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Breathing in the margins: Rethinking indoor air pollution and housing equity in urban slums

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Abstract: Indoor air pollution (IAP) is a significant public health concern, especially in informal housing and urban slums within low- and middle-income countries (LMICs). This comprehensive review of recent research focuses on the sources, impacts, and responses related to poor indoor air quality (IAQ) in these environments. Common household activities such as cooking with solid fuels, indoor smoking, and inadequate ventilation are primary contributors to elevated levels of harmful pollutants. These pollutants include fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs). Exposure to these pollutants is strongly associated with respiratory and cardiovascular diseases, with women and children being the most vulnerable due to their prolonged indoor presence. The review emphasizes that structural and socioeconomic factors—such as overcrowding, poor building design, and limited access to clean energy—exacerbate indoor air quality issues in low-income households. Although interventions like improved stoves, cleaner fuels, and natural ventilation have shown some success, their effectiveness is often limited by factors such as affordability, user behavior, and daily habits. A significant challenge remains the lack of comprehensive field-based data, which hampers the development of effective, evidence-based solutions. Additionally, indoor conditions such as dampness, mold growth, and culturally ingrained practices like incense burning and insecticide use are often overlooked but contribute substantially to poor air quality. These factors are frequently excluded from standard monitoring frameworks, reducing the accuracy and scope of current assessments. Regional differences across South Asia, Sub-Saharan Africa, and Latin America further demonstrate how climate, household infrastructure, energy access, and regulatory capacity influence indoor pollutant levels and the vulnerability of populations. This review advocates for more inclusive, locally tailored strategies that integrate housing design, public health initiatives, and community engagement to effectively reduce indoor air pollution and enhance living conditions in underserved urban areas.

Keywords: *Health disparities, Household air pollution, Indoor air pollution, Indoor air quality, Informal housing, developing countries, Low- and middle-income class, Particulate matter, Public health, Ventilation, Urban slums.*

1. Introduction

1.1. The Global Burden of Indoor Air Pollution in Informal Housing

Indoor air pollution remains a major global health concern, responsible for over 3.2 million deaths annually. This burden is particularly concentrated in developing countries such as India, where limited awareness, weak regulatory enforcement, and outdoor pollution contribute to high levels of daily exposure to indoor pollutants [1]. Recent research has increasingly highlighted the health impacts of poor IAQ, especially in low-income communities. Vulnerable groups, including infants, homemakers, older adults, and individuals with chronic illnesses, are more likely to be affected due to the amount of time spent indoors [1]. On average, individuals spend approximately 90% of their daily lives inside buildings, including homes, workplaces, and industrial settings, making indoor air quality a critical factor in overall health outcomes [1].

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Indoor air pollution has been identified as a leading global health threat, ranking as the third major contributor to disability-adjusted life years (DALYs) worldwide [2]. Within this framework, household air pollution (HAP) is considered the most significant environmental contributor to premature mortality, responsible for an estimated 3.8 to 4.3 million deaths annually over the past decade. A substantial portion of this mortality, approximately 1.5 million deaths, has occurred in India, which reflects the unequal impact of this issue in LMICs [3]. According to the Global Burden of Disease (GBD) study, exposure to air pollution contributes to around 6.67 million excess deaths each year from various health outcomes, including cardiovascular and respiratory diseases, cancers, and diabetes [4]. Indoor air pollution is of particular concern, as pollutants generated indoors are estimated to be up to 1,000 times more likely to penetrate the lungs compared to those originating outdoors [3]. The health impacts are particularly severe for women and children below the age of five, who represent nearly 60 percent of HAP-related premature deaths due to the prolonged period spent in indoor environments [3].

Figure 1 illustrates the estimated number of children residing in households that rely on solid fuels for cooking or heating purposes. Due to the lack of age-specific data, these estimates assume that the proportion of children exposed corresponds to the overall share of the population using solid fuels. The figures were calculated by multiplying the proportion of solid fuel users by the total number of children in each country, using demographic data from the United Nations Population Division. As these are approximations, they may underestimate actual exposure, particularly in rural areas where solid fuel usage and household sizes tend to be higher. Countries with extremely low (below 5%) or extremely high (above 95%) rates of solid fuel use were excluded or adjusted due to data limitations. Given that women and young children typically spend more time near cooking areas, their actual exposure is likely greater than the estimates indicate [5].

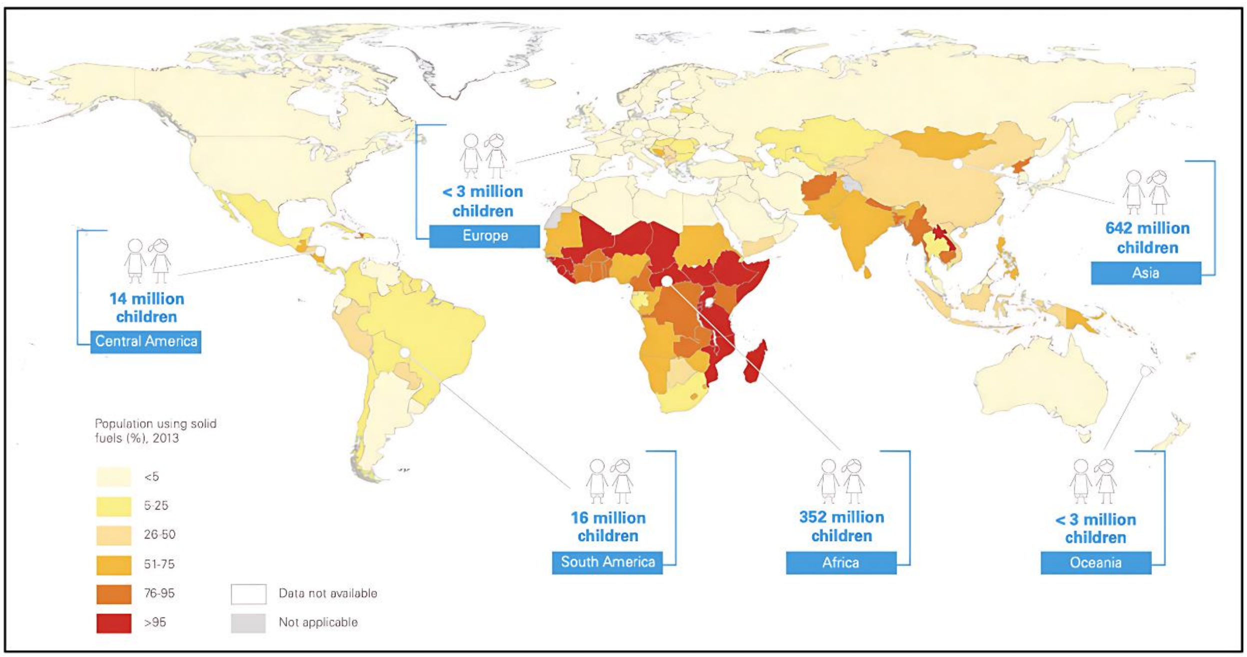

Figure 1.
World Map showing over 1 billion children living in homes where solid fuels are used in cooking and heating.
Source: United Nations Children's Fund (UNICEF) [6].

Air pollution is widely regarded as the most severe environmental risk to human health and is estimated to contribute to as many as one in every five deaths globally [7]. According to the World Health Organization (WHO), approximately seven million people die each year due to prolonged exposure to $PM_{2.5}$ in polluted air, with air pollution overall responsible for one in nine deaths worldwide [8]. Of these, ambient (outdoor) air pollution accounts for around 4.2 million deaths annually, while the remainder are linked to household exposure from the use of polluting cooking fuels and stoves [8]. Furthermore, an estimated 91 percent of the global population lives in areas where air pollution levels exceed established WHO safety guidelines [8].

1.2. The Rising Importance of Indoor Environments in Air Quality Research

In response to global challenges such as climate change and the COVID-19 pandemic, there has been a growing emphasis on creating healthier and more sustainable living environments, particularly for vulnerable urban populations [9]. As daily activities increasingly take place indoors, individuals spend a considerable amount of their time within enclosed settings such as homes, offices, schools, and restaurants [2]. For instance, research conducted in North America reports that adults spend approximately 87 percent of their time indoors, with only 6 percent in vehicles and 7 percent outdoors. Given this high level of indoor activity, exposure to indoor air pollutants has become a major concern, with clear implications for overall health and productivity [2].

Historically, air quality research has concentrated predominantly on outdoor environments, while indoor air quality received comparatively little attention until the past decade [2]. More recently, both scientific and public interest in IAQ has intensified, especially as studies have demonstrated that indoor air can often be more polluted than outdoor air. This shift has been driven in part by ongoing changes in lifestyle and the widespread use of new materials in indoor environments, which have altered the nature and complexity of indoor air pollutants and introduced new research challenges [2].

The importance of IAQ is underscored by the wide variety of pollution sources found indoors, including traditional and modern building materials, finishing products, furniture, cooking appliances, and cleaning products [2]. Numerous studies have established a clear link between poor IAQ and negative health outcomes, with some findings indicating that indoor pollutant concentrations can be two to five times higher than those found outdoors [10]. Nowadays, it is estimated that people spend approximately 85 to 90 percent of their time indoors, with more than half of that time occurring within residential spaces [10]. As one of the fundamental objectives of building design is to provide safe and comfortable indoor environments, the conditions within residential buildings are particularly important. Health is shaped and maintained in the everyday spaces where individuals live, work, learn, and interact [11]. Achieving a healthy indoor environment requires consideration of multiple factors, including outdoor air quality, construction practices, building regulations, energy efficiency, and occupant behaviour [12].

