

Review

The Relationship between the Parameters That Characterize a Built Living Space and the Health Status of Its Inhabitants

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Abstract: Housing is an essential component of the living environment, and it has a substantial effect on physical and mental well-being. Multiple housing factors, including inadequate ventilation, overcrowding, construction materials, and exposure to allergens and pollutants, have been linked to a variety of diseases, such as respiratory ailments and dermatologic, rheumatologic, and cardiovascular disorders. The present narrative review shows the current state of knowledge in the field by centralizing and evaluating scientific publications with a focus on this linkage, detailing the implications for health status and the benefits of using natural materials in construction, implementing green building concepts, and applying technological transfer, where various decision factors can contribute to improving quality of life. Therefore, it is achievable to enhance the indoor air quality (IAQ) by promoting ventilation and air filtration, decreasing mold and moisture, and employing low-emitting materials in building construction and development. Overall, promoting healthy housing environments through an enhanced IAQ and using sustainable building practices can have a substantial positive effect on public health. To reduce the risk of housing-related diseases, future research should concentrate on identifying the most effective interventions to improve the living environment–health condition axis.

Keywords: housing; sustainable building; living environment; healthy environment; sick building syndrome; indoor air quality



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1. Introduction

Despite being mistakenly viewed by many public health scholars and practitioners in various countries as an “old” topic, not deserving attention, housing represents a fundamental and traditional concept of public health [1]. The indoor environment is a significant health indicator in both developing and industrialized countries according to numerous and compelling global studies [2,3].

Americans typically dedicate approximately 90 percent of their time to being indoors [4], encountering indoor pollutant concentrations that often surpass the typical outdoor levels by 2 to 5 times [5]. Escalated levels of indoor air pollutants significantly compromise housing security and markedly impact the health of individuals [6].

Especially when combined with chronic diseases, the constructed environment has an impact on the public health. A healthy diet, an active lifestyle, and less exposure to toxic environments all seem to be effective ways to lower the incidence of long-term illnesses in the community. The majority of urban and suburban settings, unfortunately, are not well constructed to support healthy behaviors or to foster a healthy atmosphere. Public health authorities can advise people and integrate policies on healthy lifestyles, but if they reside in physically inadequate environments, their well-being will be affected [7].

A home's structural and safety elements, like the way a house is designed, built, and preserved, as well as its physical features, the inclusion or lack of safety equipment, indoor air quality (IAQ), water quality, chemical exposure, residents' actions, and the nearby area, all have an impact on the safety and health of people. There is a strong and obvious connection between these housing characteristics and several injuries and diseases. Residences' structural and safety elements can make people more vulnerable to accidents; rise the levels of lead, chromium, and nickel in the blood; and exacerbate other conditions for the worse. Asthma, cardiovascular diseases, neurological impairments, gastrointestinal issues, and even cancer are all influenced by inadequate water and indoor air features. Moreover, acute intoxication along with additional toxic effects can be caused by certain chemicals found within or near the house [8]. Figure 1 shows the negative impact of poor living conditions that can affect human health.

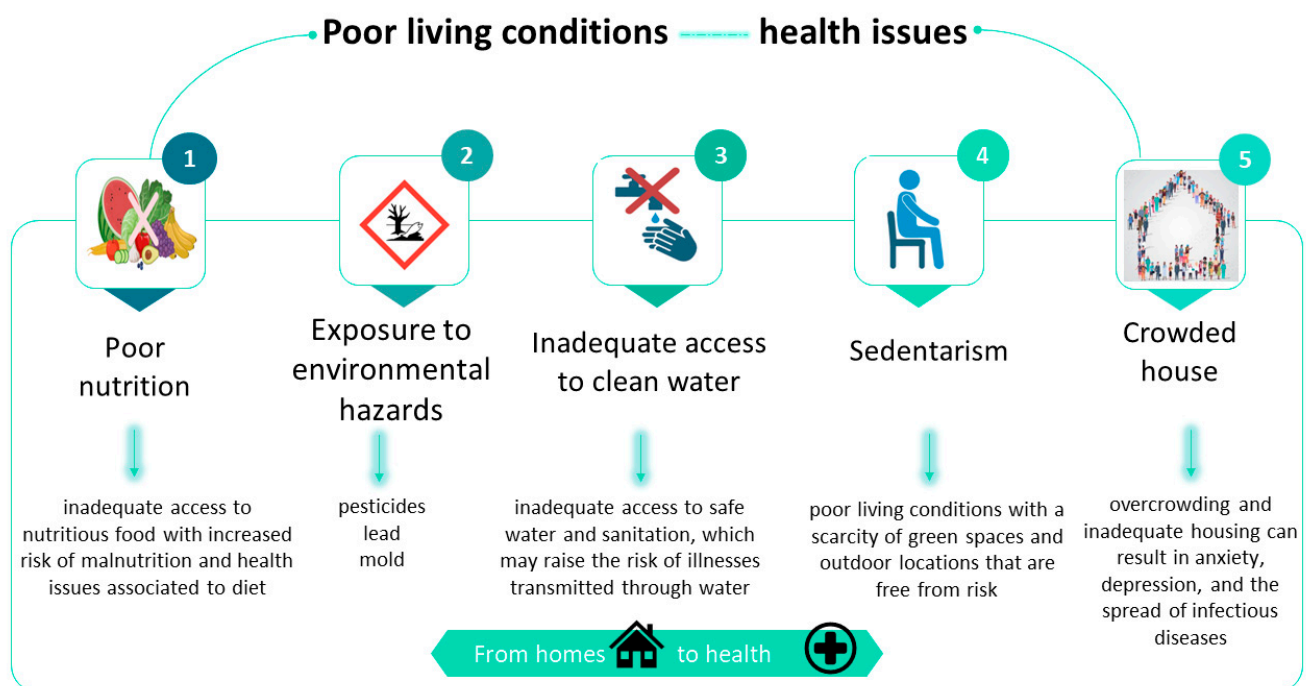


Figure 1. Impact of poor living conditions on the risk of diseases.

Considering the introduction of ecologically friendly construction ranking and certification methods in the 1990s, the trend toward environmentally friendly construction achieved significant importance. All environmentally friendly building certification programs place a strong emphasis on preserving the quality of the indoor environment. The emission of different chemicals used in construction into the indoor environment or other exposure networks, which have not been assessed and addressed in a systematic manner, makes up a significant part of indoor environmental quality (IEQ). IEQ is preserved or enhanced according to a variety of strategies in sustainable building ranking and certification systems, including promoting ingredient transparency, discouraging/banning the application of construction materials that contain specific chemicals which are detrimental to individuals or environmental well-being, improving airflow rates, and determining the air levels of chemical agents [9].

There is a significant rise in new construction materials being introduced into the market nowadays, but there are still insufficient data to fully understand their physical and chemical characteristics and assess any potential negative effects on human health and the environment. Therefore, their management must be based on both the current technology [10] and optimum waste disposal management [11].

Numerous historical contexts in which construction supplies were widely used in society revealed unanticipated sustainability implications for health and the environment [12]. Sustainable buildings have a significant impact on human health at two tremendously important levels: providing optimized indoor environments has a direct impact on individuals, while indirectly having an impact on the general population by reducing energy use and, consequently, air pollutants that aggravate asthma, cause cardiovascular illness and early death, and influence global climate change, which is linked to a multitude of detrimental effects on human health [13].

According to a green building standard, more than 3.5 billion square feet have been approved so far for such construction, demonstrating the growing popularity of sustainable building design. Green structures reduce the negative influence on the environment by using less energy and water and causing less environmental disturbance on the construction site. Sustainable buildings, which also seek to improve human health through the design of healthy indoor environments, are probably not as common. The advantages of less energy and water use are well known, but the possible advantages of green buildings for human health have only recently come into the focus of researchers [14].

The concept of addressing healthcare from the perspective of an individual's surroundings is of increasing interest in the current context of rapid technological advancement and accelerating environmental change. The present narrative review aims to:

- Provide a comprehensive overview of the connection between the living environment and health conditions, with a particular emphasis on housing factors, interior air quality, green building practices, and the implications of technology transfer for health issues according to building construction approaches;
- Update the current state of knowledge by targeting this relationship, which can generate major health risks, especially as many studies have investigated the effect of environmental factors on health outcomes but very few have examined the relationship between housing and health;
- Contribute to the scientific field by providing novel insights into the most significant stakeholders with implications for the interaction of housing factors with health and the environment in order to reduce the risks of housing-related diseases, increase IAQ, and increase awareness of sustainable building approaches.

2. Methodology of Research

The current narrative review filters, centralizes, and summarizes scientific publications provided by undertaking a thorough literature search related to the link between built living spaces (i.e., housing factors, indoor air quality, comfort standards, construction materials, etc.) and the potential health issues resulting from living conditions. Subsequently, it involves practical concepts such as green buildings, technology transfer, and the One Health concept that can contribute to improving health status. In this regard, the multidisciplinary team conducted a literature search across databases with wide coverage on the two topics addressed (i.e., MDPI, PubMed, ScienceDirect, Scopus, and Web of Science). Figure 2 illustrates the operational procedures based on PRISMA, outlining the processes involved in selecting, evaluating, and ultimately including publications as bibliographic references. This methodology aligns with the guidelines proposed by Page et al. [15].

The search algorithm included relevant terms for the addressed topic, linking some of them using the Boolean operators AND and OR. Excluding publications not in English or lacking relevance to the current paper, along with those deviating from an article or book-type format, a meticulous selection process led to the inclusion of 182 bibliographic references to authenticate the information presented in this paper.

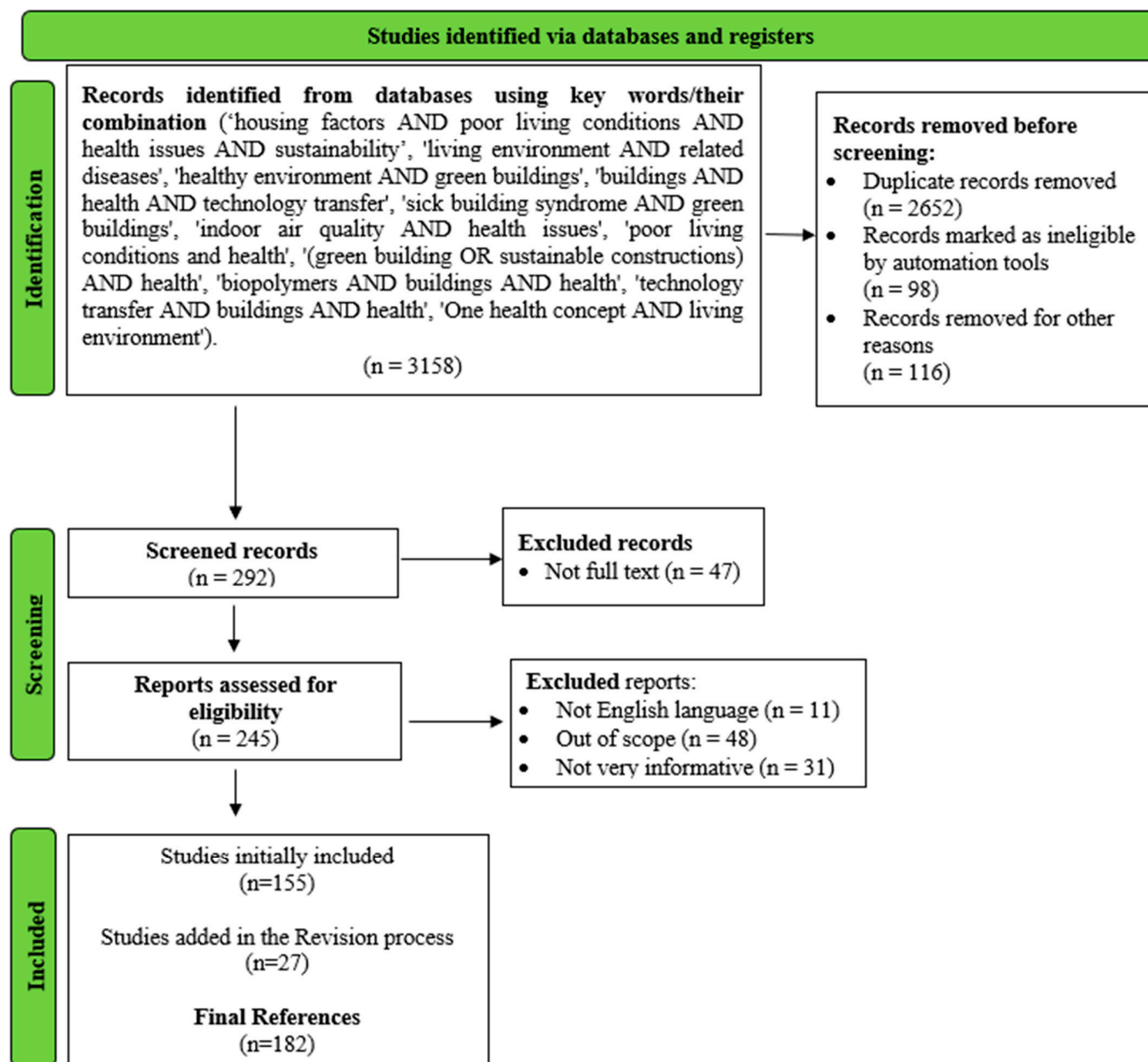


Figure 2. Literature selection depicted in a PRISMA 2020 flow diagram.

