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Systematic Review

Investigating the Disproportionate Impacts of Air Pollution on Vulnerable Populations in South Africa: A Systematic Review

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Abstract: Background: Knowledge of how different social groups in South Africa are affected by air quality is important for informing air quality regulations and determining the integrated social–environmental approach to adopt. This systematic review evaluates the impact of air pollution on these groups, investigates socio-economic factors that increase exposure, and assesses mitigation measures. **Methods:** The review followed the PRISMA guidelines and analyzed quantitative studies conducted in South Africa, which were published between 2014 and 2024. The studies' sources included databases such as Google Scholar, PubMed, and Scopus. Data from 47 eligible studies were analyzed using descriptive statistics. **Results:** Results show that women, children, and low-income communities tend to bear the brunt of poor air quality. Children are the most affected by poor air quality, with significant respiratory issues. Pregnant women are vulnerable to adverse birth outcomes. The results indicate that of the 47 studies reviewed, 51% focused on the effects of air pollution on children, whilst fewer studies (26%) focused on women. This may point to a gap in research on the specific impacts of air pollution on women. Low-income communities face increased exposure due to proximity to pollutant sources and substandard housing. The results further indicated that of the health impacts experienced by vulnerable populations, general health issues (96%) and respiratory health issues (89%) are the most prominent health impacts. **Conclusions:** The study underscores the need for stricter air quality regulations, public education, and an integrated social–environmental approach to mitigate exposure in vulnerable populations.

Keywords: air pollution; vulnerable populations; women; children; South Africa; public health; socio-economic factors; PRISMA

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1. Introduction

Air pollution is a significant public health issue, accounting for 8.1 million deaths worldwide in 2021, making it the second most important risk factor globally for mortality [1]. Air pollution is particularly of concern in developing countries where vulnerable populations face heightened exposure due to socio-economic and environmental factors [2]. In 2019, air pollution was responsible for approximately 7 million premature deaths worldwide, with 91% of these deaths occurring in low- and middle-income countries [3].

A developing country such as South Africa, which is heavily dependent on coal as a source of energy, exemplifies this vulnerability. Coal burning provides for more than 90% of the country's energy demand, which is also a pertinent source of $PM_{2.5}$ emissions [4]. This reliance on coal for energy has led to South Africa having had the fourth-highest deaths in Africa linked to $PM_{2.5}$ emissions [3]. Areas in the northern provinces of South Africa, i.e., the Vaal Triangle and the Highveld Priority Area, are particularly at risk of air pollution exposure as the bulk of the coal power plants are located there. Vulnerable groups, especially children and pregnant women, are particularly at risk due to their developing physiological systems and increased exposure to pollutants [5]. Low-income communities, often situated near pollution sources, face increased risks, compounded by limited access to healthcare and inadequate environmental regulations [6].

Additionally, South Africa's air pollution issues can be attributed to historical legacies, which resulted in the rapid growth of urbanization, poor spatial planning, and poverty [7]. Spatial injustice and residential segregation are important aspects of the historical development of South Africa's low-income residential areas, heavily influenced by colonialism and apartheid. South African cities and towns still display the legacy of geographical injustice and social exclusions influenced by political, economic, legal, and social challenges, exacerbating air pollution in poor communities [8].

The combination of industrial emissions, domestic fuel or waste burning, mining activities, domestic fuel burning, industrial activities, vehicular pollution, and sand and dust emissions creates a complex air quality landscape that disproportionately affects women, children, and low-income populations. These pollution sources expose these vulnerable groups to particulate matter ($PM_{2.5}$, PM_{10}) and nitrogen oxides (NO_2), which are linked to respiratory and cardiovascular diseases [9]. Understanding these unique factors is crucial for developing targeted mitigation strategies and informing policy decisions that address the specific needs of South Africa's vulnerable groups. Whilst several studies have been conducted globally about the impact of air pollution on vulnerable populations, limited studies have been conducted on the impact of poor air quality on vulnerable populations in South Africa, in particular on women, children, and the poor. Addressing this gap can ultimately result in more effective preventative and mitigative measures to eliminate or reduce the impact of air pollution on vulnerable populations in South Africa. This study is thus expected to raise awareness amongst policymakers in South Africa about the importance of addressing air quality matters that specifically affect the poor, children, and women, and ultimately develop mitigations that can reduce the impact of air pollution.

Significance of This Study

This systematic review study highlights a significant gap in research on the impact of air pollution on vulnerable populations in South Africa, specifically women, children, and low-income communities. Addressing this gap is crucial for developing more effective mitigation measures. The review emphasizes the urgent need for South African policy makers to prioritize air quality issues affecting these groups. It calls for stronger regulatory frameworks, stricter enforcement of emission standards, and the implementation of both indoor and outdoor air quality guidelines to improve public health outcomes, quality of life, human capital, and the economy [10]. Additionally, the review underscores the link between air pollution and serious health conditions, such as respiratory and cardiovascular diseases, and developmental issues in children. It stresses the importance of combining socio-economic interventions with environmental health programs to reduce health disparities in low-income communities, providing key insights for future policy and public education efforts.

This systematic review aims to evaluate the disproportionate impact of air pollution on vulnerable populations in South Africa by assessing (1) the vulnerabilities of children, women, and low-income communities; (2) the socio-economic factors contributing to heightened exposure; and (3) the effectiveness of current mitigation measures.

2. Materials and Methods

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11] to systematically review the impacts of air pollution on vulnerable populations in South Africa. The PRISMA framework ensures a transparent and replicable process for identifying, selecting, and evaluating studies.

2.1. Search Strategy

A comprehensive search was performed across three major databases: Google Scholar, PubMed, and Scopus. The search focused on studies published between 2014 and 2024. Boolean operators were used to refine search results, combining keywords such as "air pollution", "vulnerable population", "South Africa", "women", and "children".

2.2. Inclusion and Exclusion

To ensure the relevance and quality of the studies included in this review, specific inclusion and exclusion criteria were applied. The inclusion criteria were limited to quantitative studies that focused on South African communities, studies published within the last decade (2014–2024), and studies written in English. Studies excluded from the review were articles published in languages other than English, qualitative studies, and those that were published before 2014.

2.3. Study Selection Process

The search and selection process for this systematic review followed the PRISMA guidelines [11].

The study selection process is illustrated in the PRISMA flowchart (Figure 1), showing how 2612 records were initially identified, followed by the exclusion of 1427 duplicates. After the screening, 47 studies met the eligibility criteria (see Table S1).