1.3. Urbanization and the Slum Housing Crisis

Living in informal settlements is linked to various forms of exclusion not only in terms of space, economy, and society, but also in health outcomes [9]. Rapid urban growth, combined with population increases, has worsened public health and reduced the quality of life for many urban residents [3]. By 2030, it is expected that nearly two billion people will live in informal urban areas, mainly in sub-Saharan Africa and parts of Asia [13]. As more of the world's poor move into slums, health problems in these areas are likely to increase [5]. This highlights the urgent need to address both environmental risks and health conditions in slum communities. Improving living conditions and public health in these areas is now a key goal in international development [11].

Several global development goals have focused on improving health in poor urban settings. The Millennium Development Goals (MDGs), for example, included targets to reduce child deaths (Goal 4), improve maternal health (Goal 5), and fight major diseases such as HIV/AIDS and malaria (Goal 6) [11]. Environmental issues were also addressed in Goal 7, which aimed to increase access to clean water and sanitation and improve the lives of people living in slums (10). Goal 1, focused on reducing extreme poverty, is closely connected to other goals like education (Goal 2) and promoting gender equality and the empowerment of women (Goal 3), showing how poverty, education, and health are linked [11].

The rapid expansion of urban populations has placed increasing pressure on housing infrastructure in many cities, with Mumbai offering a clear example of this challenge. Around 52.5 percent of the city's population resides on less than 9 percent of its total land area, primarily in settlements classified as slums. This reflects a persistent shortage of affordable and secure housing, which continues to limit social development and urban progress [3]. As a result, many megacities are characterised by high-density, poorly constructed housing with inadequate access to basic services, contributing to poor living conditions for large segments of the population [3]. A slum household is commonly defined as a group of individuals living together in an urban area who lack at least one of five essential needs: access to safe water, adequate sanitation, durable housing materials, sufficient living space, or legal security of tenure [11]. In many communities, families live in kutcha houses, which are temporary shelters built from materials such as wood and plastic sheets. These structures offer minimal protection and are highly vulnerable to environmental hazards [14].

Low-income households are among the most affected by the housing shortage, which is estimated to be around 6.2 million units [15]. These households are classified as poor when their income or consumption levels fall below what is needed to meet basic physical needs such as a sufficient diet, adequate housing with essential services, access to healthcare, and education [11]. In terms of population distribution, national data shows that over 60 percent of the population belongs to the middle class, while approximately 25 percent are identified as low-income and 15 percent as upper-income households [15]. However, although middle-class households make up the majority, they are often excluded from research due to limited or inaccessible data [15]. In many cases, low-income families live in shared arrangements, where more than one family occupies the same dwelling [15]. As a result, studies have found that a significant number of these households live in homes that are too small for the number of occupants and are often overcrowded [15].

Beyond poor housing conditions, slum communities also face serious sanitation challenges. The presence of untreated human waste serves as a source of harmful bacteria and soil-transmitted parasites, which are known to result in diarrhoea and other illnesses, particularly among young children. As a result, open defecation and the lack of proper sanitation infrastructure are strongly linked to the spread of infectious diseases. Access to clean water, proper disposal of wastewater, and improved sanitation services are considered fundamental to public health and human development [11]. Research conducted in rural areas of India has documented unhygienic practices, such as food preparation and childcare being carried out with hands contaminated by human feces. Additionally, open defecation was frequently observed not in isolated areas but within or near residential spaces, where children were often seen defecating and playing in contaminated surroundings. Several studies have concluded that high mortality rates in developing countries are closely associated with poor sanitation and inadequate hygiene practices at both the household and community levels [16].

Poor sanitation and the use of unsafe water sources continue to contribute significantly to child mortality. It is estimated that one child dies every 15 seconds due to diarrhoeal diseases linked to these conditions. According to the WHO, diarrhoea causes approximately 1.7 million cases of illness and leads to the deaths of around 760,000 children under the age of five each year. The absence or limited availability of clean water for domestic hygiene is strongly associated with a range of preventable diseases, including cholera, dysentery, eye infections such as trachoma, intestinal worm infections, and diarrhoea itself [11]. Globally, diarrhoea continues to rank as the second leading cause of death among children under five years old [17].

1.4. Key Indoor Pollutants and Exposure Sources

Particulate matter (PM) is considered one of the most harmful indoor air pollutants due to its long-term association with respiratory and cardiovascular diseases. Indoor PM levels are shaped by both internal and external sources, but often exceed outdoor concentrations during indoor activities such as cooking and smoking [18]. Research has shown that average indoor concentrations of $PM_{2.5}$ are consistently higher than outdoor levels, mainly due to emissions from these activities [19]. Cooking and smoking remain the leading contributors to indoor $PM_{2.5}$ exposure [19]. However, in high-income countries, cooking is not widely recognised as a significant factor in asthma exacerbation, although it represents an important opportunity for public health interventions [20]. Evidence from the National Health and Nutrition Examination Survey (NHANES) indicates that children living in households where gas stoves are ventilated during cooking are less likely to be diagnosed with asthma compared to those in non-ventilated environments. Certain cooking methods, especially frying, release substantial quantities of particulate matter, suggesting that reducing these practices may benefit respiratory health and diet quality. Cooking also generates other harmful pollutants, including NO_2, ultrafine particles, and polycyclic aromatic hydrocarbons (PAHs), all of which may contribute to inflammation in the respiratory tract [20].

Inadequate household infrastructure, such as the absence of separate kitchens and indoor smoking, contributes significantly to poor indoor air quality [14]. In addition to residential exposure, occupational exposure is also a major concern, particularly among restaurant workers such as cooks and kitchen staff, who spend prolonged periods in poorly ventilated environments. These workers are frequently exposed to high-temperature cooking emissions, which release various harmful substances into the indoor air, including gases, vapours, and fine particles [21]. Although research on indoor air quality in restaurant settings is limited, existing studies have reported substantial concerns, especially in developing countries [21]. Furthermore, modelling studies have confirmed the central role of indoor sources in determining exposure levels to pollutants such as $PM_{2.5}$ and NO_2 [22]. In this context, the type of household fuel used also plays a critical role in shaping indoor air quality. Cleaner fuels such as liquefied petroleum gas (LPG) tend to produce lower emissions, whereas more traditional fuels like kerosene and biomass still commonly used in low-income households contribute significantly to household air pollution [23].

Household air pollution (HAP) caused by burning biomass, coal, and kerosene in open fires and basic stoves is linked to an estimated two million deaths annually. A large proportion of these deaths occur in children under the age of five from pneumonia, and in adult women from conditions such as chronic obstructive pulmonary disease (COPD), cardiovascular disease, and lung cancer. The use of polluting fuels is closely tied to poverty, as acquiring and using these fuels consumes significant time and financial resources, particularly among low-income families. Within the home, women and children are most affected by smoke exposure during cooking activities. In India, over 75 percent of households still rely on traditional fuels such as firewood, crop residues, and dried cattle dung, often burned in open three-stone fires [24]. Many pollutants produced by daily activities such as cooking or cleaning can accumulate rapidly in enclosed spaces and migrate to other rooms, increasing exposure risks. Unlike developed countries, developing countries exhibit cultural practices and activities, such as lighting candles and incense sticks, due to religious practices that increase PM and VOC [25]. These additional sources are frequently overlooked in conventional IAQ assessments, despite their significant contribution to overall pollutant exposure, particularly within culturally specific household practices.

1.5. Socioeconomic and Domestic Determinants of Respiratory Illness

Respiratory illnesses are more commonly reported among women living in households with very low incomes, particularly those earning less than 1000 Indian Rupees per month. Symptoms such as chronic coughing, wheezing, shortness of breath, and chest discomfort have been linked to both socioeconomic status and specific household conditions. Factors contributing to these health risks include indoor smoking, the use of biomass fuels, extended cooking durations, inadequate lighting, and substandard flooring and wall materials. Studies indicate that indoor pollutant concentrations are consistently higher in households with low socioeconomic status, suggesting an increased environmental burden in these settings [22]

Children living in homes where smoking occurs are significantly more likely to develop respiratory issues. Research has found that these children are nearly five times more likely to suffer from hay fever and twice as likely to have a persistent cough compared to children in non-smoking households.

Furthermore, the average indoor $PM_{2.5}$ concentration was measured to be 26 micrograms per cubic metre higher in homes with a smoker than in those without, highlighting the substantial contribution of tobacco smoke to indoor air pollution [26].

Exposure to pollutants during cooking also poses significant respiratory risks, especially for children who stay near their mothers while food is being prepared. The likelihood of developing hay fever has been shown to nearly double for each additional hour spent in the kitchen. Similarly, among adult women, the use of biomass fuels, cooking in enclosed spaces, and limited ventilation, such as closed windows and doors, were all significantly associated with higher rates of respiratory symptoms. These findings are consistent with results reported in other regional studies across India. Air quality measurements from the current study revealed high indoor $PM_{2.5}$ levels, with a mean concentration of 3.80 milligrams per cubic metre. This is comparable to values reported in other studies across India, such as those by Ansari and Saksena in North India, which recorded concentrations of 2.38 and 4.50 milligrams per cubic metre, respectively. Regional differences in house design and cooking behaviour may influence exposure levels. For example, women in South India generally spend less time cooking compared to women in the northern regions, which may reduce their cumulative exposure to indoor pollutants [27].

