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Air pollution and chronic respiratory diseases:
a narrative review including a case study in Campania (Italy)

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Abstract

Air pollution is a major public health risk, contributing significantly to the global burden of chronic respiratory diseases. Chronic exposure to pollutants such as PM2.5, PM10, NO_2, and O_3 is associated with documented pathogenetic mechanisms, including oxidative stress, chronic inflammation, epithelial damage, and airway remodeling, which promote the development of respiratory diseases such as asthma, COPD, and cardiovascular disease. This review examines epidemiological data at the national and regional levels, focusing on Campania, one of the Italian regions most exposed to air pollution levels above the national average. Evidence shows a significant impact on the population's respiratory health, with socioeconomic inequalities amplifying the risks for the most vulnerable communities. Analysis of environmental, epidemiological, and pathophysiological data between 2015 and 2024 confirms that, despite a slight decrease in PM10 and PM2.5 concentrations nationwide, Campania continues to record high levels, with measurable impacts on respiratory health and significant intra-regional disparities. Artificial intelligence, through machine learning models and satellite-based forecasts, offers new opportunities for improving air quality monitoring and forecasting future trends. Furthermore, the adoption of environmental justice policies could effectively target interventions in high-risk areas. To reduce the impact of air pollution, the implementation of integrated strategies that combine environmental monitoring, health policies, and advanced predictive tools, supported by artificial intelligence, is crucial for targeted and timely intervention planning.

Key words: air pollution, chronic respiratory diseases, respiratory health in Campania, PNRR, artificial intelligence

Introduction

Air pollution is now recognized as one of the most serious environmental threats to public health globally [1-3]. According to the report by the Health Effects Institute, in 2025, approximately 7.9 million premature deaths were attributable to the combined effects of ambient air pollution and household air pollution-related diseases, making it the second leading global risk factor after tobacco smoking. This figure is even more concerning since, worldwide, approximately 99% of the population lives in areas where air quality levels exceed the air quality guidelines defined by the WHO in 2021 [4,5].

Ambient (outdoor) air pollution consists of a complex mixture of gaseous components and particulate matter (PM), responsible for chronic respiratory symptoms and a relevant cause of respiratory morbidity and mortality; PM was related to approximately 4.7 million premature deaths annually [6,7]. Among modifiable risk factors, exposure to air pollution contributes to 8% of disability-adjusted life years, exceeding factors such as hypertension, smoking, and elevated fasting glucose. The main pollutants responsible for these serious health effects are airborne thoracic particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$), along with gaseous pollutants such as nitrogen dioxide (NO_2) and ozone (O_3). These pollutants are closely linked to chronic respiratory diseases (CRDs), primarily including chronic obstructive pulmonary disease (COPD), asthma, and pulmonary fibrosis, which are a major cause of morbidity and mortality globally [8-10] (Table 1).

In Europe, according to the European Environment Agency, approximately 95% of the EU's urban population is exposed to fine particulate matter ($PM_{2.5}$) concentrations above the strict World Health Organization (WHO) annual guideline of 5 $\mu g/m^3$. This chronic exposure significantly reduces life expectancy and drives up hospitalizations for respiratory and cardiovascular diseases [11,12].

In this regard, it should be noted that fine PM particles are considered particularly harmful to human health and, in particular, $PM_{2.5}$ particles evade the defences of the upper respiratory tract and settle deep in the peripheral airways where, due to their small size, they are not easily expelled with mucus. Furthermore, PM_1 particles (diameter < 1 μm) have an even larger penetrating capacity than $PM_{2.5}$ and can cause more serious damage, including local inflammation and passage into the bloodstream. Nevertheless, $PM_{0.1}$ particles (ultrafine particles - diameter < 0.1 μm) may be the most insidious, as their extremely small diameter allows them to penetrate not only the alveoli, but also cross the alveolar-capillary membrane, entering the bloodstream and reaching other organs, causing oxidative stress, chronic inflammation and airway remodelling [13,14]. Recent studies confirm that continued exposure