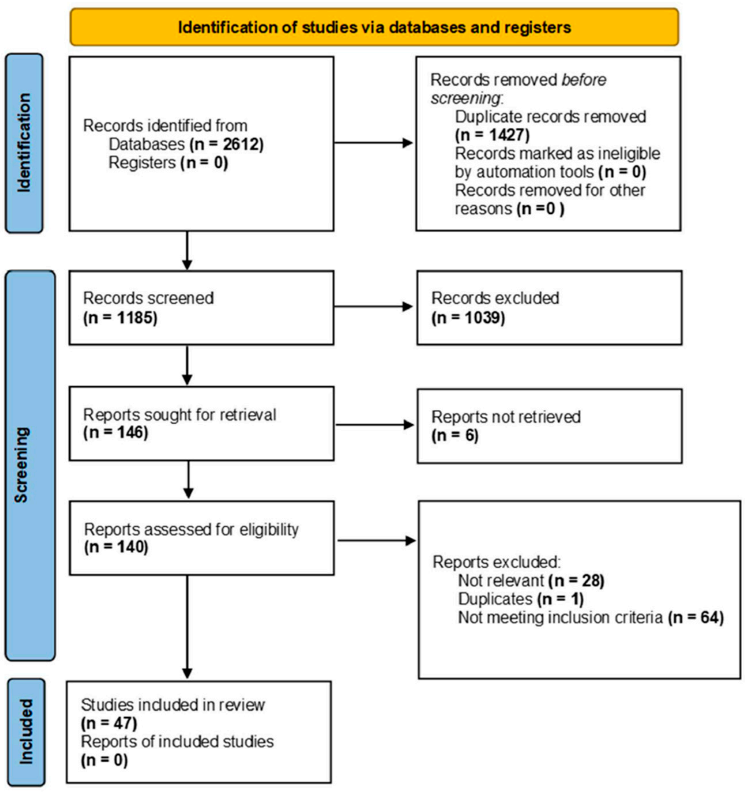

Figure 1. PRISMA flow diagram indicating search and selection process.

In the first stage, a keyword search was performed using Boolean operators to refine the search results. This initial search yielded a total of 2612 records. All records were extracted to Zotero and an Excel spreadsheet where duplicates were removed, leaving 1185 records for screening.

During the second stage, titles and abstracts were reviewed against the inclusion and exclusion criteria. This process led to the exclusion of 1039 records that were either not relevant or did not meet the inclusion criteria. A total of 146 articles were then sought for full-text review.

In the third stage, a full-text screening of the remaining articles was conducted. Of the 146 articles reviewed, 93 were excluded for reasons such as not meeting the inclusion criteria, irrelevance to the research questions, or being duplicates. In the end, 47 studies (Table S1) were identified as eligible and were included in the final review (Figure 1).

This rigorous selection process ensured that only studies relevant to the impact of air pollution on vulnerable populations in South Africa were included, providing a comprehensive basis for the review.

2.4. Data Extraction: Descriptive and Statistical Analysis

Data was extracted to an Excel spreadsheet where the records' study characteristics, population demographics, air pollutants, health outcomes, and mitigation measures were categorized. The data extracted from the eligible studies were analyzed by running descriptive statistics on the Statistical Package for Social Sciences software (SPSS Version 29.0.2.0). Descriptive statistics were used to analyze data from 47 studies. The calculation of percentages was used to represent the proportion of studies focusing on certain aspects. Data such as the prevalence of health outcomes linked to exposure to pollutants (in particular, $PM_{2.5}$, PM_{10}, NO_2, and SO_2) across various population groups were compiled using descriptive statistics. An analysis comparing effects by demographic characteristics, including age, gender, and socio-economic factors, was also conducted. This made it possible to comprehend the effects of air pollution on particularly vulnerable groups in South Africa in a more distinctive manner. Future studies could employ meta-analyses for a deeper statistical interpretation of the strength of these relationships. The technique of a meta-analysis involves methodically integrating relevant qualitative and quantitative study data from multiple chosen studies to produce a single, more statistically powerful conclusion. More individuals, more subject variety, or cumulative impacts and outcomes make this conclusion statistically stronger than the analysis of any one study [12].

3. Results

3.1. Characteristics of Included Studies

The 47 quantitative studies (Table S1) included in this review focused on the impacts of air pollution on children, women, and low-income communities in South Africa. Some of the percentages in Figures exceeded 100% because some studies focused on multiple vulnerable populations. This means that the combined totals may exceed 100%. The percentages shown in each graph are indicative of the proportion of studies reviewed that included each specific category, e.g., study type, or health impacts. For example, a single study might examine the effects of air pollution on both children and low-income communities, leading to an overlap in the percentages. To improve clarity and readability, we rounded the numbers in these figures to two significant digits. This adjustment ensures that the data are presented more concisely and understandably, while still accurately reflecting the distribution of studies across different population groups.

These studies predominantly examined the exposure to $PM_{2.5}$, PM_{10}, NO_2, and SO_2, which are primarily emitted from industrial processes and the burning of solid fuels [13].

The studies also highlighted the heightened vulnerability of children and pregnant women to adverse health effects, particularly respiratory and developmental issues [14].

3.2. Study Designs Identified

The systematic review included a variety of study types, with the most common being cross-sectional studies and cohort studies (see Table S1). Cross-sectional studies made up a significant portion (21%) of the reviewed literature, focusing on assessing air pollution exposure and health impacts at a single point in time. These studies were particularly useful for examining the immediate effects of air pollution on different population groups, especially children and low-income communities. Cohort studies, including both birth cohort and prospective cohort designs, followed participants over time to assess the long-term health impacts of air pollution, such as respiratory issues and developmental health problems.

3.3. Study Population Distribution

3.3.1. Demographic Information from the Studies

Additionally, 28 of the 47 studies (approximately 60%) focused on more than one vulnerable population, such as children and low-income communities or women and low-income communities (see Table S1). In terms of population groups, the greater proportion (51%) of the studies reviewed focused on the effects of air pollution on children (Figure 2), reflecting their heightened vulnerability to the adverse health impacts of poor air quality. Children, due to their developing immune and respiratory systems, are particularly susceptible to the harmful effects of pollutants such as $PM_{2.5}$ and PM_{10}, which can lead to chronic respiratory conditions like asthma, bronchitis, and other long-term health issues. Nkosi et al. (2017) reported high PM_{10} levels at schools near mine dumps, affecting children's respiratory health [15], whereas Olaniyan et al. (2017) discussed long-term respiratory morbidities observed in adolescents [16]. This concentrated focus on children underscores the critical importance of protecting this demographic from environmental hazards. Women were also a key demographic in several studies, with particular attention paid to the impacts of air pollution on pregnant women. However, fewer studies focused on women, especially when compared to children, which may point to a gap in research on the specific impacts of air pollution on women.