The present manuscript is organized and structured into 9 sections based on the design and principles of a narrative review, coupled with a search for and evaluation and update of the state of knowledge within the link between the indoor living environment and health issues. The first section introduces the conceptual framework and methodology for selecting the scientific literature and clearly addresses the purpose of the paper. The 2nd section refers to the most common pathologies that can result from living conditions. The 3rd section presents the implications of the link between building materials and possible health issues and presents a series of quality standards as well as the implications of biopolymer composites for the development of sustainable and healthy buildings. The 4th section details the impact of indoor air quality on health status and presents the primary sources of indoor pollution in relation to the area of the house. Section 5 is devoted to presenting the importance of green buildings for health, while the 6th section introduces the implications of technology transfer on the link between building construction and health. Section 7 addresses the concept of One Health for sustainable and healthy development, while Section 8 is dedicated to a series of discussions and future perspectives. The last section presents the relevant conclusions.

3. Diseases Resulting from Living Conditions

3.1. Respiratory Diseases

3.1.1. Asthma

The direct link between poor housing quality and asthma lies in exposure to indoor allergens. Homes lacking active maintenance exhibit common structural issues, fostering allergen exposure. Water intrusion, stemming from plumbing and roof leaks or damp basements, can lead to mold growth and attract pests. Cracks, poor housekeeping, and leaks correlate positively with cockroach allergens. Houses constructed before 1951 show elevated dust mite levels. Basements or crawl spaces predict a heightened allergen presence. Older home carpets accumulate substantial dust loads, resulting in exposure to dust mites, pet dander, and pests [16].

Several in-home environmental exposures that can aggravate asthma in children have been documented. The electronic health record (EHR) statistics on exposures are lacking for numerous children with asthma, even though spatially linking environmental and social exposures to EHRs can help with exposure evaluation, epidemiology, and clinical treatment. For better management of the issue, it has been assumed that the presence of interior allergens triggers asthma [17].

Dermatophagoides farinae and *Dermatophagoides pteronyssinus* are the two most prevalent types of dust mites. Our innate and adaptive immune systems are stimulated by dust mite antigens, and *Dermatophagoides farinae* causes inflammatory cell apoptosis in the bronchial epithelial cells [18,19]. Nearly 85% of allergic and asthmatic kids have sensitivity to one or both types of dust mites. Dust mite exposure is linked to altered respiratory function, higher bronchial hyperresponsiveness, and greater inflammatory responses in infants who have developed a dust mite allergy [20,21].

Multiple medical investigations have shown links between potential hazards in the home environment and the poor health conditions of its inhabitants [22]. A low IAQ has mainly been considered responsible for the onset and worsening of asthma [23]. Since the incidence of asthma can be two to four times higher in vulnerable groups like racial/ethnic minority groups, recent immigrants, and people living in poverty, where living space ambient exposures may be elevated, reducing the interval for which they are exposed to indoor contaminants is particularly crucial for these groups [24].

In a cross-sectional research work, over fifty percent of the investigated houses had detectable amounts of significant allergens (i.e., *Alternaria alternata*, cockroaches, dogs, dust mites, cats, and mice), and the majority of the residences had at least three allergens at elevated levels [25]. The most researched allergens in the onset of asthma and one of the most frequent sources of allergens in homes are considered to be dust mites [26].

The prevalence of asthma symptoms increased in two buildings where the polyvinyl chloride floor material had shown evidence of dampness-related deterioration of di-ethyl hexyl-phthalate, as indicated by the existence of 2-ethyl-1-hexanol in the composition of the indoor air. Increased relative humidity in the top concrete floor structure and ammonia in the floor were also linked to symptoms of asthma [27].

In a case-control study, asthma risk was associated with the presence of plastic wall materials and wall-to-wall carpeting at work, in particular when there were mold issues, in logistic regression evaluation adapted for confusion. Asthma onset was also associated with the use of floor-leveling plaster at home over the previous 12 months. Moreover, these results emphasize how important it is to take into account the impact of the materials used in floors, walls, and other surfaces inside the home on health [28].

Investigations on the relationship between solid fuel use and the onset of asthma have only been conducted in rural areas in developed countries, in which heating with coal and wood is generally more prevalent. Cooking with wood or coal has been linked to a higher risk of developing pediatric asthma, according to one Burden of Lung Disease survey on people in Southeastern Kentucky. The research found no correlation between heating solid fuels and the incidence of asthma [29].

3.1.2. Lung Cancer

- Housing conditions are believed to influence cancer care and its results through various mechanisms, with substandard housing potentially elevating the likelihood of lung cancer [30]. Among the factors that affect IAQ and are implicated in the development of lung cancer are volatile organic compounds (VOCs), passive smoking, and solid fuel emissions [31].
- Presently, exposure to radon in residential settings is acknowledged as the primary cause of lung cancer among non-smokers and the second leading cause among smokers, second only to tobacco [32]. When uranium and radium decompose in the soil, radon is produced as a radioactive natural gas [33]. A 2019 research work conducted in Spain found that non-smoker lung cancer sufferers had radon exposure levels in their homes that were higher than 200 Bq/m³ [32]. Additionally, between 2.2% and 12.4% of lung cancer fatalities in France in 1999 were linked to radon presence in their homes.

The respiratory health of residents is also at risk due to asbestos fiber exposure. A significant health issue linked to prolonged contact with asbestos in living spaces and the environment is malignant mesothelioma [34,35]. Numerous occupational and epidemiological investigations have concluded that inhaling asbestos increases the risk of mesothelioma and lung cancer. According to a study on heavily asbestos-exposed employees, the risk of lung cancer was higher, and a comparable rise in risk for people exposed to relatively low levels of radiation for a period of 20 years was registered [36]. The length of an asbestos fiber determines how carcinogenic it is. Short asbestos fibers are not as hazardous to humans as long and medium-length asbestos fibers (>5 µm). Chrysotile has been reported to be the most frequently encountered type of asbestos fiber in lung plaques caused by exposure to asbestos, according to an autopsy investigation involving Italian shipyard workers. The majority of the fibers had an average length of 8 mm [37].

When coal is burned inside a house for heating or cooking, PM and gas emissions are generated, altering the IAQ and showing the possibility of triggering carcinogenic processes. These emissions might include several cancer-causing substances like carbon monoxide, polycyclic aromatic hydrocarbons (PAHs), formaldehyde, and benzene [38]. A higher chance of developing lung cancer is linked to an increased indoor smoke concentration [39]. Figure 3 depicts the environmental and household determinants of lung cancer [40].

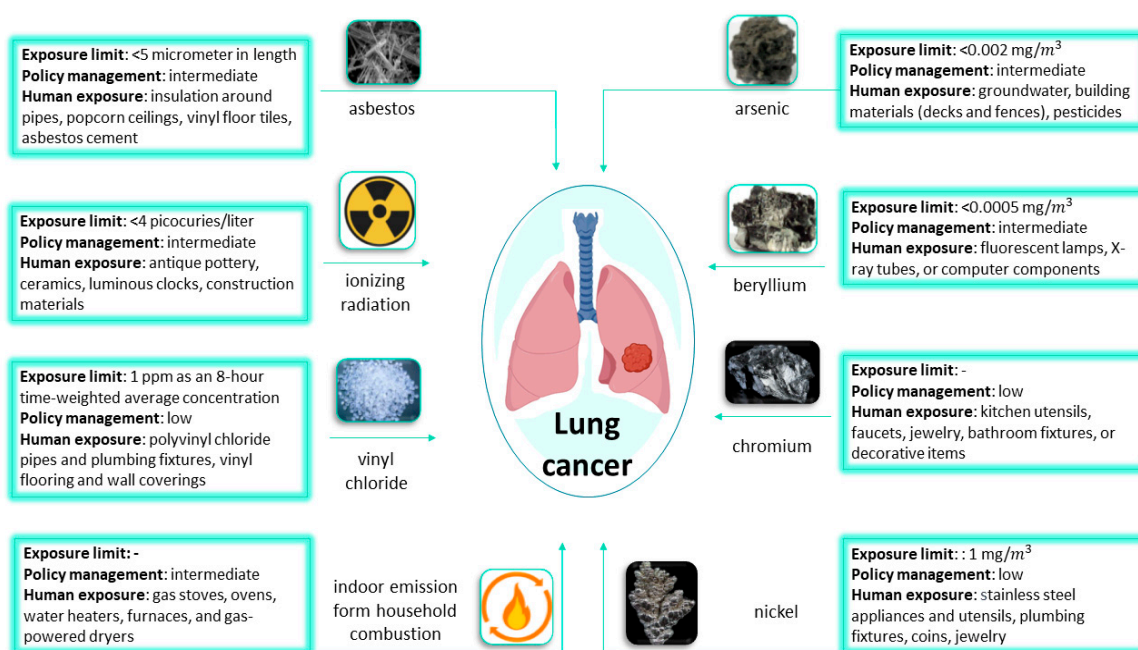


Figure 3. Risk factors in the development of lung cancer.

3.1.3. Chronic Bronchitis

Apartments, mobile homes, houses, and townhouses were among the various housing options after the National Health and Nutrition Examination Survey was conducted from 1999 to 2006. The respiratory symptoms associated with exposure to a low IAQ included dyspnea, coughing, wheezing, and sputum; respiratory ailments such as chronic bronchitis, chronic obstructive pulmonary disease (COPD), emphysema, and asthma were also present. The analyses comprised 11,785 subjects who were 40 years of age or older. Subjects residing in mobile homes were found to be more susceptible to respiratory impairments in contrast to those in single-family residences. Moreover, for people residing in apartments, it seemed considerably less probable for them to suffer from respiratory disorders.

The construction and building sectors pose a problem for worker health and safety protection, despite significant efforts to limit dust exposure. Exposure to silica and asbestos dust for construction workers has been determined to cause restrictive lung illnesses [41]. Yet, non-specific building dust is another potential danger that construction workers face. The occupational exposure limit (OEL) for the amount of dust that can be inhaled varies from country to country, although it is set at 5 mg/m³ in the USA, in nearly every country in Europe, and in all Scandinavian states. A recent Dutch study, however, revealed that the construction sector surpassed this respirable dust exposure limit in 11% of assessments [42].

Monsó studied 105 non-smoking animal breeders who worked in enclosed buildings, and the results suggested that the main cause of breeders' COPD may be related to the increased organic dust levels found in these environments. The scientific outcomes suggested that the likelihood of having COPD increases with an increasing dust concentration [43].

