Renewable and Sustainable Energy Reviews 183 (2023) 113460

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

What is the "DNA" of healthy buildings? A critical review and future directions

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ARTICLE INFO

Keywords:
Healthy building
Indoor environment
DNA framework
Sustainability
Life-cycle
Future directions

ABSTRACT

Since the outbreak of COVID-19, buildings that provide improved performance have aroused extensive discussion. Nowadays, the connotation of healthy building is becoming complex, performance metrics for healthy buildings vary significantly from different regions in the world and there may be information asymmetry among stakeholders. Consequently, building health performance cannot be effectively achieved. However, previous studies have launched extensive reviews on green building, and there remains a lack of comprehensive and systematic reviews on healthy buildings. To address the above issues, therefore, this research aims to (1) conduct a thorough review of healthy building research and reveal its nature; and (2) identify the current research gaps and propose possible future research directions. Content analysis using NVivo were applied to review 238 relevant publications. A DNA framework of healthy buildings, which clarifies the characteristics, triggers, guides and actions, was then constructed for better understanding of the nature of them. Subsequently, the application of DNA framework and the directions of future research were discussed. Six future research directions were finally recommended, including life-cycle thinking, standard systems improvement, policies & regulations, awareness increase, healthy building examination, and multidisciplinary integration. This research differs from previous ones because it painted a panorama of previous healthy building research. Findings of this research contribute to reveal knowledge map of healthy buildings, guide researchers to fill existing knowledge gaps, provide a standardized platform for healthy building stakeholders, and promote high-quality development of healthy buildings.

1. Introduction

The construction industry is generally considered to significantly influence the society, economy and environment, for instance, it contributes to energy consumption, national economy, and environmental pollution [1,2]. However, buildings also threaten human health during their construction and operation [3,4]. Public health is largely dependent on the environment [5]. The World Health Organization (WHO) has found that environmental factors affect human health by up to 17% (Healthy China Initiative 2019–2030) and that the annual burden of disease attributable to environmental-related factors account for 25%–33% [6]. In addition to natural environmental issues (e.g. air, water, and soil) caused by climate change, the most significant influencing factor on people's health is the risk of home environment such as indoor environmental pollution in buildings. One possible reason that humans spent tremendous amounts of time (approximately 90% of the day) staying indoors even before the Coronavirus Disease 2019 (COVID-19) pandemic [7], and another reason is that buildings provide the closest habitat for humans and can safeguard people's physical and mental health from the outside [8]. However, with industrialization, changes in the disease spectrum, multiple risk factors exist in the environment where people reside [6,9,10]. Inadequate recreational facilities [11] and increased demands for health [4] have led to the fact that traditional buildings can no longer meet the needs of people. Problems such as poor indoor air quality, loud noise, poor-quality materials, poor design, and low humidity can lead to sick building syndrome (SBS) [12,13], headache, nausea, and cough [14,15]. Recently, outbreaks of viruses including COVID-19, Severe Acute Respiratory Syndrome (SARS), and swine flu have brought the built environment into focus [15,16].

Healthy buildings are designed and built based on people's needs for health [17] and aim to improve health performance metrics such as indoor air quality, water quality, sound insulation, light and psychological comfort of buildings for occupants [18]. However, no consensus

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https://doi.org/10.1016/j.rser.2023.113460
Received 3 November 2022; Received in revised form 7 June 2023; Accepted 9 June 2023
Available online 20 June 2023
1364-0321/

List of abbreviations

DNA	Deoxyribonucleic Acid
COVID-19	Coronavirus Disease 2019
WHO	World Health Organization
SARS	Severe Acute Respiratory Syndrome
SBS	Sick Building Syndrome
RNAs	Ribonucleic Acids
HVAC	Heating, Ventilating and Air Conditioning
IAQ	Indoor Air Quality
HSE	Health and Safety Executive
BIM	Building Information Modeling
CFD	Computational Fluid Dynamics
VOCs	Volatile Organic Compounds
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CDC	The U.S. Centers for Disease Control and Prevention
AI	Artificial Intelligence
IoT	Internet of Things
BASs	Building Automation Systems
IEQ	Indoor Environmental Quality
AAL	Ambient Assisted Living
BI	Business Intelligence
UVGI	Ultraviolet Germicidal Irradiation

has been reached on the definition of healthy buildings [19], and the connotation or extension of healthy buildings has changed due to changes in environment. What's more, standards on healthy building vary in the health performance metrics due to regional differences. Previous research on indoor health and comfort in diverse buildings such as schools, offices and apartments show a growing discrepancy between current standards and the needs of end occupants [20]. Meanwhile, designers, constructors, and operators of buildings may learn inconsistent information and perspectives [18], resulting in healthy buildings that are heavily designed and severely disconnected from the construction and operation phases, with no guarantee of healthy building quality [21]. Additionally, the increased costs associated with advancement of healthy buildings [22], insufficient promotion of healthy building concepts [23] and lack of occupant experience [24] have led to an unrealized market demand.

However, problems mentioned above are not solved because more attention is given to green building and low carbon building. Several review studies have previously investigated green and low carbon buildings, including incentives [25], green building technologies [26], low carbon technologies [27], and energy efficiency strategies [28]. It can be seen that these review studies focus on one aspect of green building and low carbon research. Similarly, detailed reviews of some metrics of healthy buildings have been carried out, including indoor air quality (IAQ) [29–31], indoor environmental quality (IEQ) [32,33], occupant productivity [34], human comfort [35], ventilation technology [36], rating system [16] and engineering control precautions [37]. For example, Pourkiaei and Romain discussed the IAQ index used for different purposes [29]. Saini et al. provide a comprehensive review of indoor air quality monitoring systems [31]. Ganesh et al. discuss the different factors affecting IEQ and their impact on occupant health and thermal comfort [32]. Nevertheless, healthy buildings research covers a wide range and related to multiple disciplines such as architecture, management, behavior, and public health [15]. Research around a particular direction of healthy building can lead to some important research directions being overlooked, making it difficult to reveal the knowledge system of healthy building. In terms of building a knowledge body for the entire area, some scholars have provided an overview of the area of green building and low carbon building. For example, Luo et al. used scientometric methods to review 378 publications related to low carbon buildings, describing a knowledge roadmap needed for low carbon building research [38]. Zuo and Zhao identified common research themes, gaps and future research opportunities based on a critical review of green building [2]. For healthy buildings, only Lin et al. described the research and development of healthy buildings in China [19]. However, focusing on only one country is very one-sided. It follows that similar efforts have not been invested in healthy buildings and a systematic literature review has not been developed for healthy buildings.

Furthermore, existing literature reviews were mainly reviewed manually. Some studies have shown that using qualitative software to support this process (data analysis) is a newer practice [39]. Recently, NVivo has been considered ideal for analyzing the literature because of its flexibility and its ability to classify and thematize data [40,41]. For example, Gislason et al. applied NVivo to a rapid review and thematic analysis of 58 publications that discussed the relationship between climate change and adolescent mental health. Similarly, Zou et al. conducted a content analysis of 227 publications using NVivo to identify the causes and strategies of the building energy performance gap [42]. However, this is not common in the existing reviews of healthy building related scope.

To fill these gaps, this study aims to holistically review the existing research on healthy buildings using NVivo and reveal the nature of healthy building. Deoxyribonucleic acid (DNA) is a type of nucleic acid, one of the four biological molecules contained in living cells. Consisting of two polynucleotide chains intertwined into a double helix, it carries the genetic information necessary for the synthesis of Ribonucleic acids (RNAs) and proteins, which are essential for the development and proper functioning of living organisms. Herein, a DNA framework for healthy buildings was described to achieve the above objectives. The framework consists of four main sections: i) Characteristic [C], in which current definitions of healthy buildings were classified, healthy building was redefined and metrics included in healthy buildings were pointed out; (ii) Trigger [T], which lists the main driving forces for the development of healthy buildings; (iii) Guide [G], which summarizes and compares international standards related to healthy buildings, and clarifies the problems of existing standards and the subsequent development direction; (iv) Action [A], which describes the technical measures adopted to ensure a high performance of healthy building. The DNA framework provides an ontology for stakeholders of healthy buildings to regulate the representation of healthy building health performance. Finally, why the DNA framework is needed, who can use it, when it can be used, the target occupants, the appropriate time of using this DNA framework and future research directions for healthy buildings were discussed to better promote the implementation of healthy buildings.

This paper intends to outline the DNA framework of healthy building, and provide constructive recommendations for future research. The main contributions of this paper are in the following aspects:

- Formulate a comprehensive and systematic redefinition of healthy building
- Describe the knowledge map of healthy building and develop a DNA framework
- Understand the current research gap and propose future research directions for addressing the gap

The novelty of this study is reflected in two aspects. First, this study provides a knowledge body on healthy buildings and develops a DNA framework for healthy buildings that bridges the gap of previous research reviews on specific areas of healthy buildings. Second, the qualitative data analysis software NVivo was incorporated into the traditional manual review to explore the knowledge domain of healthy buildings.

2. Research methods

Existing research on healthy buildings were reviewed and analyzed systematically to identify current knowledge gaps and determine future research directions. Fig. 1 illustrates the main process of the systematic review in this study. Specifically, the first step was data collection, which identified the source and number of publications. The second step was data analysis, where a DNA framework for healthy buildings was developed to obtain an overview of the current research. And finally the application of the proposed DNA framework was discussed as well as the future research directions.