1.6. Purpose and Scope of This Review

Given the well-documented health risks associated with indoor air pollution, this literature review seeks to provide a comprehensive synthesis of current research, with particular attention to informal housing and urban slum settings. The objectives of the review are to Karmakar, et al. [1] identify the primary sources of indoor air pollutants across various regions; Mannan and Al-Ghamdi [2] examine the health impacts on vulnerable groups, particularly those living in low-income and densely populated settings; Lueker, et al. [3] assess the effectiveness of current policies, technologies, and community-level interventions; Isaifan [4] evaluate the methodological strengths and limitations of current studies; and Vlahov, et al. [5] highlight key research gaps to inform future investigations and policy development. This review considers pollutants found in both residential and commercial indoor environments, with a focus on key trends and areas that remain insufficiently explored within indoor air quality research. The overall aim is to support the development of inclusive, sustainable, and energy-efficient housing policies tailored to the needs of low-income communities, particularly in developing countries [28]. By connecting environmental health, housing conditions, and policy, this review contributes to ongoing efforts to develop equitable and practical solutions for improving indoor living conditions in underserved communities.

2. Methodology

This review was conducted to collect and compare scientific studies on indoor air pollution (IAP) in informal housing and urban slums. The primary objective was to understand the sources of indoor pollution, its associated health effects, the common research methods used and identify existing gaps in the literature. The review followed the PRISMA guidelines to ensure a transparent and structured approach.

2.1. Search Strategy

A comprehensive literature search was conducted between May and June 2025 using three major academic databases: PubMed, Web of Science, and Google Scholar. The search strategy included a combination of keywords such as “indoor air pollution,” “household air pollution,” “indoor air quality,” “urban slums,” “informal housing,” “developing countries,” “health disparities,” “particulate matter,” “low- and middle-income class,” “public health,” and “ventilation.” The listed keywords were used to search the journal titles, abstracts, and keyword fields for the initial selection of peer-reviewed papers [2]. Filters were applied to limit results to studies published in English between 2006 and 2025 and specifically focused on LMICs.

To illustrate the global progression of indoor air quality (IAQ) research, studies from all world regions were included. Alongside journal articles, a limited number of conference papers and government reports were also reviewed to enhance the overall quality of the analysis [2].

2.2. Inclusion and Exclusion Criteria

Studies were included in this review if they were published in English in peer-reviewed journals, conducted in LMICs, focused on indoor air pollution or indoor air quality, and examined residential settings, particularly informal housing, urban slums, or low-income communities. Studies were excluded if they focused solely on outdoor air pollution, were conducted in high-income countries, or lacked direct measurement or discussion of indoor air quality (IAQ) or household air pollution (HAP).

To ensure comprehensive coverage of the available evidence on indoor air pollution, no restrictions were placed on the type of air pollutant assessed for indoor exposure. All pollutants were considered eligible for inclusion to capture the full scope of existing research and to identify emerging patterns within the literature. Studies were included if they estimated exposure to a specific pollutant or an indicator of poor indoor air quality in populations differentiated by socioeconomic status. Socioeconomic status (SES) was accepted when defined through social indicators, such as education, or economic indicators, such as income. However, studies that assessed indoor exposure solely based on race or ethnicity were excluded. A range of exposure assessment methods was accepted, including direct monitoring, modelling, self-reported exposure, and biological markers, provided that the exposure occurred within the home environment rather than in schools or outdoor settings [29].

2.3. Study Selection Process

The study selection process consisted of three stages. First, duplicate records were removed to ensure the uniqueness of the remaining studies. Second, the remaining records were screened for relevance based on their titles and abstracts. Third, the full-text articles of potentially eligible studies were reviewed to assess eligibility for inclusion. A total of 116 records were identified through database searches (PubMed and Web of Science), and 11 additional records were identified through other sources, including Google Scholar. After removing duplicates, 114 unique records were screened. Of these, 10 were excluded, and 104 full-text articles were assessed for eligibility. A further 52 studies were excluded after full-text assessment for not providing data relevant to the review. In total, 52 studies were included in the final qualitative synthesis. A PRISMA flow diagram summarizing the study selection process is presented in Figure 2.

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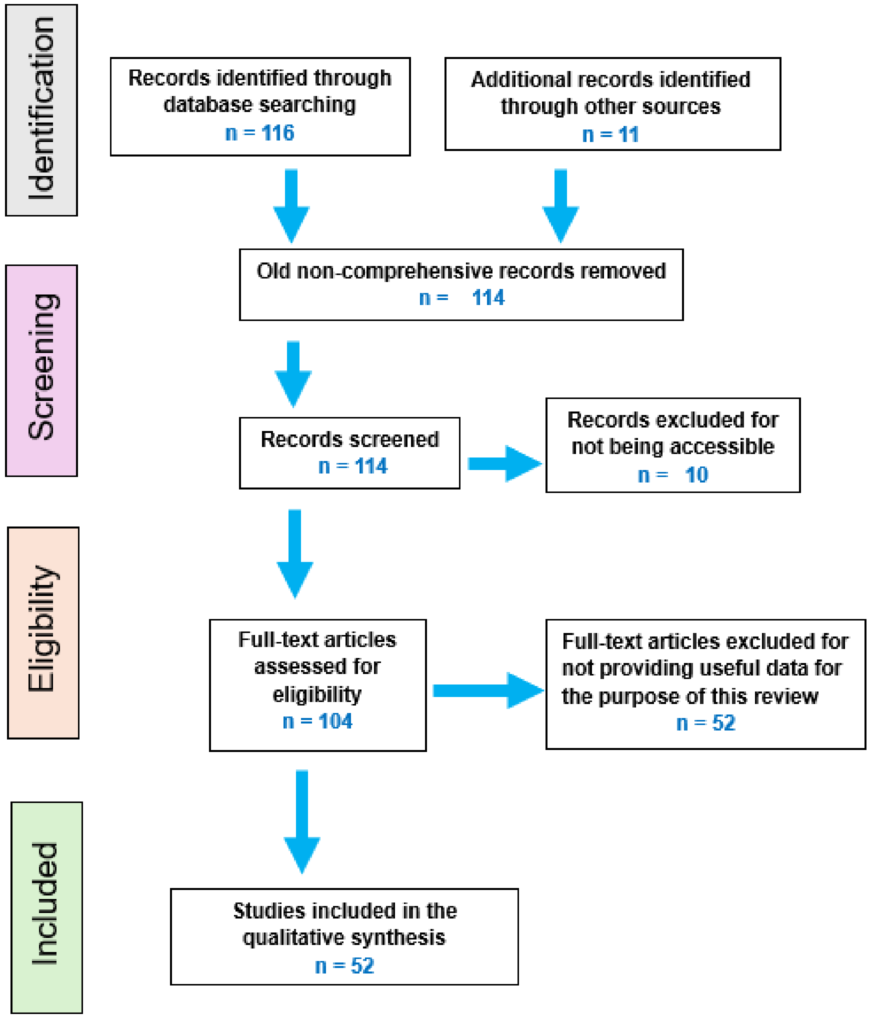

Figure 2.
PRISMA diagram of the literature selection process.

2.4. Data Extraction and Synthesis

Relevant data were systematically extracted from the selected studies to support a structured thematic synthesis. The extracted information included the types and sources of indoor air pollutants, characteristics of housing and infrastructure, affected demographic groups, socioeconomic conditions influencing exposure, and the presence or absence of mitigation strategies or policies. These elements were then organised and synthesised into five core themes: Karmakar, et al. [1] primary sources and classifications of indoor pollutants; Mannan and Al-Ghamdi [2] housing and infrastructural conditions contributing to poor indoor air quality; Lueker, et al. [3] health outcomes and demographic vulnerabilities, with particular attention to women and children; Isaifan [4] socioeconomic inequalities influencing exposure levels; and Vlahov, et al. [5] the role of policy and technological interventions, including their effectiveness, accessibility, and level of community involvement. Together, these themes provided a foundation for evaluating the complex health, social, and environmental implications of indoor air pollution in informal housing and urban slum settings [30].

3. Results

Understanding the geographic distribution of indoor air pollution (IAP) research is essential for identifying global exposure trends and highlighting areas where evidence remains limited. While IAP is a global concern, its health burden disproportionately LMICs, where inadequate housing and informal settlements are widespread. However, existing research is geographically uneven, with some regions more extensively studied than others.

To provide a global perspective on the scope of IAP research in informal housing, Figure 3 presents a world map indicating the countries covered in this review. Countries included in the analysis are shown in blue, while other LMICs are shown in green, and HICs appear in yellow. This visual representation highlights the diversity of socio-economic and regional settings addressed in the literature. India is among the most extensively studied countries, particularly urban centres like Mumbai, where solid fuel use and insufficient ventilation contribute significantly to indoor air pollution. In South America, research from countries such as Colombia and Chile has reported high levels of particulate matter in informal urban settlements. In East Asia, studies conducted in China have documented elevated concentrations of $PM_{2.5}$ and VOCs in residential indoor environments. This geographic overview underscores how variations in climate, housing infrastructure, and economic conditions shape the characteristics and severity of indoor air pollution around the world.