In a cross-sectional study, 40 controls, who had no active contact with construction dust, and 85 construction employees were examined. Using the National Institute for Occupational Safety and Health (NIOSH) method no. 0600 and a brand-new Fourier-transform-infrared-spectroscopy-based technique, the employees' exposure to silica aerosols and particulates not otherwise specified (PNOS), respectively, was observed. The average worker exposure to inhaled PNOS was 0.13 (0.019) mg/m³, and to silica, it was 9.8 (0.35) mg/m³. As opposed to the control group, the construction workers' mean lung activity indicators were considerably reduced. A modest restriction was present in the lungs of 51.8% of construction workers, whereas blockage was present in 4.70% of cases [44].

A connection has been found between COPD and household air pollution (HAP) in exposed people in comparison to people who were not subjected to biomass smoke. Little is understood regarding the way HAP can contribute to COPD progress in low- and middle-income countries, with most of the investigations on COPD focusing on tobacco exposure in high-income environments. Even though there are inconclusive data indicating a direct causative link between COPD and HAP, it is possible that lifetime exposure to HAP has direct and indirect consequences (poor social and economic position, recurrent acute lower respiratory tract infection (ALRI)) on pulmonary activity that favor COPD [45].

The association between the domestic usage of solid fuels and the occurrence of COPD in high-income settings has not been as well examined due to the lesser utilization of solid fuels in developed countries. Even so, a few research investigations have suggested that the use of solid fuels for heating and the incidence of COPD in the United States may be related. According to a 2010 case-control study by Sood and collaborators investigating 425 females with wood smoke exposure present and 1087 controls, self-reported exposure to wood smoke was independently linked to a heightened prevalence of airflow obstruction and chronic bronchitis. The odds ratio for airflow obstruction is 1.96 (95% confidence interval: 1.52–2.52), and for chronic bronchitis, it is 1.64 (95% confidence interval: 1.31–2.06). These odds ratios suggested an increased likelihood of experiencing airflow obstruction and COPD among individuals with self-reported wood smoke exposure compared to those without such exposure. Moreover, wood smoke exposure emerged as a significant predictor of all the studied outcomes related to COPD, with a significance level of $p < 0.001$ in all analyses [46].

The incidence of COPD was determined by the National Health Interview Survey, and community-level usage of solid fuels (i.e., wood and coal) for heating was determined by the US Census. A subsequent nationwide study, representative at the national level, explored the influence of sociodemographic factors on the prevalence of COPD both at a nationwide scale and specifically among individuals who had never smoked. The estimated prevalence of COPD among individuals who had never smoked was 4.3% (95% confidence interval: 4.1–4.6%). Urban, non-poor communities exhibited the lowest prevalence. Among non-smokers, residing in rural areas was also linked to COPD (odds ratio, 1.34; p -value < 0.001), as was the use of coal for heating in the neighborhood (odds ratio, 1.09; p -value < 0.001). The results showed that a greater community-level use of coal for heating was linked to a higher probability of self-reported COPD among never-smokers [47].

3.1.4. Respiratory Infections

Analyzing the findings across the reviewed articles, four distinct categories of housing-related risk factors for respiratory infections emerge: indoor air pollution factors, housing structural-related factors, outdoor environment factors, and housing non-structure-related factors [48].

According to experimental studies, children who are socioeconomically at risk of respiratory disorders are more likely to live in areas with high pollution levels, including ozone, coal dust, and PM. Based on the size and solubility of the particles, their ability to settle in the respiratory tract can cause oxidative stress and the onset of inflammation, which are signs of an inflammatory response, increasing the susceptibility to infections [49].

A total of 179 (67.5%) of 265 under-five participants in one particular study resided in homes that mostly used biomass fuel. In the study area, 16% of people had acute respiratory infections. Children who live in homes that use biomass fuel are four times more likely than their peers to experience acute respiratory infections. There was a strong correlation between the incidence of acute respiratory infections and household size. Children under the age of five who reside in houses with six or more members are 1.7 times more likely than their peers to acquire acute respiratory infections. Separate kitchens were another factor that was linked to acute respiratory infections because children who lived in homes without separate kitchens had a four times higher risk of acquiring these conditions than those who lived in houses with separate kitchens. When compared to houses that use clean fuel, those using biomass fuel had higher indoor PM concentrations. The level of PM was statistically higher in the kitchen compared to the living room. Families with parental smoking had considerably higher levels of PM than those without parental smoking [50].

Over 4 million people worldwide die every year as a result of being subjected to HAP resulting from the use of domestic solid fuels, making it the most significant environmental risk factor that influences disability-adjusted life years [51]. Moreover, ALRI in children was revealed to be 78% more likely when HAP is present [52].

3.2. Cardiovascular Diseases

The significant impact of indoor exposures on overall personal exposure was quickly recognized by investigations linking the analysis of activity patterns with monitoring the levels of important air contaminants inside and outside [53,54]. Additionally, “European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures” recently completed a broad prospective group investigation and meta-analysis in 11 European cohorts and found that long-term exposure to PM is linked to the prevalence of coronary impairments, and this correlation persists at exposure levels lower than the current European limit values (40 $\mu\text{g}/\text{m}^3$ for PM_{10} , 25 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$) [55]. In several small studies, subjection to biomass fuel smoke was also linked to subclinical cardiovascular conditions. Women in Guatemala who used biomass fuel before taking part in a study involving upgraded cookstoves experienced alterations in the ST segment of their electrocardiogram [56].

Following the cookstove trial, these alterations improved, indicating a reduction in myocardial ischemia. Furthermore, a cross-sectional investigation of 266 people conducted in Puno, Peru, revealed that long-term exposure to biomass fuel smoke was linked to a greater carotid intima-media thickness and a higher incidence of carotid atherosclerotic plaques [57]. Studies on the relationship between the indoor air pollution from biomass fuels used in residences and consequences like cardiovascular death and coronary heart disease have produced contradictory results. There have been very few studies that have looked at the cardiovascular outcomes in people who use biomass fuels, despite the Global Burden of Disease Study estimation of the global impact of HAP owing to the use of biomass fuels. This estimate was based on the documented link between ambient exposure to air pollution and cardiovascular diseases. The usage of biomass fuel may be linked to coronary heart disease, according to recent evidence [58]. Elderly people who were exposed to biomass fuel smoke for longer, in a study of people who lived in the Brazilian Amazon, had higher cardiovascular death rates than controls who were the same age [59].

It is presumed that lead toxicity may affect 26 million people worldwide, which would result in the loss of 9 million disability-adjusted years of life [60]. Lead exposure through lead paint and pipes is present in both developed and developing countries, although, generally speaking, the incidence of lead exposure in low- and middle-income countries has not lowered to the extent that has been registered in numerous developed countries [61]. Additionally, some data indicate that lead exposure is linked to a reduction in heart rate variability [62]. Numerous studies in low- and middle-income countries, such as Mexico and Bangladesh, have found that chronic arsenic exposure is linked to subclinical cardiovascular illness, which includes a greater carotid intimal-medial thickness [63].

Numerous studies showed a connection involving cardiovascular disease and $PM_{2.5}$. According to Gold et al., for every $5\text{--}6\text{ }\mu\text{g}/\text{m}^3$ rise in $PM_{2.5}$, cardiovascular disease rates rise significantly, from 0.5% to 1.5%. Additionally, they revealed that acute exposure to particulate air pollution was associated with a 69% rise in cardiovascular mortality. However, acute exposure to $PM_{2.5}$ increased the risk of dying from cardiovascular illness to 69% compared to 28% from respiratory impairments [64].

Variations in blood pressure have been studied in multiple studies examining the connection between cardiovascular disease and air pollution. It is generally recognized that high blood pressure and air pollution both extend the risk of cardiovascular disorders. These investigations have indicated a strong correlation between high blood pressure and particle pollution. According to these evaluations, Boston patients' systolic and diastolic blood pressure increased by 2.8 and 2.7 mm of mercury (mmHg), respectively, during the course of five days for every $10.5\text{ }\mu\text{g}/\text{m}^3$ increase in $PM_{2.5}$ levels. Studies of a similar nature, performed on patients in Detroit, revealed that elevated $PM_{2.5}$ amounts were associated with a higher systolic blood pressure. These studies demonstrate a strong link between high blood pressure and PM [65].

3.3. Dermatological Diseases

Human skin is negatively influenced by the rise in air pollution. Environmental air contaminants such as oxides, ozone, PAHs, PM, and VOCs may be absorbed by the skin. Despite the fact that human skin serves as a physiological obstacle against pro-oxidative contaminants in the air, chronic exposure to extremely high levels can cause changes in skin homeostasis, linked to both ageing and inflammatory skin disorders. One of the main health issues identified by the environmental research is the risk of skin cancer being triggered by air pollution [66]. More information is now accessible regarding the influence of PM on skin impairment, particularly skin ageing. Even though the epidermis is unaffected, tiny PM can enter the bloodstream and harm the dermis. The skin barrier and transdermal passage, beginning with the sweat glands and hair follicles or via the stratum corneum, are also modified by PM [67]. The impact of $PM_{2.5}$ with significant levels of heavy metals was recently confirmed. A rise in reactive oxygen species (ROS) and tumor necrosis factor-alpha (TNF- α) was seen in RAW 264.7 macrophage cells subjected to this

form of PM_{2.5}. By reducing the TNF- α and ROS levels, exposure to melatonin-containing nanoparticles mitigated the harmful effects of PM_{2.5} [68].

Organic substances identified as persistent organic pollutants (POPs) influence the ecosystem at a worldwide scale. Industrial processes, traffic, trash, and agriculture are among the factors that produce POPs. Some factors might have a natural origin, like the ones that are released following volcanic eruptions. POPs can be carried over great distances. Ecosystems and human health are negatively impacted by them. POPs resist natural and environmental deterioration, causing bioaccumulation [69].

Twelve POPs, also known as the “dirty dozen”, were detected by the Stockholm Convention in 2001. POPs can be divided into three groups, depending on their source: (i) pesticides which, despite being prohibited, are nevertheless employed in some countries; (ii) POPs with industrial origins, such as polychlorinated biphenyls (PCBs); and (iii) unanticipated byproducts of industrial processes. The latter substances include PAHs, dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs). Yet, the PCDF and PCDD family, with PCDFs and PCDDs sharing similarities regarding their chemical constituents and structure, is frequently referred to as the “dioxins” group. Particular PCBs that resemble dioxin and exhibit toxicity comparable to dioxin are also known as “dioxins” [70].

PAH is very lipophilic and quickly penetrates the skin. It is possible for PAHs to create covalent bonds with DNA during phase I of their metabolism, resulting in PAH-DNA adducts [71]. Furthermore, the ROS produced by the metabolic activation of PAH can deteriorate DNA, resulting in increased toxicity and carcinogenic and/or mutagenic consequences [72].

3.4. Rheumatism

The second most frequently mentioned environmental contributor linked to the incidence of rheumatoid arthritis (RA) is silica exposure. Various prospective and case-control investigations have found links between RA in males and particular professions such as rock drilling, granite labor, and stone crushing after adjusting for smoking. Workers in the fields of pottery, sandstone, or refractory materials (i.e., aluminosilicate or silica) were found to have an inverse relationship between silica exposure and the incidence of RA, according to a single case-control research work [73]. No correlation was found between the risk of RA and occupational pesticide exposure in two major Swedish investigations [74,75].

A cross-sectional investigation of male pesticide sprayers in Greece found that elevated pesticide exposure (the total amount of pesticide exposure over the course of a person's lifetime) was linked to RA [76]. There are insufficient data to definitively associate certain occupations with an elevated risk of RA, including workers in the plastic, steel, military, and electronic industries, where they may be exposed to potentially harmful airborne agents, mineral oil, styrene, and open-air burn pit smoke [77].