2.1. Retrieving publications

The review started with identifying publications related to healthy building. Databases including Web of Science, Science Direct, Ei CompenexWeb, Taylor & Francis and Google Scholar were selected to identify relevant papers. To avoid missing important publications, Google Scholar was used in the first phase for its comprehensiveness [42–44]. However, research related to healthy buildings can be seen as a combination of multiple disciplines, including architecture, management, behavior, and public health [15]. Therefore, to achieve a comprehensive search of health building-related research, a supplementary search involving several databases was conducted in the second phase, including Web of Science, Science Direct, Ei CompenexWeb and Taylor & Francis. The keywords "healthy building", "healthy architecture", "healthy home", "built environment", "indoor environment", "occupant health", "well-being", were used for investigation in this paper. Since the concept of healthy building has only been emerging since 1980, the time frame was not limited. In the first phase, a total of 1260 publications were found and examined individually. The initial screening eliminated articles that were clearly irrelevant to healthy building, and finally 199 publications were extracted. Subsequently, 39 additional publications were identified from Web of Science, ScienceDirect, Ei CompenexWeb, and Taylor & Francis. Ultimately, a total of 238 publications were collected.

2.2. Analyzing contents using NVivo

The purpose of the content analysis is to provide an analytical framework for a more systematic investigation of healthy buildings. The 238 sources identified in the previous step are included in the study for qualitative content analysis. In this process, NVivo, a well-known computer software for qualitative data analysis, was employed for the

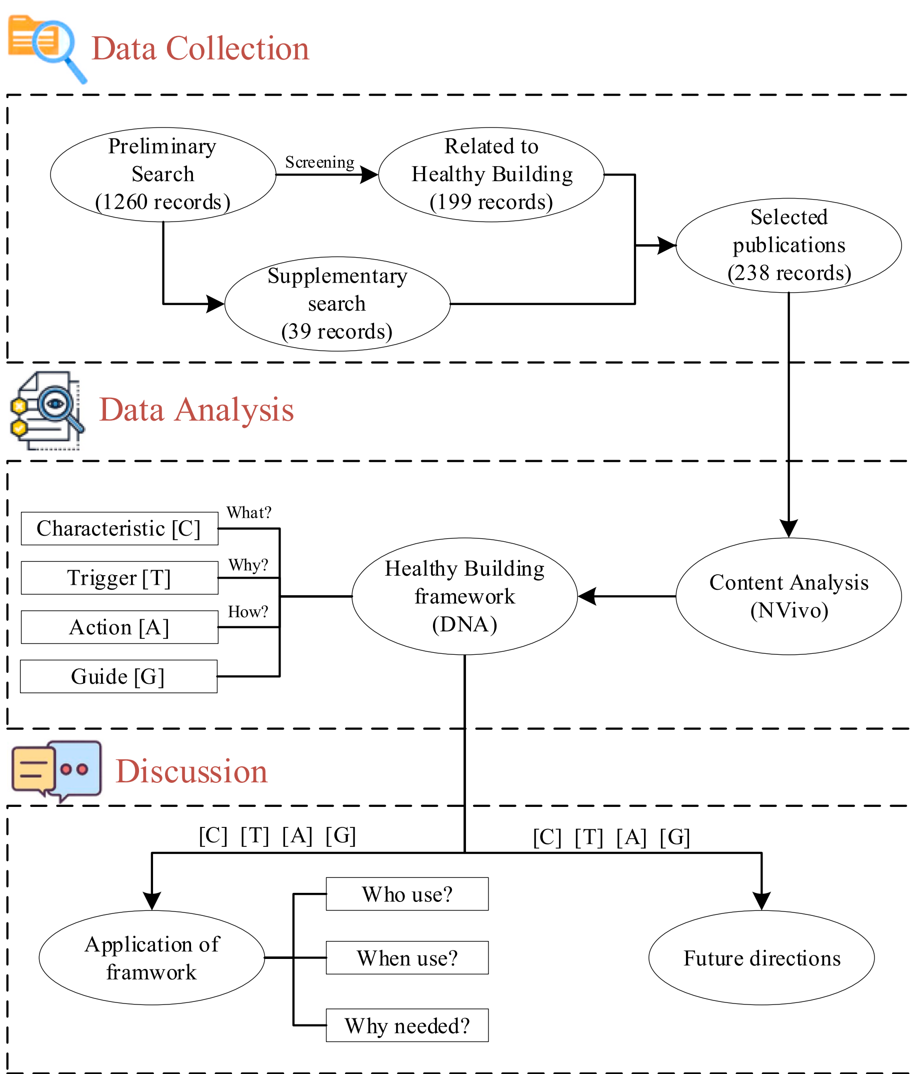

Fig. 1. Process of systematic review on healthy building research.

content analysis. The 238 publications collected previously were imported into the software as sources, and subsequent analyses were performed with the "node" function. A node is a collection of references (including sentences, paragraphs, the whole article, and report) about a specific topic, theme or relationship. In this study, references on the same topic will be gathered into one node by "coding". Taking the paper *Control strategies for indoor environment quality and energy efficiency-a review* as an example, the sentence "The demand for better indoor environment has led to a wide use of heating, ventilating and air conditioning (HVAC) systems" is related to occupant demand and technology tools, thus two nodes are created, namely "occupant need" and "technology", and the sentence under them is coded. Specially, some nodes may have two or more than two levels of node structure. According to this principal, all sources can be coded. Notably, initial codes might be iteratively revised and refined throughout the coding process. To ensure the reliability and validity of the analytical results, several rounds of coding were conducted.

After all sources were coded, a framework was created based on the analysis of 238 publications (Fig. 2). Three different shapes represent different meanings. The diamond represents the boundary of this study and contains all publications related to healthy building; the pentagon represents the issues related to healthy buildings; and the ellipse represents the nodes created during the coding process. Arrows indicate the relationship between various numbers, including "result in" and "contribute to". For instance, the arrow between "technology" and "how?" indicates that technology can promote the performance of healthy building. The number in each shape indicates the total number of publications related to a specific topic. For example, 41 publications provide a clear definition for a healthy building, 11 publications compared healthy buildings with other types of buildings, and 127 publications related to the indicator of healthy buildings. It is worth noting that one publication may be related to multiple topics.

3. DNA framework of healthy building development

3.1. Introductory overview

When a pair of DNA strands are wound together in a double helix, each strand carries nitrogenous bases protruding inwards, including adenine (A), thymine (T), cytosine (C) or guanine (G). Bases are firmly bound together according to complementary base pairing rules (A with T and C with G), relying on hydrogen bonds, which contributes to the stability of DNA [45]. DNA has been widely used in various scientific fields such as tissue regeneration, disease prevention, inflammation inhibition, bioimaging, biosensing, anti-tumor drug delivery and therapy. The concept of DNA was introduced into this study to systematically review the research on healthy building to reveal its nature and direct future research. Inspired by the nitrogenous bases of DNA, namely, A, T, G, C, and combined with the content analysis of all publications, the research on healthy building can be described by four main parts, namely characteristic [C], trigger [T], guide [G] and action [A], which constitute the DNA framework of healthy building (Fig. 3). ***Characteristic*** mainly states the definition and metrics of healthy building and aims to answer the question on what a healthy building is. ***Trigger*** represents the triggers that stimulate the development of healthy buildings and focuses on answering the question of why healthy buildings are needed. ***Guide*** focuses on international standards, guidelines and building rating systems that encompass health and well-being, aiming to reveal the shortcomings of existing standards and achieve improved building health performance. ***Action*** is an effective and targeted measure to improve the performance of healthy buildings, with the aim of answering how to obtain healthy buildings.

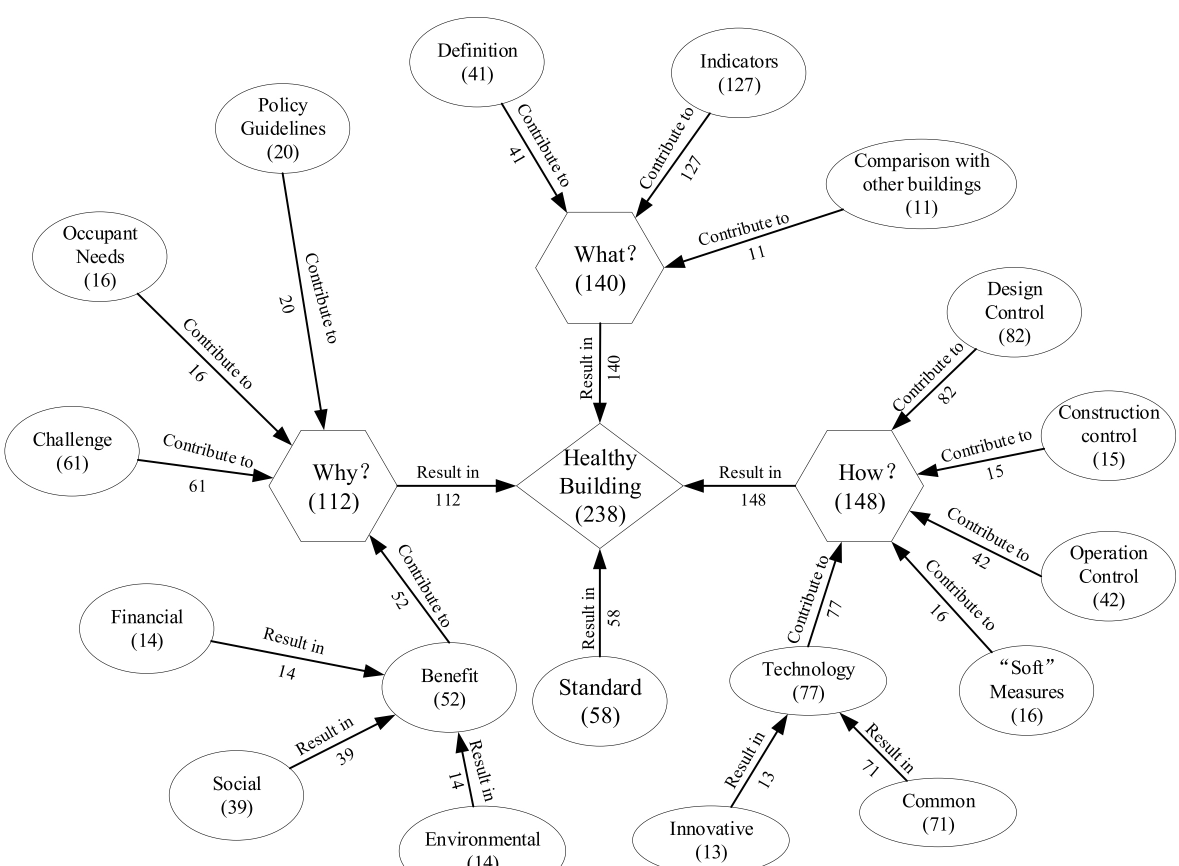

Fig. 2. A framework developed using NVivo.

