relative to pre-intervention conditions, ensures comparability across studies, while the inclusion of absolute changes for parameters like temperature addresses situations where percent changes may not be appropriate.

3. Results

3.1. Overview of included studies

The 27 selected studies were classified into four clusters using the VOSviewer based on the co-occurrence of keywords. To minimize subjective interpretation, a systematic analyzing approach proposed by Bukar et al. [67] was adopted. Since the size of the nodes indicates their frequency, only the three largest nodes in each cluster were considered for cluster explanations. The results are presented in Fig. 3a. Cluster 1 (green) is about air quality and thermal comfort; cluster 2 (yellow) is about the healthy indoor environment; cluster 3 (red) is about the effects of the solutions on participants; and cluster 4 (blue) is about the impacts on energy consumption in residential buildings. Fig. 3b illustrates the average publication years of these studies in which the terms appeared. Notably, it is acknowledged that publication dates may not reflect when studies were conducted and that shifts in keyword usage or evolving terminology (e.g., IAQ to IEQ) may influence the observed trends.

Tables S2 and Table S3 in the supplementary information provide the extracted data used to characterize the studies and their findings. Specifically, Table S2 focuses on the general study descriptions, while Table S3 compiles detailed quantitative data related to specific IEQ and health-related outcomes observed before and after interventions.

The 27 selected studies were performed in 11 countries and regions (see Fig. S1); mainly in the USA (37 %), Europe with three countries (11 %), and China mainland (11 %). Although the concept of healthy building has been emerging since 1980, and the first relevant article was from 2000 [68], the number of related publications has increased over the past few years (see Fig. S2). The proposed building technology solutions in the selected studies were grouped into seven categories. HVAC systems dominate the research focus (see Fig. S3), comprising more than half of the studies (14 studies) [51,68–80]. The miscellaneous category, which includes studies proposing various innovative building technologies, accounts for 15 % (4 studies) [81–84]. The biophilia category accounts for 11 % of the studies (3 studies) [85–87], followed by both daylighting & lighting [52,88] and control & automation [89,90] each with 7 % (2 studies). Façade systems [91] and materials [92] were each explored in only one study.

As shown in Table S2, the reviewed studies utilized three primary methods of research: field experiments (fExp), simulations (Sim), and laboratory experiments (lExp), with the distribution of these methods across various building technology solution categories illustrated in Fig. S4 in the supporting information. Each type of study utilized various strategies, as detailed in Figure S5 and Fig. 5. Field experiments (fExp) encompass three different strategies, primarily relying on straightforward measurement techniques (Meas), representing 12 out of the 17 studies. Additional strategies include surveys (Surv) in two studies [85,86], which utilize questionnaires (Ques), interviews (Inter), or both, as well as a combination of measurement and survey methods (Meas + Surv) in three studies [52,69,83]. In simulation-based studies, four strategies were employed: one study used whole building simulation models (wbSim), combined with airflow network models (AirNetM) for energy and air quality modeling [72], two studies utilized whole building simulation modeling for energy performance analysis [73,82], one study applied computational fluid dynamics (CFD) for airflow simulations [79], and another used airflow network modeling alone for ventilation modeling [84]. Additionally, a hybrid approach combined field measurements with whole-building simulation models (Meas + wbSim) to predict temperature and energy consumption [91]. Laboratory experiments (lExp) focused on controlled measurements, with measurement-based approaches (Meas) used in three studies [71,75,89], and a combination of measurements and surveys in one study [87].

The reviewed studies encompass the three targeted building types (see Fig. S6). 13 studies focused on home scenarios, eight studies on office environments, two studies examined school settings, and four were categorized as general. The “general” category includes studies addressing technologies not limited to a specific building function. The investigation of HVAC systems spanned all building types, with a notable emphasis on home (half of 14 studies) and office scenarios (five out of 14 studies). The miscellaneous category was exclusively focused on home settings. Two studies in school settings addressed HVAC systems [77] and biophilia [85], respectively.

About the number of buildings investigated across various building types, 19 out of 27 studies tested the proposed solutions in a single building only, while six studies involved fewer than 10 buildings. Detailed distribution of buildings is provided in Fig. S7. In terms of human subject involvement, the majority of studies (21 out of 27) did not include subjects in the evaluation of the proposed solutions, as depicted in Fig. S8. Specifically, 93 % (13 out of 14) of HVAC system studies did not involve human subjects. In contrast, all three studies [85–87] in the biophilia category included human participants. The control & automation, façade systems, and materials categories generally did not involve subjects. The duration for evaluating the proposed solutions varies widely. One-third of the 27 studies were short-term (a few minutes to one week) in categories like HVAC systems (five studies), biophilia (three), and control & automation (one). Another third, involving HVAC systems (five studies), miscellaneous (three), and materials (one), lasted from one month to one year. More details are in Fig. S9.