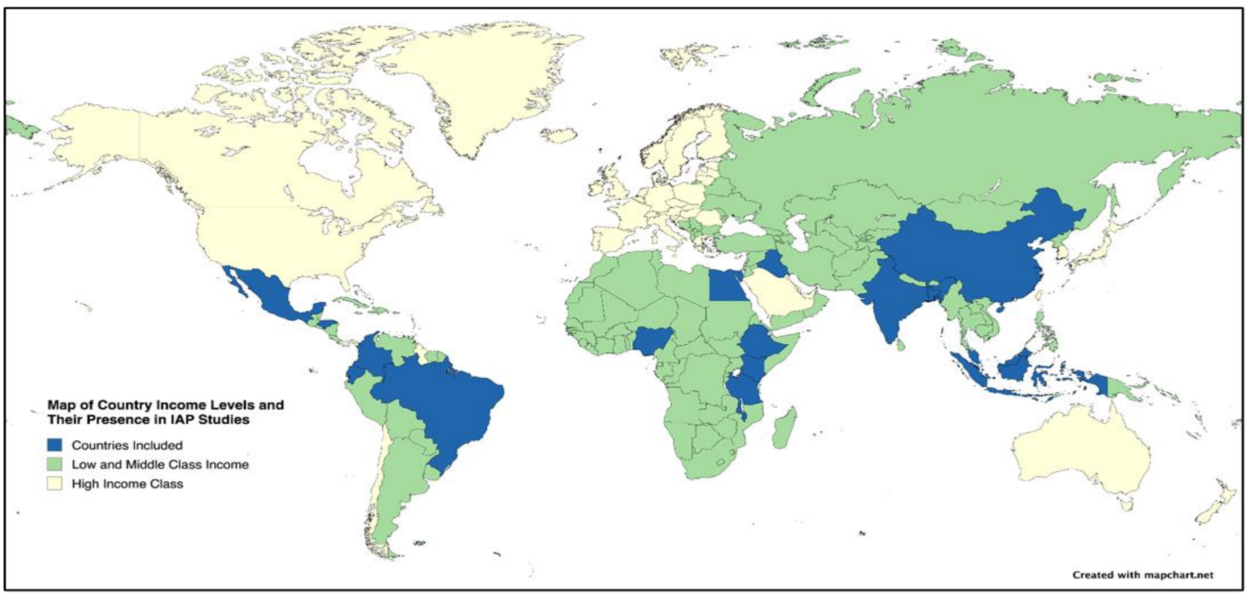

Figure 3.
Map showing countries included in this review (blue), other LMICs (green), and HICs (yellow). It gives an overview of where studies on indoor air pollution in informal housing have been carried out and how these locations compare globally.

3.1. Indoor Pollution Dynamics in Informal Housing

The reviewed literature highlights significant disparities in indoor air quality (IAQ) across low- and middle-income communities, particularly within informal housing and urban slum environments. Multiple studies, particularly those from India and other developing regions, consistently report that indoor pollutant levels vary according to household activities, with cooking and cleaning identified as primary contributors [1]. Indoor air quality is influenced not only by ambient outdoor air quality but also by pollutants produced through daily domestic practices. Poor indoor air quality has been associated with a range of health outcomes, including asthma, lung cancer, dizziness, fatigue, and headaches. Some studies suggest that the introduction of indoor plants may serve as a potential strategy to reduce IAP and improve overall air quality [10].

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Figure 4 presents the main sources of IAP in LMIC households, as identified in the reviewed studies. Common contributors include the use of biomass fuels for cooking, unvented stoves, inadequate ventilation, and indoor tobacco smoking. Additional sources, such as kerosene heaters and the indoor combustion of biomass, also contribute significantly to indoor pollution. The figure illustrates how everyday household practices and structural housing conditions significantly influence indoor pollutant levels. Identifying these sources is critical for designing effective strategies, including the promotion of cleaner cooking fuels, improved ventilation systems, and the reduction of indoor smoking, to mitigate health risks in informal and low-income housing settings.

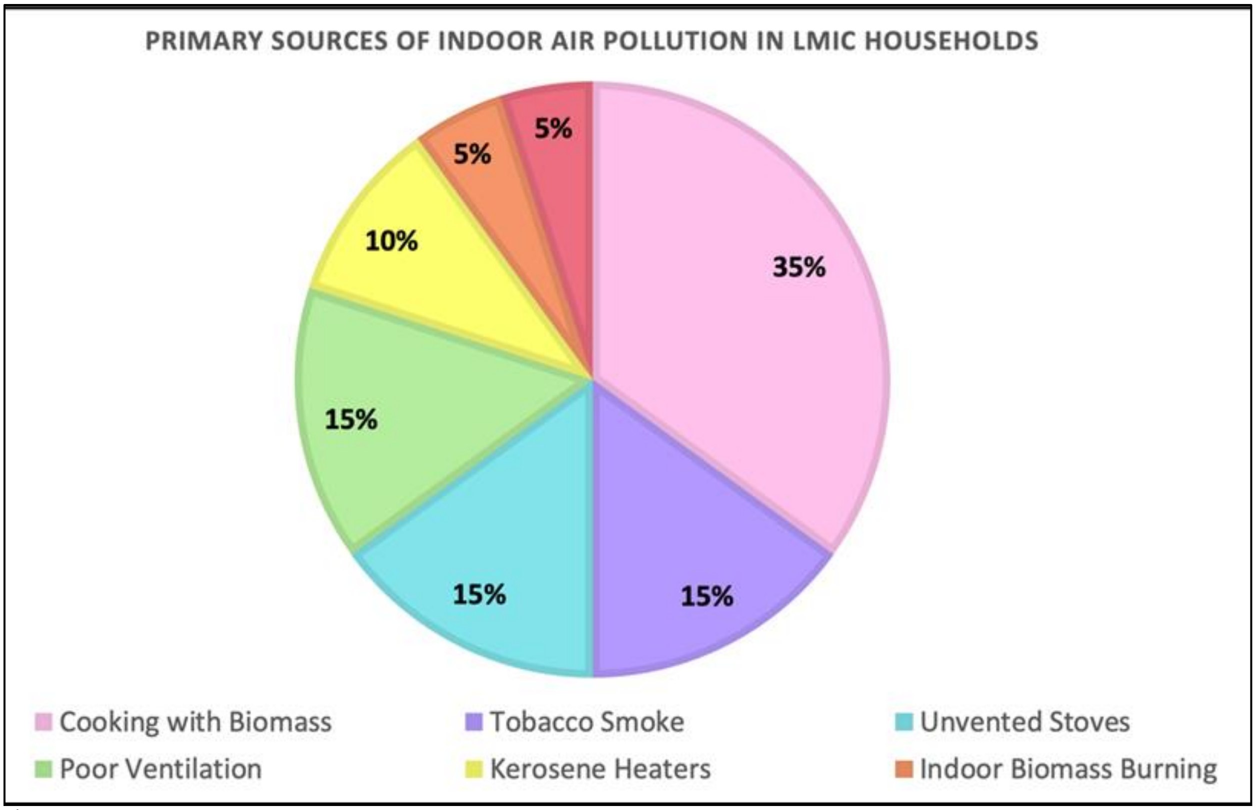

Figure 4.
Primary Household Sources of Indoor Air Pollution in LMICs.

3.2. Health Outcomes in Vulnerable Groups

Indoor air pollution continues to pose a serious health risk in informal and low-income urban housing, with women and children being the most affected due to prolonged exposure to indoor environments. Studies from urban South India reported a notable increase in respiratory symptoms among low-income women and children, particularly in households where indoor smoking was common [27]. A key contributing factor was the elevated level of fine particulate matter, with a mean $PM_{2.5}$ level of 3.8 mg/m³, which significantly exceeded the WHO's recommended 24-hour limit of 0.025 mg/m³ [27]. In sub-Saharan Africa, similar health risks have been linked to the continued use of traditional cooking methods involving solid fuels, which result in chronic exposure to indoor smoke and related pollutants [31].

The impact of indoor air pollution on women and children is of particular concern. Despite progress in reducing overall child mortality, an estimated 350–500 million children continue to reside in informal settlements, where under-five mortality rates remain higher than in rural or formal urban areas, primarily due to pneumonia and diarrhoea [32]. Although asthma is the most common non-communicable disease among children in low- and middle-income countries, its association link with informal settlements has been inferred mainly through associations with poverty and poor air quality, rather than established through direct comparative research [32]. With approximately one billion people worldwide living in slum conditions, the precise respiratory health implications of these living conditions remain insufficiently understood [32].

Studies have shown that respiratory symptoms are highly prevalent among residents of informal settlements. One investigation reported that all mothers experienced at least one respiratory symptom, with wheezing (53%) and coughing (43%) being the most cited. Among children, cough was reported in 34% of cases, followed by runny nose (23%) and wheeze (17%) [27]. The same study found that nearly half of the households exhibited signs of indoor dampness, a condition frequently associated with the poor drainage and recurring flooding common in slum areas [33]. Structural deficiencies were also observed, including the absence of windows in many rooms and a lack of exhaust fans in kitchens and bathrooms, which contribute to poor ventilation [9]. Adequate ventilation is widely recognized as essential for maintaining healthy indoor air quality [9]. The presence of phlegm was more common among individuals living in homes affected by dampness and mould compared to those without, which is consistent with previous research [33]. Visual mould was observed in approximately 51% of homes during the dry season and 34% during the rainy season [9]. Damp conditions support the growth of mould spores, which can trigger allergic reactions, contribute to material degradation, and elevate indoor pollutant concentrations, factors that increase the risk of respiratory illness [33]. Although evidence linking dampness to respiratory symptoms in adults is limited, studies such as that by Simoni and Lombardi in Italy have identified a higher incidence of phlegm in children exposed to damp living environments [33]. These findings highlight the importance of addressing indoor dampness in efforts to improve respiratory health in informal housing [33].