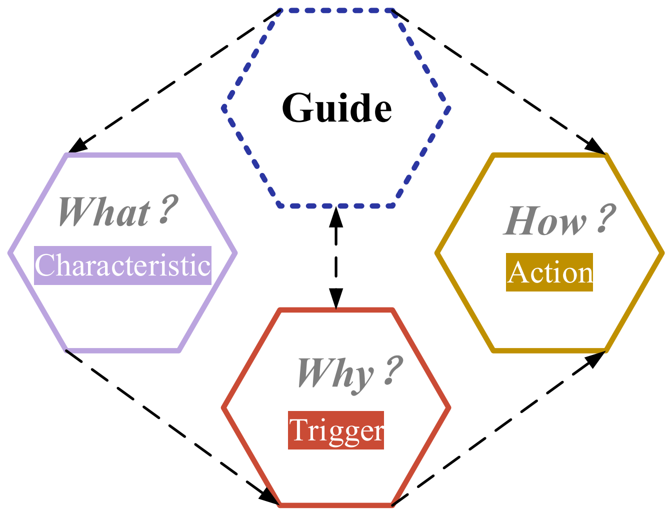

Fig. 3. Four key components of healthy building framework.

3.2. Characteristic

The mapping of the characteristics of healthy building depicts what a healthy building is and the metrics it contains (Fig. 4).

3.2.1. Definition of healthy building

Affected by global environmental pollution problems and energy crisis, new concepts, projects have been widely used, such as green buildings and healthy buildings. A comparative study of the differences between the above concepts was developed specifically. For example, after comparing the concepts of green, sustainable and healthy buildings, Al Alwan and Saleh (2020) pointed out that green and sustainable buildings focus on the building itself and environmental protection, whereas they failed to emphasize human health [46]. Traditional focuses have been placed on technologies rather than occupants. Therefore, it is widely recognized that healthy buildings are the next chapter of green buildings [47]. This demonstrates that health and well-being becomes another metric of green development, and that more attention was paid to physical and mental health of occupants.

The term "healthy building" can date back to the 1980s, but was not commonly used until the late 1990s. It was originally considered as the opposite of sick building, problem building, or complaint building. The widely accepted definition was that there was no indication that the buildings would cause diseases and no apparent reason to believe that it would make people sick [48]. However, how to maintain building health from the design, construction and operation phases becomes a difficult task for subsequent practical applications. Health issues caused by buildings have long attracted worldwide attention, but there is no unified definition of healthy building internationally. And the concept is gradually changing as healthy buildings develop and people's understanding of them deepens. This is also related to the fact that healthy building is concerned with how buildings contribute directly to human health, which involves numerous components. The International Conference on Healthy Architecture held in 2000 described healthy building as a way to experience building indoor environment, which includes not only physical elements such as temperature, humidity, noise, light, and air quality, but also subjective psychological elements such as spatial layout, color, and materials used. In addition, important factors such as job satisfaction and interpersonal relationships need to be added [19]. Thus, a healthy building is not about whether the building itself is healthy or not, but whether the building can give a healthy environment to the people in it. Many countries, research institutions and scholars have provided similar definitions of healthy building [15,18,19,21,28,49–58], detailed information can be found in Supplementary Material A1. Generally, these definitions revolve around the World Health Organization's definition of health as physical health, mental health, and good social adjustment [59].

Nevertheless, these definitions have not yet considered the impact of the whole life cycle of buildings on human health. In the early 1990s, the WHO suggested that healthy buildings should promote the health, comfort and productivity of occupants throughout the life cycle [60]. D'Amico et al. (2020) stated that healthy buildings contain factors such as IAQ, ventilation, thermostatic comfort, natural and artificial lighting, and plant safety that can be directly controlled at all stages of the building process [61]. Mao et al. (2017) considered healthy building as one that achieves the health of the building itself, maintains the health of the surrounding environment and pays more attention to the physical and mental health of the builders as well as the occupants during the whole life cycle of the building [4]. And health should be emphasized through the whole life cycle of building design, with increased consideration of the post-occupancy phase of the building [62]. Therefore, a healthy building should be a new type of product that transforms and upgrades from multiple dimensions, such as comfort and health, living space, energy conservation and environmental protection, and ecological environment, based on the entire life cycle of traditional buildings

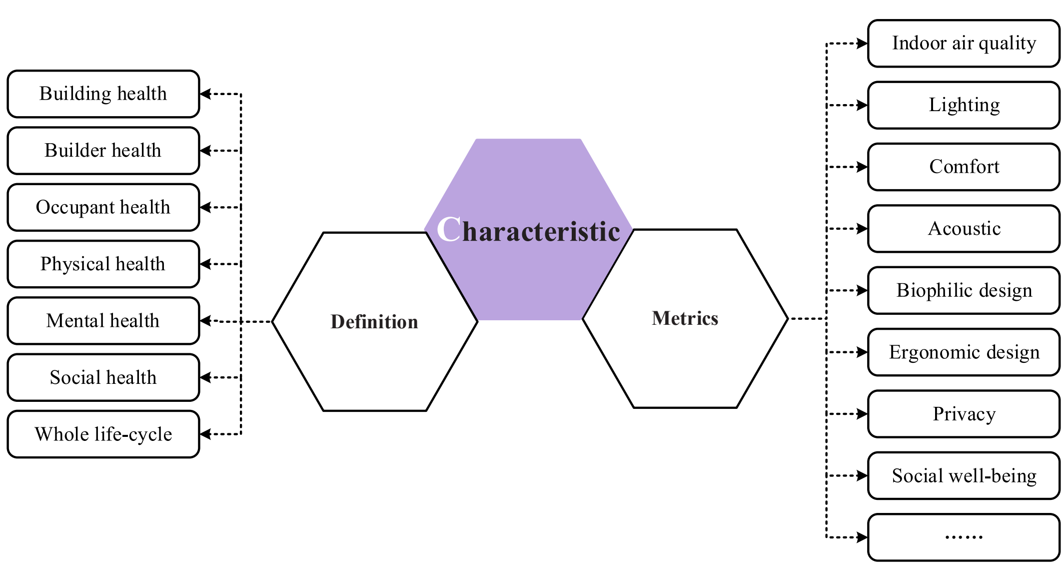

Fig. 4. Characteristic of healthy building.

[56].

It is thus important to redefine healthy building as it should be a "big health" system project that covers the concept of green building and sustainable building, links human health-related factors in the whole life cycle, involves the internal and external environment of the building, integrates various social resources, and is closely related to the health of the building itself, its builders and occupants.

3.2.2. *Metrics of healthy building*

Many metrics, including IAQ, temperature, humidity, and lighting, contribute to a healthy building. Understanding these metrics will help ensure that the buildings do not negatively impact occupants, workers, or surrounding environment. Since air pollution is a significant environmental hazard, improving air quality is extremely important. As one of the main metrics, IAQ has been examined from various perspectives, including air filtration technologies [36], material effects [61], air simulation [63,64], air guidelines [65], strategies [66], and impact on occupant health [67,68] and comfort [32,69]. There are other indoor environmental issues, including lighting, comfort, acoustics, safety, and biophilic design and ergonomic design. Meanwhile, many attributes of the building environment, such as privacy, functional suitability, aesthetics, odor, tidiness, and social aspects, could affect human psychological or physical health as well [70,71]. However, research on these factors is still in a state of scarcity compared to IAQ, which is consistent with the results of Lin et al. who reported that evaluation criteria focus more on indoor environment and ventilation strategies, and more research should be conducted in the future on acoustic comfort, lighting comfort, water quality [19].

Existing well-known certification systems for measuring building sustainability, such as *Leadership in Energy and Environmental Design (LEED, USA)*, *Building Research Establishment Environmental Assessment Method (BREEAM, UK)*, and *Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB, Germany)*, have also introduced health metrics, which stress indoor air quality, light and thermal comfort, while other metrics are only partially covered [72]. Among the evaluation standards for healthy buildings, such as *WELL Building Standard (WELL, USA)*, *Fitwel certification (Fitwel, USA)*, *Green Mark for Healthier Workplace (GM-HW, Singapore)*, *Healthy Building: A Guide for Developers and Contractors to Build and Transform (HB, France)*, *Standard of Building Biology Testing Methods (SBM-2015, Germany)*, *Assessment standard for healthy building (ASHB, China)*, *The 9 Foundations of a Healthy Building* [73], health metrics are fully covered (Fig. 5). As noticed from Fig. 5, most standards emphasized the indoor environment, while few considered physical, chemical, microbiological and indoor air quality risk metrics caused by the interior and exterior of the building. Additionally, most metrics are directly related to the prevention and control of infectious diseases, while few focus on metrics that affect mental and social health. Given the rise of mental and social health issues, more attention should be paid to metrics related to them [74]. And it is worth noted that in the context of the pandemic, healthy buildings should focus on epidemic prevention in the next stage.

3.3. *Trigger*

Triggers represent the stimuli that drive the development of healthy buildings, including external and internal factors (Fig. 6).