to $PM_{2.5}$ is associated with a worsening of respiratory symptoms and an accelerated progression of lung diseases such as COPD and asthma [15-19].
In particular, air pollution is estimated to directly contribute to over 4 million premature deaths each year from diseases such as asthma, COPD and other respiratory conditions, and is also considered the main modifiable risk factor for these diseases, with $PM_{2.5}$ responsible for approximately 50% of global COPD mortality and a significant worsening of asthma [17,18]. Furthermore, scientific evidence has shown that chronic exposure to $PM_{2.5}$ is strongly associated with reduced lung function and increased hospital admissions for respiratory diseases, with a greater impact on people with pre-existing comorbidities [19,20].
According to the WHO, CRDs are among the leading causes of death and disability, contributing significantly to the global burden of disease. Data from the Global Burden of Disease (GBD) project confirm that COPD is currently the third leading cause of death worldwide, while asthma and interstitial lung diseases contribute significantly to years lived with disability (DALYs) [21,22].
In the European and Italian context, the burden of CRDs is consistent with the global picture, but with some specificities. In Italy, chronic respiratory diseases account for approximately 6–7% of total mortality, a lower share than in other middle-income countries, but still relevant. However, compared to GBD data, the Italian burden emerges as characterized by: lower overall mortality compared to the global average, a greater impact in terms of aging and chronicity, and a significant proportion of years lived with disabilities (YLDs) [23,24].
In this scenario, COPD remains the disease with the largest impact on mortality, while asthma contributes mainly to morbidity, and pulmonary fibrosis, although representing a smaller share in terms of prevalence, shows an increasing weight in GBD data, especially in high-income countries, due to population ageing and improved diagnostic capabilities [25,26].
This narrative review examines the pathogenic mechanisms underlying the damage caused by environmental pollution to the airways, presenting epidemiological data on chronic respiratory diseases linked to environmental pollution in Italy. Particular attention has been paid to the situation in Campania, a region in southern Italy characterised by particularly high levels of air pollution.
Finally, this review was conducted by searching for the following keywords: air pollution, chronic respiratory diseases, respiratory health in Campania, PNRR, and Artificial Intelligence in international and European databases, primarily PubMed Central and Medline, Scopus, the Cochrane Library, the Public Health Database, as well as those of the European Environment Agency, the WHO European Region, and the World Air Quality Index. Additionally, for

national and Campania data, databases such as ISPRA/SNPA - National Environmental Protection System, ISDE - International Society of Physicians for the Environment, ARPAC - Regional Agency for Environmental Protection of Campania, and MASE - Ministry of the Environment and Energy Security were consulted. Publications from a ten year periods (2015-2024) were considered.

Pathogenetic mechanisms induced by chronic exposure to pollutants

Chronic exposure to air pollutants, such as PM_{10}, coarse particulate matter ($PM_{2.5-10}$) and $PM_{2.5}$ as well as gaseous pollutants such as NO_2, activates a series of complex biological mechanisms that impair respiratory [27, 28]. Literature evidence shows that these mechanisms are primarily mediated by oxidative stress, chronic inflammation, altered cellular structure, epithelial damage and airway remodelling, which can lead to long-lasting respiratory problems [29-31] (Figure 1).

Understanding these processes is crucial for establishing the link between environmental exposure and disease onset, as well as identifying potential prevention and treatment strategies. The main pathogenic mechanisms involved include:

– *Oxidative Stress*

Air pollutants, particularly $PM_{2.5}$ and NO_2, promote the production of reactive oxygen species (ROS), which are highly reactive molecules capable of damaging epithelial cells and lung tissue. ROS contribute to the degradation of cellular lipids and the formation of oxidation products, which in turn promote the formation of atherosclerotic plaques, thus increasing the risk of cardiovascular disease. The oxidation of cellular lipids and proteins causes damage to cell membranes and the extracellular matrix, facilitating the progression of pulmonary fibrosis and endothelial dysfunction. The ability of pollutants to generate chronic oxidative stress also underlies persistent inflammation in the respiratory tract [32-34].