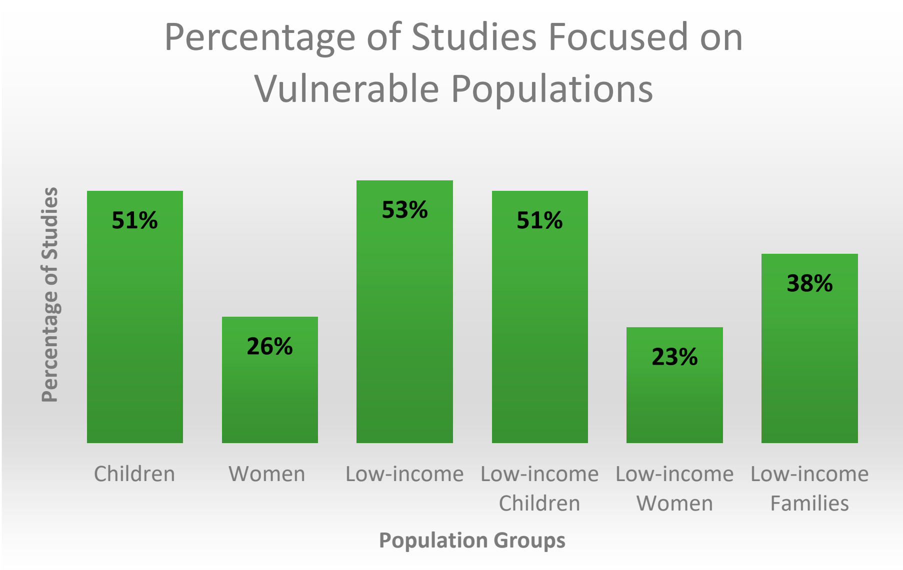

Figure 2. Percentage of studies focused on vulnerable populations.

3.3.2. Socio-Economic Vulnerabilities

A recurring theme across the studies was the disproportionate exposure of low-income communities to poor air quality (see Table S1). The term "low-income" is defined in the National Poverty Lines 2019 report by Statistics South Africa as households earning below the national median income level [17], which can vary depending on the specific context of each study. For example, in South Africa, low-income households are often defined as those earning less than ZAR (South African Rand) 3500 per month. The term "low-income groups" refers to the broader category of individuals or households within this income bracket, while "low-income families" specifically refers to households with children.

In addition, several studies examined the effects of air pollution on low-income populations, further highlighting the significant role socio-economic factors play in determining both exposure levels and health outcomes [14,18]. Low-income communities are often located in proximity to pollutant sources, such as industrial sites and high-traffic areas, which exacerbates their exposure. Furthermore, these communities typically have limited access to healthcare, compounding the health risks associated with air pollution. For instance, Rentschler and Leonova (2023) found that low-income communities near industrial zones experienced higher rates of respiratory and cardiovascular diseases due to prolonged exposure to pollutants [6].

These communities often reside near industrial zones, coal power plants, and unpaved roads, exposing them to higher concentrations of harmful pollutants [6,19,20]. Moreover, the reliance on solid fuels for cooking and heating in low-income households significantly contributes to indoor air pollution, which predominantly affects women and children [21]. The studies that did focus on women, particularly pregnant women, such as a study by Mitku et al. (2023) revealed their increased vulnerability to air pollution, including risks of poor birth outcomes and developmental issues in children [22]. Studies that concentrated on low-income women and children demonstrated the compounded vulnerability experienced by these groups, where socio-economic status and demographic factors intersect to exacerbate health inequalities related to air pollution exposure. The studies also emphasized that socio-economic disparities, such as limited access to healthcare and inadequate housing, further exacerbate the health risks associated with air pollution.

Studies that focused on low-income women and children demonstrated the compounded vulnerability experienced by these groups, where socio-economic status and demographic factors intersect to exacerbate health inequalities related to air pollution exposure. For example, a study by Shezi et al. (2021) found that pregnant women in low-socio-economic households in Durban had a higher incidence of adverse birth outcomes, including low birth weight and preterm births, due to exposure to indoor $PM_{2.5}$ [23]. Albers et al. (2015) linked household fuel use to respiratory health issues in children [24]. Language et al. (2018) emphasised how respiratory health in low-income South African communities is affected by respirable particulate matter in residential houses [25].

This compounded vulnerability underscores the need for targeted interventions that address both environmental and socio-economic factors to mitigate the health impacts of air pollution on these populations [26].

Overall, the review revealed that children and low-income populations were the primary focus of air pollution studies in South Africa, with fewer studies specifically targeting women. Additionally, most studies focused on more than one vulnerable population, which highlights the intersectionality of vulnerabilities and the need for comprehensive research that addresses multiple demographic factors. This also suggests an area for further investigation regarding the long-term impacts of air pollution on women, especially outside of pregnancy.

3.4. Measured Pollutants from Studies

The systematic review identified particulate matter, particularly PM_{10} and $PM_{2.5}$, as the most frequently measured pollutants across the studies (see Table S1). Lim et al. (2024) identified sources of $PM_{2.5}$ exposure for children with asthma [27]. This focus is likely due to their well-established and profound impact on human health. Olaniyan et al. (2020) found significant respiratory health impacts of NO_2 and $PM_{2.5}$ on children in informal settlements [19]. Fine particulate matter such as $PM_{2.5}$ is especially concerning because it can penetrate deeply into the respiratory system, leading to a variety of adverse health outcomes, including respiratory and cardiovascular diseases, particularly in vulnerable populations such as children, the elderly, and those in low-income communities [28,29].