3.3.1. *Triggers related to health issues*

Extreme climate or weather events such as rising temperatures, floods, droughts, are steadily increasing around the world, posing threats to the health of current and future populations worldwide. According to the WHO, climate change will cause an annual casualty of approximately 250,000 worldwide from 2030 to 2050 [75]. This is because climate change can cause acute and chronic diseases as a direct consequence of increased temperatures, food and water insecurity, air pollution and vector-borne diseases [76]. Numerous studies have shown that environmental problems such as global air pollution, water pollution, and noise pollution have caused various health problems [77]. For example, increased air pollution seriously amplifies the risk of respiratory diseases [78], water contamination leads to respiratory infections, asthma, cardiovascular problems and infectious diseases [79], and the main effects of noise pollution include insomnia, reduced efficiency and even deafness and mental breakdown [80]. Also, social issues such as demographic changes (e.g., aging population), food insecurity, and

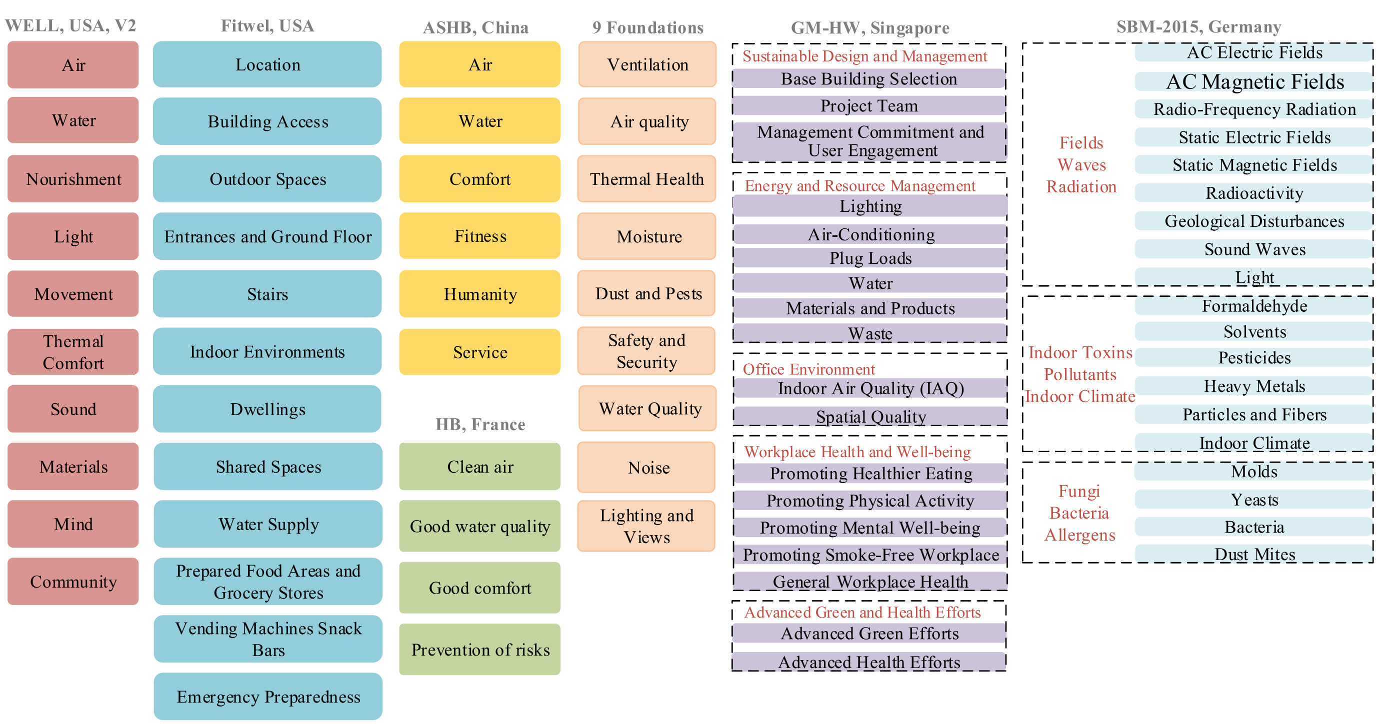

Fig. 5. Main metrics included in the international common healthy building standards.

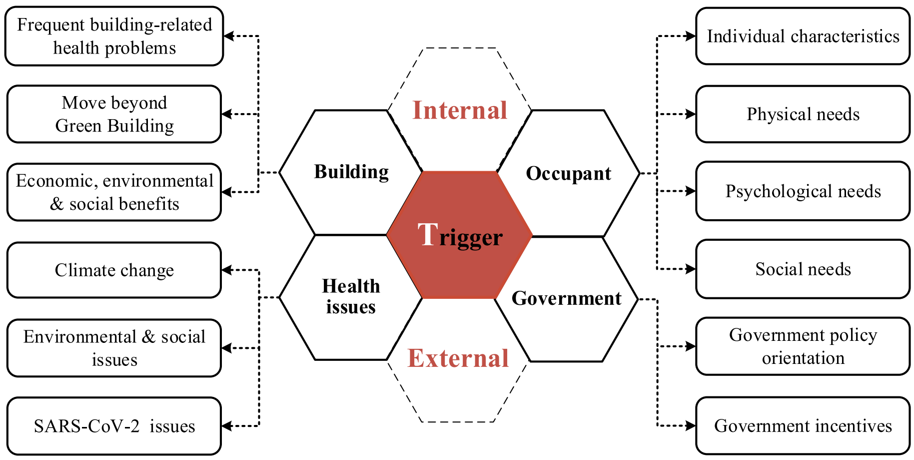

Fig. 6. Triggers of the development of healthy buildings.

lifestyle changes (e.g., longer working hours) have raised new requirements on health [81]. Approximately 50% of the United States population suffers from chronic diseases [82]. According to *Chinese National Health and Nutrition Big Data Report*, 70% of Chinese are at a risk of overwork death, 76% of white-collar workers are in a state of sub-health, 20% suffer from chronic diseases, and 86% of deaths are due to chronic diseases. With increased workloads, sub-health and chronic diseases are almost everywhere. Meanwhile, from 2019, when the COVID-19 ravaged the world, to the current stage of its regular presence, buildings and communities have become the basic line of defense against the epidemic as people are forced to continue their studies, work and life in doors for prolonged hours. Various conflicts between people and building, such as the lack of indoor sports space [83] and the lack of property services of epidemic prevention [84], have become apparent, forcing people to pay more attention to the health attributes of building. Researchers around the world are still learning how COVID-19 is transmitted in indoor environments, and these have stimulated the industry to think about how buildings can effectively ensure the health of their occupants during extreme events and over long periods of time. Thus, these complex health issues need to be addressed urgently where healthy buildings present one of effective approaches.

3.3.2. Triggers related to government

Regulations and policies are significant drivers that compel stakeholders to take relevant actions such as those formulated to promote green building [85]. Various policies, such as the global integration of the health industry and China's "Healthy China", have been elevated to national strategies. Governments are revising existing standards or developing new ones to include health and well-being elements. Hence, driven by market demand and policies, health has become an important attribute to assess the development of an industry. Since the realization of healthy buildings inevitably requires technical measures, new costs should undoubtedly be invested. The experience of green building development confirms that, on the one hand, with available financial incentives, real-estate developers would presumably invest in healthier buildings [86,87]. On the other hand, for occupants, the direct effect of government incentives is the most economical purchase of housing that meets individual health needs. Indeed, low-income households are most likely to live in substandard housing [59,88], widening the health gap between low-income and high-income groups. Therefore, government incentives can stimulate consumer demand, promote investment, and the agglomeration of healthy buildings.

3.3.3. Triggers related to occupant

The *Healthy Building White Paper* states that a healthy building must prioritize the health needs of its occupants, so to meet the physical, psychological and multi-level social needs of living [4]. Physical need is the need of human beings to maintain the physiological balance of the body and to meet the normal mechanism of life [89]. The main physical needs of occupants for a healthy building include: (i) IAQ. It is one of the most critical factors in maintaining safety, productivity and health of building occupants [90]; (ii) Thermal comfort. Thermal conditions can affect learning [91], cognitive performance [92], disease transmission [93] and sleep [94]; (iii) Acoustical. This has a high correlation and causal relationship with mental health, stress and blood pressure [95]; (iv)Illuminance. Well-lit has a crucial impact on sleep and wake rhythms. Color, view, or exposure to the outdoor environment also can affect the mental health of occupants [57]; (v)Water. The WHO considers water-borne diseases to be one of the major health problems in the world, especially for children in developing countries [96]. According to the Health and Safety Executive (HSE), a total of 602,000 workers experienced work-related stress, depression or anxiety from 2018 to 2019, which placed a significant impact on morale, motivation, productivity and work performance [97]. Therefore, supporting mental health of occupants is a key strategic consideration in healthy buildings for all organizations. Psychological needs (safety, love, privacy, esteem and comfort) are considered one of the basic human needs [98]. The realization of these needs is achieved mainly through architectural aesthetics and interior design to delight and enrich people's spirits, such as consideration of space layout and color, privacy protection, landscape design and material selection [19]. Social needs of the occupants include aspects such as sense of belonging, social engagement and social relationships [99]. Ni et al. (2020) consider social well-being as the ability to establish meaningful relationships with others [100]. At present, due to the lack of space for interactions in the enclosed housing units, communication between neighbors is reduced, hindering residents from meeting the social needs of interpersonal communication [97,101]. Substantial evidence demonstrates that the spatial organization design of buildings can create open areas for individual reflection and group socialization to reduce isolation, increase social connection, and promote social well-being [18]. Meanwhile, wider community exposure can bring a sense of well-being to occupants [102]. Furthermore, the driving forces of occupants are related to their individual characteristics, such as age, physical condition, and individual health awareness. Now, healthy buildings must adapt to new driving forces, such as growing personalization [57].

3.3.4. Triggers related to building

Traditional buildings and communities have struggled to handle new challenges posed by climate change, urbanization, population aging, changes in disease spectrum, changes to ecological environment and lifestyle. Building-related health issues continue to arise frequently, and

SBS has long been a concern for builders and occupants. Indoor air quality, thermal comfort, lighting and noise are considered important metrics in green building. However, little attention is paid to the people in the building, and surprisingly, there is an irreconcilable contradiction between meeting the requirements of energy conservation and improving human comfort [21]. Therefore, healthy building is proposed as an appropriate complement to green buildings.

