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Review

Health at Risk: Air Pollution and Urban Vulnerability—Perspectives in Light of the 2030 Agenda

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Abstract

Air pollution is one of the major global environmental challenges, particularly in urban and industrial areas, where multiple sources emit pollutants that compromise air quality and threaten human health. This study aims to analyze the effects of air pollution on the health of vulnerable urban populations, emphasizing monitoring techniques for key pollutants and comparing national and international air quality standards through a literature review. It also discusses the implications of these pollutants considering the 2030 Agenda, highlighting environmental education as a strategy for pollution mitigation, public awareness, and strengthening air quality policies. A qualitative and descriptive methodology was adopted, based on national and international research publications between 2005 and 2023, using databases such as PubMed, Scopus, Web of Science, LILACS, and Google Scholar, with descriptors including "Air Pollution," "Industrialization," "Public Health," and "Environmental Education." The results indicate that industrial and transportation activities are the main sources of air pollution, contributing to an increase in cases of asthma, lung cancer, and cardiovascular diseases, as well as negatively impacting ecosystems and the economy. Even when pollutant levels comply with legal standards, vulnerable populations experience higher morbidity and mortality rates, highlighting the need for more stringent protection policies. Comparisons between the standards of the World Health Organization (WHO), the European Union (EU), the United States Environmental Protection Agency (EPA), and the National Council for the Environment (CONAMA) reveal significant disparities in exposure limits. The WHO and the EU, aligned with Sustainable Development Goals (SDGs) 3 and 13, advocate for stricter limits, while EPA and CONAMA regulations remain less stringent. This gap emphasizes the importance of internationally harmonized, evidence-based, and equitable air quality policies. Combating air pollution requires an integrated approach that combines stricter regulations, continuous monitoring, emissions control strategies, and environmental education. Promoting environmental awareness among children and young people can encourage behavioral changes and civic engagement. Environmental education, along with political and social responsibility, remains a fundamental path to mitigating health impacts and promoting sustainable development, in line with the 2030 Agenda.

Keywords: air pollution; environmental health; environmental education; air quality monitoring; cardiovascular diseases; respiratory health; vulnerable populations; public health policies

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1. Introduction

The acceleration of population growth began in the 18th century, mainly with the Industrial Revolution, which boosted economic development and marked a decisive point in modern history. This period promoted technological advances capable of transforming modes of production, social relations, and urban structures. The introduction of steam engines, the mechanization of production, and the growth of factories during the First Industrial Revolution stimulated the economy but also generated precarious working conditions and significantly increased air and water pollution [1].

During the Second Industrial Revolution, the widespread use of electricity and mass production accelerated urbanization and further increased the demand for raw materials, energy, and labor. Consequently, the exploitation of natural resources intensified, leading to the accumulation of pollutants in the atmosphere, capable of compromising the safety and well-being of living organisms, as well as causing damage to flora and fauna on a global scale. These processes highlight the close relationship between economic growth and environmental degradation [1–3].

The growing demand for manufactured goods stimulated rural exodus and population concentration in urban centers, accelerating urbanization and contributing to the intensification of air pollution [2]. In addition, the increasing use of fossil fuels to meet energy demands has raised atmospheric concentrations of CO_2, establishing this gas as one of the main drivers of global climate change [3,4]. Thus, industrialization and intensive resource exploitation, combined with increased use of fossil fuels, have led to accelerated urbanization, population concentration in large cities, pollution and climate change, problems recognized as difficult to mitigate on a global scale [4,5].

Recent epidemiological evidence shows that prolonged inhalation of fine pollutants, such as particulate matter ($PM_{2.5}$), is associated with systemic inflammatory changes and placental dysfunction, interfering with fetal growth and gestational duration. Globally, it is estimated that approximately six million premature births and three million low birth weight newborns occur as direct consequences of exposure to air pollution. These effects are more pronounced in low- and middle-income countries, where environmental regulations are less stringent and access to medical care is limited, exacerbating inequalities in maternal and child health [6].

In addition to its impact on pregnancy and neonatal development, air pollution is a major environmental risk factor for premature mortality [7]. According to the World Health Organization (WHO), approximately seven million premature deaths occur annually due to exposure to pollutants from vehicles, the combustion of fossil fuels, and the use of domestic biomass [7,8].

Recent international reports further reinforce the seriousness of air pollution. According to the IQAir report [9] Only seven countries achieved air quality levels considered safe by the WHO standards in 2023, highlighting the ongoing challenge of meeting international guidelines. Previous WHO data indicated that approximately 99% of the world's population breathes air with pollutant concentrations above recommended limits, disproportionately affecting low- and middle-income countries. In Europe, more than 90% of the urban population remains exposed to harmful levels of fine particulate matter, indicating that even regions with advanced environmental policies still face serious challenges related to air pollution [9].

Exposure to air pollution contributes to morbidity and mortality through respiratory and circulatory complications, including increased blood pressure, changes in coagulation, increased blood viscosity, and reduced heart rate variability, all factors that increase health risks [10–14]. Certain population groups are particularly vulnerable. The elderly, with reduced recovery capacity, suffer intensified effects, including a higher incidence of cardiovascular disease, stroke, and myocardial infarction, especially among those with pre-existing conditions. Air pollution has also been associated with cognitive decline, increased risk of dementia, and reduced life expectancy [13].

Children represent another highly vulnerable group due to the immaturity of their respiratory, immune systems, and neurological systems. Early exposure to air pollution can impair lung maturation, reduce future respiratory capacity, and increase the risk of chronic diseases such as asthma and bronchitis. Evidence also suggests impacts on neurological development, compromising cognitive functions and academic performance [14].

In large urban centers, air pollution is driven primarily by the rapid expansion of motor vehicle fleets, the main source of pollutant emissions. High population density creates a vicious cycle: the larger the population, the greater the number of vehicles and, consequently, the emissions. The accumulation of air pollutants directly affects residents, who are continuously exposed to its harmful health effects [13–16].

Air pollution consists of various physical, chemical, and biological contaminants, including particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), tropospheric ozone (O_3), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), nickel (Ni), arsenic (As), copper (Cu), zinc (Zn), tin (Sn), cobalt (Co), and vanadium (V). Noise and heat pollution, frequently present in densely populated urban areas, further exacerbate environmental and health challenges [8,10,17].

Among these elements, the heavy metals Pb, Cd, Hg, Ni, As, and Cu are particularly dangerous due to their environmental persistence, bioaccumulation, and toxicity even at low concentrations. The main sources include vehicle emissions, industrial processes, waste incineration, fossil fuel combustion, and atmospheric deposition from contaminated soils and building materials. Chronic exposure is associated with neurological, renal, respiratory, and cardiovascular dysfunctions, as well as mutagenic and carcinogenic effects [10,17,18].

Urbanization has intensified exposure to pollutants, particularly in developing countries, where vehicle emissions, industrial activity and poor environmental governance increase health inequalities [9]. This unequal distribution of risks reflects a pattern of urban vulnerability, in which marginalized populations suffer disproportionate health impacts.