In addition to particulate matter, other key pollutants, namely nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3), were also frequently monitored in many of the studies. For instance, Rodney et al. (2024) found significant levels of NO_2 and SO_2 in preschools, which have been linked to respiratory issues in children [30]. Similarly, Mentz et al. (2018) highlighted acute respiratory symptoms associated with short-term fluctuations in ambient pollutants, including NO_2 and SO_2, among school children in Durban [31]. Olaniyan et al. (2020) reported significant respiratory health impacts of NO_2 and $PM_{2.5}$ on children residing in informal settlements [19]. Additionally, Olufemi et al. (2019) identified health risks for students in schools near coal mines, where elevated levels of O_3 were observed [32]. Millar et al. (2022) noted respiratory health issues among adolescents living in the Highveld Air Pollution Priority Area, where O_3 levels were a concern [33]. Mentz et al. (2018) also discussed the impact of CO exposure on acute respiratory symptoms in school children [31]. Furthermore, Christensen et al. (2024) mentioned the joint effects of prenatal exposure to indoor air pollution, including CO, on early-life inflammation [34].

These pollutants originate from various sources:

- Nitrogen Dioxide (NO_2): It is primarily emitted from vehicle exhaust, industrial processes, and the burning of fossil fuels. NO_2 is known to cause respiratory issues and exacerbate conditions such as asthma and bronchitis [2].
- Sulfur Dioxide (SO_2): It is mainly produced by the combustion of coal and oil at power plants and industrial facilities. SO_2 can lead to respiratory problems and aggravate existing heart diseases [2]. Carbon Monoxide (CO): It is emitted from motor vehicles, industrial processes, and residential heating. CO exposure can impair oxygen delivery in the body, leading to cardiovascular and neurological effects [2].
- Ozone (O_3): It is formed by the reaction of sunlight with pollutants such as volatile organic compounds (VOCs) and NO_2. Ozone at the ground level is a major component of smog and can cause respiratory issues and other health problems [2].

The presence of these pollutants in the studies underscores the broad range of emission sources contributing to air pollution, such as industrial activities, vehicular emissions, and the burning of household fuels like coal and wood. The inclusion of multiple pollutants reflects the complex and multifaceted nature of air pollution in South Africa, where various emission sources interact and collectively exacerbate public health risks. The diversity of pollutants measured further highlights the pressing need for comprehensive air quality management strategies that address the range of emission sources responsible for the deteriorating air quality in the country (see Figure 3).

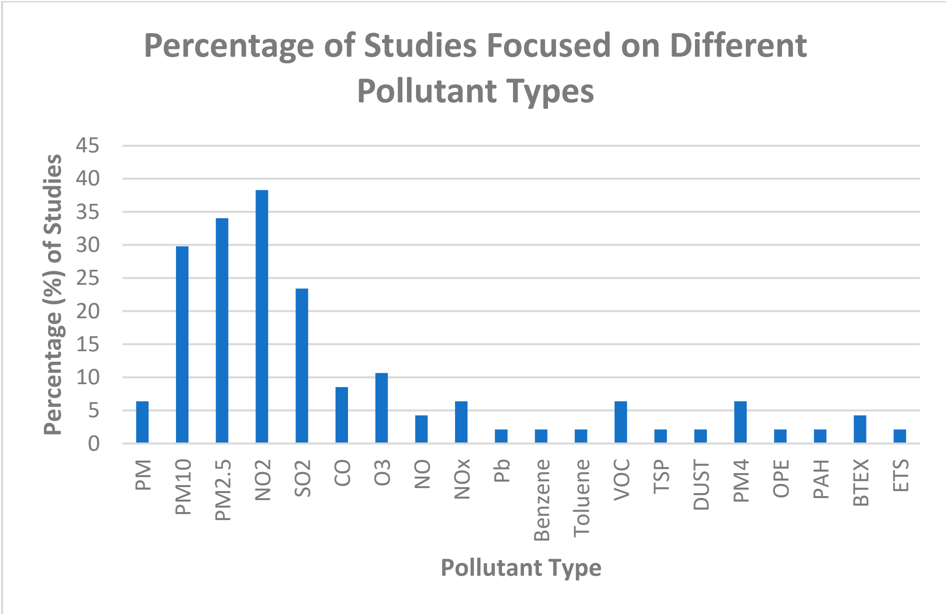

Figure 3. Percentage of studies focused on different pollutant types (PM_4—Particulate matter with aerodynamic diameter of 4 µm and smaller; OPE—Organophosphate ester; PAH—Polycyclic aromatic hydrocarbon; BTEX—Benzene, toluene, ethyl-benzene, and xylene; ETS—Environmental tobacco smoke).

3.5. Health Impacts

Figure 4 shows the health impacts associated with air pollution exposure compiled from the reviewed studies. The systematic review identified general health issues (96%) and respiratory health issues (89%) as the most predominant health impacts associated with air pollution exposure. These findings align with the global literature on the health effects of air pollution, emphasizing the urgent need for targeted interventions to protect vulnerable populations in South Africa.

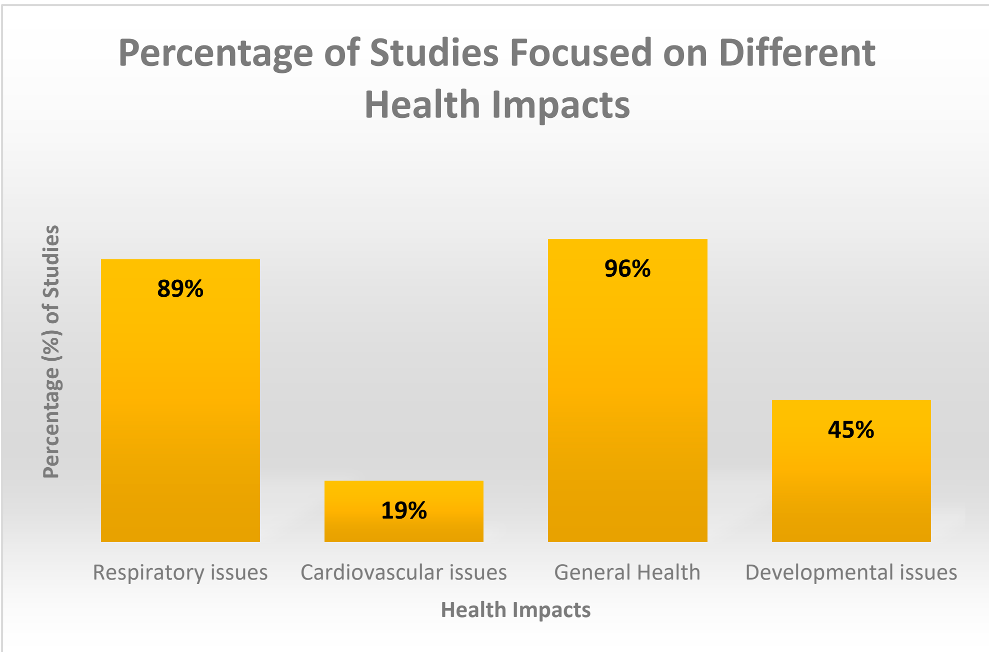

Figure 4. Percentage of studies focused on health impacts associated with air pollution exposure.