Furthermore, healthy buildings bring numerous economic, environmental and social benefits. Firstly, health is a fundamental basis for people to create social and economic values, that SBS (more common among commuters) may affect worker productivity. Productivity increases significantly when people are working in healthy buildings. Improved lighting can increase individual productivity by 0.7–23% and reduce headaches and SBS symptoms by 10–25% [56]. When employees were in buildings that focus on health and well-being, they experienced a 42% reduction in incidence of SBS symptoms and a 2% reduction in sick leave rates [103]. The productivity gains from healthy buildings also have considerable economic benefits. This is because sickness absenteeism caused by building-related illnesses and voluntary absenteeism due to a strong aversion to unpleasant work environment can entirely reduce individual productivity [104]. Other economic benefits include increased health care savings, lower health care costs for occupants and employees, faster recovery for patients, and improved staff retention [18]. Secondly, by selecting appropriate ventilation strategies, such as advanced HVAC control [105], natural ventilation [106], it is possible to improve energy efficiency and reduce energy consumption while simultaneously maintaining good indoor air quality [107,108]. Various air filtration technologies can effectively improve indoor air quality by reducing pollutant concentrations and removing air pollutants [36]. Finally, the most important social benefit of healthy buildings is to improve the health and well-being of occupants who live and work in them [103]. This is somewhat different from the focus on social sustainability in green buildings. Valdes-Vasquez and Klotz believe that it is important to involve stakeholders, including end users, to assess the social impact of green buildings and to consider the local community [109]. Previous studies have confirmed that healthy buildings can help reduce energy consumption, water consumption, and provide clean air, spatial environments, and health-friendly public facilities. In addition to the benefits mentioned above, occupants, as the ultimate recipients of the building's functions, need multiple levels of health and well-being. Therefore, increased social connection and improved mental health are features that distinguish healthy buildings from other buildings [18].

3.4. Guide

To implement healthier buildings, several international and government standards, guidelines and building rating systems that incorporate the concepts of health and well-being have been developed, such as BREEAM, LEED, WELL and Fitwel (Fig. 7).

3.4.1. Certifications with health elements

As afore discussed, the industry is not starting from scratch, as different health metrics are addressed in LEED, BREEAM, and DGNB.

Fig. 7. Guide for healthy buildings.

However, the percentage of human health-related scores varies widely across standards, with studies noting that human health-related scores in BREEAM account for only 15% [110] and 16% in LEED [111]. And each certification has its own drawbacks. Specifically, although LEED contains guidance on improving indoor air quality, promoting physical activities, nutrition, mental health and comfort, some strategies do not clearly state their potential health benefits and/or require practitioners to choose a specific health-related action. So practitioners must intentionally apply LEED to maximize its potential benefits Since BREEAM introduced a formal, separate category of "health and well-being" was introduced in the 1998 edition, it has focused on health and well-being needs associated with the built environment, with corresponding measures to address key issues such as ventilation, thermal and visual comfort, and air quality. But it sets performance in a result-oriented way, rather than over-prescribing design solutions. This means that factors such as building layout or aesthetics are not currently included. Compared with other certification systems, DGNB assesses the overall performance of a building rather than on specific measures. DGNB system has its own standards to assess air quality in the indoor environment, and limited buildings with harmful air to occupants will not receive a DGNB certificate. Nevertheless, rare health metrics are covered and additional emphasis has been placed on assessing sustainable buildings and urban areas.

3.4.2. Target healthy building certifications

While the term 'healthy building' is relatively new, several more targeted certification programs have emerged which offer specific scientifically derived standards to guide the practice. Sophisticated certifications systems for healthy buildings at this stage include WELL Building Standard (WELL, USA), Fitwel certification (Fitwel, USA), Green Mark for Healthier Workplace (GM-HW, Singapore), Healthy Building: A Guide for Developers and Contractors to Build and Transform (HB, France), Standard of Building Biology Testing Methods (SBM-2015, Germany), Assessment standard for healthy building (ASHB, China), among which the most widely used are WELL and Fitwel. WELL is a performance-based system for measuring, certifying and monitoring developed environmental characteristics that affect human health and well-being, and it explores how to optimizes the design, operation and behavior of the places where people live and work. Fitwel is a competitor to WELL that addresses similar building health factors, which allows the assess of not only individual sites, but also the surrounding community.

All these standards are developed by national health building design and research institutes, which can be used to evaluate healthy buildings. These evaluation standards are generally consistent in structure but different in specific evaluation objects, evaluation requirements and grade classification. Considering evaluation targets, various standards are applicable to different building types. For instance, WELL v2 is applicable to all building types and different evaluation indicators have been developed for different building types [112]; the Fitwel is applicable to residential and office spaces [113]; and the GM-HW is only applicable to office buildings [114]. For evaluation requirements and grading, the WELL calculates building score by summing them for prerequisites and optimization conditions, and then classifying certification as silver, gold and platinum [112], and if the prerequisites are not met, WELL certification will not be obtained. Fitwel is rated based on the application of 55 evidence-based design and operational health strategies, resulting in a Fitwel rating of one, two and three stars based on the total score [74]. ASHB divides indicators into control points, scoring points and bonus points, and measures the degree of healthy design and healthy operation through measures or results after meeting control points. Finally healthy buildings are classified into one, two and three stars based on the sum of evaluation and bonus points scores [115]. Meanwhile, healthy building systems are complex and vary among countries and building types, so they differ significantly in terms of function, regional climate, environment, and occupant behavior, resulting in each standard shows differences in specific items and the weight of indicator [116]. For example, the proportion of water in ASHB is as high as 16%, second only to air (24%) and comfort (22%), while that in WELL is only 8%, which is similar to fitness (8%) is tied for the two least weighted indicators. And, WELL pays more attention to the influence of psychological factors on human health, with spiritual accounting for 17%, second only to air, while ASHB does not involve spiritual indicators. But ASHB factors take into account the aging in China, it also involves human and service for senior activities and health care facilities. Hence, regional characteristics, such as the stage of social development and living habits, should be thoroughly considered during the formulation of standards and the selection of indicators. Nearly all evaluation is based on dose exposure, explicitly, determining a certain dose of safe or comfortable exposure to light, sound, air quality, water quality, and room temperature. Amatkasmin et al. (2022) stated that a healthy indoor environment should not be defined by safe exposure levels alone, but should be more occupant-centered, considering psychological and physical health effects of occupants [117]. Although the current standards cover many health elements, they rarely offer guidelines beyond health and comfort-related elements, such as epidemic prevention [115] that is a very important lesson that the COVID-19 has taught us, and do not consider a fuller, psychological conceptualization of wellbeing [118]. Therefore, judging health performance of buildings from dose exposure alone is not comprehensive enough. More research on specific health effects of buildings on occupants is needed to further improve living standards.

3.5. Action

Healthy buildings can be achieved with measures that are undertaken before, during, or after they have been constructed (Fig. 8).

3.5.1. Before building construction

Prior to architectural design, pre-design target performance identification is tasked as the highest priority [62,70]. So, it is extremely important to identify healthy building performance indicators. During design stage, site selection, structural design, and architectural design are regarded as the top three key factors [4]. Selecting a building site is one of the most important decisions when designing a building, as a wrong choice can generate negative health and environmental impacts as well as significant economic losses. Therefore, actions including providing more reliable, safe and affordable transportation options, promoting public health, improving overall air quality, exposing to nature, reducing greenhouse gas emissions, and investing in creating healthy, safe, walkable communities can be performed. Meanwhile, the site can be selected with full consideration of ecological protection and low-carbon convenience, using the surroundings with a good ecological environment (e.g., green spaces such as forests and parks and blue spaces such as lakes and rivers [119,120]) and supporting facilities (e.g., medical care, all-age education, healthy food, convenient living) to create eco-friendly and healthy community for occupants [121]. At the beginning of the design, spatial layout should be considered comprehensively to enhance the sociality and happiness of the occupants and promote social interaction. In addition to factors such as building use requirements and building mechanics, the basic attributes of the building itself, such as the shape, size, orientation, image, and occupant density, should be included. The size of building largely affects human behavior in buildings [122]; building orientation is related to whether occupants' requirements for ventilation, lighting, daylight and landscape are met [123]; visual effects produced by the form, light and shadow, color, texture and spatial openness of architecture can directly or indirectly affect people's mental health [124]. And, biological design is often used to improve the indoor environment through natural landscaping with indoor plants, fresh air and natural sounds in the phase of healthy building design. Introducing sustainability elements, such as energy efficiency, at the beginning of the design may be able to offset some air pollutant emissions and thus improve health benefits. During this stage, corresponding design services such as building information modeling (BIM) or BIM-based performance simulation play a primary role and can help create a healthier building from the start [125,126]. Other design services including computational fluid dynamics (CFD) modeling [61], box-model with mass balance method [61], DeST