Globally, the 2030 Agenda for Sustainable Development recognizes clean air as essential to achieving multiple Sustainable Development Goals (SDGs), including Health and Well-being (SDG 3), Sustainable Cities and Communities (SDG 11) and Climate Action (SDG 13) [19]. However, many studies still address air pollution in isolation, without fully integrating its social, territorial and health dimensions. This gap highlights the need for analyses that connect environmental data with indicators of urban vulnerability and political structures [19].

Therefore, this study aims to analyze the impacts of air pollution on urban vulnerability within the context of the 2030 Agenda, identifying convergences and gaps between international air quality standards, public health outcomes, and sustainable development policies. By synthesizing recent scientific evidence and institutional reports, this review seeks to support public policies capable of mitigating air pollution and reducing socio-environmental inequalities. Specifically, the analysis is structured around four main axes:

Comparison of air quality standards and limits established by national and international regulatory bodies.

Strategies for monitoring and mitigating pollution.

Effects of air pollution on human health.

The role of environmental education and its relationship with SDGs 3, 11 and 13.

This approach aims to integrate scientific evidence to support the development of more protective public policies and strengthen environmental awareness, focusing on promoting health and sustainability.

2. Materials and Methods

This study is characterized as a narrative literature review with a qualitative and descriptive approach, aiming to critically analyze national and international scientific publications on the impacts of air pollution on human health and its interrelationships with environmental and educational policies.

2.1. Search Strategy and Data Sources

The literature review was conducted in several scientific databases, including PubMed, Scopus, Web of Science, LILACS, and Google Scholar, covering the period from 2005 to 2025.

The following descriptors were combined using Boolean operators:

"Air pollution", "Industrialization", "Public health", "Environmental impact", "Air quality", "Heavy metals", "Biological monitoring", "Environmental education", "Morbidity" and "Mortality".

2.2. Inclusion and Exclusion Criteria

The inclusion criteria consisted of peer-reviewed articles, published within the defined period and available in full text format, focusing on air pollution in urban contexts.

Duplicate studies, publications outside the thematic scope, and documents without full text access were excluded.

2.3. Data Analysis

The data analysis was conducted using a qualitative thematic synthesis, allowing for the identification and organization of findings into four main thematic areas:

(a) Comparison of air quality standards and limits established by international and national regulatory bodies, such as the World Health Organization (WHO), the European Union (EU), the United States Environmental Protection Agency (EPA), and the Brazilian National Environment Council (CONAMA).

(b) Strategies for monitoring and mitigating pollution.

(c) Effects of air pollution on human health.

(d) The role of environmental education and its connections with the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

This qualitative approach enabled an interpretative and integrative analysis of the reviewed literature, facilitating dialogue between scientific evidence, public policies, and the objectives of the 2030 Agenda for Sustainable Development.

2.4. Methodological Framework

The following conceptual framework (Figure 1) illustrates the methodological structure adopted in this review, outlining the sequential steps of data collection, selection, and synthesis.

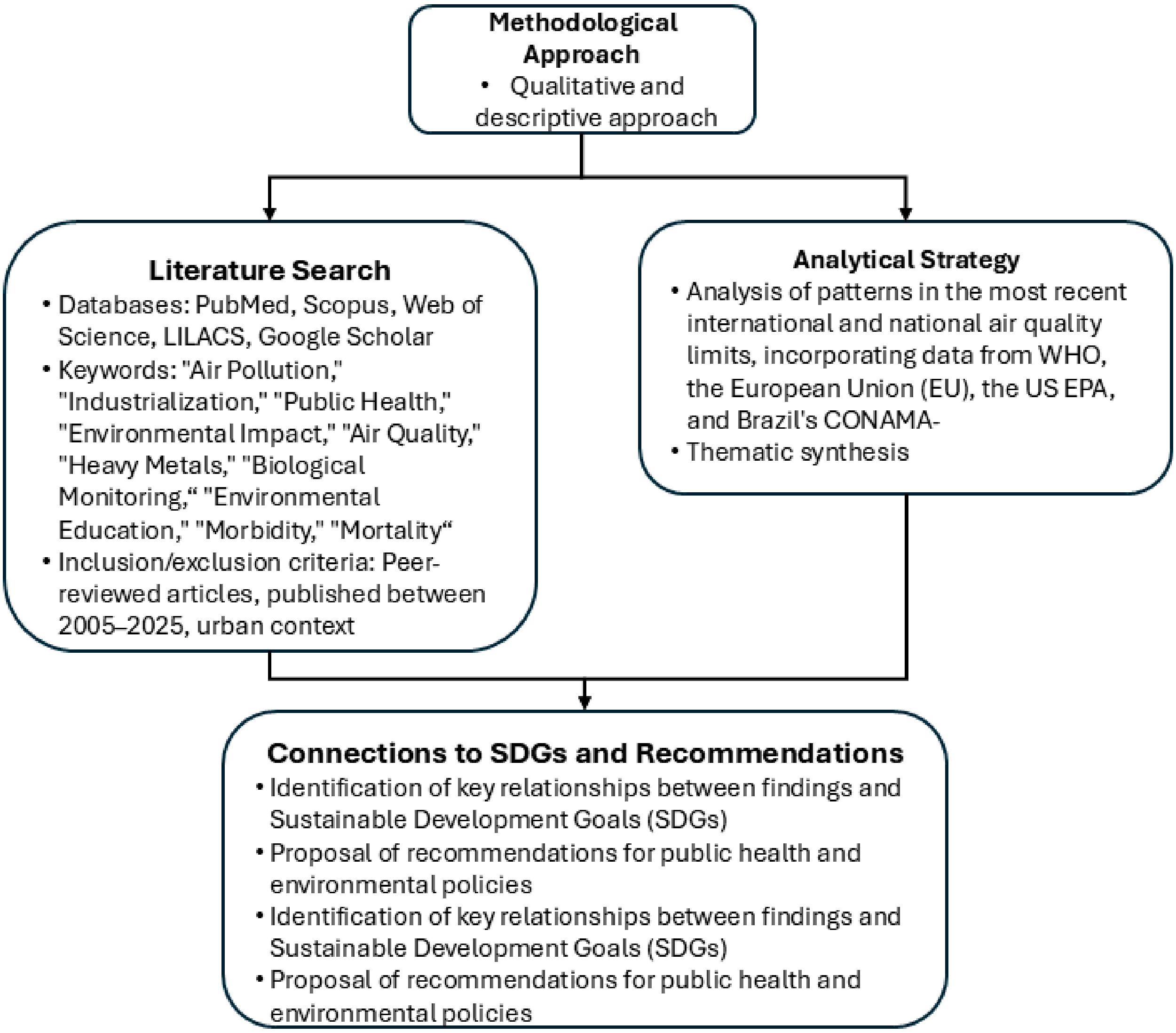

Figure 1. Conceptual framework of the is review. Source: The authors.