Building on these findings, the same study identified several social and behavioural contributors to respiratory health outcomes. Unmarried respondents reported a higher prevalence of wheezing compared to their married counterparts, which may be attributed to a greater likelihood of engaging in behaviours such as indoor smoking [33]. This pattern was further reflected in housing-related disparities, with children living in public housing exhibiting a significantly higher risk of asthma than those in private family homes. This difference was linked to increased exposure to indoor allergens, including cockroach and mouse residues, which were more commonly present in public housing units [34]. Beyond respiratory conditions, indoor air pollution has also been associated with adverse mental and cognitive health outcomes. Exposure to polluted environments, both indoors and outdoors, may contribute to neurocognitive disorders through pathways involving neuroinflammation, oxidative stress, and cerebrovascular dysfunction [35]. Moreover, thermal discomfort in low-income households has been identified as a contributing factor to psychological distress, further underscoring the broader health implications of poor indoor environmental quality [35].

3.3. Influence of Fuel Types and Ventilation Practices

The quality of indoor air in informal housing is strongly influenced by both fuel type and ventilation conditions. Evidence from recent studies demonstrates that households that kept windows closed while cooking experienced significantly elevated levels of $PM_{2.5}$, reaching 1.36 mg/m^3, compared to just 0.45 mg/m^3 in homes where windows were opened [27]. The choice of cooking fuel further contributed to exposure risk. Firewood use was associated with a notable increase in $PM_{2.5}$ concentrations, rising by approximately 1.368 mg/m^3 [27]. Indoor smoking presented an additional concern, with households that prohibited smoking reporting lower $PM_{2.5}$ levels (1.12 mg/m^3) than those that permitted it (2 mg/m^3) [27]. These findings underscore the importance of household practices in shaping exposure to indoor air pollution in low-income settings.

In response to these challenges, the use of mechanical ventilation systems such as extractor fans or range hoods has been proposed as a cost-effective way to reduce pollution during cooking. Occupants in homes lacking these systems were found to have up to four times higher exposure to $PM_{2.5}$ than those

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with functional ventilation [19]. However, in many low-income settings, financial limitations prevent the widespread adoption of such technologies. As a result, passive ventilation techniques, including manually opening windows based on time of day or temperature, are often employed as an alternative means to control indoor air conditions [36].

Although passive strategies offer practical advantages, their effectiveness is not always consistent. The performance of natural ventilation is influenced by external factors such as wind speed, temperature differences, and building design [36]. For instance, when indoor and outdoor temperatures are similar or wind movement is minimal, ventilation may be limited, reducing pollutant removal [37]. Improved airflow can be achieved by opening windows positioned at both high and low levels, especially across multiple storeys [38]. In low-income housing, traditional architectural features such as pitched roofs, minimal internal partitions, and ceiling fans have historically promoted cross-ventilation and enhanced indoor comfort [15]. In warm, humid environments like Mumbai, thermal comfort has been associated with outdoor air velocities between 1 and 5 metres per second, underlining the importance of incorporating airflow design into housing planning [23]. These natural methods often remain the primary approach to managing indoor conditions in resource-constrained settings [23].

Beyond ventilation techniques, broader considerations around building performance and energy use also play a crucial role in improving indoor environmental quality. Sustainable housing strategies now emphasise the use of recycled materials and hybrid ventilation systems capable of maintaining steady airflow while regulating temperature and humidity [8]. Innovative solutions such as double-height passive cooling systems (DHPC) have been proposed to address heat buildup and poor air circulation in high-density residential buildings [8]. Additionally, modifications such as enlarging window openings have been shown to significantly reduce peak indoor temperatures [37]. Other low-cost strategies, including insulated walls and widely available building materials, can further improve thermal comfort [37]. Nonetheless, long-term progress will require broader policy interventions. Tackling inefficiencies in low-income housing and reducing reliance on high-cost energy sources will depend on coordinated regulatory reforms that support sustainable and integrated housing solutions [39].

3.4. Comparative International Findings

Building on findings from local studies, international research has reported similar patterns of indoor air pollution in informal housing. In Santiago, Chile, 24-hour average $PM_{2.5}$ concentrations were found to be significantly higher in slum areas compared to public housing. This suggests that residents in informal settlements face greater exposure not only due to ambient pollution but also due to indoor practices that contribute to poor air quality, such as cooking with solid fuels and limited ventilation [40].

Comparable conditions have been documented in India. In the Dharavi slum of Mumbai, $PM_{2.5}$ concentrations during the winter season reached 505 $\mu g/m^3$, a level substantially higher than the 192 $\mu g/m^3$ recorded by the U.S. Consulate during the same period. These differences highlight a key limitation in centralized air quality monitoring, which often does not reflect short-term or community-specific exposure levels in densely populated low-income settings [3]. Together, these studies emphasize the need for more localized monitoring approaches and targeted interventions in informal urban environments.

3.5. Structural and Design Limitations in Slum Housing

Building on the broader geographic and environmental disparities discussed earlier, recent research has turned attention to how structural design and spatial planning in informal housing directly shape indoor air quality. In Mumbai, slum rehabilitation housing is frequently reported to have inadequate ventilation pathways, poor daylight access, elevated indoor temperatures, and high concentrations of indoor pollutants. These conditions are often worsened by underdeveloped infrastructure systems, contributing to consistently poor indoor environmental quality [3]. Reports of mould growth and an increased burden of respiratory illnesses are common, often linked to overcrowding and insufficient ventilation [3].

Despite increased recognition of housing as a key social determinant of health, research continues to pay limited attention to architectural and spatial design in low-income settings [15]. A recurring issue is the limited size and rigid layout of homes, which restrict their use for multiple basic activities such as cooking, resting, studying, and socialising [15]. Furthermore, the absence of defined minimum space standards has contributed to overcrowding and poorly ventilated living spaces, reducing indoor comfort and airflow [15]. Even in formal social housing developments, existing minimum space regulations often lead to compact designs that limit natural ventilation, particularly in enclosed areas [36].

In addition to spatial limitations, construction quality significantly influences environmental performance. In Brazil, for example, most low-income housing is built on-site using basic materials such as bricks, cement, and wood, with little application of prefabricated or energy-efficient components [15]. This construction method often results in thermally inefficient and poorly ventilated homes. Similar challenges persist in other developing regions, where weak or absent building codes have contributed to energy-inefficient and environmentally unsustainable housing [39]. Evidence from Mumbai's low-income group (LIG) settlements confirms these patterns. Many units lack designed airflow paths, contributing to excessive indoor heat, insufficient sanitation, and persistent indoor air pollution [23]. Dense building layouts obstruct airflow, limit ventilation, and contribute to the accumulation of indoor pollutants in already vulnerable communities [23].

Table 1 outlines structural, socioeconomic, and behavioural factors in informal housing that can lead to poor indoor air quality. These include limited ventilation, overcrowded spaces, use of solid fuels, and poor building materials. Each factor influences how pollutants accumulate indoors and affects the health and well-being of residents, especially in low- and middle-income settings.

Table 1.
Key Characteristics of Informal Housing That Influence Indoor Air Quality.

Factor category	Specific factor	Description / Impact on IAQ
Structural	Poor Building Materials	Homes are often built with low-quality materials, which absorb moisture, allow dust entry, and support mold growth
	Inadequate ventilation	Many units lack proper windows or vents, limiting airflow and causing pollutants to build up indoors
	Small living spaces	Limited space means pollutants from cooking or heating are concentrated, increasing exposure levels
	High Housing Density	Dwellings are tightly packed, reducing outdoor air circulation and allowing pollution to spread between homes
	Unpaved Floors	Dirt floors generate dust and hold moisture, contributing to poor air quality and mold development
Socioeconomic	Overcrowding	Too many people in small spaces raise indoor humidity, carbon dioxide
	Limited access to clean energy	Many households rely on firewood, charcoal, or kerosene, which produce harmful smoke and gases
	Poverty and low-income	Financial constraints make it difficult to afford cleaner fuels, better housing, or improved stoves
	Informal settlement conditions	Lack of planning and regulation leads to poor sanitation, waste buildup, and inadequate infrastructure, all of which affect air quality
Behavioural	Indoor waste burning	Burning trash indoors releases toxic smoke and chemicals into living spaces
	Indoor smoking	Smoking inside the home increases harmful pollutants like carbon monoxide and fine particles
	Poor maintenance of cooking devices	Broken or inefficient stoves produce more smoke due to incomplete combustion

3.6. Mitigation Strategies and Fuel Alternatives

Following the identification of key structural, socioeconomic, and behavioural factors contributing to IAP, it is also important to consider the range of strategies proposed to reduce indoor pollution in informal housing settings. In recent years, research has increasingly examined practical interventions aimed at improving household air quality in low- and middle-income communities. These efforts focus particularly on enhancing ventilation and encouraging the use of cleaner cooking fuels, both of which have shown promise in reducing pollutant levels indoors.

Among these strategies, fuel switching is frequently cited as an effective measure. For instance, a World Bank study conducted in Madagascar found that ethanol produced significantly fewer emissions compared to biomass fuels traditionally used in low-income households. In the same study, larger kitchen spaces were also associated with improved indoor air conditions, likely due to better diffusion of smoke and pollutants. Moreover, the introduction of improved wood stoves fitted with chimneys led to noticeable reductions in CO concentrations within cooking areas, demonstrating the value of relatively low-cost technological solutions [41].

These findings highlight the potential of simple yet targeted interventions in reducing indoor air pollution. Cleaner fuels, better kitchen design, and basic ventilation improvements can all contribute to healthier indoor environments. However, the success of these strategies depends not only on their effectiveness, but also on affordability, accessibility, and the willingness of households to adopt new practices.