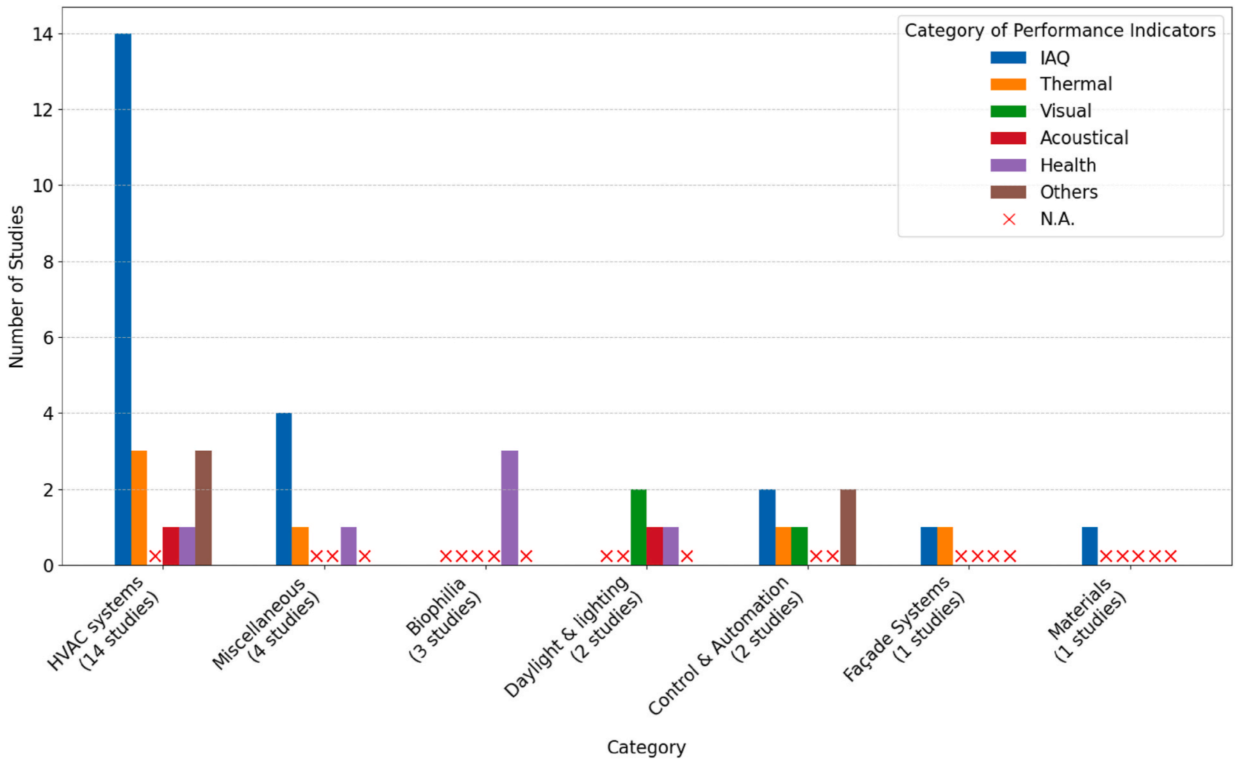

Fig. 4. Distribution of studies across building technology solution categories by performance indicators. Notes: a study might use more than one category of indicator, while some categories of indicators might not be used in specific categories.

3.2. Reported changes in IEQ and health-related outcomes

The type of performance indicators used in the selected studies include IAQ, thermal comfort, visual comfort, acoustical comfort, health, energy, and others. Fig. 4 summarizes the distribution of studies across various building technology solution categories, with a focus on different types of performance indicators measured in each study. The x-axis lists the building technology solution categories, and the total number of studies per category is indicated in parentheses beneath the category name. The y-axis shows the number of studies. Each color in the bars corresponds to a different type of indicator as presented in the legend. It should be noted that a study might use more than one type of indicator, while some types of indicators might not be used in specific categories. This figure illustrates the wide variation in the types of performance indicators evaluated across categories.

Fig. 5 provides an integrated summary of proposed building technology solutions and their impact on IEQ and health performance indicators. This figure categorizes the 27 studies (in the second column) into seven different building technologies in the first column, and the specific solutions are detailed in the ninth column, while the third to eighth columns detail the used methods (including study location, building type, study duration, number of the involved buildings, number of the involved subjects, and type of study). The collected 39 performance indicators are categorized into six key aspects: IAQ (with 25 indicators), thermal comfort (five indicators), visual comfort (two indicators), acoustical comfort (two indicators), health (categorized into general, physical, and mental), energy and other aspects. Each row corresponds to a specific technology solution from a study (in total of 60 solutions) and details its impact on the performance indicators, which were quantified by relative changes (explained in Section 2.3, with reported quantitative data compiled in Table S3). These relative changes compared the proposed building technology solutions with corresponding baseline solutions, which are also provided in Table S3. The matrix uses color-coded cells to visually display the degree of improvement or worsening observed in each study:

- Bright lime green denotes a general improvement, while amber indicates a general worsening, typically when specific quantitative data could not be retrieved from the article.
- Dark green shows an improvement of more than 100 %, while dark brown indicates a worsening of more than 100 %.
- Medium green represents a 50%–100 % improvement, whereas orange reflects a 50%–100 % decline.
- Light green indicates a 0%–50 % improvement, while peach signals a 0%–50 % worsening.
- White cells indicate that no measurement was conducted for that specific indicator.
- Cells with an asterisk denote reported changes that are statistically significant, and reported p-values are compiled in Table S3.

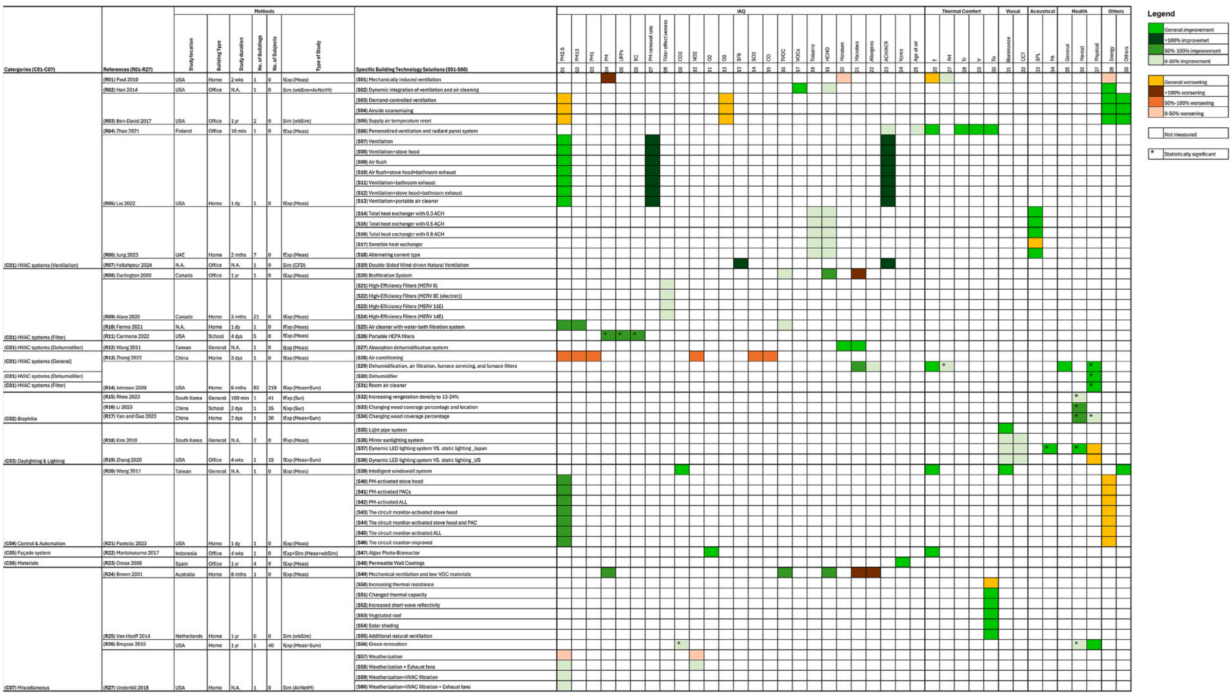

Fig. 5. Overview of various building technology solutions proposed in the reviewed studies with their impact on IEQ and health performance indicators.