3.5. COVID-19

In 2018, the World Health Organization (WHO) issued guidelines on housing and health. They pinpointed the environmental risk factors associated with inadequate housing, such as overcrowding, compromised air and water quality, and insufficient access to proper plumbing and sanitation. These factors were identified as contributors to the prevalence of infectious diseases, particularly those transmitted through the air and respiratory system [78]. However, the COVID-19 pandemic, especially due to the requirement for people to stay isolated at home to reduce virus transmission [79], has opened up a framework for studies regarding the relationship between the living environment and health issues.

Numerous research endeavors have delved into the impact of the COVID-19 pandemic on mental well-being. Not having the opportunity to utilize outdoor spaces and experiencing household overcrowding displayed suggestive associations with unfavorable outcomes [80]. Residing in densely populated households, living in solitary conditions, or

lacking access to outdoor amenities could play a pivotal role in contributing to diminished mental well-being during a lockdown [81,82].

Insufficient housing infrastructure heightens the vulnerability of urban impoverished communities during unforeseen circumstances like the COVID-19 pandemic. Generally, these dwellings faced issues such as inadequate lighting and ventilation. Overcrowding was apparent, with residences and settlements in urban impoverished zones exhibiting disproportionate sizes and congested thoroughfares. The substandard quality of these residences rendered them scarcely resilient to adverse conditions like rainfall and inundation [83].

Researchers examined a potential connection between the proportion of households with substandard living conditions and the increased incidence and mortality rates of COVID-19 across 3135 counties in the United States. An extensive analysis of the nationwide data at the county level revealed that counties with a higher percentage of households facing inadequate housing conditions experienced increased rates of COVID-19 incidence and associated mortality. These results advocate for the consideration of targeted health policies aimed at supporting individuals residing in substandard housing conditions as part of ongoing initiatives to alleviate the adverse outcomes linked to COVID-19 [84].

Therefore, it is highly important to continuously develop guidelines tailored to pandemics and epidemics. This entails the allocation of ample resources dedicated to fulfilling the right to suitable housing for everyone.

3.6. Sick Building Syndrome

The term “sick building syndrome” (SBS) refers to a situation when inhabitants of a building perceive sudden changes in their comfort or health that appear to be directly proportional to their time spent there. It is difficult to determine a specific disease or cause. The affected people can appear concentrated in a certain area of the structure or zone, or they may be dispersed across it [85].

Several variables can affect SBS, including environmental factors and pollutants like carbon monoxide (i.e., heaters, stoves, and furnaces), bio-aerosols (i.e., viruses, bacteria, dust, molds, mites, pollen, or animal excrement), VOCs (i.e., solvents, formaldehyde, etc.), physical factors (i.e., vibration, lighting, temperature, photo duplication, noise), fibers and dust (i.e., dirt, asbestos, fiberglass), trapped outdoor pollutants (i.e., industrial or vehicle exhausts), and variables specific to the building itself (i.e., fresh air ventilation intervals, air conditioning, inadequate building maintenance and cleaning services, interior temperature, and relative humidity) and elements specific to an individual, including gender, smoking, work discontent, increasing computer use, allergy history, etc. [86].

The risk variables that cause SBS amongst healthcare workers (HCWs), who frequently deal with contact with chemicals, a heavy workload, and biological hazards at work, are poorly understood. The purpose of one study was to assess the relationship between SBS and its symptoms in HCWs. In a comprehensive hospital-based cross-sectional study conducted in southern Vietnam in 2017, a total of 207 HCWs (160 females and 47 males) were enrolled. To gather information on the SBS-related symptoms, working demographics, settings, and circumstances, in-person interviews were undertaken. Measurements were made regarding the indoor atmosphere. General symptoms, skin symptoms, and mucosal irritation scores were added to obtain SBS scores, which ranged from 0 to 24. The average SBS score was 9.7. Females reported higher SBS scores more frequently than males (10.2 vs. 7.9, $p < 0.001$). The SBS scores were greater among females (2.0) for fluctuating room temperature (1.7, p value of 0.406), for stuffy “bad” air dust (1.9, with a p value of 0.741), for atopy (1.8, p -value of 0.052), and for dirt (3.8, p -value of 0.368) [87].

Another survey included 890 participants who were assessed in terms of their pollution-related complaints using the Total Complaint Score (TCS). Fresh wall paint; the presence of odor, mold, or fungus on the walls; and the smell of decaying or mold all raised the mean TCS. The TCS was strongly linked with the noise level, fresh wall paint, stress intensity, the presence of rotting or mold, comfort, the number of employees in the room, cleanliness,

social relationships, the presence of odors, and the use of chemical cleaning materials in the room and negatively correlated with the size of the room and the number of windows [88].

The aim of another study was to identify the links between the environmental parameters evaluated in a general hospital in Slovenia and SBS symptoms. In order to determine the potential health hazard factors for SBS symptoms in the patients of a Slovenian general hospital, a self-assessment study combined with field measures was performed. The highest number of variations was registered in the hospital wards under observation for lighting intensity (83.3%), noise level (73.6%), and room temperature (55.3%). IEQ has been shown to be statistically significantly correlated with skin-related SBS symptoms. The data obtained may help the development of an integrated plan for environmental health initiatives focused at improving hospitals' IEQ [89].

In Yazd, Shahid Sadoughi University of Medical Sciences performed a survey among caregivers in its three teaching hospitals. Data from the MM040EA questionnaire on the quality of the indoor environment and SBS were used in this study. SBS was identified in 86.4% of cases. There was no correlation between the syndrome's incidence and employment history, gender, age, or type of work shift. Nurses most frequently reported experiencing tiredness, headaches, and dry hands. There was a correlation between SBS and a lack of airflow, a bad workspace odor, and the amount of work [90].

In health clinics, SBS is common for healthcare workers. Healthcare personnel, especially those working in the examination space, are at risk of health problems as a result of the poor IAQ caused by inefficient air handling unit maintenance. The degree of indoor air pollution rises as a result of a crowded building interior, which also affects the air quality. Most of the complaints regarding poor air quality are related to drought; variable temperatures; dry, stuffy air; and unpleasant odors, as well as dust. In order to guarantee a secure indoor environment for residents, it is necessary to regularly examine the physical and biological IAQ variables in health clinics. To lessen exposure to SBS dangers, it is important to carry out a risk evaluation and introduce control measures. A number of factors, like engineering intervention, managerial support, policy, and money, must be taken into consideration while setting a preventive approach [91].

4. Sustainable Construction: Standards, Materials, and Biocomposites

The use of traditional construction materials is linked with potential harmful impacts on human health that have led to awareness of their risks and a redefinition of our health priorities. Table 1 highlights some of the most relevant building materials posing health risks [92–95].

Table 1. The links between different building materials and possible health problems.

Building Items	Construction Materials—Substances	Adverse Health Effects
Adhesives	Silicone, epoxy resins, polyurethane, acrylic latex—isocyanates, lead, formaldehyde	Skin irritation and sensitization, respiratory conditions, cancer, neurological and endocrine effects
Ceilings	Gypsum, fiberglass)—asbestos, formaldehyde	Pulmonary disease, eye and skin irritation, cancer,
Composite wood	Particleboard, plywood—isocyanates, formaldehyde	Skin and eye irritation, pulmonary effects, cancer
Flooring	Tile, wood, polyvinyl chloride—phthalates, formaldehyde, plasticizers	Eye and skin irritation, lung cancer, endocrine effects
Thermal insulation	Rigid foam, spray foam, fibre—asbestos, formaldehyde, polybrominated diphenyl ethers	Reproductive effects, lung disease, endocrine effects
Carpets	Nylon, wool—styrene, xylenes, formaldehyde, ethylbenzene	Respiratory effects, eye and skin irritation, cancer
Electrical equipment	Switches, thermostats—mercury, polychlorinated biphenyls	Endocrine and lung effects, lung cancer, neurological effects

In contrast to traditional materials, the term green building material (GBM) refers to any recyclable, healthy, ecological, or high-performance product that is capable of reducing its effects on the environment and the health of people during its life cycle, which includes production, operation, resource use, consumption, recycling, and disposal [96]. It can lessen IAQ contaminants because it is particularly made from safe, organic, and natural materials. The key method for managing the IAQ in green building plans focuses on the management of indoor air monitoring. IAQ has been found to have an impact on inhabitants' health, productivity, and comfort due to pollutants and environmental temperatures. In addition to meeting customer needs and directing standards, GBMs can assist in redirecting IAQ liability demands [9].

Several standards must be successfully met for a building to be considered healthy. The majority of the standards delineate several classifications related to indoor environmental quality. Among them, the most widely used standards are ISO 17772, ISO 7730, EN 15251, EN 16798, ISHRAE 10001, and GB/T 50785 [97].

The technical operation, mechanical stability, and fundamental safety of a building's occupants all rely on the construction and sound design of the building. Indirectly or directly, a variety of additional variables also have an impact on the well-being of its residents. These variables include the usage of office equipment or everyday chores like cleaning, cooking, or using pesticides, as well as the air conditioning, ventilation, and heating systems, along with the activities of the residents [98].

The planning and assessment of indoor environments within buildings heavily hinge on established national and international standards such as those of the International Organization for Standardization (ISO), Euronorm (EN), and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). These standards outline the indoor environmental conditions deemed acceptable for the majority of occupants. IEQ encompasses four primary environmental facets: thermal comfort, IAQ, lighting, and acoustics. While it is essential for designers to address all the IEQ factors, the standards frequently segregate the requirements for each category [97,99]. For instance, the ASHRAE standards concentrate on either thermal comfort or ventilation to ensure an acceptable IAQ [97]. For optimal thermal comfort, the ASHRAE standards recommend sustaining indoor temperatures between 20 °C and 23 °C in the winter and 22 °C and 27 °C in the summer. ASHRAE further advises that the relative humidity levels be maintained in the range of 30 to 60% in order to maintain suitable indoor environmental conditions [100]. In contrast, CEN and ISO strive to consolidate various factors into a unified standard, but they can vary depending on the regional or national regulations. While they have successfully integrated comprehensive requirements for thermal comfort and IAQ, their coverage of lighting and acoustics is only partial. These aspects are typically covered by distinct standards [99].

The Chartered Institution of Building Services Engineers suggested comfort standards that took into account various parameters, recommending optimal levels of their values, such as temperature (dry bulb) = 19–23 °C; relative humidity = 40–70% depending on the heating system; a minimum of 8 L per second per person of fresh air delivery; a maximum of 46 dBA of sound; and about 500 lux for general office work and 750 lux for activities where a higher sensitivity for certain actions is required [101].

However, the disparity between the standard specifications and actual individual thermal comfort results from physiological variations and personal preferences. Although slight deviations may not have a direct impact on health, significant variations can cause discomfort and negatively influence both productivity and well-being. Incorporating adaptable design components, acknowledging specific requirements, and sustaining feedback mechanisms can contribute to the achievement of equilibrium, thereby guaranteeing that indoor environments accommodate occupant preferences and standardized ranges in an effort to promote optimal health and comfort. Variations in thermal comfort among individuals are crucial considerations in the design and operation of built environments, especially as differences have been observed between the actual comfort range and the

values specified in the standard recommendations. Clothing choices and physiological factors like metabolic rate and vasoconstriction/dilation contribute to these differences. Factors such as circadian rhythm, cold syndrome, fitness, and physical disabilities also impact thermal comfort [102]. A study revealed a tendency toward cold discomfort and workspace overcooling, challenging the accuracy of the Predicted Mean Vote as an index for air-conditioned buildings. Unconventional personal and contextual factors were found to influence individual thermal comfort, with notable differences between field studies and ASHRAE's data distributions. These findings emphasize the importance of addressing diverse individual needs in thermal comfort design because extreme deviations from the recommended comfort conditions may have a significant impact on health status [103].