Most of the studies revealed that health impacts amongst the population are associated with informal settlements or nearby air pollution industries [35–37]. For example, Bagula et al. (2021) reported ambient air pollution and cardiorespiratory outcomes among adults residing in informal settlements [18]. Ngamlana et al. (2024) highlighted the impact of coal-fired power plants on ambient air quality [38]. Olufemi et al. (2019) identified health risks for students near coal mines, while Bhuda et al. (2024) linked air pollution to atopic eczema in preschool children [32,39]. Millar et al. (2022) reported respiratory health issues among adolescents in the Highveld area, and Aniyikaiye et al. (2024) discussed spatial assessment of $PM_{2.5}$ exposure in a brickmaking community [33,40]. While Mpanza et al. (2020) reported on the impacts of dust on a liquidated mining village in Gauteng, South Africa [41].

Children are particularly vulnerable, with numerous studies reporting high incidences of asthma, bronchitis, and other respiratory ailments. For instance, DeLay et al. (2022) emphasized the susceptibility of children to these conditions [42]. In the Drakenstein child health research, Vanker et al. (2018) emphasised the negative effects on children's health of early exposure to indoor air pollution and environmental tobacco smoke [43].

The relationship between socio-economic status and children's health was reflected in studies such as Matandirotya et al.'s work (2022), which highlighted the plight of children in low-income urban settlements [17]. Olaniyan et al. (2020) found that school children residing in informal settlements with high levels of NO_2 and $PM_{2.5}$ exposure had significantly higher rates of respiratory issues, including asthma and bronchitis [19]. Additionally, Olaniyan et al. (2019) discussed asthma-related outcomes in children from informal settlements [44].

The relationship between indoor particulate matter and lung function in children was also revealed [45]. Mentz et al. (2019) demonstrated how daily variability in air pollutants affects lung function in school children [46]. Furthermore, Mentz et al. (2018) also highlighted the acute respiratory symptoms linked to short-term pollutant fluctuations [31]. Jafta et al. (2019) established a link between indoor air pollution and childhood pulmonary tuberculosis [47]. Olutola et al. (2018) reported a high prevalence of wheezing and coughing in children living in industrial areas, who experienced higher rates of asthma and bronchitis due to elevated $PM_{2.5}$ levels [48]. Similarly, Shirinde et al. (2014) associated wheezing and selected air pollution sources in an air pollution priority area with respiratory health issues in children [49].

Cardiovascular diseases, such as hypertension, were also observed in populations exposed to long-term air pollution, particularly in adults living in highly polluted regions. Everson et al. (2019) identified an association between personal exposure to NO_2 and volatile organic compounds and markers of cardiovascular risk in women in Cape Town, South Africa [50]. Chungag et al. (2021) discussed the impact of seasonal variation in indoor air pollution on obesity and blood pressure [51]. Rentschler and Leonova (2023) reported that low-income communities near industrial zones experienced a higher prevalence of cardiovascular diseases due to prolonged exposure to pollutants like $PM_{2.5}$ and SO_2 [6].

This review also revealed a compounded impact on both women and children. Everson et al. (2020) linked personal exposure to NO_2 and benzene in the Cape Town region with shorter leukocyte telomere length in women [52]. Another study by Johnson et al. (2021) demonstrated that prenatal exposure to fine particulate matter significantly increased the risk of developmental issues in children, highlighting the long-term health impacts of air pollution on this vulnerable group [14]. Christensen et al. (2024) mention the joint effects of prenatal exposure to indoor air pollution and psychosocial factors [34]. Shezi et al. (2022) discussed adverse birth outcomes linked to maternal exposure to $PM_{2.5}$ [23]. Pregnant women exposed to air pollutants are at higher risk of adverse birth outcomes, including low birth weight and premature births. Nagiah et al. (2015) examined oxidative stress and air pollution exposure during pregnancy, highlighting general health issues [53]. Similarly, Anderson et al. (2018) investigated the impact of nitric oxide pollution on oxidative stress in pregnant women [54]. Vanker et al. (2015) studied the home environment and indoor air pollution exposure in an African birth cohort, noting significant health impacts [55]. Mitku et al. (2020) highlighted the impact of NOx exposure during pregnancy on birth weight [56]. Shezi et al. (2021) found that maternal exposure to indoor $PM_{2.5}$ in low-socio-economic households in Durban was associated with a higher incidence of low birth weight and preterm births [23]. Christensen et al. (2022) found cognitive development issues linked to in utero exposure to pollutants [57]. Wright et al. (2023) called for further research on the risk of orofacial cleft lip/palate due to maternal ambient air pollution exposure [58]. These findings underscore the compounded vulnerability of pregnant women in low-income communities, where both indoor and outdoor air pollution contribute to adverse health outcomes [59].

These studies highlighted the significant health burden of air pollution on adults in these communities [6,23], exacerbated by socio-economic factors such as limited access to healthcare and inadequate housing.

3.6. Mitigation Measures

Many of the studies reviewed (see Figure 5) emphasized the need for stricter environmental regulations (36%) to limit emissions from industrial sources and promote cleaner household energy alternatives. For example, Ngamlana et al. (2024) highlighted the significant impact of coal-fired power plants on ambient air quality in the Mpumalanga province and recommended the implementation of stricter emission standards and regular monitoring to reduce pollution levels [38]. The study also suggested transitioning from coal to renewable energy sources as a long-term solution to improve air quality.