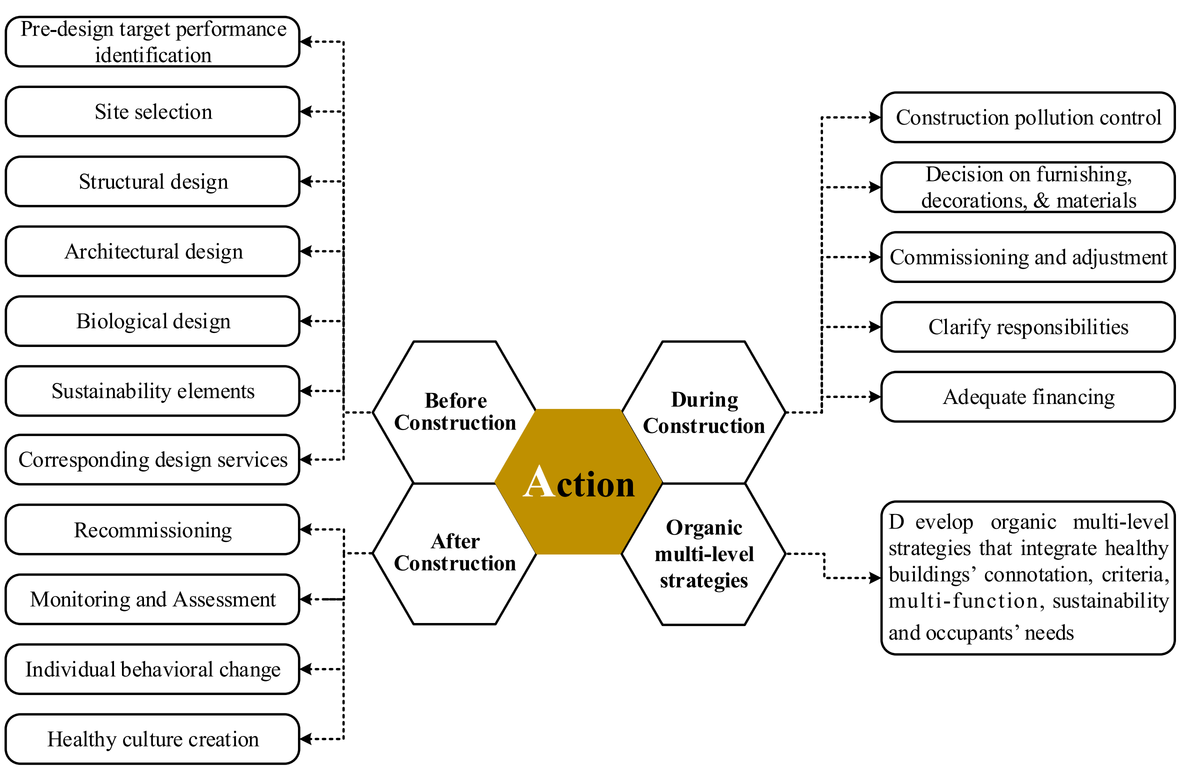

Fig. 8. Actions of realizing healthy building.

simulation [127], EnergyPlus [106] and life cycle assessment [59] all allow to assess how different design will affect the building in the future.

3.5.2. During building construction

From Fig. 2, a majority of existing studies focused on the design phase rather than the construction phase of healthy buildings. This finding is also consistent in green buildings, where Muller et al. (2019) reported that most green building research focused on the design phase rather than the construction phase [128]. However, Mao et al. (2017) stated that air pollution, waste water and solid wastes, noise pollution, and elevated radiation generated by contamination of construction materials from certain construction activities (e.g., cutting materials) will directly affect the health of workers and residents near the construction site [4]. Therefore, to mitigate the effects of construction pollution on workers, certain actions are considered necessary and effective, such as application of personal protective equipment (solid helmets, safety glasses, reflective undershirts, closed shoes, gloves, etc.), temporary barriers around hazardous equipment and necessary occupational health training, as they can directly reduce the level of exposure to contaminants and maintain a healthy working environment [129,130]. Application of high-quality building materials is a key measure to achieve high indoor air quality, as this affects exposure levels of indoor pollutants such as dust, mold and volatile organic compounds (VOCs) [21]. Key products include furniture, flooring, paints and coatings, adhesives and sealants, wall coverings, wood products, textiles, insulation and decorative materials [56]. Natural materials has always been associated with advanced health and well-being, with studies proving that employees surrounded by natural wood surfaces have higher personal productivity and concentration [131]. Moreover, studies have shown that the use of natural and environmentally friendly building materials can reduce greenhouse gas emissions by 5%–99%, helping to improve the resource efficiency of the built environment and achieve emissions reductions at the product level, thereby effectively mitigating climate change [132]. Therefore, decisions about home furnishings, decorations, and materials are also a major important action.

Meanwhile, continuous commissioning and adjustment throughout the construction phase is a major undertaking to ensure a healthy building performance [70], which will ensure that equipment and systems are optimized and the completed building is free of harmful contaminants. A third-party commissioning agency can ensure that the building is constructed in accordance with American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) or mandatory LEED, WELL and Fitwel certification system requirements, and will also ensure that the various equipment and facilities in the building are working properly. And, actual construction process can also lead to indoor air quality problems, partly due to separation of responsibilities between the professionals involved in design and construction teams, and that financing and bidding constraints can lead to a lack of construction quality, resulting in unsatisfactory building health performance [50]. Therefore, clarifying the responsibilities of all parties and obtaining adequate financing is a necessary action to maintain health performance during construction [133].

3.5.3. After building construction

After the building is constructed, actions to maintain the health performance of the building mainly consist of :

(i) *Recommissioning.* Healthy buildings may lose their healthy characteristics due to changing circumstances as time proceeds [70]. It is necessary to determine if the building still meets criteria of the health performance after these changes, which can be performed through sustainability assessment. Therefore, recommissioning is especially important in this phase. On the one hand, previously uncommissioned buildings become healthier after being commissioned [134]. On the other hand, if the building has been commissioned during construction, recommissioning helps assess whether repairs or adjustments are needed to upgrade the building. This is especially important because older buildings were often built to less stringent standards than modern ones. Consequently, they often do not meet today's health standards [135]. For example, by adopting an appropriate HVAC system can improve ventilation and help prevent the spread of respiratory illness in indoor spaces. However, older systems may need to be updated or have improved ventilation and filtration capabilities to meet current ventilation standards, such as the updated ventilation guidelines released by the U.S. Centers for Disease Control and Prevention (CDC).

(ii) *Monitoring and Assessment.* Acoustics, daylight, air quality and filtration, thermal control, proper HVAC systems, humidity levels, and amenities are all factored into healthier buildings. Studies have revealed that high-performance ventilation strategies reduce respiratory illnesses by 9–20% [56]. Therefore, it is particularly important to monitor, control and evaluate each health performance indicator of healthy buildings. Emerging technologies empowered by artificial intelligence (AI) that enable real-time sensing, learning, decision-making and prediction, for instance, the Big data, cloud computing, the Internet of Things (IoT), show great potential for implementing healthy buildings. These smart objects with powerful sensing and connectivity capabilities could revolutionize the way we monitor our environment and even change almost every aspect related to healthy buildings [18]. Specific actions include building automation systems (BASs) [136], IEQ inspections, ambient assisted living (AAL), Internet of Things (IoT) [31], installation of sensors such as IAQ sensors, window state sensors, wireless structural health monitoring sensors [137] and mechanical ventilation sensors [138], "sensible -knowable-controllable" intelligent health environment system, home based health intelligence service platform, robots capable of performing tests, wearable health monitors, multimodal and multi-scale data for health performance assessment [50]. Several common data analysis tools, including BIM [139] and business intelligence (BI), can digitally centralize elements, extract and analyze large amounts of data, thus enabling real-time online monitoring of data and more accurate and rapid management decisions. Additionally, another key to determining the effectiveness of a healthy building strategy is to monitor indicators of occupant experience, with common actions including post-occupancy evaluations of occupants [140,141]. When occupants are dissatisfied with a facility, this may signal that it is non-functional, inefficient or irrelevant [140]. In the long term, we will see several personal air quality monitors in the future, which allow people to measure airborne particles and gases in time [142].

(iii) *Individual behavioral change.* Except for the inherent design in the built environment, other components depend on the behaviors of occupants. Evidences have shown that building occupants play an important role in maintaining a healthy indoor environment, and their behaviors including personal cleaning habits, ventilation habits, exercise habits, furniture and appliance purchasing choices, and how occupants use them can also affect the building health performance [56,138]. For example, occupants who use air conditioning while sleeping often exhibit more SBS symptoms than those who use natural ventilation [143].

(iv) *Healthy culture creation.* A healthy community starts with the development of a culture of health. For one thing, necessary services are an effective grip on the external promotion of human health. For example, promoting physical activity is one of the numerous ways to support health in the built environment [144]. The services provided mainly include setting up cultural exchange venues suitable for different age groups, designing spaces that support attentive dining, policies that encourage healthy food choices, providing medical services and emergency assistance, building a healthy building information service platform, providing occupants with a healthy building usage manual before moving in, conducting satisfaction surveys after moving in Ref. [141]. For another, regular health promotion activities are effective to safeguard cultural health [18], namely, monitoring residents' health by providing free physical examination, improving the awareness of health through disease prevention and control measures against infectious diseases, and providing psychological and behavioral support through psychological counseling.

3.5.4. Organic multi-level strategies

As afore discussed, it is clear that it is beneficial to take some appropriate measures to promote healthy building performance before building construction, during building construction and after building construction. However, healthy buildings contain metrics, such as IAQ, that are complex problems that can not be fundamentally solved by implementing a few simple actions [145]. The reason is that healthy buildings concern occupants, and as people's understanding of health increases and technology changes, the demand for health becomes higher. For example, a number of innovative technologies have been developed to reduce the transmission of COVID-19. Possibly effective actions include installing HVAC systems with ultraviolet germicidal irradiation (UVGI) and bipolar ionization to improve air quality, adding non-contact routes such as smartphone-controlled elevators, automatic door opening with face recognition, changing the geometry of the roof to introduce more open spaces [37]. However, these actions may cause some other problems, such as inappropriate use may increase energy consumption and economic costs. More importantly, increased technological innovation may result in more environmental issues, including but not limited to chemical pollution (including ozone, sulfur dioxide, nitrogen dioxide, formaldehyde, etc.) [146]. For example, studies have shown that electronic filters, while helping to remove particulate matter, may also generate new pollutants such as ozone and increased concentrations of ozone-induced byproducts such as formaldehyde and nonanal [147,148]. Therefore, a full risk assessment and measurement before the application of innovative technologies is required. And CDC has released new ventilation guidelines based on user health considerations, which provides detailed recommendations on how to make indoor air healthier and help combat viral airborne hazards [149]. Key action to achieve a healthy building is to develop organic multi-level strategies that must integrate the following factors: changes in the connotation of healthy buildings, criteria for healthy buildings, diversity of functions, occupants' needs and building sustainability [150]. This aligns with the findings of Ghaffarianhoseini et al. who found that addressing SBS and maintaining a healthy indoor environment should not be limited to a single formula, as any health-related building is related to multiple interacting factors [15].