The worsening of IEQ is linked to chemical emissions from construction materials, which can be a significant source of passive emissions within houses. To prognosticate the emissions of chemicals from building materials while taking indoor sorption into account, a high-throughput mass-balance-based model was suggested. More than 300 different chemical-product associations were used to determine the exposures from the Pharos databases, out of which 73% (or 25%) included information on non-cancer (or cancer) toxicity. Formaldehyde and diisocyanates were detected as chemicals of considerable concern [104].

Biopolymers are synthetic materials made from natural sources like bacteria and plants. In comparison to petroleum, renewable resources are the main providers of biopolymers [105]. The most prevalent biopolymer taken into consideration as a matrix for biocomposites in different studies is polyhydroxy butyrate (PHB). PHB is a biodegradable and organic polymer and has several key advantages over petrochemical plastic materials, including biodegradability and being made from affordable renewable carbon sources. Moreover, it is more affordable to produce from sugar or maize starch, releasing fewer greenhouse gas emissions over the course of its life cycle and being the foundation for a true cradle-to-cradle carbon cycle [106]. According to several reports, its mechanical qualities are comparable to, or even superior to, those of conventional thermoplastics [107].

Biopolymer composites composed of hemp fiber and cellulose acetate offer a promising approach to the development of sustainable, healthy buildings and residences. By merging the inherent durability and environmental friendliness of hemp with the adaptability of cellulose acetate, these composites offer a variety of beneficial characteristics. In addition to exceptional mechanical strength, durability, and stability in their dimensions, hemp-reinforced biocomposites additionally have inherent fire retardancy, as well as low toxicity, contributing to a safer living environment. In addition, the use of hemp as a reinforcement in cellulose acetate matrices improves the biodegradability and recyclability of the composites, conforming to the concepts of a circular economy and reducing their environmental imprint. Incorporating PHB and its co-polymers with natural fibers such as flax, jute, or kenaf further improves the performance of biopolymer composites, providing an optimal combination of strength, thermal stability, and environmental tolerance. These biopolymer composites have enormous potential for the construction industry, allowing for the creation of greener, more sustainable buildings and homes [108–110].

Figure 4 illustrates a comparative analysis of the values of some important parameters among the most widely used biocomposites that may replace traditional composite structures [109]. Young's modulus represents the stiffness or rigidity of a material. It quantifies how much a material deforms under an applied force. A higher Young's modulus indicates a stiffer material. Ultimate stress is the maximum stress a material can withstand before failure. It provides insight into the material's strength under extreme conditions. Higher ultimate stress values indicate greater strength. Strain to failure represents the extent to which a material can deform before rupturing. It indicates a material's ductility or flexibility. Higher strain to failure values suggest a more ductile material that can undergo significant deformation before breaking [111–113].

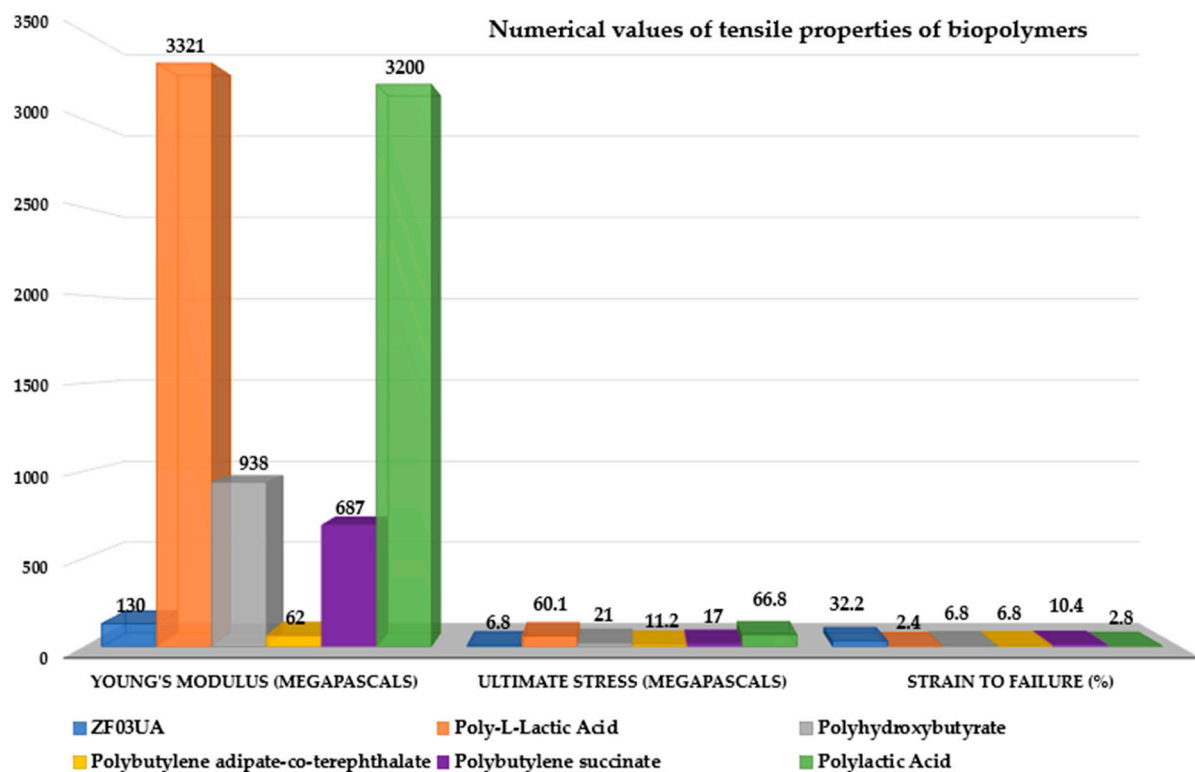


Figure 4. Tensile properties of biopolymers.

Overall, by offering versatile solutions for the construction sector, biocomposite materials bring forth advantages such as design flexibility, efficiency in construction, good specific properties, a light weight or mass, durability, the possibility of obtaining panels for restoration, corrosion resistance, and insulation properties that may improve the health status of inhabitants [114].

5. Indoor Air Quality Impacting Health Status

Considering that most individuals spend 90% of the day inside, primarily at home or at work, indoor environmental factors have a significant impact on human health [115]. WHO estimates that 3.8 million people die every year as a result of indoor air pollution (IAP) [6].

Numerous substances, including fibers; PM; VOCs; biological particles like fungi, bacteria, and pollen; inorganic and organic pollutants; and gases (i.e., carbon monoxide, ozone, and radon), can have an impact on IAQ. Numerous studies and research articles on a variety of scientific topics (i.e., medicine, chemistry, environmental sciences, etc.) have been published on the vast amount of variables that have an influence on IAQ [116].

Studies have demonstrated that indoor air is more polluted than outdoor air; therefore, lately, researchers and the general public have focused on issues related to IAQ [4]. Figure 5 shows the consequences for human health of indoor biological, chemical, and gas-related contaminants [117–122].

The complex mixture of the inorganic and organic compounds that compose PM, which varies depending on the time of year and the environment, includes elemental carbon and organic carbon [123]. Indoor particles include both particles that were produced indoors and ambient particles of various size fractions that came from outdoors [124]. The loss of lung function and cardiovascular diseases associated with ambient PM exposure may be the results of inflammation. Due to the increased capacity of ultrafine particles (UFPs) to promote inflammation and oxidative stress in the lungs, interior UFP exposure is particularly concerning [125].

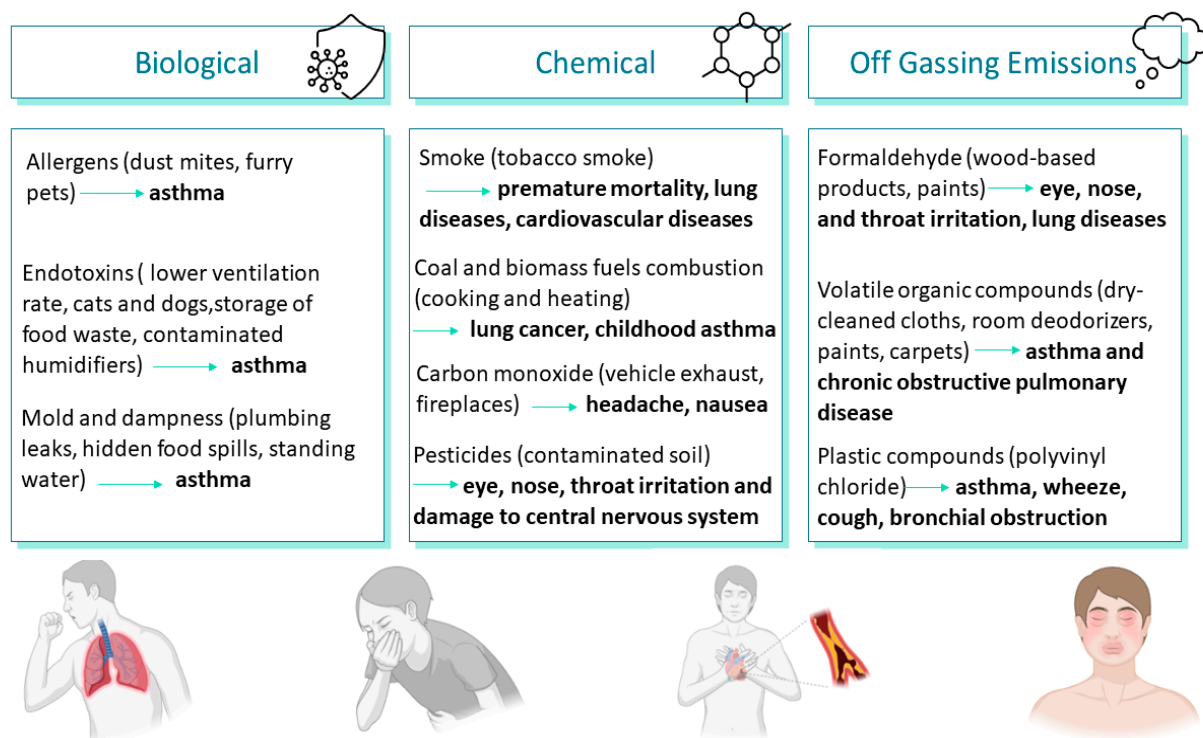


Figure 5. Indoor contaminants with specific impact on human health.

The objective of one scientific study was to explore the impact of in-home PM on the asthma symptoms among children, with a specific focus on distinguishing between non-atopic and atopic individuals. Among the results, it has been found that children from disadvantaged socioeconomic communities, mostly African Americans, spend most of their time at home. A total of 69% of a cohort of 150 children were atopic, and the rest of the subjects were non-atopic. After adjusting for variables like confounders, elevated in-home coarse ($PM_{2.5-10}$) and fine ($PM_{2.5}$) particle levels were linked with considerable increases in asthma symptoms and rescue medication consumption in both non-atopic and atopic children. Both children who are not atopic and those who are atopic have worsening asthma symptoms as a result of indoor particles [126]. Particularly for non-atopic asthma, for which there are few environmental management strategy recommendations, environmental control measures that lower particle concentrations may be an effective way to improve asthma outcomes [125].

Strong correlations between individual exposures and home microenvironment levels suggest that the home is the main determinant of individual VOC exposures, accounting for 11 to 75% of the variance. Ambient concentrations in the workplace and central sites were less associated with personal levels, only accounting for up to 11–22% of the variability at the reduced exposure end of the concentration interval. On the importance of the connection of personal exposure with ambient concentrations, a modest seasonal effect was discovered. When utilizing fixed area measurements to extrapolate exposures, this effect must be considered [127].