Notes for Fig. 5: Within the fourth column about "Type of Study": fExp = field experiments, lExp = lab experiments, Sim = Simulations, CFD = computational fluid dynamics, wbSim = whole building simulation models, which use a tool like EnergyPlus to evaluate a building's performance, AirNetM = airflow network modeling (simulates air movement in buildings to optimize ventilation and IAQ, using tools like CONTAM), Meas = objectively measurement-based approaches, Surv = survey, which utilize subjective questionnaires (Ques), interviews (Inter), or both.

When reviewing the figure, readers should note that the reported changes vary widely due to the diverse range of indicators used across studies. This makes direct comparisons between the effectiveness of solutions challenging even though quantitative changes are presented. This fact was considered as we sought to identify trends.

The results in the following sub-sections are organized according to the main categories shown in the first column of Fig. 5 (**C01** to **C07**). Within each category, the proposed solutions (**S01** to **S60**) are introduced, and their corresponding references (**R01** to **R27**) are identified. For instance, a code such as **C01-R04-S06** indicates that the solution is part of the first category (**C01**), derived from reference number four (**R04**), and labeled as solution six (**S06**). This coding scheme appears in both the main text (result sections) and Fig. 5, allowing readers to easily trace any given solution to its category and source. Each sub-section first describes the relevant solutions, followed by an explanation of the performance indicators, and concludes with an assessment of how each solution impacts these indicators. This integrated approach ensures that the discussion in the text corresponds directly with the visual representation in Fig. 5, enabling a clearer and more systematic understanding of the findings.

About indoor air quality (IAQ): PM = particulate matter, which refers to a mixture of solid particles and liquid droplets measured in the air. In one study [81], PM measurements focused specifically on respirable particles with a size cut-point of 4.0 μm, rather than the commonly used sizes such as 10, 2.5, or 1 μm. Additionally, one study [77] measured the number of particles rather than their mass. PM_{10}, $PM_{2.5}$, PM_1 = particulate matter with a diameter of 10, 2.5, 1 μm or less, respectively. UFPs = ultrafine particles with a diameter of less than 0.1 μm. BC = black carbon, a type of particulate matter that consists of pure carbon in several linked forms. PM removal rate was used as an indicator in one study [76], which is calculated based on the decline in $PM_{2.5}$ concentrations over time. Filter effectiveness was used as an indicator in one study [74], which involved measuring the overall particle loss rates in homes with and without a filter installed, or with a filter while the HVAC system is on vs. when it is off. CO_2 = carbon dioxide, NO_2 = nitrogen dioxide, O_2 = oxygen, O_3 = ozone, SF_6 = sulfur hexafluoride, SO_2 = sulfur dioxide, CO = carbon monoxide, TVOC = total volatile organic compounds, VOCs = volatile organic compounds, as one study [72] analyzed 16 various species of VOCs. HCHO = formaldehyde, Microbes = airborne spore counts (bacteria, yeast, mold), Vpres = indoor and outdoor partial vapor pressures, ACH/AER = air exchange rate (/h).

In terms of "thermal comfort": T = air temperature (due to the nature of this indicator, relative changes were not quantified. Instead, general improvements or worsening are shown in the figure, based on the objectives and outcomes presented in the original studies. Notably, one study [69] reported a slight increase in temperature after intervention without specifying if it was beneficial. Here, this outcome is presented as a 'general improvement' in the figure.), RH = relative humidity, Tr = mean radiant temperature, V = wind speed, To = operative temperature.

Regarding "visual comfort": E = illuminance (lux), CCT = correlated color temperature.

Concerning "acoustical comfort": SPL = sound pressure level (dB(A)), PA = perceived acoustical comfort, or satisfaction with background noise and acoustic privacy.

"Others" refer to economic aspects (i.e., work performance) in one study [73], and rain and wind detection in another study [89].

3.2.1. HVAC systems (C01)

As illustrated in Fig. 5, half of the 14 reviewed HVAC studies researched ventilation systems [70,72,73,75,76,78,79], four on filters [51,68,74,77], two on general HVAC improvements [69,80], and one on dehumidifiers [71].

Among the ventilation-related studies, the majority (six studies) focused on mechanical ventilation systems, which can be grouped into three categories. The first group involves general mechanical ventilation strategies: Paul et al. (2010) [70] investigated mechanically induced ventilation (**C01-R01-S01**), and Zhao et al. (2021) [75] examined personalized ventilation combined with radiant panel systems (**C01-R04-S06**). The second group focuses on ventilation combined with pollutant removal: Han et al. (2014) [72] proposed an approach integrating dynamic integration with air cleaning (**C01-R02-S02**), while Liu et al. (2022) [76] evaluated combinations of ventilation with stove hoods, bathroom exhausts, portable air cleaners, and air flushing techniques (**C01-R05-S07/S13**). These strategies aimed to address indoor pollution sources by integrating general ventilation with targeted pollutant removal methods while providing sufficient airflow. The third group pertains to heat recovery and energy-efficient ventilation systems: Ben-David et al. (2017) [73] assessed demand-controlled ventilation, airside economizing, and supply air temperature reset, which dynamically adjust operating conditions based on different scenarios for performance optimization and energy-saving (**C01-R03-S02/S05**); Jung et al. (2023) [78] investigated systems like total heat exchangers (which recover both sensible and latent heat) operating at different air change rates per hour (0.3, 0.5, and 0.8 ACH), sensible heat exchangers (recovering only sensible heat), and alternating current types (**C01-R06-S14/S18**). These studies explored how heat recovery mechanisms in ventilation systems can influence overall HVAC performance. Additionally, natural ventilation was examined in one study by Fallahpour et al. (2024) [79], who studied double-sided wind-driven natural ventilation utilizing wind pressure differences to facilitate airflow without mechanical assistance (**C01-R07-S19**). However, none of the reviewed studies directly compared natural and mechanical ventilation, highlighting a gap in the literature that could provide valuable insights into their relative effectiveness.