3. Air Pollutants: Classifications, Standards and Monitoring

Air pollution releases toxic and respirable agents into the atmosphere, responsible for unpleasant odors, soot, and particles that directly affect the respiratory and circulatory systems. The association between air pollution and a wide range of respiratory, cardiovascular, and neurological diseases, as well as increased mortality, has been consistently documented in the scientific literature [12,13,16,19–21].

Air pollutants consist of a complex mixture of elements, including particulate matter (PM) and gases emitted by transportation, industry, power plants, and the combustion of fossil fuels and biomass. Pollutants can be classified as primary, when emitted directly from sources (e.g., vehicle exhaust fumes), or secondary, when formed through chemical or photochemical reactions between pollutants or with natural atmospheric constituents. The main primary pollutants include nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs). Particulate matter is the most prevalent pollutant and can originate from both primary and secondary sources, being classified according to particle size [22,23].

Pollutants can also be categorized based on their emission sources: mobile sources, primarily motor vehicles in urban areas, and stationary sources, including industrial facilities, mining operations, power generation, and industrial combustion processes. Stationary sources are often geographically confined, allowing for direct assessment of emissions. They emit significant amounts of sulfur dioxide and fine particulate matter, compromising local air quality and affecting the health of nearby residents [23,24]. In September 2021, the WHO published its Global Air Quality Guidelines, the first update since 2005. This revision was based on a comprehensive set of scientific studies on the impacts of air pollution on health, resulting in a significant reduction in limit values for several pollutants. Key changes included reducing the annual limit for fine particulate matter ($PM_{2.5}$) from 10 $\mu g/m^3$ to 5 $\mu g/m^3$ and for NO_2 from 40 $\mu g/m^3$ to 10 $\mu g/m^3$, reflecting evidence of adverse effects even at lower concentrations [8].

In September 2021, the WHO published its Global Air Quality Guidelines, the first update since 2005. This revision was based on a comprehensive set of scientific studies on the impacts of air pollution on health, resulting in a significant reduction in limit values for several pollutants. Key changes included reducing the annual limit for fine particulate matter ($PM_{2.5}$) from 10 $\mu g/m^3$ to 5 $\mu g/m^3$ and for NO_2 from 40 $\mu g/m^3$ to 10 $\mu g/m^3$, reflecting evidence of adverse effects even at lower concentrations [8].

In the European Union, Directive (EU) 2024/2881, adopted in February 2024, established stricter targets for 2030, in line with WHO recommendations. The annual limit for $PM_{2.5}$ was set at 10 $\mu g/m^3$ and for NO_2 at 20 $\mu g/m^3$. The directive also introduced stricter limits for sulfur dioxide (SO_2), to be determined by Member States based on local conditions and maintained the limit for lead (Pb) at 0.5 $\mu g/m^3$. These measures reinforce the EU's commitment to improving air quality and protecting public health [23].

In the United States, the Environmental Protection Agency (EPA) updated the National Ambient Air Quality Standards (NAAQS) in February 2024, reducing the annual limit for $PM_{2.5}$ from 12.0 $\mu g/m^3$ to 9.0 $\mu g/m^3$. This revision, based on the latest scientific evidence, aims to reduce the risk of cardiovascular and respiratory diseases and premature deaths associated with air pollution. For other pollutants 24-h $PM_{2.5}$, PM_{10}, NO_2, SO_2, ozone (O_3), CO, and Pb—the reference values remained unchanged [24].

In Brazil, the National Environment Council (CONAMA) updated the country's air quality standards through Resolution No. 506/2024, which replaces Resolution No. 491/2018. The new regulation introduces Intermediate Standards (PI-1 and PI-2) and Final Standards (PF), to be implemented gradually over ten years, in line with the 2021 WHO guidelines [25]. It also requires the updating of the Technical Guide for Air Quality Monitoring and Evaluation by 31 December 2024, and determines that state and federal environmental agencies adapt their notification systems by 1 January 2026 [25].

These updates from the WHO, EU, EPA, and CONAMA demonstrate a coordinated global effort to strengthen air quality monitoring and mitigate the health impacts of air pollution.

3.1. Comparative Air Quality Standards

Table 1 below presents the most recent international and national air quality limits, incorporating data from the WHO, EU, EPA, and CONAMA (National Council for Air Pollution Risk Assessment). The results reveal significant discrepancies, particularly regarding particulate matter ($PM_{2.5}$ and PM_{10}), emphasizing the need to revise Brazilian standards in accordance with the more restrictive WHO recommendations. Table 1 below presents the most recent international and national air quality limits, incorporating data from the WHO, the EU, the EPA, and CONAMA of Brazil.

The results reveal significant discrepancies, particularly regarding particulate matter ($PM_{2.5}$ and PM_{10}), emphasizing the need to revise Brazilian standards in accordance with the more restrictive WHO recommendations.

Table 1. International and national air quality standards: A comparative overview.

Pollutant	WHO, 2021 [8]	European Union, Directive 2024/2881 [23]	EPA, USA, 2024 [24]	CONAMA, Brazil, Res. 506/2024 [25]
$PM_{2.5}$ * (24 h)	15 μg/m^3	25 μg/m^3 (target for 2030: 15 μg/m^3)	35 μg/m^3	60 μg/m^3 (PI-1)
$PM_{2.5}$ * (annual)	5 μg/m^3	10 μg/m^3 (target for 2030)	9 μg/m^3 (2024 proposal)	20 μg/m^3 (PI-1)
PM_{10} * (24 h)	45 μg/m^3	50 μg/m^3	150 μg/ m^3	120 μg/m^3 (PI-1)
NO_2 * (1 h)	200 μg/m^3	200 μg/m^3	188 μg/m^3 (100 ppb)	260 μg/m^3 (PI-1)
NO_2 * (annual)	10 μg/m^3	20 μg/m^3 (target for 2030)	100 μg/m^3 (53 ppb)	60 μg/m^3 (PI-1)
SO_2 * (24 h)	40 μg/m^3	Defined by the Member States	196 μg/m^3 (1 h, 75 ppb)	125 μg/m^3 (PI-1)
O_3 * (8 h)	100 μg/m^3	120 μg/m^3	140 μg/m^3 (70 ppb)	140 μg/m^3 (PI-1)
CO * (8 h)	4 mg/m^3	10 mg/m^3	10 mg/m^3 (9 ppm)	10 mg/m^3 (PI-1)
Lead (annual)	Not defined	0.5 μg/m^3	0.15 μg/m^3 (quarterly average)	0.5 μg/m^3 (PI-1)

* $PM_{2.5}$ = particulate matter ≤ 2.5 μm; PM_{10} = particulate matter ≤ 10 μm; NO_2 = nitrogen dioxide; SO_2 = sulfur dioxide; O_3 = ozone; CO = carbon monoxide; Pb = lead. Source: The Authors.

3.2. Monitoring and Sources of Pollution

The concentration, dispersion, and transport of air pollutants depend not only on emission sources but also on atmospheric physical and chemical processes. Topographic and meteorological factors, such as pressure, temperature, humidity, wind direction, and speed, directly influence these dynamics [15,26].