A correlation between the formaldehyde concentration and the year a house was built has been found, as well as when moving into a freshly built structure under a year old. Differences in benzene, ethyl-benzene, VOC, and toluene levels were discovered with the usage of artificial air fresheners. When using oil as a heating fuel, the xylene content was considerably greater. The building type had an influence on the styrene concentrations, which were substantially higher in both commercial complexes and residential houses. Using an air cleaner considerably reduced the number of bacterial aerosols present indoors. When there was nearly no ventilation, there were high benzene and nitrogen dioxide levels [128]. Figure 6 illustrates the connections between indoor air pollutants and various

standard rooms of a house using a chord diagram [129]. Analyzing indoor pollutants and their distribution among various rooms provides valuable insights into potential health risks and the need for targeted mitigation strategies. The chord diagram visually showcases the interconnected relationships, emphasizing pollutants' prevalence in specific areas. This representation highlights the complexity of indoor air quality, pinpointing rooms with diverse pollutants. Identifying common pollutants between rooms, such as dust or chemicals, suggests shared sources demanding comprehensive intervention. Additionally, exclusive contaminants like asbestos in attics underscore specific concerns.

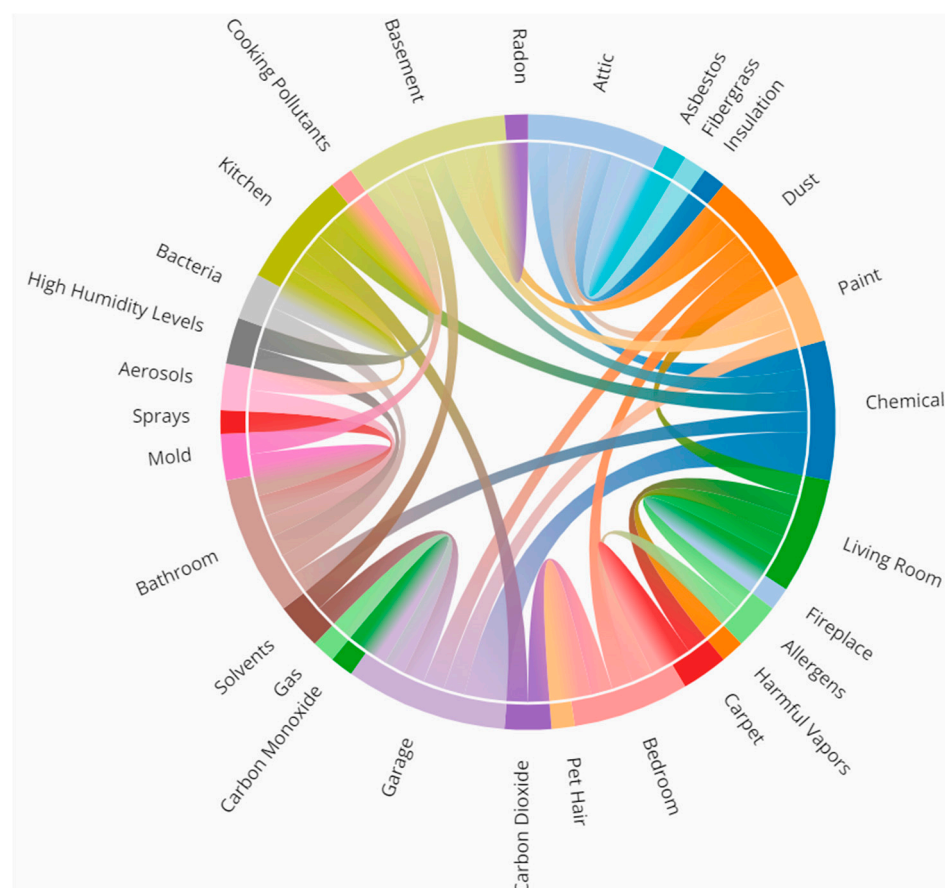


Figure 6. Primary sources of indoor pollution in relation to the area in the house.

In Perth, Western Australia, children between the ages of 6 months and 3 years participated in a population-based case–control research work. Children from the aforementioned age group who had not been diagnosed with asthma were the controls ($n = 104$) and were selected at the Health Department of Western Australia's recommendation. The cases ($n = 88$) were children who had asthma as their main diagnostic at discharge, selected from the Princess Margaret Hospital's emergencies and accidents department. A structured questionnaire was used to gather data on the health status of the children included in the study and household factors. In the homes of each participant, the living room underwent measurements of its relative humidity, VOC exposure, and mean temperature during winter and summer. In comparison to the controls, the cases were subjected to considerably higher amounts of VOCs. The majority of the separate VOCs seemed to be important asthma risk factors, with benzene having the greatest risk potential, followed by toluene and ethylbenzene. The probability of developing asthma grew nearly two and three times, respectively, with each 10-unit rise in the toluene and benzene levels [130].

The goal of another experimental study was to establish the connection between home conditions and respiratory health. A selected group of 715 homeowners had their homes submitted to an engineering analysis and had air samples collected. The study findings

indicated that airborne mold testing and occupant complaints regarding visible mold in the residence were substantially correlated with children's respiratory conditions and the airborne mold levels. According to the results, there is a need for more precise guidelines on the maximum permissible colony-forming units/m³ levels for mold genera, which are relevant for residences. Regardless of the mounting evidence of the harmful consequences of mold exposure, issues related to indoor mold will still have an influence on people's health as long as regulations are missing [131].

In the second stage of the International Study of Asthma and Allergies in Childhood (ISAAC), the information collected from large cross-sectional investigations involving roughly 46,000 children, aged between 8 and 12 years and from 20 countries, was examined to determine the connection between allergic and respiratory symptoms and visible mold and dampness in homes. According to the questionnaire results, home residents reported both discomfort and dampness/mold in the home. Recent exposure was consistently and significantly associated with reported eczema, phlegm production and coughing without a cold, rhino conjunctivitis (rhinitis), and wheezing. Skin prick testing for sensitization to mixed tree pollen, home dust mites, *Alternaria alternata*, cat dander, and mixed grass pollen in 26,967 children with atopic parents showed no signs of outcome modification. According to the authors' analysis of these findings, non-allergic reactions account for the majority of the negative effects of dampness/mold on human health [132].

Air conditioning systems globally aim to enhance thermal comfort and IAQ. However, indoor pollutants, especially VOCs, pose health risks and may be correlated with the malfunction of air conditioners. Common air purification methods include photocatalytic oxidation, filtration, non-thermal plasma, and adsorption. Various air conditioning systems, such as dedicated outdoor air systems, independent temperature and humidity control systems, and cooling ceiling and displacement ventilation systems, target improved IAQ and thermal comfort. These advanced systems not only combat microbial pollution but also promote energy efficiency, emphasizing their significance in enhancing indoor air environments [133].

Ventilation significantly contributes to the health and productivity of a building's occupants. It is essential for eliminating indoor-generated pollutants or reducing their concentration to acceptable levels. The scientific data underscore ventilation's substantial impact on critical human outcomes, including communicable respiratory illnesses, sick building syndrome symptoms, task performance and productivity, the perceived air quality among occupants or sensory panels, and respiratory allergies and asthma. However, if not properly designed, installed, maintained, and operated, ventilation can have adverse effects on the IAQ and climate by introducing harmful substances or compromising the indoor environment. Thereby, it is essential to ensure and verify ventilation and air conditioning's effectiveness while avoiding harmful effects on human health [134].

6. Green Buildings' Importance in Health

In the past few decades, the green building (GB) model has become increasingly prominent as a research topic due to the growing inconsistencies between the enormous growth of construction and the resulting deterioration of the surrounding ecosystem. GBs involve the thorough supervision of acquiring environmentally conscious structures and employing asset-effective technologies throughout a building's lifespan, including placement, design strategy, installation, growth and development, repair, retrofitting, and demolition [135].

The passive house standards outline the following requirements for the recognition of passive buildings: cooling needs and space heating, thermal comfort, airtightness, and main energy needs. Despite the fact that in general buildings, comfort, quality, and energy efficiency are the current criteria, the quantitative and qualitative standards for the IEQ, specifically IAQ, daylighting, and noise issues, are not sufficiently defined, particularly when it comes to the user characteristics, the system, and the building. This frequently leads to inadequate indoor environmental conditions because the established standards are

provided as minimal values. As a result, in regular practice, designing for general comfort frequently relies on the expertise of the designer and/or investor [136]. Furthermore, issues regarding energy consumption and IAQ, in particular, are connected to human behavior and may change rapidly once a facility is occupied. Raising residents' awareness of how to modify or control construction and systems is crucial because the designed values may not determine the optimal IAQ [137].

Buildings' greenhouse gas emissions and operational energy consumption endanger the ecosystem and the overall financial status and health of humans. Ecological and healthy retrofitting of old buildings can be a useful tool for improving our overall health and quality of life [138,139]. Hence, the deployment of Smart Building Management Systems, which serve as integrated instruments for the regulation and optimization of Intelligent Buildings to ensure control, comfort, and operational efficiency, emerges as highly important [140].

Healthy constructions are part of an adequate built environment. These are places where people work or live, where health risks are completely eliminated, and where the ideal conditions are created for each person's well-being and health. In order to meet the unique needs of those with vulnerabilities and individual users, ideal settings should be engaging and healing-oriented. A building that is unhealthy exposes its occupants to disease, potential hazards, and their characteristics while they reside or work there, without providing the best possible ambiance for individuals, particularly those who are more vulnerable [136].

Biodegradable building materials, made from sustainable resources, are known as green or biocomposite materials [141]. With little harm to the environment, microorganisms alter and transform them into small compounds [142]. For the potential substitution of non- and less environmentally friendly materials utilized in the building sector as potential options for the future generation of GBMs, biocomposite products are currently being studied and produced. Buildings may use biocomposite elements for flooring, walls, framing, ceiling panels, frames for windows and doors, ornamental paneling, and cubicle walls. Natural fibers serve as reinforcements in biocomposite materials, which also contain biopolymers as matrix materials. Biopolymers are more durable and rigid in fiber form than polymeric matrix materials [143]. Biopolymers originate from organisms which include microorganisms and plants. Unlike petroleum, the main sources of biopolymers are renewable [144].

The Office of Federal High-Performance Buildings is run by the General Services Administration (GSA) in the United States. To determine how to assess their performance versus the national averages, the GSA undertook a study on 22 sustainably developed structures from representative regions of the country. Furthermore, 6 of the buildings fulfilled the requirements of Energy Star or California's Title 24 Energy Standard, while 16 of the structures complied with or exceeded Leadership in Energy and Environmental Design (LEED). The investigation collected data on the experience of residents. The top third of these structures had significantly better margins according to GSA, which found that the satisfaction of tenants was 27% higher in the 22 sustainably constructed structures than the average across the country. Greater levels of satisfaction were noted for the buildings' overall cleanliness, thermal comfort, and air quality. Although smaller ratings for sound privacy but not noise level were discovered, there were no variations in how satisfied people were with the illumination [145].

Researchers think that almost all buildings share a set of Health Performance Indicators (HPIs). Assessments of occupants' health, such as self-identified health, objective physiological evaluations, and asthma, as well as building efficiency and design (such as green buildings and ventilation) and environmental health variables (like biological, chemical, and radioactive risks), are a few examples [14].

The development of environmentally friendly design or sustainable construction techniques, such as the LEED grading system developed by the US Green Building Council (USGBC), was influenced by the health issues that resulted from conventional structures with insufficient ventilation. Without sacrificing occupants' health, LEED seeks to lower

a building's environmental mark. Buildings, both new and old, can receive credits for implementing management, functioning, and green design. Depending on how many credits a building is eligible for, LEED then allocates it a rating. The LEED certification process comprises a module on IEQ, which provides regulations for using low-emitting components, providing natural light views to building residents, enhancing ventilation and filtration, enhancing thermal and lighting conditions, managing indoor chemical and pollutant sources, and monitoring ventilation, even though many of the credits are focused on energy efficiency and environmental performance [146].

The WELL Building Standard, designated as WELL v2.1 throughout, represents a comprehensive system designed to enhance occupant health. Its scope extends across 2149 projects spanning 51 countries. Originally introduced in 2015 as v1, WELL evolved and was updated to v2.1 in 2018. This system, rooted in scientific principles, encompasses a global reach, impacting diverse built environments to optimize the health outcomes for occupants. The continuous evolution from v1 to v2.1 reflects a commitment to refining and advancing the standard, ensuring its relevance and efficacy in promoting occupant health across a wide array of international projects [147].