– *Chronic inflammation*

Prolonged exposure to air pollutants stimulates the production of inflammatory cytokines, including IL-6, IL-8, and TNF-α, which trigger a persistent inflammatory response in the airways. This process underlies the development of chronic respiratory diseases such as asthma and COPD. Chronic inflammation promotes bronchial wall thickening and lung remodelling, which can lead to a progressive loss of respiratory function. TNF-α, in particular, plays a key role in macrophage activation and regulation of the long-term inflammatory response, while cytokines such as IL-8 are involved in neutrophil chemotaxis, contributing to localized inflammation that impairs the regenerative capacity of lung tissue [35-37].

– *Epithelial damage and mucociliary dysfunction*

Continued exposure to air pollutants alters the tight junctions of epithelial cells, compromising the protective barrier of the airways. This increased permeability favors the entry of pathogens and toxic substances, reducing the effectiveness of the airways' natural defence mechanisms. Alterations in mucociliary function are particularly critical, as ciliary dysfunction reduces the ability to remove foreign particles, microorganisms, and pollutants, increasing the risk of recurrent respiratory infections. Damaged epithelial cells also release pro-inflammatory cytokines that further exacerbate the local inflammatory reaction, leading to a cycle of continuous and progressive damage [38-40].

– *Bronchial Remodelling and Bronchial Hyperresponsiveness*

Chronic exposure to particulate matter and gaseous pollutants leads to structural changes in the airways, such as bronchial wall thickening, mucous gland hyperplasia, and pulmonary fibrosis. These changes are associated with irreversible bronchial obstruction and increased bronchial hyperresponsiveness, resulting in increased susceptibility to respiratory infections and diseases such as asthma and COPD. Bronchial remodelling is a pathological process that involves the deposition of collagen and other extracellular matrix proteins, which alters the structure of lung tissue and reduces the elasticity of the lungs. This makes the airways more susceptible to stenosis and fibrosis, further compromising respiratory function. Furthermore, chronic inflammation leads to loss of epithelial barrier integrity and increased bronchial responsiveness, a typical feature of respiratory diseases such as asthma [41-43].

Epidemiological evidence of relationship between air pollution and respiratory diseases

These pathogenic mechanisms, as demonstrated by international epidemiological studies and meta-analyses, contribute to the development and worsening of numerous chronic respiratory diseases, such as asthma, chronic bronchitis, and COPD. Prolonged exposure to air pollutants not only directly damages the lungs, impairing their functional capacity, but also increases vulnerability to pre-existing health conditions, exacerbating respiratory and cardiovascular comorbidities [16,44,45].

From a quantitative epidemiological perspective, large-scale cohort studies and meta-analyses confirm significant associations between chronic exposure to major pollutants and chronic respiratory disease. A meta-analysis of seven studies reported that a 10 μg/m^3 increase in $PM_{2.5}$ is associated with an increased risk of developing COPD with a pooled hazard ratio (HR) of 1.18 (95% CI: 1.13–1.23), while a 10 μg/m^3 increase in NO_2 is marginally associated with an

HR of 1.07 (95% CI: 1.00–1.16), indicating a significant effect even at relatively low levels of chronic exposure [20].

In a cohort study of approximately 5.1 million adults followed for 15 years, each interquartile range (IQR) increase of 3.4 μg/m³ in $PM_{2.5}$ was associated with an HR of 1.07 for COPD development (95% CI: 1.06–1.08). Similar positive associations were found for NO_2 and O_3, with an increased risk of more than 3 cases of COPD per 100,000 persons for each IQR of exposure [46].

Analyses of European cohorts (ELAPSE project) show that $PM_{2.5}$, NO_2, and BC are associated with increased mortality and morbidity even at levels below current regulatory limits, with concave (supralinear) relationships suggesting greater proportional effects at low pollutant concentrations [47].