Studies conducted in 2024 by the São Paulo Environmental Company (CETESB) indicate that approximately 40% of fine particulate matter ($PM_{2.5}$) in the São Paulo Metropolitan Region originates from vehicular sources. This pollutant is either emitted directly by vehicles or formed through atmospheric reactions involving precursor gases such as VOCs and SO_2 [10]. Vehicles also contribute indirectly through the resuspension of road dust and the release of substances that promote the formation of secondary aerosols. Although industries and other stationary sources also contribute, their share is comparatively less significant. NO_2 emissions also result predominantly from urban traffic, reinforcing the central role of automobiles in regional air pollution. Moreover, VOCs present in exhaust gases not only pose direct health risks but also contribute to the formation of tropospheric ozone (O_3), a secondary pollutant with serious environmental and public health implications [10,27–29].

Continuous air quality monitoring involves systematic collection of atmospheric data to assess conditions over time, identify critical trends, and inform more effective control strategies. The selection of monitoring parameters should consider qualitative and quantitative aspects of local pollutants, allowing for the assessment of emission sources and the adoption of specific mitigation measures for each region [27–29].

3.3. Biomonitoring Techniques

Biomonitors, living organisms that naturally accumulate or reflect the presence of pollutants, particularly heavy metals, offer valuable tools for environmental assessment. Lichens, mosses, trees, and aged urban wood are notable for their ability to absorb elements such as Pb, Cd, and Hg. Because lichens and mosses depend exclusively on the atmosphere for nutrients, they are highly sensitive to air pollution [27–29]. Urban trees accumulate metals in their leaves, bark, and growth rings, allowing for historical analyses of atmospheric contamination, while old wood records decades of deposition. Biomonitoring can be passive, when organisms grow naturally, or active, when they are strategically positioned for sampling and analysis [30–32].

Studies demonstrate the efficiency of species such as Platanus. Orientalis and Pinus nigra are used to detect Sr and Ba in urban environments, while lichens such as Parmelia sp. are widely used to monitor Pb and Cd in industrial areas. After collection, analytical techniques such as mass spectrometry and X-ray fluorescence are employed to quantify the accumulated metals. The main advantage of biomonitoring lies in its ability to provide integrated, economical and highly sensitive data, even at very low concentrations, being particularly useful in urban, industrial and rural areas where direct monitoring may be impractical [30,31].

After analyzing the data, short- and long-term averages are compared with regulatory limits to identify critical periods and likely causes, guiding appropriate mitigation measures, such as installing filters and catalysts or replacing chemicals with less polluting alternatives [15].

In addition to supporting environmental interventions, monitoring networks are essential for building pollution inventories and assessing the impacts of pollutants on human health and ecosystems. They allow policymakers to evaluate the effectiveness of interventions and adjust strategies as needed [33].

4. Greenhouse Gases and Air Pollutants: Climate and Health Implications in Urban Contexts

Greenhouse gases (GHGs) are naturally occurring atmospheric components that trap heat near the Earth's surface, regulating the planet's temperature and making life possible. However, since the Industrial Revolution, human activities have significantly increased the emission of these gases, intensifying the greenhouse effect and driving global climate change. The main GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and water vapor (H_2O). Each of these gases differs in its radiative efficiency, atmospheric lifetime, and global warming potential (GWP), which measures a gas's ability to trap heat relative to CO_2 [34,35].

Carbon dioxide is the most abundant anthropogenic greenhouse gas, resulting mainly from the combustion of fossil fuels, industrial processes, cement production, and changes in land use, such as deforestation. Although CO_2 is not considered a toxic pollutant at ambient concentrations, elevated levels may indirectly indicate poor air quality or inadequate ventilation in confined spaces [36,37].

Unlike toxic pollutants such as CO, NO_2 or SO_2, Regulatory agencies such as the World Health Organization (WHO), the European Union (EU), the United States Environmental Protection Agency (EPA), and CONAMA (Brazil's National Atomic Energy Council) do not establish maximum exposure limits for CO_2 in ambient air. This is because CO_2 is not classified as an immediately toxic agent, but rather as a greenhouse gas responsible for long-term climate effects. However, in indoor or occupational environments, concentrations above Levels of 1000 mg/L may be considered unacceptable. ppm may indicate inadequate ventilation, while levels above 5000 ppm are considered harmful according to occupational safety standards [38].

Recent global assessments indicate that anthropogenic CO_2 emissions reached 36.8 gigatons in 2023, remaining at record levels despite commitments made under the Paris Agreement [39,40]. The transport and energy sectors continue to be the main contributors, with road traffic alone accounting for almost 20% of global CO_2 emissions. Methane is a hydrocarbon gas emitted by natural processes, such as the decomposition of organic matter in wetlands, and by anthropogenic sources, including agriculture (particularly livestock farming), fossil fuel extraction, and waste management. Despite its shorter atmospheric lifetime (about 12 years), CH_4 has a global warming potential approximately 28 times greater than that of CO_2 on a 100-year timescale [11].

The increase in its concentration represents a serious climate threat, particularly because methane is a precursor to tropospheric ozone (O_3), which contributes to respiratory diseases, crop losses and damage to ecosystems. Therefore, reducing methane emissions is considered one of the fastest and most effective strategies to slow global warming [11].

The increase in greenhouse gases such as CO_2, CH_4, and N_2O, although some are not directly toxic, intensifies global warming and indicates the presence of harmful air pollutants. These gases, combined with rapid urbanization and the reduction of green areas, contribute to the urban heat island effect and increase the risks of respiratory, cardiovascular, and metabolic diseases among vulnerable populations. Thus, climate and environmental impacts are strongly interconnected, reinforcing the need for integrated mitigation and health protection strategies [41].

Nitrous oxide (N_2O) is the third most significant long-lived greenhouse gas, after CO_2 and CH_4. It is emitted mainly by agricultural activities, particularly the excessive use of nitrogen fertilizers, as well as by industrial processes and the combustion of fossil fuels. N_2O has a global warming potential approximately 265 times greater than CO_2 and can remain in the atmosphere for more than 100 years [41]. In addition to its contribution to global warming, N_2O also plays a role in the depletion of the stratospheric ozone layer, increasing exposure to ultraviolet radiation and raising the risk of skin cancer and other health problems [42].

Ozone occurs naturally in the stratosphere, forming a protective layer that absorbs harmful ultraviolet (UV) radiation. However, in the troposphere—the lowest layer of the atmosphere—ozone is considered a secondary pollutant, formed by the photochemical reaction between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under sunlight. Tropospheric ozone is a major component of photochemical smog and has serious consequences for health and the environment. It irritates the respiratory tract, worsens asthma symptoms, reduces lung function, and increases hospital admissions for respiratory failure [43–45].

4.1. Particulate Matter and Its Effects on Health

Among all air pollutants, particulate matter (PM), especially fine particulate matter ($PM_{2.5}$), represents the greatest threat to public health. Due to their small diameter, these particles can penetrate deep into the lungs and even enter the bloodstream, triggering systemic inflammation and oxidative stress. Chronic exposure to $PM_{2.5}$ is associated with a wide range of cardiovascular and respiratory diseases, including asthma, chronic obstructive pulmonary disease (COPD), ischemic heart disease, stroke, and lung cancer. Emerging evidence also links fine particulate matter to metabolic dysfunction, neurodegenerative disorders, and reduced life expectancy [46–48].