Among the filtration studies, various filter types were examined: Darlington et al. (2000) [68] explored biofiltration using plants and microorganisms within HVAC systems (**C01-R08-S20**); Alavy et al. (2020) [74] assessed high-efficiency filters with various Minimum Efficiency Reporting Values (MERV) ratings (MERV 8 to MERV 14E) (**C01-R09-S21/S24**); Fermo et al. (2021) [51] investigated an HVAC-integrated air cleaner with a water-bath filtration system (**C01-R10-S25**); Carmona et al. (2022) [77] evaluated portable HEPA filters used alongside existing HVAC setups (**C01-R11-S26**). Additional studies focused on other HVAC improvements: Zhang (2022) [80] examined air conditioning systems (**C01-R13-S28**), while Johnson (2009) [69] evaluated multiple HVAC enhancements, including dehumidification, air filtration, furnace servicing, room air cleaners, and furnace filters (**C01-R14-S29/S31**); Wang (2011) [71] investigated an absorption dehumidification system (**C01-R12-S27**).

In terms of performance indicators, particulate matter (PM) — including $PM_{2.5}$, PM_{10}, PM_1, UFPs, BC, and other size fractions — was the most commonly used indicator across half of the 14 reviewed HVAC studies. Only one study [77] assessed PM as a standalone indicator (**C01-R11-S26**), while the remaining six studies evaluated PM in conjunction with other air quality indicators. Among these seven studies, four reported reductions in PM concentrations, with one achieving a statistically significant improvement of 50–100 % (**C01-R11-S26**) [77]. Conversely, three studies observed increases in PM levels, with one study reporting a more than 100 % worsening (**C01-R01-S01**) [70]. This particular study, however, began with a relatively low initial PM concentration (approximately 9 μg/m^3).

The second most commonly used indicator was organic chemicals, including TVOCs, toluene, HCHO, and other volatile organic compounds. These were assessed in four studies, all of which reported slight improvements, especially when filtration systems, i.e., biofiltration, were implemented (**C01-R08-S20**) [68]. Microbes, specifically airborne spore counts, were used as a performance indicator in three studies. One of these studies [68] reported a more than 100 % worsening, with microbial counts increasing from 78 CFU/m^3 pre-intervention to 223 CFU/m^3 post-intervention (**C01-R08-S20**). The thermal comfort aspect of indicators was used in three studies (**R01**, **R04**, **R14**), with air temperature assessed in three [69,70,75]. Two of them reported general improvements (**R04**, **R14**). Acoustical comfort was evaluated in one study (**R06**) [78], which assessed noise levels (within the used threshold of 40 dB(A)) when testing the effectiveness of the ventilation strategies proposed. Lastly, health indicators were only directly assessed in one study [69], which employed subjective occupant questionnaires to evaluate the impact of HVAC interventions on a variety of health conditions (**R14**). The study reported a general improvement across a range of symptoms and ailments, including reductions in cough, wheezing, shortness of breath, nasal congestion, dry sore throat, skin rashes, allergy flare-ups, and asthma attacks. The quantitative changes are provided in Table S3.

3.2.2. Biophilia (C02)

Three studies explored the impact of biophilic design on occupant health and well-being, focusing on indoor vegetation density (**C02-R15-S32**) [86] and the incorporation of natural materials, specifically indoor wood coverage (**C02-R16-S33**, **C02-R17-S34**) [85,87]. All studies used health-related performance indicators and reported statistically significant improvements. To be more specific, Rhee et al. (2023) [86] employed both the perceived restorativeness scale (PRS-11) and psychophysiological measurements (EEG) to evaluate the impact of different vegetation densities (**C02-R15-S32**). Their findings showed a 15 % improvement in restorativeness, with the optimal vegetation density range identified between 13% and 24 %. Li et al. (2023) [85] evaluated the effectiveness of wood-based solutions using overall restorative quality (RQ), measured by six sub-indicators: being away, fascination, extent, compatibility, naturalness, and preference (**C02-R16-S33**). They reported a 70 % increase in students' perception of restorativeness when wood component implantation increased from 0%-20 % to 60%–80 %. Yan & Guo (2023) [87] assessed the psychological and physiological effects of different wood coverage levels (**C02-R17-S34**). Psychologically, participants rated their experience using a semantic differential method across nine adjective pairs, such as "Succinct-Sophisticated" and "Natural-Artificial." The study found that 30 % of wood coverage produced the most positive psychological response, with a 77 % improvement compared to 15 % of wood coverage. Physiologically, heart rate and systolic blood pressure were measured before and after exposure. Heart rates decreased at all wood coverage levels, with the greatest reduction at 90 %.

3.2.3. Daylight & lighting (C03)

Two reviewed studies examined different daylighting and lighting systems, including optical daylighting (**C03-R18-S35/S36**) [88] and dynamic LED lighting systems (**C03-R19-S37/S38**) [52]. Specifically, Kim & Kim (2010) [88] provided an overview of optical daylighting technologies, particularly light pipe and mirror sun lighting systems (**C03-R18-S35/S36**). While ideally, a well-designed building would ensure that all rooms have direct access to natural daylight, reducing the need for such technological solutions, these systems are valuable for spaces where daylight access is limited. They capture and distribute natural light, thereby improving visual comfort in these constrained environments. The study measured illuminance and correlated color temperature (CCT) and reported improvements ranging from 4 % to over 100 % after implementing these sunlighting systems in both a test room and a living room.