WELL v1 focused on seven core concepts: air, water, nourishment, light, fitness, comfort, and mind. In the context of housing, these concepts translate into meticulous considerations. For instance, the air quality category emphasizes optimal ventilation, filtration, and control over indoor pollutants. This is pivotal for mitigating the respiratory issues often exacerbated by the poor indoor air quality in residential spaces [148].

WELL v2.1 brings improvements to the application standards, and in addition to the seven concepts of WELL v1, adds and characterizes three more (i.e., sound, materials, community) [149]. Figure 7 presents the ten concepts in the WELL building standard [150].

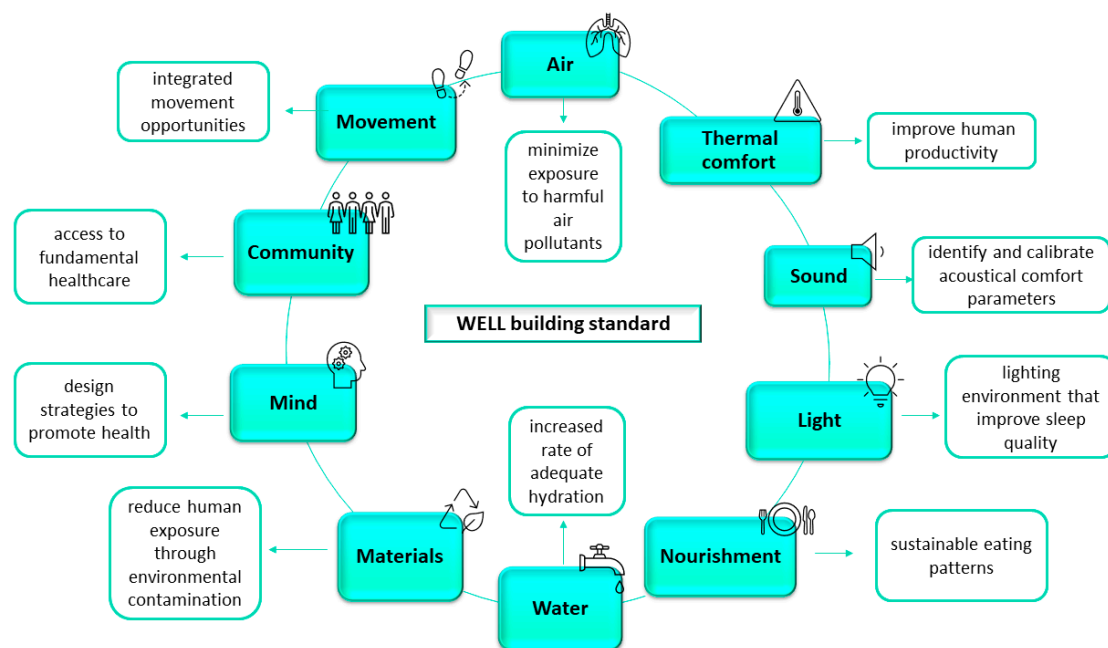


Figure 7. WELL building standard concepts.

WELL focuses on the key elements for residential health, advocating for potable water to support hydration and nutritious food access. In lighting, it prioritizes natural and artificial sources for circadian rhythm regulation, crucial for sleep–wake cycles and overall health. Fitness promotion through design features encourages physical activity at home. Comfort considerations, including temperature, noise control, and ergonomic furniture, contribute to residents' well-being. The mind category targets mental health, addressing stress reduction and community fostering. WELL certification recognizes housing's profound impact on health and productivity. By integrating evidence-based design principles,

it aims to prioritize health and elevate the overall quality of life for individuals and communities. Our evolving understanding of the housing–health connection positions the WELL Building Standard as a pioneering framework setting high standards for optimizing occupants’ well-being in residential spaces [149].

Incorporating restorative areas into a building’s design can help patients, individuals, and workers by reducing stress, enhancing lung function, and enhancing sleep quality. Other benefits include better acoustics and air quality and increased access to natural light and the environment [151]. Individuals who have accessibility to soothing visual and aural stimuli, like seeing nature, art, or quiet areas, may need fewer painkillers and have better sleep [152,153].

Medical errors among personnel have been associated with higher noise levels, uncomfortable room temperatures, and poor illumination. A lack of restful sleep among nurses has been associated with job stress, which may have a detrimental effect on their work efficiency. There is a correlation between less time spent in hospital and increased fitness in nursing facilities that are strategically planned to keep patients moving [154].

Wider hallways, accessible and visually appealing stairways, and outdoor spaces for walking are all elements of building design that encourage mobility. The selection of materials for the surface of floors, walls, countertops, and furniture, as well as the quality of air and water, easy access to handwashing stations, humidity levels, and movable windows, all have a direct bearing on the risk of infection spread [155].

Trips, slips, and falls are frequent incidents for hospital patients and medical staff that hinder rehabilitation and frequently lead to short- or long-term incapacity and/or chronic pain. The choice of the material for flooring (i.e., resilient versus carpet) may contribute to the prevention of such incidents. Safety might also be affected by how easily surfaces can be cleaned and maintained, which is an essential issue for hospitals [156].

When Palo Alto, California’s Lucile Packard Children’s Hospital began an important extension in 2007, its senior executives and board made a commitment to ambitious environmentally friendly design goals. The 521,000-square-foot LEED platinum-certified structure uses 60% less energy than the average in the entire region. Moreover, Palo Alto Power became the initial municipal utility in the United States to be powered entirely by energy from renewable sources (i.e., solar, wind, biomass), and Stanford University’s central facility’s effectiveness reduced carbon emissions by close to 90%, which means eradicating the carbon from 16 million pounds of coal. To irrigate the large native and drought-tolerant landscaping, cisterns collect condensation, rainwater, and dialysis-reject water, resulting in a forty percent decrease in water consumption [157].

The Manhattan main campus of NYU Langone Health was the first institution in the world to be certified by the Performance Excellence in Electricity Renewal criteria and with USGBC’s LEED Platinum rating. The campus on the coast is powered by two cogeneration facilities. It has a 12,000-square-foot green roof to better manage rainfall accumulation peaks and significant flood control systems. Since making sustainability a high priority, NYU Langone has cut its emissions of greenhouse gases by 37% and takes part in the Healthier Hospitals Safer Chemical Challenge, which has resulted in the removal of potentially hazardous chemicals from more than 30% of its yearly acquisitions of medical furniture. The Green First program at NYU Langone features more locally sourced and healthier food options, electric car fleets, water preservation measures, and waste minimization. Major interior improvements are also guided by the Fitwel and WELL authorization programs [158].

A total of 109 volunteers were gathered from 10 high-performing structures in five American cities, which met or exceeded the ventilation requirements of ASHRAE Standard 62.1-2010, with reduced total VOC levels. The week of evaluation, job functions, labor types, and residents were used to match up buildings in each city. The associated buildings’ green certification status was an important factor in differentiating them. Throughout the same week, workers underwent a greater order decision-making capacity cognitive function exam twice, while the indicators of the IEQ were tracked. When

controlling for job category, annual wages, and level of education, employees in green-certified buildings performed better in cognitive function tests by 26.4% and displayed 30% less symptoms of sick building syndrome compared to those in non-certified facilities. The findings imply that the advantages of green certification requirements go beyond measurable IEQ elements [159].

However, the data in the scientific literature may diverge, presenting disparate outcomes. While green-certified buildings demonstrate enhanced cognitive function and reduced sick building symptoms among their inhabitants, the satisfaction levels across building classes, particularly A, B, and C, present contrasting results. The A class does not provide any discernible satisfaction advantage for individuals or practical building occupancies. Moreover, the tightly controlled air temperature in Class A spaces does not yield higher satisfaction compared to non-tightly-controlled spaces (Classes B and C) [160]. This underscores the nuanced interplay between environmental factors and occupant well-being, emphasizing the need for a comprehensive approach to designing healthier and more satisfying work environments.

7. Technology Transfer in Building Construction and Health

The design of innovation approaches, the establishment of legal frameworks, and the application of financial tools are insufficient to ensure sustainability. It entails societal, mental, and behavioral changes that are highly dependent on financial assistance at every level of education. In addition, technology transfer (TT), when used as a tool for sustainability in the analyzed field, should be consistent with the objectives of sustainable housing in order to reduce health risks [161]. Furthermore, TT is essentially an activity focused on the sharing of information. The triple helix of governments–academia–private sector enables innovation growth in relation to a rise in stakeholder eligibility, with every single element being interchangeable [162].

Based on World Bank data, five states (i.e., China, Japan, the United States, Republic of Korea, and Germany) accounted for 73% of the world's carbon-efficient technology patent output between 2010 and 2015, while the remaining countries registered only 27% [163]. A significant number of academics have noted that the transfer of green technologies is largely market-oriented and also characterized by limited competition and knowledge inequality [164,165].

According to the spontaneous collaboration model, the transfer of green technologies is vulnerable to market failure and generally occurs in economically developed areas, leaving areas with limited development unable to obtain sufficient knowledge about external green technologies, further widening the gap between green and developed areas [166]. The approach given here needs to be improved in order to handle a number of research topics that are now unaddressed. To begin with, there is insufficient attention paid to worker exposure throughout the construction phase and when disposing of construction materials [167].

The case studies and exposure models assessed in different studies, however, only pay attention to the exposures that occur during use, not focused on the housing side. Actually, the employees who dispose of construction materials may be subjected to greater levels of several substances, including semi-VOCs, metals, and asbestos, which are primarily released during the remodeling or deconstruction of existing materials [168,169].

Calculating the chemical emissions and associated exposures for sophisticated construction materials is the second field of investigation. Particleboard and other construction materials are frequently treated with veneer or laminate, or they are coated or painted. The chemical profile and/or physical characteristics of these superficial layers may differ from the substance beneath them, which could change the way chemicals are transferred from the material that lies underneath to the interior environment. In order to make them appropriate for large-scale, high-throughput computations, more modifications are required for the present models used to predict the emissions of chemicals from multi-layer materials because they are typically complex and computation-intensive. Additionally, correlation

techniques must be created in order to calculate the model input variables associated with these surface layers [170,171].

By changing and/or eliminating problematic building legacy products before they are heavily integrated into society, adequate up-front study can mitigate and avoid future legacy problems. The examples used to illustrate this point are latex paint and the Tartan rubber flooring used in gymnasiums. These two construction materials were made from phenylmercuric acetate (PMA), which is a form of mercury. Prior to its 1991 ban, 25–30% of latex paint contained PMA as a preservative, to prevent the growth of mildew, bacteria, and other fungi [172].

8. The One Health Concept Integrating Green Building into a Larger Context

Our ability to address urgent public health issues that may endanger civilization is increased by the transdisciplinary, multisectoral, and integrated approach known as One Health. The underlying idea is that health is connected to the biosphere's interfaces with plants, animals, people, and the environment. WHO has acknowledged One Health as the preferred strategy to address health concerns needing complex strategies [173].

Thirty percent of the world's emissions of greenhouse gases, which warm the globe, come from buildings. The building industry has the potential to offer one of the greatest possibilities to enhance environmental health. Green buildings typically utilize between 20 and 40 percent less energy than conventionally built buildings. Furthermore, there is a health advantage associated with the energy that sustainable constructions conserve. Using less energy reduces the amount of dangerous air pollutants released into the atmosphere, which is good for human health [174].

Product manufacturers, engineers, architects, and builders are trying to support organizations and enterprises across the environmentally friendly design and building sector. Additionally, using toxic-free construction materials is only one aspect of protecting human health. Business executives and clients are putting the health of residents on level with energy and resource preservation, with concepts that bring the therapeutic effects of nature into the work environment and illumination that controls energy levels [175].