WHO data estimates that air pollution contributed to approximately 7 million premature deaths worldwide, with around 90% of these deaths occurring in low- and middle-income countries [49]. These findings reaffirm air pollution as one of the main environmental risk factors for global mortality, comparable to the risks associated with smoking and malnutrition.

4.2. Climate Change and Urban Health

Air pollution disproportionately affects low-income and marginalized populations, who often live closer to emission sources such as roads, industrial zones, and waste disposal sites. These communities tend to have limited access to healthcare, poor housing conditions, and less adaptive capacity to cope with pollution-related risks. Studies in Latin America show that children and the elderly in densely populated urban areas have higher hospitalization rates for respiratory illnesses during periods of high $PM_{2.5}$ and O_3 concentrations [3,6,12–14].

The interaction between climate change and air pollution exacerbates health impacts, creating a feedback loop that intensifies urban vulnerabilities. Higher temperatures accelerate the formation of secondary pollutants, such as ozone and aerosols, while changes in precipitation patterns reduce the dispersion of air pollutants. These combined effects worsen respiratory and cardiovascular conditions and can contribute to the geographic expansion of vector-borne diseases (e.g., dengue, Zika, and chikungunya) due to altered temperature and humidity patterns that favor mosquito proliferation [50–52].

In this context, reducing greenhouse gas emissions and improving air quality monitoring are necessary not only to mitigate climate change but also to protect public health. Urban resilience strategies should integrate environmental management, energy transition, and health promotion policies, guided by the principles of the 2030 Agenda for Sustainable Development.

4.3. Urban Vulnerability and Socioeconomic Inequalities

In Brazil, research conducted in cities such as São Paulo, Rio de Janeiro, and Belo Horizonte shows that low-income neighborhoods face the greatest environmental impacts, confirming the existence of a gradient of environmental injustice in exposure to air pollution [24,27,50]. The impacts of air pollution on human health have been the focus of numerous toxicological and epidemiological studies [3,6,10,12–14].

Some of these studies have shown that, even when pollutant concentrations in certain environments comply with local government regulations, continuous exposure of local populations to these air pollutants is associated with a range of adverse health effects, including an increased risk of cardiovascular, pulmonary, and cerebrovascular diseases [11,40,42]. Table 2 below presents a summary of the most relevant pollutants, their main sources, and the main health effects associated with prolonged exposure.

According to data from the European Union, air pollution is responsible for around 240,000 premature deaths per year due to exposure to fine particulate matter. Human activities related to industry, transport, agriculture and energy production are the main sources of emissions, affecting not only health, through diseases such as asthma, lung cancer and cardiovascular problems, but also ecosystems and the economy, with estimated costs between €231 and €853 billion per year [23].

A review conducted by Kim, Kabir and Kabir demonstrates that exposure to airborne particles is consistently associated with increased respiratory and cardiovascular diseases, as well as neurological impacts and a higher risk of mortality. The results also indicate greater vulnerability among children, the elderly and individuals with pre-existing conditions, highlighting the importance of strategies aimed at mitigating air pollution [11].

The degree of danger posed by particulate matter largely depends on its chemical composition, particularly its heavy metal content. For example, during the Great Smog of London in December 1952, approximately 4000 deaths occurred during the days of highest pollutant concentrations, a number that rose to around 12,000 when the effects in the following months were considered. Analyses of preserved lung tissue revealed that, in addition to soot particles, there were particles containing metals such as Pb, Zn and Sn among those deposited in the lungs of the victims [48].

Table 2. Effects of air pollution on the health of vulnerable populations.

Pollutant	Primary Sources	Main Health Effects
Particulate Matter ($PM_{2.5}$ and PM_{10})	Vehicle emissions, industrial activities, biomass burning	Associated with asthma, bronchitis, chronic obstructive pulmonary disease (COPD), increased cardiovascular mortality and lung cancer [41].
Nitrogen dioxide (NO_2)	Traffic emissions, combustion processes	It causes airway irritation, reduced lung function and increased susceptibility to respiratory infections [42].
Sulfur dioxide (SO_2)	Combustion of coal and oil, refineries, and industrial operations.	It can trigger bronchospasm, worsen asthma and increase the risk of cardiovascular disease [43].
Carbon monoxide (CO)	Motor vehicles, industrial processes	It reduces oxygen transport in the blood, leading to fatigue, dizziness and potentially fatal results at high concentrations [44].
Ozone (O_3)	Photochemical reactions involving NOx and volatile organic compounds (VOCs)	It causes eye irritation, reduces lung function, promotes chronic airway inflammation, and is associated with the development and progression of dementia [45].
Volatile Organic Compounds (VOCs)	Solvents, chemical industries, fuel combustion	Associated with neurotoxic effects, cancer, depression, liver and kidney dysfunction [46,47].

Source: Authors.

Recent studies conducted in cities such as Birjand, Iran, have shown that $PM_{2.5}$ can act as a vector for heavy metals, including Cd, As, Co, and V. The presence of these metallic fractions is associated with an increased risk of respiratory and cardiovascular diseases. Therefore, it is essential to monitor not only the total concentrations of $PM_{2.5}$, but also variations in the heavy metal composition of this material, in order to more accurately assess the related health risks [50].

A 2019 study by Liu et al. demonstrated that daily exposure to pollutants such as $PM_{2.5}$ and CO is associated with increased mortality and hospital admissions, even when pollutant levels remain below legally established limits. These findings suggest that current standards may underestimate the real health risks, highlighting the need for more restrictive public policies based on recent epidemiological data [41].

Furthermore, an analysis of data from 652 cities in 24 countries revealed positive associations between exposure to $PM_{2.5}$ and PM_{10} and daily mortality from all causes, as well as from cardiovascular and respiratory diseases. These associations were observed even when pollutant concentrations were below WHO-recommended air quality standards, suggesting that current legal limits may not provide sufficient protection for public health [41].

Another large-scale international study analyzed the impact of short-term exposure to air pollutants such as $PM_{2.5}$, PM_{10}, and NO_2 on asthma related outcomes. The systematic review found that these pollutants are associated with an increased risk of hospitalizations and emergency room visits due to asthma exacerbations, with moderate levels of evidence. In addition, exposure to heavy traffic worsened disease control, while interventions aimed at reducing outdoor pollution showed favorable results, although with low certainty. The study also highlighted that extreme temperatures, both heat waves and periods of intense cold, can increase the risk of asthma exacerbation and mortality, reinforcing the combined influence of air pollution and climate change on respiratory health [53].

Research conducted in Chile has shown that air pollution, especially PM_{10} and O_3, negatively affects children's academic performance. High concentrations of these pollutants were associated with lower grades in reading and mathematics. Municipalities that exceed international limits could potentially improve results by up to 3.5% of the standard deviation [54].