Zhang et al. (2020) [52] assessed the impact of dynamic LED lighting systems using both physiological and behavioral indicators (**C03-R19-S37/S38**). Physiological measurements included electrodermal activity (EDA) to assess stress levels, as well as heart rate, respiration rate, and sleep parameters such as total sleep time, sleep onset latency, and sleep efficiency to evaluate circadian rhythms and sleep quality. Behavioral indicators included perceived stress, measured through the Perceived Stress Scale (PSS-10), along with daily stress ratings. Participants also kept sleep diaries and rated their alertness using the Stanford Sleepiness Scale (SSS). Additionally, satisfaction and productivity were measured using the Cost-effective Open-Plan Environments (COPE) survey [93], capturing feedback on lighting conditions, productivity, and overall satisfaction with background noise and acoustic privacy. The findings revealed that dynamic LED lighting improved visual comfort and showed potential benefits in reducing afternoon sleepiness and slightly enhancing mood, with improvements ranging from 0 % to 50 %. However, dynamic lighting also had negative effects on perceived sleep quality and duration, highlighting the complex balance between the visual and non-visual effects of lighting on health and well-being.

3.2.4. Control & automation (C04)

In total two literature articles were found about the control and automation of environmental systems in utilizing (Internet of Things) IoT sensors (**C04-R21-S40/S46**) [90] and intelligent windowsill systems (**C04-R20-S39**) [89]. Specifically, Pantelic et al. (2023) focused on cooking emission control using IoT sensors and connected air quality interventions. The control algorithm architecture implemented a network of sensors, actuators, and cloud-based services, primarily utilizing Microsoft Azure. The system monitored environmental conditions through $PM_{2.5}$ sensors and controlled various interventions such as HVAC systems and portable air cleaners (PACs) (**C04-R21-S40/S46**). The building automation system (BAS) sent control signals to the HVAC system, and the system's efficacy was demonstrated by significant reductions in $PM_{2.5}$ concentrations through automated interventions, showcasing over 80 % reduction in integrated $PM_{2.5}$ levels compared to baseline conditions.

Wang et al. (2017) presented the design and implementation of an Intelligent Windowsill System (IWS) using a fuzzy microcontroller (**C04-R20-S39**). This system employed Bluetooth-enabled smart handheld devices (SHDs) for remote monitoring and control. The IWS integrated various environmental sensors to gather data on indoor illumination, temperature, and CO_2 concentration, as well as outdoor wind and rain conditions, which were processed using fuzzy logic to automatically adjust electric curtains and windows. The system's fuzzy control strategy was validated through laboratory experiments, reporting its capability to generally improve indoor comfort and respond to changing environmental conditions effectively.

3.2.5. *Façade system (C05)*

Only one article [91] was found to explore innovative facade solutions, including the integration of algae photo-bioreactors, brise-soleil, and horizontal fixed shading devices (**C05-R22-S47**). In the study, the performance of those three facade systems was assessed in an experimental case study. The algae photo-bioreactor stood out by reducing solar heat gain and improving air quality through photosynthesis, achieving a significant temperature differential (ΔT) of 6.4 K, compared to 3.4 K for brise-soleil and 3.5 K for horizontal shading devices. This system also maintained adequate indoor illuminance levels, averaging 1049 lux, meeting office standards. The algae facade's ability to block over 90 % of daylight while ensuring sufficient indoor light highlights its energy efficiency.

3.2.6. *Materials (C06)*

One study [92] examined materials used in passive climate control for office buildings, focusing on their effects on humidity regulation over 1-year periods (**C06-R23-S48**). The study analyzed materials including concrete, bricks, plaster, paint, wood, and coatings, using partial vapor pressure as a key indicator to assess moisture control. It was found that impermeable materials such as plastic and certain paints provided limited humidity regulation. In contrast, permeable materials like paper and plaster effectively moderated indoor humidity, especially during low ventilation.

3.2.7. *Miscellaneous aspects (C07)*

Five studies have examined diverse building technologies and their impact on IEQ conditions and/or health [80–84]. Specifically, Brown (2001) [81] examined air toxics in a newly constructed Australian home (**C07-R24-S49**). The study found that in a tightly sealed house with a ducted mechanical ventilation system equipped with heat recovery and the use of low-VOC materials (such as laminate flooring, water-based acrylic paints, and solid timber or fully laminated particleboard furniture), levels of VOCs and formaldehyde decreased by 50 %–100 % within eight months, reaching safe levels. However, microbial pollutants, including viable fungi, bacterial spores, and allergens, increased by over 100 %, indicating a worsening of biological contamination despite improvements in chemical pollutants.

Van Hooff et al. (2014) [82] investigated the effectiveness of various passive climate adaptation measures in reducing operative temperature and mitigating overheating in residential buildings. The measures evaluated included increased thermal resistance, altered thermal capacity, increased albedo, vegetated roofs, solar shading, and additional natural ventilation (**C07-R25-S50/S55**). The results showed that exterior solar shading and natural ventilation were the most effective at reducing overheating and lowering operative temperatures. In contrast, increased insulation led to a rise in overheating hours.

Breysse et al. (2015) [83] examined the benefits of green renovations in a low-income public housing apartment building, which included improvements to the building envelope, installation of new heating, electrical, and ventilation systems, air sealing, new insulation, and the implementation of a no-smoking policy (**C07-R26-S56**). The study relied on participants' self-reported physical and mental health, assessed through the Veterans RAND 12-Item Health Survey (VR-12), which provided both mental and physical health scores. Additionally, IAQ indicators (i.e., CO_2 levels) were monitored. The results showed statistically significant improvements in CO_2 levels and mental health, along with a reduction in falls across the all-ages study group.

Underhill et al. (2018) [84] modeled the resilience of energy-efficient retrofits in low-income multifamily housing, focusing on weatherization, exhaust fans, HVAC filtration, and their combinations (**C07-R27-S57/S60**). Using the CONTAM multizone airflow and IAQ analysis program, the study simulated the effects of these retrofits on indoor $PM_{2.5}$ and NO_2 concentrations during activities like cooking and smoking. The results showed that comprehensive retrofits, including weatherization, local exhaust ventilation, and enhanced HVAC filtration, led to a 0–50 % reduction in $PM_{2.5}$ and NO_2 levels. However, weatherization alone resulted in a 0–50 % increase in these pollutant concentrations.