3.7. Sources and Effects of Harmful Indoor Pollutants

While fine particulate matter has been a central focus in indoor air pollution research, it represents only one aspect of the broader range of harmful substances generated through household combustion. The use of solid fuels in inefficient or unventilated stoves results in the release of a complex mixture of pollutants, with emissions varying by fuel type, stove design, and combustion conditions [4]. Among the most commonly identified compounds are PAHs, VOCs, CO, and NOx, all of which have been linked to adverse health outcomes [4].

One of the most significant consequences of incomplete combustion is carbon monoxide. As an odourless and colourless gas, carbon monoxide poses a serious health risk due to its undetectable nature without specialised sensors. Primary sources of indoor CO include unvented cooking and heating devices, leaking chimneys, and poorly maintained combustion systems [4]. In inadequately ventilated spaces common in informal or low-income housing, CO levels can quickly reach hazardous levels, increasing the risk of poisoning and long-term respiratory effects.

The presence of nitrogen-based pollutants further contributes significantly to the degradation of indoor air quality. Nitrogen oxides (Nox), particularly nitrogen monoxide (NO) and nitrogen dioxide (NO_2), are typically produced during combustion and are associated with a range of household sources, including gas stoves, ovens, space heaters, fireplaces, and tobacco smoke. Indoor NOx concentrations may also be elevated due to outdoor air infiltration, especially in buildings located near major roads or industrial areas. This highlights the combined influence of both indoor and outdoor pollution sources in shaping indoor air conditions [4].

Volatile organic compounds constitute another group of pollutants of increasing concern. VOCs are released through various routine activities, including cooking, smoking, and the use of cleaning agents, personal care products, and air fresheners. Emissions from building materials, carpets, and furniture further contribute to indoor VOC levels through off-gassing over time. In addition, VOCs may enter indoor spaces via chemical reactions or the infiltration of contaminated outdoor air through ventilation systems [4]. Due to their chemical persistence and persistence, VOCs are considered a major contributor to long-term indoor exposure.

Evidence from recent studies has further demonstrated the health implications of these pollutants. Comparative research conducted in China and Japan between 2006 to 2007 revealed that indoor VOC concentrations were consistently higher than outdoor levels in both countries, with residents in China

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exposed to cancer risks ten times greater than those reported in Japan [2]. Similarly, assessments of non-residential environments, such as fast-food and family restaurants, have found that carbon dioxide (CO_2) concentrations frequently exceed standard limits, largely due to poor ventilation systems. These findings emphasise the broader consequences of inadequate airflow on indoor air quality in both domestic and public settings [21].

Table 2 presents a comparison of common sources of indoor air pollution in LMICs and their associated health impacts. It highlights key household activities such as cooking with solid fuels, smoking indoors, and using unvented stoves that contribute to high levels of harmful pollutants like $PM_{2.5}$, CO, and VOCs. The table additionally illustrates the regions where these activities are most common, including South Asia, Sub-Saharan Africa, and Latin America, and underscores their significant health consequences. These range from respiratory diseases and cardiovascular issues to developmental challenges in children, demonstrating the urgent need for targeted interventions in these regions.

Table 2.
Comparison of Indoor Air Pollution Sources and Health Impacts in LMICs.

Pollution Source	Main pollutants	Impact on IAP	Example Region/Country	Health Impact
Cooking with Solid Fuels	$PM_{2.5}$, CO, VOCs	High particulate matter, poor air circulation	India, Paraguay	Respiratory illnesses, asthma
Use of Unvented Stoves	$PM_{2.5}$, NOx, CO	Elevated pollutant levels in indoor air	India, Kenya	Lung disease, cardiovascular issues
Tobacco Smoking Indoors	CO, $PM_{2.5}$, VOCs	Significant increase in indoor pollutants	South India, South Africa	Increased cancer risk, respiratory diseases
Poor Ventilation Systems	$PM_{2.5}$, VOCs, Radon	Trapping of indoor pollutants, low air exchange	Mumbai, China	Respiratory symptoms, risk of lung cancer
Indoor Biomass Burning	$PM_{2.5}$, CO, VOCs	High concentrations of harmful pollutants	Sub-Saharan Africa, India	Respiratory infections, childhood development issues

3.8. Regional Disparities in Indoor Air Pollution

Indoor air pollution levels vary significantly across regions, largely due to differences in fuel use, cooking practices, and household ventilation. Studies have shown that households using solid fuels such as wood or dung are exposed to particularly high concentrations of $PM_{2.5}$, with kitchen levels ranging from approximately 150 to 1,200 $\mu g/m^3$ depending on location and fuel type [4]. These elevated concentrations are most commonly reported in sub-Saharan Africa and parts of South and East Asia, where the use of solid fuel remains widespread [4].

The health impacts associated with this exposure are particularly severe in areas where solid fuel use is most prevalent. In sub-Saharan Africa, for instance, the age-standardised mortality rate linked to HAP is estimated at 200 per 100,000 people, roughly six to seven times higher than the global average of 30 per 100,000 [4]. Similar patterns are observed in Southeast Asia, where pollutant levels consistently exceed international guidelines. PM_{10} and $PM_{2.5}$ concentrations in this region frequently exceed the WHO's recommended annual limits by more than fivefold, with evidence indicating a continuing upward trend of around 1% per year [42].

Differences in indoor air quality have also been widely documented. Research shows that pollutant concentrations, particularly $PM_{2.5}$ and CO_2, are generally higher in kitchens than in other parts of the home, reflecting the influence of room function and ventilation on exposure levels [42]. Regional case studies further illustrate this pattern. In Kuala Lumpur, Malaysia, indoor $PM_{2.5}$ levels were found to range between 21 and 35 $\mu g/m^3$, while PM_{10} concentrations ranged from 44 to 56 $\mu g/m^3$ [42]. In contrast, studies from informal settlements in Chile reported comparatively lower $PM_{2.5}$ levels than those observed

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in households using open fires or coal and wood stoves, where concentrations often exceeded 528 μg/m³ [40].

3.9. Community-Level Engagement and Behaviour Change

Community engagement has emerged as a critical component in addressing indoor air pollution, particularly in informal and low-income settings. Several interventions have focused on increasing public awareness of the health risks associated with indoor smoke, while also promoting safer cooking practices and access to cleaner fuels. In Madagascar, for instance, community-based approaches led by nongovernmental organisations supported local entrepreneurship by encouraging the adoption of ethanol as a household fuel. These efforts included training programmes on stove production and the installation of small-scale ethanol distilleries, which contributed both to cleaner energy use and local job creation [41].

Alongside broader community initiatives, small changes in daily practices and home design have also been shown to improve indoor air quality. Behavioural factors can significantly affect $PM_{2.5}$ exposure levels, particularly in homes where traditional cooking methods are used [19]. The introduction of improved cookstoves with chimneys and the use of larger or more ventilated cooking areas have been associated with lower concentrations of indoor pollutants [41]. These relatively simple adjustments can offer substantial health benefits, especially when combined with targeted education and awareness efforts.

When community-based interventions are aligned with local needs and practices, they are more likely to lead to lasting changes in behaviour. Programmes that integrate cleaner fuel access, improved ventilation, and household-level education have demonstrated greater success in reducing exposure to harmful emissions. This evidence highlights the importance of combining technical solutions with community engagement to promote sustainable improvements in indoor air quality across informal settlements.

4. Discussion

4.1. Indoor Air Pollution in Informal Housing

Indoor air pollution (IAP) continues to pose a serious public health challenge in informal settlements, particularly within LMICs. Key pollutants, including $PM_{2.5}$, VOCs, and CO, primarily originate from everyday household activities such as cooking with solid fuels, smoking, and the use of cleaning agents. Poor ventilation and the presence of multiple indoor emission sources frequently result in pollutant levels that exceed those found in outdoor environments. The conditions within these homes are often shaped by poverty, inadequate infrastructure, overcrowding, and limited access to clean water and sanitation services [43]. Dwellings are typically small, constructed with low-quality materials, and lack proper ventilation. In many cases, a single room functions as a kitchen, living area, and bedroom, exposing all household members including women, men, and children to cooking emissions and indoor smoke [43]. While housing quality and energy access are often regulated and monitored in high-income countries, residents in informal settlements face significant structural and economic barriers that prevent the adoption of similar protections. As a result, exposure to indoor pollution remains disproportionately high in these settings.

In urban Indian contexts such as Mumbai, resettlement housing developments raise significant concerns regarding indoor air quality. These projects are frequently implemented under financial constraints, with limited access to reliable energy and reduced flexibility in architectural design [3]. Given that a substantial portion of the city's low-income population is expected to be relocated into such environments, addressing the associated environmental health risks is essential. By contrast, public housing developments in high-income countries are typically regulated by building codes that ensure minimum standards for ventilation, space, and thermal comfort. Resettlement units in India often fall short of these benchmarks, leading to elevated exposure to indoor pollutants. When combined with overcrowding and restricted access to clean energy sources, these conditions create living environments in which indoor air pollution remains a persistent and inadequately addressed public health concern.

Behavioural and structural factors further influence exposure levels. In households located in informal settlements, the frequency of indoor smoking is slightly higher than in public housing, with indoor $PM_{2.5}$ levels found to be significantly elevated in homes where multiple cigarettes are smoked daily [40]. Poor building design and overcrowded living conditions also contribute to elevated humidity and insufficient air exchange, creating environments conducive to mould growth and the spread of respiratory infections [3]. Such environmental conditions are less prevalent in formal housing in developed countries, where stricter building codes and greater enforcement of smoke-free regulations contribute to lower indoor pollution exposure.