4. Discussion

There is a great potential to apply the proposed DNA framework for healthy buildings (Fig. 9).

4.1. Who can use the DNA framework for healthy buildings?

The DNA framework for healthy buildings presented in this paper will provide guidance to investors and developers, designers, engineers, operators and managers, facility managers, health and wellness specialists, policy makers, occupants, chemists, biologists, and environmentalists. Investors and developers, the decision makers, can use the DNA framework to determine strategic choices, such as site selection and building character. Designers can use the DNA framework to understand needs of occupants, clarify design goals based on the behaviors of occupants to support them at the forefront of design. Engineers can meet health standards by clarifying the healthy building actions listed in the DNA framework, communicating with the design unit, and adopting cut-edge technologies, sophisticated equipment and facilities. Operators

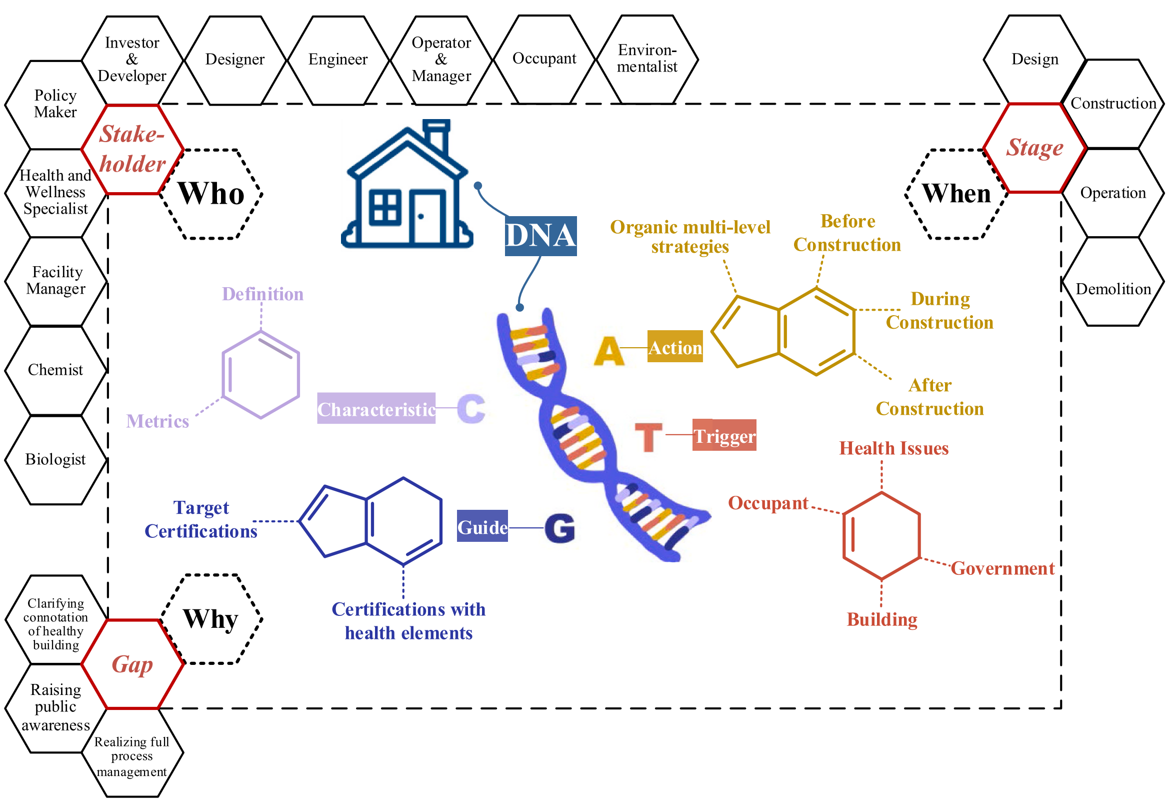

Fig. 9. Graphic representation of the application of DNA framework for healthy buildings.

and managers will use the knowledge gained from the DNA framework to regulate and manage the operational performance. Facility managers will understand the needs of occupants, adjust technical support and production standards of provided equipment in time to improve the healthy performance of products. Health and wellness specialists can use the DNA framework as a vehicle to shift passive treatment of diseases to active prevention and better disseminate the concept of health. Policy makers will apply the DNA framework to set higher and more adaptable requirements and guide the formulation of policies and regulations, as well as monitoring, implementation and evaluation mechanisms. Occupants are the ultimate demand subject of healthy buildings. They can learn the performance of healthy buildings from the DNA framework and combine it with their purchase power and demands for health to pursue maximum benefits when purchasing houses. Chemists and biologists can use this framework to systematically understand the nature of healthy buildings, which will help them deal with indoor pollution and propose appropriate methods and recommendations to safeguard the health of occupants. There is a general consensus that buildings consume large amounts of energy and release greenhouse gases that contribute to climate change. The DNA framework of healthy buildings can inspire environmentalists to improve energy efficiency and engage in the life cycle of buildings with the goal of promoting human and environmental health, thus truly improving building sustainability.

4.2. *When can the DNA framework for healthy building be used*?

A healthy building should be an all-round healthy one that covers the whole life cycle, including design, construction, operation and demolition phases. Therefore, the DNA framework proposed for healthy buildings can be used in the whole life cycle of the building. For design, the DNA framework allows developers and investors to select planning site and guide rapid decision-making in the early stage; and allows designers to more accurately analyze people's demands for healthy buildings, and apply such methods as CFD simulation, DeST, and noise simulation to simulate the wind, light, acoustic and thermal environment, as well as the vision of healthy buildings, and accurately predict building performance. During construction, the DNA framework will guide constructors to adopt appropriate technologies, equipment, and materials to achieve a high healthy building performance. Meanwhile, benefiting from DNA framework, constructors will concentrate more on the health of construction workers at construction sites and the pollution caused by materials, and formulate strategies to create healthy construction sites. In the operation phase, the DNA framework can provide building operators or managers with guidelines for assessing healthy building performance after occupancy, realizing measurable and verifiable healthy building performance indicators, effectively assessing physical, social and psychological conditions of occupants, and further providing target services and activities. During demolition, the DNA framework allows the assessment of the technical solutions adopted to maintain the health of occupants throughout the whole construction. It allows relevant stakeholders to develop appropriate renovation and demolition plans to reduce the impact of pollution on nearby occupants and workers during the demolition process.

4.3. *Why is the DNA framework needed for the realization of healthy buildings*?

The proposed DNA framework contributes to these following three aspects:

(i) *Clarifying connotation of healthy building.* Although plenty of research has been conducted on healthy buildings, most of the existing studies focus on indoor environmental health and the indicators that largely account for the evaluation standards such as air and comfort, they failed to emphasize the influence of the external environment on the construction of healthy buildings, and the health of the building itself and the building constructors. Therefore, the DNA framework can broaden the research scope for scholars and requires the relevant personnel to value the health of the building indoor environment while not neglecting the external environment.

(ii) *Raising public awareness.* The core of healthy buildings is people since they are the direct occupants of healthy buildings and have the closest relationship with them. However, due to lack of publicity, potential occupants lack a deep understanding of healthy buildings, and still experience a shallow level of ventilation and lighting, etc. Therefore, the DNA framework provides a broad knowledge framework for potential occupants of healthy buildings while focusing on their health, strengthens potential occupants' understanding of the connotation of healthy building, motivates occupants to purchase or lease healthy building projects, and promotes the formation of market-pulled scale development trend of healthy buildings.

(iii) *Realizing full process management.* Air, water, light and other indicators of healthy buildings are all result control, such as testing indoor air quality after renovation, and address it if it does not meet standards. But based on our redefinition of healthy building, the health performance should be monitored in multiple nodes during the whole life cycle of the building, so that pollution sources can be found and dealt with timely, which is continuous rather than a one-time evaluation. Meanwhile, although the existing standards or evaluation systems aim to provide occupants with safe and healthy buildings, they mostly focus on the design stage, rarely on construction and operation stages, and most of evaluations are also based on the testing results. However, the proposed DNA framework can provide guidance for corresponding personnel to explore technical support system covering the whole life cycle of the building, including healthy building design, construction, operation and maintenance, evaluation, performance testing, etc., and create a whole life cycle management mechanism from source control, process management to feedbacks.

4.4. *Future research direction*

Based on the above discussion, the main issues to be further explored for promoting healthy buildings were shown in Fig. 10.

4.4.1. *Life-cycle thinking*

As noticed from Figs. 2, 82 and 42 publications were collected around the design and operation phases respectively, while only 15 focused on the construction of healthy buildings. This indicates that research on healthy buildings mostly focus on design phase and neglects to pay attention to other phases. Therefore, one gap of previous healthy building research is that it fails to consider the whole life cycle in a holistic manner. As afore discussed, the review of building health performance during the construction and operation phases, in addition to timely identification of health hazards for repair, allow us to understand the core needs of occupants and develop timely contingency plans for emergencies, such as the COVID-19 pandemic, and to dovetail with and guide the design phase, thus promote the health of the building. As the benefits of healthy buildings continue to be noticed, the analysis of data obtained during the construction and operation phases, such as post-occupancy evaluations, information on occupant behavior and health, and why and how building occupants interact with the environment, will help the certification become more intuitive, as it may circumvent the risks and vulnerabilities caused by these factors. So, future research of healthy building should be extended to the whole life-cycle since each stage will contribute to the healthy building.