4. Critical review

This review aims to provide a comprehensive synthesis of the research related to building technology solutions that intend to contribute to the "healthy building" movement. The healthy building movement is increasingly recognized for prioritizing occupant health. Over the past few years, the number of related publications has increased (see Fig. S1). However, we acknowledge that the overall volume of published research across many fields has also been growing substantially during this period [94,95]. Therefore, this observed increase may not necessarily indicate a disproportionately growing interest in healthy buildings without further comparative analyses. Nevertheless, as shown in Fig. 3b, there is growing recognition of the impact that indoor environments have on occupant health and well-being. This underscores the need to critically assess the technological solutions that claim to enhance IEQ conditions and health. This review addresses the status of research in this field, by focusing on technologies specifically designed to promote health alongside environmental responsibility. The main focus of this discussion is on the IEQ and health indicators used in existing studies and how health has been addressed. In addition, insight into the effectiveness of solutions is provided, and areas for further research are identified in order to better realize the potential of healthy buildings in homes, offices, and schools.

4.1. Key IEQ and health indicators in healthy buildings

The review identified 39 IEQ and health indicators that were used in the process of assessing building technology solutions. With some exceptions, there was little agreement in the indicators used for the different research presented. Most indicators were related to IAQ, thermal comfort, visual comfort, and acoustical comfort, identifying a narrow view of the IEQ. In some cases, health aspects were identified, and in this review, those were categorized into physical, mental, and general health. Notably, only three of the included papers [52,69,83] reported both IEQ measurements (e.g., microbes, temperature, CO_2, illuminance) and occupant health symptoms within the same study, and none of these delved into a detailed causal analysis of how changes in IEQ specifically affect health outcomes. IAQ-related performance indicators emerged as the most widely assessed across all studies, consistent with the established links between air pollutants and health issues, including respiratory and cardiovascular diseases, as well as cancer risks [96–99]. Within the IAQ category of indicators, $PM_{2.5}$ was the most frequently used, appearing in 23 out of 60 building technology solutions. Other PM size fractions, such as PM_1, PM_{10}, and UFPs, were collectively used in 19 solutions. Organic gases like TVOC, toluene, and HCHO were evaluated in 17 solutions. Other pollutants were assessed in one or just a few papers. Biological pollutants, such as fungal spores and allergens, were monitored in six solutions. The ventilation rate, as an air quality performance indicator, was also examined in several cases. This indicator can partially reflect the impact of various pollutants that may be unmeasurable or unknown. The identified IAQ indicators are largely aligned with schemes like the WELL Building Standard [22] and TAIL [100]. However, others, such as radon, were not taken into account in the studies. For HVAC solutions, such an indicator may be relevant.

Thermal comfort, though evaluated in fewer studies (six studies), remains a crucial component of IEQ, as it significantly impacts occupant well-being and productivity [101,102]. Key indicators used to assess thermal comfort include operative temperature (used in seven solutions), air temperature (five), relative humidity (two), radiant temperature (one), and air velocity (one). Regarding visual comfort, which has been shown to significantly influence occupant satisfaction, health, and performance [103,104], two indicators were commonly used: illuminance (in five solutions) and correlated color temperature (CCT, three). Acoustical comfort often underestimated but essential for work performance and overall comfort [105], was evaluated using two indicators: sound pressure level (SPL, in five solutions) and perceived acoustical comfort (one). Though several of these indicators may not be correlated clearly to specific building technology solutions, e.g. HVAC and visual comfort indicators, others do, e.g. HVAC and acoustical comfort indicators.

Unlike the IEQ aspects objectively measured primarily through sensor-based data, health indicators were largely subjectively assessed through field surveys, interviews, or questionnaires, where participants reported outcomes such as comfort, work performance, and sleep quality. Seven solutions proposed in four reviewed studies [52,69,83,87] incorporated physiological measures, including heart rate, blood pressure, and respiratory symptoms (cough, wheezing, shortness of breath). Additionally, psychological health was evaluated in five solutions proposed in five studies [52,83,85–87] using indicators such as mental stress, mood, satisfaction, perceived well-being, and sleep. More specific indicators included restorativeness (e.g., the Perceived Restorativeness Scale [106]), naturalness, fascination, and compatibility, all of which are essential for understanding the broader impact of building environments on mental and physical health. In addition to subjective and physiological assessment of health indicators, the Disability-Adjusted Life Years (DALYs) concept provides an objective measure of long-term health impacts from indoor exposures [107]. By quantifying the cumulative health burden from pollutants like $PM_{2.5}$ and formaldehyde, DALYs offer a more comprehensive understanding of how building environments affect both immediate comfort and long-term health. Similarly, Morantes et al. [108] recently developed a health-centered approach to quantify and compare chronic harm caused by indoor air contaminants using the DALYs metric. Such developments open up the possibility of quantifying health in the context of buildings.

4.2. Effects of building technologies on IEQ and health indicators

The analysis demonstrated that various building technology solutions have distinct impacts on individual IEQ aspects and, assumingly, health outcomes, though the latter was most of the time not objectively determined. HVAC systems, being the most studied category, showed significant improvements in IAQ and thermal comfort. For example, demand-controlled ventilation strategies effectively reduce indoor pollutants (e.g., $PM_{2.5}$, O_3) compared to the constant ventilation strategy (9.4 L/s per occupant), thereby enhancing air quality and improving occupants' work performance [73]. However, the study [78] highlighted the need for careful consideration of acoustical comfort in HVAC designs to avoid noise-related disturbances. This indicates the importance of evaluating HVAC systems holistically, considering all aspects of IEQ rather than focusing on individual indicators in isolation. A comprehensive approach is essential to fully assess the potential of (innovative) building technologies. When it comes to health, this understanding is not evident in many of the studies that link a building technology solution to health. The biophilic design and solutions in the reviewed studies, incorporating natural elements like indoor vegetation [86] and wood materials [85,87], consistently demonstrated positive impacts on mental health and stress reduction of occupants of different ages. These indicate the psychological benefits of nature-inspired design. In contrast to the HVAC solutions, these studies paid limited attention to how biophilic elements impact broader IEQ indicators like air quality or thermal comfort. There were concerns about potential health risks from fungal or bacterial components in potting soils, but the benefits generally outweighed these risks [109]. Daylighting and lighting technologies primarily improved visual comfort [88,110] and had mixed effects on non-visual health outcomes [52]. Control and automation technologies, particularly those utilizing IoT sensors [90], showcased potential in optimizing indoor environments by dynamically adjusting ventilation based on real-time data. Façade systems and materials solutions, although less frequently studied, offered innovative approaches to enhancing IEQ through improved energy efficiency, humidity regulation, and systematic IAQ management.