Chemical exposure through household insecticide use presents another concern. In many informal homes, insecticides are frequently used to control disease vectors such as mosquitoes. However, routine spraying has been associated with a higher prevalence of respiratory symptoms particularly among children including phlegm and nasal congestion [33]. These products release volatile organic compounds and other hazardous pollutants that may settle on household surfaces or persist in indoor air, especially when overused or applied in poorly ventilated environments [33]. This pattern aligns with previous findings linking early childhood respiratory illness to household pesticide exposure [33]. By contrast, residents in high-income countries often benefit from safer, regulated pest control options and greater public awareness of chemical exposure risks indoors. The absence of similar protections in informal housing increases the risk of chronic exposure, particularly for vulnerable populations such as young children.

Mitigating these risks requires more than structural improvements alone. Promoting safer pest control alternatives, such as non-chemical strategies, and encouraging practices like allowing adequate time before reoccupying sprayed rooms may reduce harmful exposures. Integrating these low-cost behavioural changes into broader housing and public health efforts could improve indoor environmental conditions in informal and resettled communities. Addressing these challenges will also require targeted, context-sensitive interventions alongside broader reforms to reduce housing-related health inequalities at a global scale.

4.2. Housing Conditions and Health Impacts

Housing quality plays a fundamental role in shaping indoor air quality and broader health outcomes, particularly in informal settlements where conditions are often substandard. Overcrowding, poor ventilation, and flawed architectural design contribute to the accumulation of indoor pollutants, elevated indoor temperatures, and increased moisture levels. These environments create conditions that are not only physically uncomfortable but also hazardous to respiratory and cardiovascular health. A safe and durable home is typically expected to provide protection from environmental stressors such as extreme temperatures, dampness, mould, and noise, while also ensuring structural integrity and sufficient space for household activities [11]. However, such standards are rarely met in informal housing, where residents frequently occupy small, poorly constructed dwellings with minimal airflow.

Environmental and behavioural factors within informal housing settings play a significant role in shaping IAQ. Among these, indoor humidity has been identified as a key variable influencing pollutant concentrations. Elevated humidity levels can cause $PM_{2.5}$ and PM_{10} to absorb moisture, increasing particle size and limiting their dispersion. This results in higher concentrations of pollutants within indoor spaces, particularly in poorly ventilated environments [33]. Conversely, increases in indoor temperature may help reduce humidity and promote air circulation, thereby contributing to a decline in particulate matter levels [33]. Despite this potential benefit, both high and low indoor temperatures have been linked to negative health outcomes, especially among vulnerable groups such as children and the elderly. These findings highlight the complex relationship between indoor climate conditions and pollutant behaviour, underscoring the need for housing strategies that address both thermal comfort and air quality in low-income urban settings.

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Inadequate housing conditions in informal settlements also expose residents to a range of non-chemical environmental stressors that negatively affect mental and physical well-being. Limited access to natural daylight, lack of visual connection to the outdoors, and continuous exposure to noise pollution have been associated with increased rates of depression and psychological distress in urban populations [11]. These challenges are especially prevalent in informal housing, where essential design features that support occupant health are frequently missing [3]. Ventilation, a critical aspect of indoor environmental quality, is often insufficient or entirely overlooked. In many dwellings, kitchens are located within living and sleeping spaces, which increases the risk of continuous exposure to cooking-related emissions. Modifying these layouts to improve airflow and creating physical separation between cooking areas and living spaces has been recommended as a necessary intervention to reduce indoor air pollution and enhance overall living conditions [31].

Beyond physical health outcomes, overcrowding in informal housing has been consistently associated with a range of psychosocial and developmental challenges. Limited living space, lack of privacy, and continuous exposure to noise contribute to elevated stress levels, disrupted sleep, and reduced capacity for essential activities such as studying, particularly for children [11]. In many cases, these conditions have been linked to increased risks of interpersonal conflict, including domestic violence and child abuse. Such findings underscore the importance of recognizing housing design not only as a matter of structural adequacy but also as a key factor influencing mental health, personal safety, and overall well-being. Ensuring adequate space for rest, learning, and routine daily activities represents a critical yet frequently neglected dimension of housing interventions aimed at improving quality of life in low-income urban communities [9].

4.3. Influence of Ventilation and Fuel Use

Ventilation practices and household fuel choices are critical determinants of IAQ in informal housing environments. In poorly ventilated spaces, pollutants released from cooking, heating, and other combustion activities tend to accumulate, leading to high levels of exposure. Studies have shown that adults who cook in outdoor areas experience significantly fewer respiratory issues compared to those cooking indoors. Specifically, the risk of shortness of breath was found to be 40% lower among individuals whose cooking spaces were located outside the main living area [33]. This difference is largely due to improved dispersion of pollutants in open-air settings, which prevents the buildup of harmful smoke and gases. In contrast, cooking indoors in confined spaces where windows are often kept closed due to safety or weather concerns allows for the concentration of PM and gaseous pollutants such as CO and NO2, increasing the likelihood of respiratory illness [33].

The type of fuel used also plays a major role in exposure levels. Solid fuels such as firewood, charcoal, and agricultural residues remain widely used in informal and rural households due to their low cost and accessibility. However, these fuels produce high levels of $PM_{2.5}$ and other toxic pollutants when burned inefficiently. Homes relying on biomass fuels often report indoor $PM_{2.5}$ concentrations far exceeding the WHO's recommended limits, particularly when ventilation is limited. In many rural settings, over 80% of households still depend on firewood for cooking, while cleaner fuels like LPG are adopted by fewer than 20% of homes [31]. This reliance on biomass is driven by affordability and availability, but it poses major health risks, especially for women and children who spend more time near cooking areas.

Quantitative evidence further illustrates the health risks of biomass use. One study reported that median $PM_{2.5}$ concentrations in households using biomass reached 1.32 mg/m^3, compared to just 0.16 mg/m^3 in homes using LPG or other clean fuels [27]. These findings reinforce the importance of fuel switching as a public health intervention. Yet, the adoption of cleaner fuels in informal settlements remains limited by economic, infrastructural, and cultural barriers. For many households, even when LPG is available, its use may be restricted to specific meals or occasions, while traditional stoves remain the primary method of cooking. These insights highlight the urgent need to prioritise ventilation improvements and cleaner fuel adoption as integral components of broader public health and housing strategies aimed at reducing indoor air pollution in informal settlements.

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4.4. Research Gaps and Regional Differences

Despite increasing recognition of IAP as a major public health issue, the existing evidence focused on informal settlements remains limited and unevenly distributed across regions. Much of the existing literature is fragmented, with considerable variation in methodologies, study settings, and pollutant indicators, making cross-comparison and generalisation difficult. This lack of standardisation has hindered the development of comprehensive guidelines tailored to the realities of low-income housing environments [13].

A notable disparity exists between regions, with Sub-Saharan Africa remaining significantly under-researched in comparison to South and East Asia. While urban centres in countries like India and China have received growing attention due to their rapid urbanisation and concentrated slum populations, many African cities facing similar challenges continue to be overlooked. This imbalance in the evidence base limits the global understanding of indoor environmental risks and contributes to the exclusion of certain regions from policy dialogues and funding priorities.

Moreover, most studies focus narrowly on household-level exposures, often overlooking indoor environments in communal settings such as schools, healthcare centres, and informal workplaces. These spaces play a central role in daily life within slum communities and may contribute substantially to overall exposure. The absence of research in such contexts presents a critical gap in understanding the full scope of indoor air pollution in densely populated, resource-constrained areas.

Beyond spatial and institutional limitations, there is also a lack of research exploring how socio-cultural practices and behavioural patterns intersect with household energy use and ventilation habits. For instance, interventions promoting the adoption of clean fuels often assume straightforward behavioural change, without fully considering the economic pressures, safety concerns, or traditional norms that influence fuel choice. This disconnection between intervention design and lived realities may partly explain the limited uptake of improved stoves or cleaner energy options in many informal settlements.

Although some national housing initiatives, such as India's affordable housing policies, have succeeded in expanding access to formal dwellings, the long-term environmental health implications of these units remain insufficiently evaluated. Few programmes incorporate air quality metrics or ventilation standards into their design frameworks, raising concerns about the sustainability and adequacy of housing improvements in addressing indoor environmental risks [3].

Collectively, these gaps point to the need for a more comprehensive, interdisciplinary research agenda that accounts for both physical and social determinants of indoor air quality in informal settlements. Future studies should aim to capture the complexity of real-world exposure across diverse settings, while also informing context-sensitive policy interventions that prioritise health equity in the built environment.

4.5. Community-Based Interventions

Community-based interventions have emerged as a promising strategy for addressing indoor air pollution (IAP) in informal settlements, particularly when they combine cleaner energy alternatives with education, capacity building and economic support. These interventions often promote the use of ethanol-based fuels, improved stove technologies and local employment opportunities, offering a multifaceted approach to environmental health improvement. For instance, a World Bank initiative in Madagascar projected that over the course of three decades, more than one million households could transition to ethanol as their primary cooking fuel, illustrating the potential scale of impact when such programs are supported by long-term planning and investment [41].

The success of these interventions is closely tied to community engagement. Local participation not only fosters a sense of ownership but also ensures that interventions are tailored to the social and cultural context. Non-governmental organizations (NGOs) have played a vital role in facilitating this process by supporting local entrepreneurs, offering training in stove production and ethanol micro distillery installation and raising awareness about the health and environmental benefits of cleaner fuels [41].

These efforts not only help reduce harmful household emissions but also contribute to local economic development by creating jobs and supporting small-scale enterprises.