4.4.2. *Standard systems improvement*

While a number of countries have established standards or guidelines

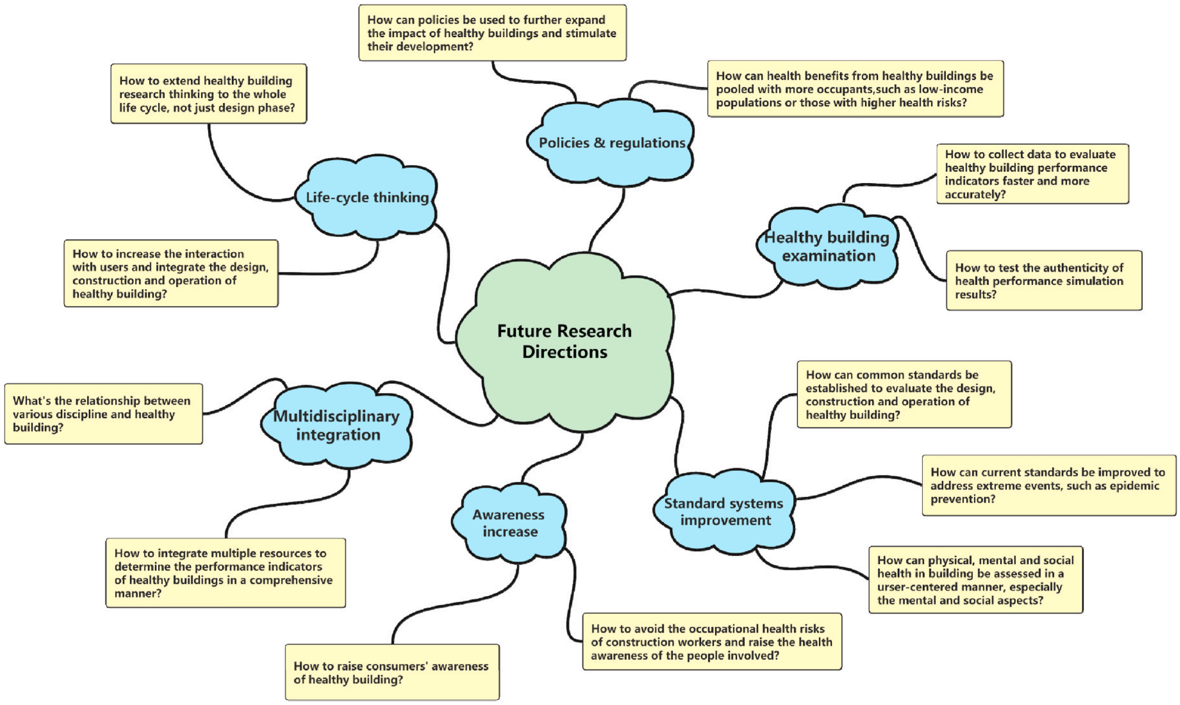

Fig. 10. Future research directions for healthy building.

for healthy buildings in conjunction with features, the metrics of concern vary widely and there is a lack of common standards and guidelines to assess how buildings are designed, constructed and operated to promote the health of their occupants. Additional research is needed to improve the standards and develop appropriate guidelines, as existing standards are not clear for extreme events (e.g., prevention of epidemics). Additionally, most of the indicators revolve around safeguarding health of indoor environment and promoting the individuals' physiological health, while little attention was paid to psychological and social aspects due to lack of relevant research. Thus, a deeper understanding of how building and occupant-related parameters can be linked is needed to promote physical, mental and social health in buildings. Nearly all of the standards for evaluating each indicator are developed based on dose exposure, and while this is more convenient and intuitive, it is not comprehensive since it is not user-centered. Therefore, future research should further understand the sources of indoor pollutants and their comprehensive impact on health.

4.4.3. Policies & regulations

Historically a large-scale change will require a shift in policy and demand that creates a top-down and bottom-up approach. For government, this means the formulation of new policies, incentives, and enforceable regulations. For healthy buildings, this may mean introducing and enforcing sustainable procurement policies, providing incentives to support the development of new technologies. For example, structures that demonstrate healthy design and construction should be eligible for dedicated funding and financing as well as market dividends. For end-users, there should be programs for low-income people or people with higher health risks. If healthy buildings become the broader population's expectation, the incentive to attract and retain talent will also motivate the government to develop policies accordingly. However, there is a large vacancy in research related to these policies on healthy buildings, and how to promote health-conscious individual behaviors and consumer awareness is still a priority for future research.

4.4.4. Awareness increase

Early project planning is critical to incorporating healthy building practices. Since healthy buildings should be centered on the health of the occupants, not only experts need to be involved in the process, but the needs of the occupants are very important, which requires the awareness of the occupants to improve. And there is still room for public health awareness and individual behaviors related to health promotion to improve, and if people can be successfully convinced of improvements in building health and safety under the context of the pandemic, then more people will seek healthy buildings. In addition, as can be seen from the redefinition of healthy buildings above, the awareness of construction workers cannot be ignored, which can be achieved through cross-sectoral collaboration and training. As more healthy building performance indicators are tracked, a data exchange platform could be established in the future to publish the progress of healthy building projects and the effects of certain contaminants on the health of occupants.

4.4.5. Healthy building examination

Just as people undergo regular physical examination, buildings should be routinely inspected for their performance as they may lose their healthy characteristics over time. Traditionally, post-occupancy evaluations have been the primary method to investigate people's experience in the building. However, it is difficult to obtain relevant data because occupants do not want to be disturbed, and most of the data at this stage are obtained based on surveys or interviews. With improvements in sensors, Wi-Fi, building automation aystem, data on healthy building performance metrics can be collected more quickly, accurately and cost-effectively. While these technologies enable the tracking of different types of data, they also have different drawbacks. For example, although building automation system can collect data from different sensors to provide necessary security control, HVAC system monitoring, lighting system, etc., the amount of data it collects is huge and may contain sensitive information that affects the privacy of the occupants [151]. Although Wi-Fi enables monitoring of occupancy, it cannot monitor indicators related to occupant behavior [42]. Accordingly, future research needs to develop appropriate methods to collect data, while surveys or interviews could be used as a supplement. Moreover, studies on simulation for healthy building performance, such as CFD modeling, DeST simulation, EnergyPlus, have always been the focus. These simulation software provide predictions of thermal comfort, energy consumption, environment and other indicators of healthy buildings, but the application of these simulation software requires a large amount of data and the output of the results is difficult to verify [152]. The core of healthy building is human-centered. The disadvantage of these simulation software is that the simulation of occupant behavior is random and unsystematic, and does not greatly match real occupant behavior. Meanwhile, few of them can test the authenticity of health performance simulation results in practice. Therefore, for future research, more efforts should be invested to test the models, use practice to guide the simulation, and narrow the gap between simulation and reality.

4.4.6. Multidisciplinary integration

Healthy buildings involve multiple disciplines such as architecture, public health, psychology, nutrition, humanities and social sciences, and physical fitness. As aforementioned, the development of organic multi-level strategies involves multiple areas of energy conservation, monitoring, technology, assessment, economics, and environment. Therefore, achieving this action requires comprehensive and systematic research that integrates multidisciplinary thinking. As healthy buildings combine health and architecture, there is also a trend of interdisciplinary research in this field. Therefore, the relationship between various fields, health and architecture requires continuous and in-depth research. As shown in Fig. 2, although there is a wealth of research supporting healthy building strategies, little information is known about the real performance of healthy buildings upon completion and occupancy. Therefore, a multidisciplinary effort to integrate multiple resources, including research institutions, universities, real estate industry, product manufacturing, medical service industry, property management, the age-friendly industry, and the fitness industry, has become an issue that must be faced in the development of healthy buildings. For example, the building industry should work with third parties, such as public health schools and certified project operators, to determine the performance metrics of healthy buildings comprehensively.

5. Conclusions

As a spatial carrier, the impact of building on occupants' physical and mental health is not only limited to the physical space of the building, but also includes the proper and health culture of the building. Healthy buildings are still in a sprouting stage, and a big gap still exists compared with green building in many aspects such as incentive policy, technical system and market maturity. It is foreseeable that healthy buildings will become the new direction of future construction industry. Therefore, a DNA framework for healthy buildings was constructed following a systematic review, which contains: i) characteristic, ii) triggers, iii) standard, and iv) actions. Ultimately, this paper redefines healthy buildings, clarifies the shortcomings of existing standards. By analyzing the current state of healthy building, it is concluded that future research should focus more on: i) life-cycle thinking; ii) standard systems improvement; iii) policies and regulations; iv) awareness increase; v) healthy building examination; vi) multidisciplinary integration.

This research novelly utilizes NVivo to conduct a content analysis of healthy building related publications, revealing a wealth of knowledge on healthy buildings from extensive literature and providing an effective method for revealing a panoramic view of an area of study. In contrast to previous studies that have focused only on green building or one metric of healthy building, this study provides a comprehensive and systematic DNA framework for healthy building, answering the three main questions of what healthy building is, why it needs to be developed, and how to achieve it. The results of this study help researchers understand the nature of healthy buildings, fill existing knowledge gaps, thus extend the body of healthy building knowledge.

Despite the research objectives have been achieved, this study has two limitations. Firstly, only five databases, Web of Science, Science Direct, Ei CompenexWeb, Taylor & Francis and Google Scholar, were searched, which may lead to other important publications being missed. Therefore, other databases such as Wiley should be included in the future. Secondly, the content analysis using NVivo is based on the authors' summary of the literature analysis. Although we try to maintain objectivity in the analysis process, it is still somewhat subjective. Hence, other methods such as bibliometric analysis should be considered for inclusion in the future.

Credit author statement

Hui Liu: Investigation, Writing - Original Draft, Writing - Review & Editing. Xiaoxiao Xu: Conceptualization, Writing - Review & Editing, Funding acquisition. Vivian W. Y. Tam: Writing - Review & Editing. Peng Mao: Conceptualization, Supervision, Funding acquisition.

Funding

This work was supported by National Natural Science Foundation of China [Grant Nos. 72071115 and 72101118].

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.

Data availability

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113460.

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