4.3. Current research gap and future direction

Despite the advancements in building technologies, the review identified several research gaps.

In general, according to the literature strategy and the exclusion criteria applied, only a very limited number of relevant papers were identified in this literature review that explicitly sought to relate research in building technology to health and healthy buildings. This shows that although the concept of healthy buildings has been in use for several decades, it is not yet adopted in general. This may be due to the fact that a single definition of a healthy building has yet to be agreed upon (see Table S1). In addition, health was generally not considered as part of the performance indicators in the included papers. An indirect effect on health is implicitly assumed by most authors, generally reflected in the effect on IEQ performance indicators when a (new) technology is applied. Statements about health and health effects on building occupants, in the studies analyzed, therefore seem premature. There is an urgent need to agree on the definition of a healthy building and the performance indicators that should (at a minimum) be linked to it, so real improvements in the health of building occupants can be determined. While existing schemes provide relevant indicator lists, they may still fall short of fully defining a healthy building. However, in alignment with the healthy building movement, we should strive to create buildings that are progressively healthier.

Notably, the following points reflect gaps and directions derived from the limited body of evidence our scoping review uncovered. They should be interpreted as indicative rather than definitive, given the emerging status of the field.

Reflecting on the papers reviewed, firstly, homes and offices dominated the reviewed studies, reflecting the considerable time people spend in these environments. Schools, by comparison, received less attention, despite the complexity of their environment and the critical developmental stages of children who spend many hours there [111,112]. Future research can address this imbalance by more thoroughly investigating school settings, while acknowledging that this recommendation arises from a limited set of initial studies. A broader evidence base will better inform how healthy building technologies could be adapted or refined for learning environments.

Secondly, most studies concentrated on HVAC systems—such as ventilation and filtration—given their established impact on IAQ and thermal comfort. Although this emphasis is understandable, other technological solutions (e.g., façades, building materials, and acoustical interventions) remain underexplored and not explicitly connected to occupant health in much of the literature. Future work should aim to expand these research areas to offer a more holistic perspective on how diverse design elements and strategies might collectively enhance health outcomes. Here again, additional data are required to validate the potential benefits beyond HVAC solutions. Furthermore, although our review mainly identified active building solutions, it is important to recognize the significant role of passive design strategies—such as natural ventilation and shading—in improving IEQ and health and their comparison to active solutions. Combining both optimizes building performance and occupant well-being.

Thirdly, there is a need for more comprehensive studies that integrate multiple IEQ indicators to provide a holistic understanding of indoor environmental quality [113]. Many reviewed studies examined individual IEQ indicators, a narrow approach that neglects the interplay among various environmental factors. For instance, acoustical comfort is seldom studied alongside thermal, visual, or air-quality metrics, despite its proven relevance to occupant well-being. Integrating multiple IEQ dimensions can yield more robust and realistic assessments of how building technologies affect health. While this call for broader assessments arises from a still-evolving evidence base, employing multi-domain studies early on could avoid knowledge silos and enable more comprehensive building design approaches.

Fourthly, few studies evaluated long-term changes in occupant health and IEQ, with most reporting findings from relatively short observation periods. Without longitudinal data, understanding the sustained benefits—or unintended consequences—of specific interventions is difficult. Conducting longer-term research could more decisively reveal how building technologies influence occupant well-being over time. Although the small sample size from which this statement is currently derived limits definitive conclusions, expanding the duration of future evaluations will help clarify which measures have genuine, lasting value.

Fifthly, while health is increasingly recognized as a key consideration in built environment design [37,114], few reviewed studies directly assess how specific building technology solutions impact health. Many of the reviewed articles explicitly labeled themselves as contributing to 'healthy buildings,' yet focused predominantly on improving IEQ indicators, rather than directly measuring health outcomes. This suggests that while the intent is to support occupant well-being, the actual link to occupant health remains implicit or underexamined. Some authors relied primarily on occupant satisfaction surveys [69,85,86] as a proxy for occupant health, which may not sufficiently capture physiological or long-term effects. Moreover, certain studies underscore the complexity of establishing causal links between building interventions and occupant health, recommending more robust or longitudinal research [77,90]. Consequently, it appears that although these studies present building technologies for 'healthy buildings,' they often do not incorporate medical, physiological, or psychological data to validate health impacts, thereby indicating uncertainty in how to systematically measure and report health improvements. Given the complexity of linking technologies to health outcomes, this gap highlights the need for more interdisciplinary research that incorporates both physiological and psychological health assessments. Future studies could deepen these connections to better inform building design practices that promote overall well-being. If we want to proceed in developing building technology that supports the health of the occupants, such cooperation between different experts is regarded as crucial. Given that the research field is still young, this step must be approached incrementally, building on the modest yet informative body of work available.

Sixthly, a noticeable geographical bias among the reviewed papers suggests that knowledge regarding healthy building technologies remains unevenly distributed. Expanding research to encompass diverse climates and cultural contexts will offer a more global picture and clarify which solutions generalize well or require local adaptation. Increased representation will also help refine a universal or region-specific definition of healthy buildings, recognizing that the current data set is still small.

Seventhly, the evaluation methods used across the reviewed studies varied significantly, leading to inconsistencies in assessing the effectiveness of building technologies. Differences in study design and the types of IEQ indicators measured make it challenging to compare results directly. Standardizing evaluation methods and adopting comprehensive assessment frameworks will enhance the comparability and reliability of future research findings. In this context, it is important to remember that a specific building technology solution is part of a building, and the result is usually influenced by the integral (total) building design. This does not make the development of the assessment framework any easier.

Lastly, although our review did not focus on energy efficiency, carbon emissions, or resource management as primary outcomes, our findings reveal that many building technologies (e.g., advanced HVAC systems, optimized daylighting, passive design) can simultaneously reduce energy consumption and promote occupant health. For instance, demand-controlled ventilation can preserve indoor air quality while preventing unnecessary heating or cooling loads. Future research integrating occupant health outcomes into net-zero building frameworks will help ensure that buildings are not only energy-efficient but also holistically sustainable—meeting the comfort, productivity, and health needs of occupants alongside carbon reduction targets.