The ESCALA study (Studio de Salud y Contamination Air Pollution in Latin America) was a multicenter research project conducted between 2006 and 2009 in nine Latin American cities, including Rio de Janeiro, São Paulo, and Mexico City. Coordinated by Isabelle Romieu (Mexico), Nelson Gouveia (Brazil), and Luis A. Cifuentes (Chile), the project aimed to evaluate the short-term effects of exposure to air pollution—specifically fine particulate matter (PM_{10}) and ozone (O_3) on mortality from various causes and in different age groups [55].

Using a standardized analytical framework, the study applied distributed lag models (DLM 0–3) to estimate the percentage increase in mortality risk associated with a 10 $\mu g/m^3$ rise in the 24-day average concentration of PM_{10}h and the 8-day maximum moving average of O_3. The results indicated a significant increase in mortality from natural causes and specific outcomes such as respiratory diseases, cardiovascular diseases, and chronic obstructive pulmonary disease (COPD) in several cities, including Rio de Janeiro and São Paulo. The study also evaluated the influence of socioeconomic status (SES) on susceptibility to air pollution. In São Paulo, the risk of death from natural causes was higher among individuals with high SES, whereas in Rio de Janeiro the highest risk was observed among those with low SES. For respiratory diseases, particularly COPD, the greatest risks were identified in both the low- and high-SES groups across Brazilian cities [55].

A study conducted in São Paulo analyzed the relationship between meteorological variables, such as temperature, relative humidity, and precipitation, and PM_{10} levels with hospitalizations for respiratory illnesses in children from 2003 to 2013. Using advanced statistical models (GLM with negative binomial distribution and DLNM), the authors identified significant associations between increased PM_{10} and the risk of hospitalization, particularly when concentrations exceeded 35 $\mu g/m^3$. Furthermore, specific climatic conditions, temperatures between 17.5 °C and 21 °C, high relative humidity (84–98%), and low precipitation, were associated with higher hospitalization rates. These results reinforce that both air pollution and weather conditions play an important role in exacerbating respiratory diseases in children living in densely populated urban areas [14].

Similarly, the study by Moura et al. [12], carried out in Nova Iguaçu, Rio de Janeiro, Brazil analyzed the relationship between air pollution and hospitalizations for pulmonary diseases in the elderly. The results showed a significant association between increased concentrations of air pollutants and higher hospitalization rates in this population, highlighting the vulnerability of the elderly to poor air quality.

In contrast, research focused on exposure to natural and unpolluted environments has demonstrated substantial health benefits, such as the study by Chae, Lee et al. conducted in 2021, which evaluated the effects of forest therapy on human immune function. The results showed that phytoncides, volatile organic compounds released by trees, have beneficial effects on the immune system, stimulating the activation of natural killer (NK) cells, responsible for destroying tumor cells and defending against viral infections, as well as promoting the production of anticancer proteins [56].

Furthermore, phytoncides are associated with reduced stress, blood pressure, and cortisol levels, positively influencing the autonomic nervous system and helping to combat chronic fatigue without side effects. The study also recommends the expansion of green areas, urban parks, and ecological corridors as effective strategies to mitigate stress- and immunity-related diseases, as well as the implementation of public policies to prevent deforestation and uncontrolled urban expansion in forest regions, ecosystems that are fundamental to maintaining environmental and human health [56].

In this context, the impacts of air pollution and the benefits of exposure to natural environments highlight the need for an interdisciplinary approach that integrates the areas of health, environment, and education to foster collective awareness, promote sustainable practices, and cultivate socially engaged and critical citizens. Incorporating the theme of air quality and environmental benefits into school curricula can improve understanding of pollution risks, encourage behavioral changes, and strengthen social participation in the formulation and monitoring of public policies aimed at mitigating emissions, combating socio-environmental inequalities, and promoting health equity.

5. Environmental Education, Public Awareness and Policy Implications

Environmental education goes beyond technical knowledge; it promotes ethical responsibility, solidarity, and critical citizenship. When incorporated into school curricula and community programs, it empowers individuals to recognize the interdependence between human well-being and the health of ecosystems. Through dialogue, reflection, and participatory learning, environmental education can transform environmental concern into practical action. By cultivating ecological awareness from childhood and reinforcing it throughout life, societies can develop a culture of sustainability aligned with the principles of the 2030 Agenda and the Paris Agreement [19,57,58].

Educational programs focused on environmental literacy are essential tools for strengthening ecological awareness, combating misinformation, and increasing public trust in science. By promoting critical thinking, these programs facilitate understanding of the causes and consequences of pollution, as well as the adoption of sustainable practices aimed at preserving health and the environment [19,57,58]. Furthermore, they contribute decisively to building effective responses to environmental crises, demonstrating that the integration of education, public policy, and science constitutes a comprehensive and necessary approach to mitigating air pollution.

5.1. Implications for Policies and Governance

To ensure real progress, environmental policy must be based on cross-sectoral collaboration, integrating the sectors of environment, health, education, energy and transport. In this sense, policies should prioritize strengthening emission standards for vehicles and industries, expanding air quality monitoring networks in urban and rural areas, promoting clean and renewable energy sources, encouraging sustainable urban mobility (such as cycling infrastructure and public transport) and investing in public education and community engagement programs. At the same time, international cooperation remains essential, since the transboundary nature of air pollution and climate change requires global governance mechanisms and shared commitments among nations. Agreements such as the Paris Agreement (2015) and the COP28 Global Balance Sheet (2023) highlight the importance of the continuous evaluation of national commitments to emission reduction, as well as the strengthening of local adaptation strategies [19,40].

The successful implementation of these measures depends on scientific evidence, transparent communication, and active public participation. Table 3 below presents the main reviewed scientific articles that directly address the objectives of this study, structured around four thematic axes: (a) comparison of air quality standards established by national and international regulatory bodies; (b) strategies for monitoring and mitigating air pollution; (c) the effects of air pollution on human health; and (d) the role of environmental education in line with the Sustainable Development Goals (SDGs). The selected studies were published between 2000 and 2025, covering different geographical and methodological contexts, and provide empirical evidence that reinforces the relevance of the topic and contributes to the development of more effective and integrated public policies.

Table 3. Thematic Areas: Air Quality, Human Health, Monitoring, and Environmental Education.