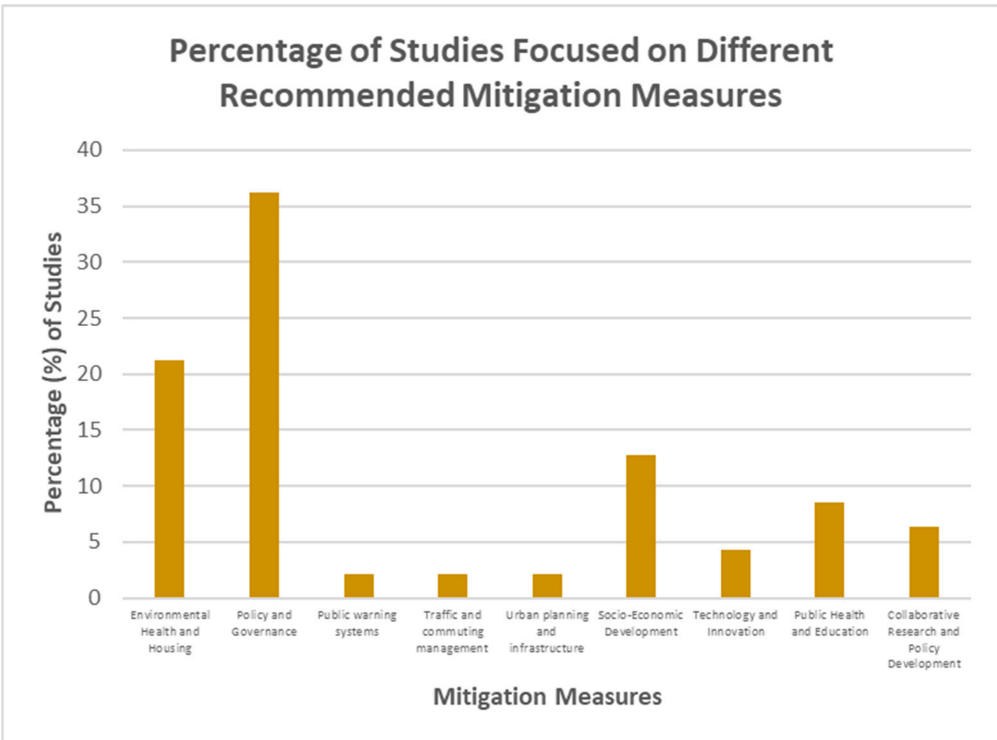

Figure 5. Percentage of studies focused on different recommended mitigation measures.

Several studies also highlighted the importance of public health education campaigns (9%), particularly in low-income areas, to raise awareness about the health risks associated with air pollution and how to reduce exposure [23,60]. For instance, a study by Adesina et al. (2022) found that community-based education programs focusing on the risks of indoor air pollution and promoting cleaner cooking methods significantly reduced exposure to harmful pollutants in low-income households [61]. These programs included training on the use of cleaner fuels and improved ventilation practices, which helped to mitigate the health impacts of indoor air pollution.

In addition to regulatory and educational measures, some studies recommended the implementation of localized air quality monitoring systems to provide real-time data on pollution levels. These data can be used to inform policy decisions and target interventions more effectively. For example, Muyemeki et al. (2022) proposed the establishment of a network of air quality monitoring stations in the Vaal Triangle Priority Area to track pollution levels and assess the effectiveness of mitigation measures over time [60].

The review also identified the promotion of cleaner energy alternatives as a critical strategy to improve indoor air quality, particularly in low-income communities. Studies suggested that transitioning from solid fuels to electricity or renewable energy sources, such as solar power, could significantly reduce indoor air pollution and associated health risks. For instance, a study by Shezi et al. (2021) recommended the adoption of solar cookers and improved stoves in low-income households to reduce reliance on solid fuels and improve indoor air quality [23].

Effectiveness of Measures Undertaken

Several studies reviewed further provided insights into the success and challenges of various interventions. For instance, Ngamlana et al. (2024) reported that stricter emission controls in industrial areas led to a significant reduction in $PM_{2.5}$ levels, improving air quality and reducing respiratory issues among local residents [38]. Similarly, community-based education programs on cleaner cooking technologies, as discussed by Adesina et al. (2022), resulted in a notable decrease in indoor air pollution and associated health risks [61].

Overall, the studies reviewed emphasized the need for a multifaceted approach to mitigate the health impacts of air pollution, combining stricter environmental regulations, public health education, localized monitoring, and the promotion of cleaner energy alternatives. These measures are essential to protect vulnerable populations in South Africa and improve overall public health outcomes.

4. Discussion

Section 24 of the South African Constitution is the overarching legislation that mandates the state to protect the environment. The Constitution gives effect to the Country's National Environmental Management: Air Quality Act (39 of 2004), which sets out guidelines for pollutant emissions and aims to protect and enhance air quality. The Act establishes a framework for managing air quality through national, provincial, and local government structures. It includes provisions for setting ambient air quality standards, controlling emissions from various sources, and implementing air quality management plans. Other notable legislation pertaining to air quality are the National Dust Regulations of 2013, the National Ambient Air Quality Standards of 2009, and the National Framework for Air Quality Management in South Africa, 2017.

Despite the comprehensive framework provided by NEMAQA, there are significant challenges in enforcement, particularly in low-income areas where air quality monitoring stations are sparse. For example, the Vaal Triangle and Highveld Priority Areas, which are heavily industrialized regions, often experience high levels of air pollution due to emissions from coal-fired power plants and other industrial activities. Furthermore, studies have shown that air quality monitoring in these areas is insufficient, leading to gaps in data and difficulties in enforcing regulations. This may be a result of a shortage of skilled human resources, a limited number of air quality monitoring stations, municipal budget constraints, and a lack of education and awareness-raising campaigns [62].

Internationally, South Africa has committed to several treaties and agreements aimed at reducing air pollution and greenhouse gas emissions. Notably, South Africa is a signatory to the Paris Agreement, which aims to mitigate the effects of global warming by reducing greenhouse gas emissions. However, the local implementation of these commitments often lags behind global standards [63]. For instance, while the Paris Agreement primarily targets global warming, its secondary effects on air quality are significant; yet, the enforcement of related measures remains limited.

Comparatively, countries like the United States and members of the European Union have more stringent air quality regulations and enforcement mechanisms. The U.S. Clean Air Act, for example, mandates the Environmental Protection Agency (EPA) to set and enforce national air quality standards, with strict penalties for non-compliance. Similarly, the European Union's Ambient Air Quality Directive sets binding air quality standards and requires member states to implement air quality plans and programs to meet these standards. In contrast, South Africa's enforcement mechanisms are less robust, often hindered by limited resources, lack of technical capacity, and socio-economic challenges. For example, the enforcement of emission standards for industrial sources is often inconsistent, and there is limited capacity for regular inspections and monitoring. Additionally, the socio-economic context, including high levels of poverty and unemployment, complicates the implementation of stricter regulations, as there is often resistance from industries and communities reliant on polluting activities for their livelihoods.