Overall, these research gaps and directions should be viewed as emerging insights derived from a scoping review of limited yet indicative literature. As more studies adopt common frameworks, incorporate robust health metrics, and examine a wider array of building environments and technologies, the field will progress toward a more cohesive understanding of what constitutes a truly healthy building.

4.4. Practical implication and limitations

From a practical standpoint, our synthesis of effective solutions—such as HVAC design, filtration systems, automated controls, and façade improvements—offers clear guidance on selecting and implementing strategies that optimize both indoor environmental quality (IEQ) and occupant well-being. While performance-based approaches can serve as an insightful point of departure for designing healthy buildings, they often remain theoretical in practice because such performance is not easy to assess in the early design stage—particularly for innovative or emerging building technologies. Rigorous assessment of new solutions in terms of their health impacts can be complex, and reliable metrics or standardized testing protocols may not yet be available for all technologies. Consequently, expanding the availability of evaluated building technologies—with demonstrable benefits to occupant health—would help designers and decision-makers select systems that align with both the design concept and best-practice health criteria. Such evidence-based guidance would bridge the gap between innovative design aspirations and real-world implementation, ensuring that healthy buildings not only achieve technical performance goals but also foster truly occupant-centric environments. Policymakers and governmental bodies can leverage this evidence to propose building codes, incentives, or certification requirements focused on occupant health, with the potential for reducing resource consumption and emissions when applicable. In turn, occupants, employers, and building owners may draw on these insights to advocate for renovations or new construction that prioritize occupant comfort and well-being, ultimately improving health outcomes, reducing absenteeism, enhancing productivity, and potentially lowering job change intentions.

It is important to note that this review focused on research explicitly contributing to the “healthy building movement,” where health improvement was a primary outcome. While the findings show a growing number of publications addressing “healthy building” concepts, reflecting the increasing focus on health in both academia and industry, there are several limitations to our approach.

First, the scope of building technology solutions in the literature is extensive and varied. Many studies aim to improve occupants’ health and comfort, even if they do not explicitly use the term “healthy building.” As a result, our search strategy, which combined the keywords “healthy building” and “IEQ,” may have missed relevant studies that discuss health-related outcomes under different terms. On the other hand, by explicitly combining “healthy building” and “IEQ” in our search terms, it was ensured that the studies included in the review were directly focused on the intersection of building technologies, IEQ, and health outcomes. This focused scope helps in deriving more precise and actionable insights specific to the “healthy building” context. Despite this focused search strategy, we see that health is not a standard performance assessment criterion yet and that its assessment is diffuse and not consistent, potentially due to a lack of unified definition [115].

Another limitation is that we did not include “building technology” as a dedicated search term. We found that studies often label related interventions under diverse terms (e.g., ‘innovative HVAC strategies’ or ‘biofiltration measures’, etc.). Our initial search was intentionally broad (“healthy building” × “IEQ”), and we relied on our first inclusion criterion requiring a proposed technology or solution. This qualitative screening ensured the final sample genuinely covered building technology interventions, despite variable terminology.

The third limitation of this review is the inability to distinguish between the shifts in keyword usage trends and actual shifts in research focus over time. While the VOSviewer tool effectively visualizes associations among terms extracted from the literature, it does not provide contextual information regarding how these terms are utilized within the studies. Also, automatic clustering methods—like the one employed by VOSviewer—can result in some “fuzziness”, where certain terms may not intuitively appear to fit a cluster’s dominant theme. Consequently, the interpretation of clusters may be influenced by overlapping categories, where terms used in different contexts can lead to ambiguous conclusions. Future research should consider employing qualitative analyses to complement bibliometric methods, thereby providing a more comprehensive understanding of how keyword usage evolves and its implications for research focus.

Additionally, most proposed solutions in the reviewed studies showed positive impacts on selected IEQ and health indicators. This may reflect a positive publication bias, where studies with favorable results are more likely to be published than those reporting null or negative findings. Such bias can overestimate the effectiveness of certain building technologies and overlook potential challenges or failures. Nevertheless, creating healthier buildings with new building technology solutions is possible.

5. Conclusions

This review focuses on building technology solutions for healthy buildings and examines how they affect IEQ and health in homes, offices, and schools. Overall, the review confirms that advancing building technologies could be crucial for creating healthier indoor environments. However, with only 27 eligible studies found, the research on the effectiveness of building technologies in promoting healthy indoor environments is still meager compared to the vast range of existing technologies. Key findings are as follows:

- Most research does not seem to make the connection to health, or is unsure how to do that.
- In terms of identification of key IEQ and health indicators, across the 60 building technology solutions reviewed, 39 IEQ and health indicators were identified.
- IAQ, along with thermal, visual, and acoustical comfort, were mostly objectively evaluated, with particulate matter and volatile organic compounds serving as primary indicators for IAQ.
- Health indicators were largely measured subjectively through surveys on physical and mental health outcomes, with limited use of physiological data.
- Regarding the impact of building technology solutions on IEQ and health, HVAC systems, the most studied category, showed significant improvements in IAQ and thermal comfort.
- Biophilic design showed positive impacts on mental health.

Additionally, five research gaps should be paid attention for future studies:

- There is a lack of studies that directly assess the impact of building technologies on health outcomes.
- Comprehensive studies are needed to integrate multiple IEQ indicators for a better understanding of complex interactions and their effects on health.
- Many studies also had short durations, restricting insights into lasting impacts on IEQ and health.
- Variations in study designs and indicators highlight the need for standardized assessment frameworks.
- More research is needed to target diverse climatic and cultural contexts to provide a comprehensive understanding of these technologies' global applicability.

Nevertheless, because the field is relatively young and the body of work is limited, it may be premature to call for major shifts in research scope—from study durations and domains (e.g., schools) to inclusion of multi-domain IEQ indicators and standardized health evaluations—without stronger evidence. The review does, however, indicate that this field is emerging, underscoring the need for more extensive and rigorous investigations to substantiate and expand upon these initial findings.

CRediT authorship contribution statement

Hailin Zheng: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dadi Zhang:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization. **Marcel Schweiker:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Marcel Loomans:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.112086.

Data availability

No data was used for the research described in the article.

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