The LEED program of the US Green Building Council and the International WELL Building Institute's WELL Building Standard, which establish standards for health-centered designs and practices, effect on the environment, and energy and resource efficiency, support these efforts. To develop techniques that have a beneficial influence on health, for instance, businesses must collaborate with a public health expert or organization as part of a new LEED pilot credit called Integrative Process for Health Promotion [176].

The supporters of the new paradigm emphasize that a company's biggest expense is its people, not its energy or water expenses, from a financial standpoint. Even modest increases in employee well-being can reduce absenteeism, boost productivity and retention, and generate significant savings. Numerous studies are used by public health advocates as arguments for better working conditions. According to experts, the novel integrated strategy represents the third stage of green design, and it redefines what sustainability actually means [175].

It offers a solid base upon which it may be expanded considering LEED's current emphasis on inhabitants and IAQ. Health is an excellent approach to making LEED more accessible. A logical part of any holistic health approach, for instance, should be the security and well-being of the people who build, preserve, and clean buildings. The NIOSH federal organization is in charge of carrying out studies and formulating suggestions for preventing accidents and illnesses at work in the US. For those working in the building industries, NIOSH's Construction Program creates, facilitates, and supports cutting-edge safety and wellness practices at work [177].

Buildings have a daily impact on our well-being and health, no matter whether our homes, malls, jobs, medical facilities, schools, universities, or buildings utilized for recreational or religious activities. The structures around us, both non-residential and residential, are an important but frequently disregarded factor in determining our health,

as we spend most of our time indoors. The built environment affects our health in a number of ways, such as poor IAQ, inadequate ventilation, chemical pollutants from either outdoor or indoor sources, traffic noise, by making us feel excessively cold or hot, or bad illumination [178].

The One Health concept focuses on providing a cohesive strategy seeking to harmonize and enhance the well-being of individuals, animals, and ecosystems sustainably. It acknowledges the interconnectedness of human, animal, plant, and environmental health. This approach mobilizes diverse sectors and communities, operating at different societal levels, fostering collective well-being, and addressing threats to health and ecosystems. It aligns with key principles: equity, sociopolitical and multicultural parity, socioecological equilibrium, stewardship, transdisciplinarity, and multisectoral collaboration. By collectively addressing health, climate change, and sustainable development, One Health provides a logical, scientific foundation for comprehensive societal engagement [179]. Moreover, Figure 8 illustrates the One Health concept integrated toward a sustainable and healthy future. The identification and clear demarcation of sectors and disciplines, divided into three main areas (environment, animals, and humans), requires the application of the principles of communication, cooperation, and coordination that underpin the translation of the concept of One Health from theory into practice. Furthermore, the success of implementing the One Health concept relies on the inclusion of the whole of society, from small levels (i.e., rural, local, regional) to at a much larger scale (i.e., national, global), so that the ultimate goal is to achieve healthy ecosystems, animals, and humans. Actively implementing technology transfer between the relevant stakeholders engages diverse sectors, disciplines, and communities across society's levels to collaboratively promote overall welfare.

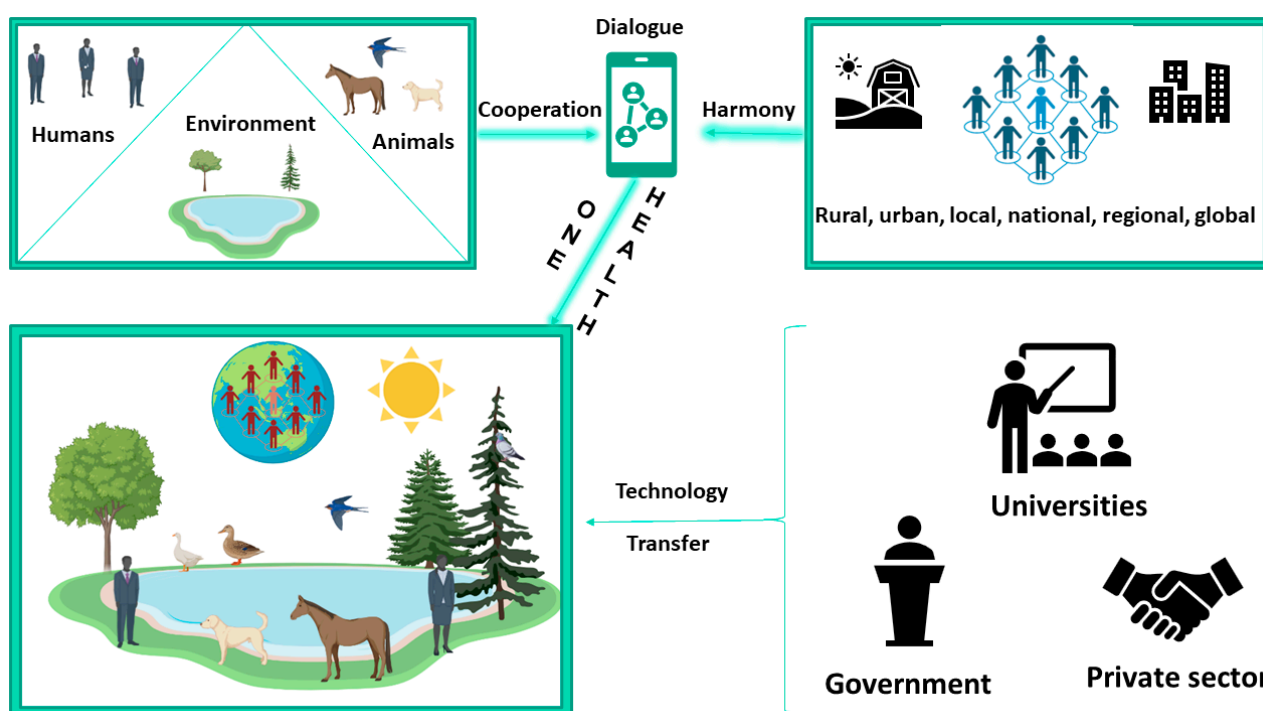


Figure 8. One Health concept for sustainable and healthy development.

The Food and Agriculture Organization, the World Organization for Animal Health, the United Nations Environment Program, and WHO developed the cross-disciplinary One Health High-Level Expert Panel in 2021 to improve their cross-sectoral partnership. This was in response to a suggestion from the French and German Ministers for Foreign Affairs at the November 2020 Paris Peace Forum. The intention behind developing the One Health idea into policy and practical actions is shown in the development and implementation

of strategies, which shows the greatest level of acknowledgment of the complexity and urgency regarding One Health [178].

The risks brought about by climate change have escalating and aggravating effects. Despite extensive research on the health effects of air pollutants like PM, ozone, and nitrogen oxides, the majority of investigations tend to concentrate on all-cause mortality or mortality from cardiovascular and cerebrovascular disorders, with little attention paid to broader One Health effects. There is evidence to support the idea that climate change will affect air quality by causing weather conditions that make air pollution episodes more likely [180].

With the development of innovative technologies like digital Earth tools and the data gathered, it is advised that a clear comprehension of the intricate Earth system should be attained. The development of digital Earth technologies can also help with predicting extreme climate and weather events. The creation of digital technologies to track energy consumption and greenhouse gas emissions is crucial for minimizing climate change. High-resolution investigation, assessment, and adaptation plans for local areas should be prioritized because the geographical disparities in how environmental change will affect different areas are extremely significant. The construction of more accurate worldwide evaluations is thought to be considerably facilitated by risk interdependence studies regarding the environment and climate change and health [181].

For the integrated One Health vision to be effectively applied, political commitment and leadership, including the allocation of resources and prioritization in an equitable manner, are necessary. Yet, it must be acknowledged that creating and putting into practice a coordinated One Health strategy is complicated and hindered by significant legal, political, financial, ethical, and societal obstacles. Furthermore, animal, human, and ecosystem health will be addressed, as well as additional concerns like clean air and energy, the decline in biodiversity, food and water security, the effects of climate change, and social disparities, depending on organizational, sectoral, political, individual, and societal involvement in its effective implementation. This strategy provides certain benefits to the health of everyone, the integration of environmental and social security, and assistance in sustainable and resilient economic growth [179].

9. Discussions and Future Perspectives

Numerous elements contribute to well-being and security within residences, encompassing the architectural and safety features of homes, such as their design, construction, and upkeep, along with their physical attributes. The presence or absence of safety measures, indoor air quality, water conditions, chemical exposures, residents' behaviors, and the surrounding environment of a house all play pivotal roles in influencing health and safety [182].

The present narrative review unraveled the intricate links between living environments and health conditions, with a specific focus on the implications of housing factors, IAQ, green building practices, and the health implications of technology transfer in building construction approaches. As we reflect on the findings, it becomes apparent that this analysis has not only contributed new insights to the scientific field but has also highlighted pertinent research gaps that require further attention. One prominent research gap addressed by the review relates to the limited exploration of the aforementioned linkage, with a major focus on health as well. While there are a plethora of studies that carefully examine environmental influences on health with a focus on environment rather than health, the specific link between housing factors and their direct impact on health has not been sufficiently explored. The link between inadequate ventilation, mold growth, and contaminants in the living environment and the increased risk of health disorders, predominantly respiratory, cardiovascular, and dermatological, is an understudied area.

In addition, the literature highlights the need to extend our attention beyond occupational exposures to encompass the risks associated with housing factors to residents' health. Factors such as the building materials, building's age, heating sources, and individual

habits contribute significantly to the quality of life and health of residents, but there is a notable lack of comprehensive studies in this area. The importance of IAQ emerges as a critical issue influencing health outcomes. This analysis adequately highlights the profound impact of pollutants, including VOCs and PM, on human health. However, gaps in the research indicate the need for more detailed studies that further investigate the long-term effects of optimal ventilation and air filtration systems in mitigating exposure to these contaminants.

Green building practices, acclaimed for their sustainability and energy-efficient components, show both promise and untapped territory. This article highlights the potential benefits of green buildings, such as an improved IAQ, reduced exposure to toxins, and increased physical activity. However, the call for future research resonates strongly in terms of understanding the long-term health effects of green building practices, highlighting the need for further investigation. Moreover, technology transfer in building construction, a transformative force in design and construction, is another area where research gaps persist. While this review acknowledges the opportunity for smart controls to optimize building performance and improve IAQ, it highlights the imperative for further investigation to understand the effectiveness of these technologies and their lasting impact on health outcomes.

If looking forward, future perspectives should include longitudinal studies that delve into the complex dynamics between housing variables and health outcomes. Mismatches between actual staff's comfort standards and those set by the existing standards require specific research exploring the optimal balance between the standardized guidelines and individual preferences for enhanced well-being. In addition, priority should be given to interventions supported by scientific evidence and aligned with sustainable policies to reduce housing-related disease risks and promote healthier living environments. The call for a multidisciplinary approach, combining architecture, environmental science, and public health, remains imperative to chart a course toward holistic solutions and resilient, health-centered communities.

10. Conclusions

Starting from the aim of evaluating the possible links between living environment and health status, the following aspects can be concluded based on a comprehensive evaluation of the scientific literature in the field:

- The link between living conditions and health status implies health risks for residents, especially when building quality standards are not met;
- Poor living conditions are mainly associated with respiratory, cardiovascular, and dermatological diseases;
- Inadequate ventilation, mold, and exposure to contaminants are among the most common items that increase health risks;
- Volatile organic compounds and particulate matter are blamed for altering health status by degrading the indoor air quality;
- Given the novelty of green building concepts and technology transfer implementations in promoting indoor health, additional research is essential to comprehensively grasp the long-term health implications of such practices;
- The imperative for more evidence-based strategies to address housing-related health risks becomes apparent.

The present paper has a general character of updating the state of knowledge, raising awareness of the health risks that may arise from living environments, and presenting conceptual frameworks that, through their implementation in the construction industry, can improve health status, but this needs to be complemented by future studies that target and adapt the data according to the country, legislation, and stakeholders.

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