The results from this review align with global trends, where vulnerable populations are disproportionately impacted by air pollution. In South Africa, like in India and China, rapid urbanization and industrialization contribute to high levels of ambient air pollution. However, socio-economic factors in South Africa, particularly related to historical inequalities, exacerbate the impact on low-income populations. These findings are consistent with studies conducted in industrial regions of China and India, where similar patterns of exposure and health outcomes are observed [3]. While coal dependency is a common factor across these nations, South Africa's political history and prevalence of informal settlements tend to increase the vulnerability of its poor communities, demanding localized solutions tailored to this context.

To address these challenges, it is crucial to strengthen regulatory frameworks and improve air quality monitoring systems. This includes increasing the number of monitoring stations, enhancing technical capacity for data collection and analyses, and ensuring consistent enforcement of emission standards. Furthermore, promoting cleaner energy alternatives and implementing targeted interventions in high-risk areas can help mitigate the health impacts of air pollution on vulnerable populations.

Overall, while South Africa has made significant strides in establishing a legal framework for air quality management, there is a need for a more effective enforcement and implementation of regulations to protect public health and the environment.

4.1. Vulnerabilities of Women, Children, and Low-Income Communities

The systematic review confirms that air pollution is associated with increased respiratory conditions such as asthma, bronchitis, and pneumonia in children. These findings align with studies that suggest children exposed to high levels of particulate matter are at significant risk of long-term respiratory conditions [62].

Pregnant women, similarly, experience heightened vulnerability to air pollution, with several studies documenting low birth weights and premature births associated with high exposure to particulate matter and nitrogen dioxide [5]. This is consistent with existing research indicating that maternal exposure to air pollutants increases the likelihood of developmental issues in offspring [64]. Although the impacts of air pollution on children have been extensively studied in South Africa, more research on women is required, particularly considering the women's roles in many low-income communities where women may spend more time indoors exposed to air pollutants from heating and cooking. Addressing this gap is important in developing air quality strategies that are specifically focused on women.

While the review confirms that children and low-income communities are disproportionately affected by air pollution, it is crucial to interpret these findings within the broader socio-economic and environmental context of South Africa. The heightened vulnerability of children can be attributed to their developing respiratory systems and higher rates of outdoor activity, which increase their exposure to pollutants. Additionally, low-income communities often reside near industrial zones and high-traffic areas, exacerbating their exposure to harmful pollutants. Low-income communities are disproportionately exposed to high levels of pollution due to their proximity to industrial areas and dependence on solid fuels for household activities. The systematic review aligns with the environmental justice literature, which highlights the intersection of socio-economic disparities and environmental health [6]. Vulnerable populations living near industrial zones experience compounded health risks due to poor housing, limited access to healthcare, and lower economic resilience [65]. For example, implementing stricter emission controls in industrial areas and improving urban planning to reduce residential proximity to pollution sources can significantly mitigate these risks. Furthermore, enhancing access to healthcare and providing community education on pollution mitigation strategies are essential steps to protect these vulnerable populations.

4.2. Gender-Specific Research and Gaps in Current Studies

The review identified that only 25.53% of the studies focused on the impacts of air pollution on women, which is significantly lower compared to the 51% of studies focused on children. This disparity highlights a critical gap in gender-specific research on air pollution and its health impacts. The low percentage of studies focused on women is concerning for several reasons.

Firstly, women, particularly pregnant women, are uniquely vulnerable to the health impacts of air pollution. Exposure to pollutants such as $PM_{2.5}$ and NO_2 during pregnancy has been linked to adverse birth outcomes, including low birth weight, preterm births, and developmental issues in children. Studies have shown that maternal exposure to air pollution can have long-term health implications for both the mother and the child. For instance, Shezi et al. (2021) found that pregnant women in low-socio-economic households in Durban had a higher incidence of adverse birth outcomes due to exposure to indoor $PM_{2.5}$ [23]. This underscores the need for more focused research on the specific health impacts of air pollution on women to develop targeted interventions and policies.

Secondly, the lack of gender-specific research limits our understanding of how air pollution affects women differently from men. Women often have different exposure patterns due to their roles in households and communities. For example, in many low-income households, women are primarily responsible for cooking and heating, which often involves the use of solid fuels that produce high levels of indoor air pollution. This increased exposure can lead to higher rates of respiratory and cardiovascular diseases among women. Without adequate research, these gender-specific exposure patterns and health impacts may be overlooked in policy and intervention strategies.

Furthermore, the low percentage of studies focused on women may reflect broader issues of gender bias in research. Historically, women have been underrepresented in health research, leading to gaps in knowledge about their specific health needs and risks. Addressing this gap requires a concerted effort to prioritize gender-specific research and ensure that women are adequately represented in studies on air pollution and health.

Overall, the low percentage of studies focused on women highlights a significant gap in current research. Addressing this gap is crucial for developing effective mitigation strategies that consider the unique vulnerabilities and exposure patterns of women. Future research should prioritize gender-specific studies to provide a comprehensive understanding of the health impacts of air pollution on women and inform targeted interventions to protect this vulnerable population.

4.3. Socio-Economic Factors Contributing to Exposure

Socio-economic status is a critical determinant of exposure to air pollution. The intersection of socio-economic factors and air pollution exposure highlights the complex nature of environmental health disparities in South Africa. The review highlights how low-income populations face multiple environmental hazards, including higher levels of ambient air pollution due to industrial activities and poorer indoor air quality caused by the use of solid fuels [38]. These factors create a cycle of vulnerability where poverty increases the likelihood of living in polluted areas, and pollution exacerbates health disparities, further entrenching poverty [6]. Socio-economic factors such as poverty, poor housing conditions, use of solid fuels for heating and cooking, and living close to air pollution sources all exacerbate the health impacts associated with air pollution on poor communities [65]. Policies aimed at improving housing quality, such as providing subsidies for cleaner cooking technologies and enhancing ventilation in homes, can reduce indoor air pollution. Additionally, economic policies that alleviate poverty and improve access to healthcare can help build resilience in low-income communities. Low-income communities consist of various types of dwellings ranging from shacks to government Reconstruction and Development Programme (RDP) housing. These dwellings are in most cases not insulated enough to protect from the cold and are also in most cases not ventilated enough when solid fuels are used for heating and cooking. Thermal comfort and indoor air quality are critical factors in low-cost housing, impacting residents' health and well-being [66]. Solid fuel use in electrified low-income residential areas remains a significant source of indoor air pollution, impacting the health of residents [67]. Concentrations of outdoor exposure have a major impact on indoor air quality in poorly constructed homes, especially in areas with high ambient air pollution levels [68]. These aspects all contribute to the impact air pollution, especially indoor air pollution, has on the health of the poor. The review also indicates that poverty, inadequate housing, and limited access to healthcare are critical determinants of increased exposure and adverse health outcomes. By integrating socio-economic interventions with environmental health programs, we can create a more holistic approach to reducing the health impacts of air pollution and promoting equity in public health.