No.	Author(s) and Year	Objective Addressed	Study Title	Source/Magazine	Key Findings
1	Nourani et al., 2025 [59].	Environmental education and school monitoring	$PM_{2.5}$ in Chilean schools	Air quality, Atmos, Health	School monitoring reveals a correlation between traffic and pollution.
2	EPA, 2024 [4].	Comparison of air quality standards	National Standards for Ambient Air Quality	U.S. Environmental Protection Agency	Update of $PM_{2.5}$ limits to reduce respiratory and cardiovascular diseases.
3	IQAir, 2024 [9].	Comparison of global standards and impacts	World Air Quality Report	IQAir	Only 7 countries met the safe air quality standards.
4	CETESB, 2024 [10].	Monitoring strategies and sources of pollution	Air Quality Report in the Greater São Paulo Metropolitan Region	Environmental Company of the State of São Paulo	Vehicle-borne sources are responsible for 40% of $PM_{2.5}$ pollution in the São Paulo Metropolitan Region.
5	Marin-Castañeda et al., 2024 [46].	Pollution and neurodegeneration	Ozone-induced neurotoxicity and dementia progression	Leading the Way in the Neuroscience of Aging	Tropospheric ozone is associated with an increased risk of dementia.
6	Tang L et al., 2024 [48].	Pollution and mental health	Exposure to VOCs and depression in adults in the US.	Chemosphere	VOCs are associated with depression and neurological dysfunction.
7	Agache I, Annesi-Maesano I, Cecchi L, et al., 2024 [53].	Effects of pollution and climate change on respiratory health	The impact of outdoor pollution and extreme temperatures on asthma-related outcomes: a systematic review for the EAACI guidelines on environmental science for allergic diseases and asthma	Allergy	Pollution and extreme weather are increasing hospitalizations for asthma.
8	Mendoza et al., 2022 [58].	Environmental education and school campaigns	Campaigns against slow walking and air quality issues near schools	Atmosphere	Reduction in CO and $PM_{2.5}$ with educational campaigns.
9	Chae et al., 2021 [56].	Environmental education and environmental benefits	Forest therapy and immune function	IJERPH	Phytoncides improve immunity and reduce stress
10	Kermani et al., 2021 [52].	of heavy metals in $PM_{2.5}$	Heavy metals in $PM_{2.5}$ in Iran	J Environ Health Sci Eng	Cd, As, Co, and V increase the risk of respiratory and cardiovascular diseases.
11	WHO, 2021 [8].	Comparison of air quality standards	Global Air Quality Guidelines	World Health Organization	Reduction in $PM_{2.5}$ and NO_2 to protect human health.
12	Moura et al., 2020 [12].	Effects of air pollution on human health	Air pollution and international cardiopulmonary diseases in Nova Iguaçu	Rev Brazil Environment	Link between pollutants and hospitalizations for lung diseases.

Table 3. *Cont.*

No.	Author(s) and Year	Objective Addressed	Study Title	Source/Magazine	Key Findings
13	Liu et al., 2019 [41].	Effects of air pollution on human health	Air pollution and daily mortality in 652 cities	N Engl J Med	Increased mortality even below legal limits.
14	Moraes et al., 2019 [14].	Effects of air pollution on children's health	Meteorological variables and hospitalizations for respiratory problems in children	Public Health Cadillac	PM_{10} and weather associated with respiratory hospitalizations in children.
15	Santos HL et al., 2019 [44].	Effects of pollution on health	Relationship between air pollutants and their health consequences.	Rev Scientist Intr@science	Pollutants are associated with respiratory and cardiovascular diseases.
16	UNESCO, 2015 [60].	Environmental education and SDGs	Education for Sustainable Development (ESD)	UNESCO	Environmental education promotes engagement and behavioral change.
17	Kim, Kabir and Kabir, 2015 [11].	Effects of air pollution on human health	Impact of airborne particles on human health	International Environment	Particles are associated with respiratory, cardiovascular, and neurological diseases.
18	Miller & Vela, 2013 [54].	Environmental education and academic performance	Air pollution and educational outcomes in Chile	IDB Working Paper Series	PM_{10} and O_3 are associated with decreased academic performance.
19	Romeo and others, 2012 [55].	Effects of air pollution on human health	ESCALA Study: Air Pollution and Mortality in Latin America	Institute of Health Effects	Increased mortality from PM_{10} and O_3 in Latin American cities.
20	Andrew et al., 2003 [51].	Historical effects of air pollution	Toxicological evidence of the London smog of 1952	Environmental Health Perspective	Heavy metals found in the lung tissue of victims of air pollution.

Source: Authors.

Despite scientific evidence linking air pollution to deteriorating health, environmental governance still faces significant challenges. Many nations, particularly developing countries, maintain less stringent regulatory standards than those recommended by the WHO, often due to economic constraints or industrial pressures [8,9,24,61].

Citizen involvement, through environmental councils, community organizations, and participatory monitoring platforms, increases accountability and strengthens the legitimacy of environmental policies.

5.2. The Transformative Role of Environmental Education for a Sustainable Future

The effectiveness of environmental policies requires an integrated approach aligned with the Sustainable Development Goals (SDGs), going beyond the mere uncontrolled reduction of emissions or localized pollution. When articulated with SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action), these policies incorporate essential dimensions such as public health, urban mobility, energy transition and land-use planning, forming a shared sustainability agenda [19].

In this context, the 2030 Agenda for Sustainable Development, established by the United Nations (UN) in 2015, recognizes education as a cross-cutting factor for achieving all 17 SDGs. In particular, SDGs 4 (Quality Education), 11 and 13 emphasize the importance of integrating environmental education into public policies to promote ecological awareness, social resilience and community involvement [19].

Promoting sustainable transport and encouraging the use of renewable energies, actions that simultaneously contribute to improving air quality and achieving global objectives related to well-being and environmental justice, can be further strengthened through awareness-raising initiatives in schools. The inclusion of educational practices focused on sustainability strengthens youth leadership and broadens the impact of public policies [61,62].

Furthermore, strengthening environmental governance and ensuring continuous monitoring of public actions are directly linked to SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships for the Goals), guaranteeing transparency, social participation and international cooperation [19].

Environmental education, therefore, should be understood as a cross-cutting axis connected not only to SDG 4, but also to SDG 12 (Responsible Consumption and Production) and SDG 17. By fostering critical awareness of the interdependence between the environment, the economy, and society, it contributes to the development of more sustainable and socially engaged communities. Thus, aligning public policies with the 2030 Agenda reinforces the idea that each local action, whether it be reducing emissions, promoting sustainable mobility, or investing in clean energy, contributes collectively to a fairer, healthier, and more environmentally balanced future.

6. The Role of Environmental Education in Mitigating Air Pollution

The 2030 Agenda for Sustainable Development, adopted in 2015 by the United Nations General Assembly and incorporated in Brazil through the Ministry of Social Development, represents a global milestone that guides public policies and actions aimed at building a fairer, more inclusive and sustainable future. The document encompasses 17 Sustainable Development Goals (SDGs) and 169 targets that integrate the economic, social and environmental dimensions, emphasizing the importance of cooperation between governments, civil society, the private sector and international organizations [19].

The Sustainable Development Goals (SDGs), to be achieved by 2030, address key themes such as poverty eradication, reduction of inequalities, quality education, health, climate change, and responsible consumption. In the environmental and urban context, SDGs 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), and 13 (Climate Action) are particularly relevant, as they directly address issues related to environmental quality and population well-being [19].

Environmental education plays a significant role in this global agenda, contributing to the formation of environmentally conscious citizens committed to the principles of conservation and sustainability. This educational approach promotes understanding of human impacts on nature and encourages the adoption of sustainable practices in daily life. Consequently, schools become strategic spaces for the development of educational initiatives that foster environmental awareness and community involvement from an early age [57,58].