However, widespread adoption remains challenging. Many households remain reluctant to adopt new cooking technologies if they are perceived as incompatible with traditional practices, difficult to install or maintain or less convenient than existing methods. Evidence shows that user preferences and perceptions significantly influence uptake. In several cases, households have rejected improved stoves due to design limitations that did not align with their cooking needs [41]. These findings highlight the importance of designing interventions that are not only environmentally effective but also culturally appropriate and user friendly.

Education plays a critical role in facilitating behaviour change. Public awareness campaigns, particularly those targeting women who are often the primary users of household energy, have been shown to be essential for increasing knowledge about the health risks of HAP and encouraging cleaner practices. However, research has found that awareness levels remain low in many informal settings, limiting the capacity of households to adopt available technologies [31]. This knowledge gap represents a key barrier to progress, suggesting that technical solutions alone are insufficient without parallel investments in education and communication.

Despite their potential, many community-based interventions operate on a small scale and are constrained by short-term funding cycles. Their sustainability depends heavily on continued government support, integrated policy frameworks, and reliable financial assistance. Long-term success requires not only technical innovation but also institutional commitment to clean air as a public health priority. Public investment in education, demonstration projects, and improved access to credit can help address financial and behavioural barriers to adoption [41]. With strategic planning and sustained support, community-based approaches hold significant potential to deliver lasting improvements in both indoor air quality and broader community well-being.

4.6. Leveraging Solar Energy and Urban Greening to Mitigate Indoor Air Pollution in Informal Settlements

Integrating solar energy systems [44-46] and urban greening initiatives [47-49] offers a promising pathway to reduce indoor air pollution while enhancing resilience and well-being in informal settlements. Solar energy can replace polluting solid fuels by providing cleaner, renewable electricity for cooking, lighting, and ventilation, thereby reducing indoor emissions of $PM_{2.5}$, CO, and VOCs. Studies in LMICs have shown that solar-powered cookstoves and water heaters significantly decrease household reliance on biomass and kerosene, leading to measurable improvements in indoor air quality and reductions in respiratory illnesses among women and children. Furthermore, the use of solar-powered ventilation systems can enhance airflow in overcrowded dwellings where natural ventilation is limited due to structural constraints, aiding in the dispersion of indoor pollutants.

Urban greening, including rooftop gardens, vertical greenery systems, and community green spaces, plays a complementary role in improving both indoor and outdoor air quality [50, 51]. Vegetation can capture airborne particulate matter and VOCs while providing shade that reduces indoor temperatures, lowering the need for polluting cooling methods such as kerosene fans or inefficient air conditioners. Plants within and around homes also improve psychological well-being, offering stress reduction and thermal comfort in dense urban areas. In addition, urban greenery contributes to stormwater management, reducing indoor dampness and mold growth, which are known contributors to poor indoor air quality in slum environments.

The combined deployment of solar energy and urban greening aligns with global sustainability goals and addresses key structural and behavioural factors influencing indoor air pollution in informal settlements. While initial costs and maintenance of solar systems and green infrastructure can pose challenges, community-led initiatives and micro-financing models have shown success in scaling these interventions in resource-constrained settings. Policymakers should consider incorporating solar energy and urban greening strategies into slum upgrading programs, aligning clean energy transitions with environmental health improvements and climate resilience. Future research should investigate the synergistic effects of these interventions on pollutant reduction and health outcomes while exploring culturally appropriate and scalable models for implementation in diverse informal settlement contexts.

4.7. Policy Implications and Future Directions

While increasing attention has been given to community-based efforts to reduce indoor air pollution, long-term success depends on stronger institutional support and policy integration. One of the key gaps in addressing IAP in informal settlements is the absence of standardized and sustained public health and housing strategies. Urban housing policies across the Global South must move beyond short-term interventions and instead embed minimum design standards that guarantee adequate airflow, safety, and living space. This includes ensuring access to affordable, clean energy options and embedding environmental health considerations into urban development planning frameworks [3].

A major barrier to progress lies in the socioeconomic inequalities that shape access to clean household energy. In low-income communities, affordability remains a significant constraint. Households that spend more than 10% of their income on cooking and electricity are considered income energy poor, which limits their ability to transition to cleaner technologies [3]. Although liquefied petroleum gas is promoted as a cleaner alternative, it remains financially and logistically inaccessible for many, particularly in rural and peri-urban areas where fuel distribution is limited and electricity connections are unreliable [52]. This highlights the importance of addressing not just the cost of energy, but also the infrastructural and logistical barriers that prevent its practical use.

To move forward, public health strategies must also consider the role of education and behaviour change. Efforts to raise awareness, especially among women who are typically the primary users of household energy, are critical to encouraging the adoption of safer practices. Studies have found that limited awareness of IAP and its health effects serves as a key barrier to behaviour change in many informal housing settings [31]. Furthermore, increasing public understanding of how fuel types, stove design, and home layout contribute to health outcomes can help facilitate cleaner household energy transitions [43]. Going forward, reducing indoor air pollution in informal settlements will require stronger government commitment through policies that support infrastructure, public education, and long-term planning.

5. Conclusion

5.1. General Findings

This review underscores that indoor air pollution in informal housing and urban slums remains a significant and often overlooked public health concern, particularly in low- and middle-income countries. The most frequently identified sources of exposure include the use of solid fuels for cooking, inadequate ventilation, indoor smoking, and substandard building materials. These factors contribute to elevated concentrations of pollutants such as PM, CO, NO2, and VOCs, often exceeding international health guidelines. The health impacts are especially severe for women and children, who are more likely to spend prolonged periods indoors and are regularly exposed during routine household activities. However, these risks cannot be attributed to individual behaviours alone. The evidence consistently indicates that exposure is shaped by broader structural conditions, including overcrowded living environments, poor housing design, and limited access to clean energy. In many cases, state-led housing interventions have failed to meaningfully address these challenges, instead reproducing similar environmental risks by prioritizing cost efficiency and density over ventilation and spatial adequacy. Furthermore, the review identifies a notable imbalance in regional research, with significant attention focused on South Asia, particularly India, while other high-risk regions such as Sub-Saharan Africa and Latin America remain underrepresented. Overall, the findings suggest that indoor air pollution in informal settlements is not only a matter of environmental health but also a reflection of deeper structural inequalities related to housing, energy access, and urban policy.

5.2. Recommendations

To effectively reduce indoor air pollution in informal housing, interventions should adopt a comprehensive approach that considers both the direct sources of pollution and the broader conditions that contribute to long-term exposure. In particular, expanding access to cleaner fuels, such as liquefied petroleum gas and ethanol, is essential in areas where many households rely on biomass due to cost and limited alternatives. To support this, financial assistance should be designed to meet the needs of low-income communities while also ensuring that clean energy options remain safe and consistently available. However, fuel access alone does not guarantee long-term success. The success of such interventions also depends on how well they align with local customs, daily routines, and safety concerns. In addition to cleaner fuels, improving housing design plays a critical role in lowering indoor pollution levels. For example, simple and affordable measures, such as placing windows strategically, improving room layouts, and encouraging natural airflow, can make a meaningful difference. These features should therefore be included as basic standards in resettlement and housing improvement programmes. Alongside structural changes, public health education is also important for encouraging safer practices, such as ventilating spaces while cooking, avoiding indoor smoking, and using household chemicals with care. Finally, supporting community-led initiatives can strengthen these efforts by ensuring that solutions are locally relevant, widely accepted, and sustainable over time.

5.3. Limitations and Future Directions

While this review followed a structured and careful approach and offers significant insights, several limitations should be acknowledged. The inclusion of only English-language studies may have excluded relevant research published in other languages, particularly from regions where indoor air quality is a significant concern but where research is not widely translated. Although multiple academic databases were searched, some relevant sources, including unpublished reports, may not have been captured. The decision to restrict the review to studies published between 2006 and 2025 may have resulted in the exclusion of earlier research that could provide important historical or long-term perspectives. Additionally, the exclusion of studies from high-income countries may have limited opportunities for comparative analysis.

There were inconsistencies in how indoor pollutants were measured and variations in how informal housing was defined, making it difficult to compare findings across studies and contexts. Despite these limitations, this review offers a comprehensive and up-to-date overview of research on indoor air pollution in informal housing and urban slum settings within low- and middle-income countries and highlights broader gaps in the literature that indicate important directions for future research.

More empirical studies are needed in underrepresented regions such as Sub-Saharan Africa and Latin America, where the health impacts of indoor air pollution are likely to be severe yet remain poorly documented. Future research should also examine indoor exposure in communal settings, including schools, healthcare centers, and informal workplaces, which contribute to cumulative exposure but are often overlooked. Consistent study designs, standardized measurement techniques, and clearer definitions of informal housing would help improve the reliability and comparability of findings. Further work is also needed to understand how cultural practices, economic pressures, and safety concerns influence household decisions related to fuel use, ventilation, and space organization in informal settlements.

Table of Abbreviations

Abbreviation	Definition
CO	Carbon Monoxide
CO2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability-Adjusted Life Years
DHPC	Direct Healthcare Professional Communication
GBD	Global Burden of Disease
HAP	Household Air Pollution
IAQ	Indoor Air Quality
IAP	Indoor Air Pollution
INR	Indian Rupee
LPG	Liquefied Petroleum Gas
LMIC	Low- and Middle-Income Countries
NHANES	Natural Health and Nutrition Examination Survey
NGO	Non-Governmental Organisation
NO	Nitrogen Monoxide
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxide
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
Proxies for SES	Proxies for socioeconomic status
SEA	South-East Asia
VOC	Volatile Organic Compounds
WHO	World Health Organization

Transparency:
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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