4.4. Effectiveness of Mitigation Measures

An effective tailored solution for mitigating air pollution in South Africa involves the implementation of community-based air quality monitoring and intervention programs. These programs can be designed to address the specific needs and conditions of vulnerable populations, such as low-income communities and informal settlements. The effectiveness of mitigation measures, such as regulatory enforcement and public health campaigns, was another critical area of focus in the studies. While South Africa has introduced air quality legislation, such as the National Environmental Management: Air Quality Act (39 of 2004), enforcement remains limited, particularly in poorer regions [21]. Strengthening regulatory frameworks and improving air quality monitoring systems are essential steps in reducing exposure. Furthermore, promoting cleaner energy alternatives, such as transitioning from solid fuels to electricity or renewable sources, is vital to improving indoor air quality, particularly in low-income communities [17]. For instance, a pilot project could be initiated in a high-risk area like the Vaal Triangle, where industrial emissions significantly impact local air quality. The project would involve the installation of low-cost air quality sensors in strategic locations within the community to provide real-time data on pollutant levels. This data would be accessible to residents through a mobile app or community display boards, enabling them to take immediate protective actions, such as staying indoors during peak pollution times.

In addition to monitoring, in terms of public health interventions, awareness campaigns targeted at vulnerable populations could play a crucial role in reducing exposure by promoting cleaner cooking methods and protective behaviors, such as reducing outdoor activity during peak pollution times [17]. Education programs focusing on the risks associated with air pollution, combined with community engagement initiatives, have been shown to significantly reduce pollution-related health risks [69]. The project could include educational workshops and training sessions for community members on the health risks associated with air pollution and practical steps to reduce exposure. These sessions could cover topics such as the use of cleaner cooking technologies, with a focus on replacing solid fuels such as wood, coal, and animal dung with clean fuel usage and making cleaner fuel usage more affordable and improving indoor ventilation, and planting vegetation barriers to reduce dust and particulate matter.

Furthermore, the project could collaborate with local industries to implement emission reduction strategies, such as upgrading to cleaner technologies and adopting best practices for pollution control. By involving the community in monitoring and mitigation efforts, the project would not only improve air quality but also empower residents to take an active role in protecting their health. This tailored solution addresses the unique socio-economic and environmental challenges faced by vulnerable populations in South Africa and provides a scalable model that can be adapted to other high-risk areas across the country, thereby ensuring that South Africa achieves the sustainable development goals (SDGs) [70].

Addressing air pollution aligns with several SDGs, including SDG 3 (Good Health and Well-being), by significantly improving health outcomes, particularly for vulnerable populations. It also supports SDG 11 (Sustainable Cities and Communities), through better urban planning and reducing emissions from industrial and vehicular sources, creating healthier living environments. Additionally, it contributes to SDG 13 (Climate Action), as reducing air pollution helps mitigate climate change, given that many pollutants are also greenhouse gases. Furthermore, promoting cleaner energy alternatives aligns with SDG 7 (Affordable and Clean Energy), by reducing reliance on polluting fuels and improving both air quality and energy sustainability.

5. Limitations of Study

It is important to recognize the limitations of this study. Firstly, this study only makes use of secondary quantitative data published between 2014 and 2024. This may result in some important studies not being included in the review and because only quantitative studies were considered, a deeper understanding of the impacts of air pollution on the livelihoods of people is not taken into consideration. Furthermore, the systematic review only focused on studies published in South Africa, which may limit the applicability of its conclusions to other areas with different environmental and socio-economic conditions;

including international studies which may provide a richer dataset for comparison and assist in identifying long-term trends in the health effects of air pollution.

The differences in methodologies used among the reviewed studies make it difficult to draw conclusions that are consistent because different studies may have measured air pollution exposure and health outcomes using different metrics and evaluation methods. The study also lacks a spatial analysis; thus, future studies should incorporate more advanced data collection methods such as Geographical Information Systems (GISs) in order to provide a spatial analysis of air pollution and its health implications across different regions in South Africa. The studies included in this review had different criteria for defining "low-income". Some used the level of the income bracket to define "low-income" whilst others defined "low-income" based on the use of solid fuels such as wood as a source of energy. Other studies defined "low-income" based on the type of housing. So, to streamline the findings of the studies reviewed, the "low-income" had to be broadened to groups that experience socio-economic disparities that make them more vulnerable to air pollution. Additionally, the studies reviewed often did not differentiate between children from low-income and high-income families, which is a limitation. However, it is important to note that children from low-income families are more likely to live in areas with higher pollution levels and have less access to healthcare and other resources that can mitigate the effects of air pollution.

Future research should aim to differentiate between these groups to provide a clearer understanding of how socio-economic status influences the health impacts of air pollution on children. Apart from the limitations, the systematic review provides an overview of the disproportionate impact of air pollution on vulnerable populations in South Africa and provides guidance for future studies and policy development.

6. Conclusion

This systematic review provides comprehensive evidence of the disproportionate impact of air pollution on South Africa's vulnerable populations, particularly children, women, and low-income communities. Socio-economic factors significantly amplify these health disparities, with poorer communities facing heightened exposure to pollutants due to industrial activities and substandard housing. The findings underscore the urgent need for stricter environmental regulations, enhanced public education, and the promotion of cleaner energy alternatives to mitigate the health impacts of air pollution. Future research should address the gaps in the literature, particularly regarding the specific impacts of air pollution on women and the long-term health outcomes for children. By integrating socio-economic interventions with environmental health programs, we can create a more holistic approach to reducing the health impacts of air pollution and promoting equity in public health. This study's results and conclusions further support the sustainable development goals, emphasizing the need for comprehensive and targeted strategies to protect vulnerable populations from the adverse effects of air pollution.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16010049/s1, Table S1: An overview of the characteristics of the studies reviewed.

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