International experience demonstrates the potential of educational initiatives integrated with sustainability and environmental quality. The Education for Sustainable Development (ESD) program, promoted by UNESCO, shows that incorporating sustainable practices into the school curriculum improves environmental learning and supports long-term behavioral changes among students and school communities [60].

In Latin America, air quality monitoring projects implemented in schools have shown promising results. In Santiago, Chile, the use of portable sensors to measure fine particulate matter ($PM_{2.5}$) in different urban areas revealed a strong correlation between vehicle traffic and pollution peaks near schools. Moreover, this initiative encouraged students to actively participate in activities related to the collection and interpretation of environmental data [59]. Similarly, in Mexico City, environmental awareness campaigns and anti-slow-march policies have achieved reductions of up to 20% in local CO and $PM_{2.5}$ concentrations during peak hours, highlighting the relevance of integrating citizen science and environmental education [59].

In Europe and the United States, combined strategies involving green infrastructure, natural ventilation, and active mobility have yielded environmental and social benefits. The Clean Air for Schools Framework program, implemented in London, combined HEPA filters, vegetation barriers, and the promotion of active transportation, achieving reductions of approximately 37% in indoor $PM_{2.5}$ levels and a 12% increase in active commuting among students [57]. In the United States, the Idle -Free Schools initiative, supported by the Environmental Protection Agency (EPA), implemented educational campaigns and signage to reduce vehicle idling time near schools, resulting in a 48% decrease in idling time and up to a 15% improvement in local air quality [63].

In Brazil, experiences such as the National Sustainable Schools Program, the Green Schools Project, and EducaClima (UNESCO/MEC) reaffirm the country's commitment to educational sustainability through interdisciplinary pedagogical practices and community-based projects. Local initiatives, such as the Clean Air in Schools Project in Curitiba, have contributed to strengthening environmental awareness, community participation, and local responses to urban environmental challenges [60].

The ESD framework promotes a transformative learning process that integrates cognitive, socio-emotional, and behavioral dimensions, encouraging sustainable attitudes in daily life. The articulation between ESD, environmental justice, and educational policies can strengthen the role of schools as centers of environmental and social transformation, particularly in vulnerable regions. This approach seeks to prepare citizens capable of making informed decisions and acting responsibly in response to issues such as climate change, biodiversity loss, and excessive resource consumption [60].

Critical and participatory environmental education has demonstrated the potential to generate measurable changes when linked to public policies, citizen science, and pedagogical innovation. The adoption of hybrid indicators that combine environmental and educational parameters can allow for longitudinal monitoring of the impacts of these initiatives, supporting the development of more effective clean air and climate education policies [57,61,62].

In Brazil, ESD aligns with the legal frameworks that guide environmental education, as established in the Federal Constitution, the National Environmental Education Policy (Law No. 9795/1999) and the National Curriculum Parameters. These documents emphasize the cross-cutting inclusion of environmental themes in school curricula, reinforcing civic education and ecological responsibility in line with international sustainability efforts [64,65].

The effective implementation of these policies requires collaboration between school administrators, educators, students, families and the community at large, through interdisciplinary and participatory approaches that promote critical reflection on the relationship between the environment and human activities. This process depends on investments in teacher training and the provision of adequate resources to support the development of contextualized pedagogical projects [65].

Environmental preservation is a shared responsibility that depends on active civic participation. It is a continuous and integrated process that aims to promote behavioral changes, strengthen citizenship, and encourage student engagement with issues such as global warming, air pollution, water conservation, and recycling.

Individual practices that contribute to reducing pollution and conserving resources include planting trees, separating waste, using energy-efficient equipment, reducing plastic consumption, and choosing sustainable products. Additionally, opting for public transport, cycling, or walking instead of using private vehicles helps to decrease pollutant emissions.

At a collective level, initiatives such as the adoption of renewable energy sources, the modernization of public transport fleets, and the implementation of urban planning strategies that mitigate pollution and promote the sustainable use of land and water play a significant role.

Incorporating environmental education into the school curriculum represents a way to strengthen citizenship, foster social participation, and consolidate commitment to sustainability. Furthermore, it is essential that the population actively monitor and support policymakers committed to environmental preservation, ensuring the protection of green spaces and improving the quality of urban life.

7. Limitations and Recommendations for Future Research

This study is based exclusively on a literature review, which limits the generalizability of the results and prevents local empirical analyses. The absence of primary data and the reliance on published research may restrict the representativeness of specific contexts. Most of the reviewed studies are short-term, making it difficult to assess the cumulative effects of prolonged exposure to pollutants. Furthermore, there are methodological challenges in distinguishing between environmental, social, and genetic variables that influence health outcomes, affecting the accuracy of the analyses.

Another relevant issue is the concentration of studies in large urban centers, resulting in significant gaps regarding medium and small-sized cities. Although these areas are less studied, they also face notable environmental problems and may present specific vulnerabilities, such as limited monitoring infrastructure and less effective public policies.

It is recommended that future research adopt integrated and interdisciplinary approaches, including direct monitoring and interviews with exposed populations, to simultaneously assess environmental impacts and health outcomes in diverse socioeconomic contexts. Comparative studies between regions with different levels of urbanization and environmental policies can contribute to a broader understanding of environmental inequalities and the risks associated with exposure to air pollutants.

Furthermore, future research should deepen the understanding of the relationship between environmental exposure, morbidity, and mortality in vulnerable groups, as well as evaluate the effectiveness of educational programs aimed at promoting environmental awareness and behavioral change.

8. Conclusions

A comparative analysis of air quality standards highlights discrepancies between the limits established by international organizations, such as the World Health Organization and the European Union, and those adopted by national regulations, including the United States Environmental Protection Agency (EPA) and Brazil's National Environment Council (CNM). In many contexts, national reference values remain less stringent, reducing the effectiveness of preventive policies and compromising the protection of public health. Measures such as adopting more stringent emission standards, promoting the transition to renewable energy sources, and expanding sustainable urban mobility are necessary to reduce pollution levels and mitigate their impact on the climate and ecosystems.

Regarding monitoring and mitigation strategies, it is important to strengthen air quality surveillance networks in both urban and rural areas and promote intersectoral policies that integrate the health, education, energy, transport, and environment sectors.

The effects of air pollution on human health are well documented, including increased incidence of respiratory, cardiovascular, and neurological diseases, worsening of pre-existing conditions, and higher mortality among vulnerable populations. These impacts highlight the need for evidence-based public policies aligned with international air quality recommendations.

Environmental education plays a significant role in raising collective awareness and promoting sustainable practices. Within the framework of the 2030 Agenda, it is directly linked to SDGs 3 (Good Health and Well-being), 11 (Sustainable Cities and Communities), and 13 (Climate Action). Integrating these goals into educational practices and public policies strengthens the social and institutional capacity to respond to the current environmental and health challenges.

Therefore, combating air pollution requires international regulatory harmonization, continuous monitoring, intersectoral mitigation actions, and participatory environmental education—elements that contribute to building an urban development model aligned with the principles of the 2030 Agenda and that promotes a healthier, more equitable, and sustainable environment for future generations.

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