These processes explain the reduction in FEV_1, the lowering of the FEV_1/FVC ratio and the reduction in alveolar-capillary diffusive capacity observed in lung function tests in exposed subjects [48-50] (Table 2).

Italy, by using Big Data (links to large amounts of geographic, environmental, and health data), two recent studies (BEEP and BIGEPI) showed important new findings at the national level. National epidemiological data show that for every 10 μg/m³ increase in $PM_{2.5}$ and PM_{10} levels, a 1.20–1.22% excess risk of hospitalizations for respiratory diseases is observed, with larger impacts on asthma and COPD in the period 2013-2015, with higher values in urban and suburban areas [51]. Between 2006 and 2015, over 4 million hospitalizations for respiratory diseases were recorded, of which 29% were for lower respiratory tract infections, 12% for COPD, 6% for upper respiratory tract infections, and 3% for asthma. The largest effects were seen in older adults and in less urbanized areas [52].

Furthermore, the increased incidence of chronic phlegm and COPD was associated with a 1 μg/m³ increase in $PM_{2.5}$ and PM_{10}, respectively, in Pisa (Tuscany) [53].

A case study: environment and health links in Campania

In Italy, epidemiological data reveal a steadily increasing trend in the incidence of respiratory diseases, with a more marked increase in influenza-like illnesses from 2020 to 2024 compared to the pre-pandemic period [54]. Furthermore, diagnoses of asthma and COPD have increased overall in recent years, also due to the progressive aging of the population. In people over 65, the prevalence of COPD exceeds 10-15%, while asthma affects approximately 6-10% of the elderly, although there is a significant rate of underdiagnoses or clinical overlap.

This phenomenon is particularly pronounced in regions with high air pollution, such as Campania, which has some of the highest $PM_{2.5}$ levels in Europe [55-57].

To adequately address the impact of air pollution on respiratory health in Campania, an integrated methodological approach combining different analytical dimensions was adopted: environmental, epidemiological, pathophysiological, and socioeconomic data. This multidisciplinary approach allows for a complex and detailed view of the problem, enabling not only the description of exposure levels, but also the exploration of the biological mechanisms through which air pollution affects health and the identification of territorial inequalities that amplify health risks. This methodology is crucial for defining more effective health and environmental policies, aimed at reducing health impacts in a fair and targeted manner [45,58-60].

Air quality data collection is a fundamental pillar for an accurate assessment of exposure to particulate matter and other air pollutants. Information comes from reliable and verified institutional sources, such as WHO [61], the European Environment Agency [11], the National Institute for Environmental Protection and Research (ISPRA) [55], the Regional Agency for Environmental Protection of Campania (ARPAC) [56] and Legambiente [57]. These institutions provide continuous monitoring and precise data on annual concentrations of air pollutants, including PM_{10}, $PM_{2.5}$, NO_2 and O_3, using a network of monitoring stations distributed across the country. This geographical and temporal coverage ensures the reliability and comparability of data, which is useful for monitoring temporal trends and seasonal variability of pollution levels [62].

A key aspect of this approach is the temporal analysis of exposure levels, supported by the creation of an epidemiological dataset covering the period 2015–2024. Using historical data provided by ISPRA and ARPAC, this dataset allowed us to monitor the evolution of fine particulate matter concentrations over time and identify significant trends in their variation. Furthermore, it allowed us to compare regional trends with national ones, thus providing a comprehensive picture of the effectiveness of past environmental policies and suggesting possible corrective actions. Additionally, the analysis of pollution seasonality enabled us to identify periods of the year with higher particulate matter levels, such as during the winter due to home heating or in the summer due to traffic and ozone formation [55,56].

These data are essential for developing targeted and timely interventions capable of reducing long-term exposure and the resulting health effects on the population.

Pollution trends in Campania: analysis of the period 2015-2024

In Italy, particulate matter levels are among the highest in Europe, with PM_{10} and $PM_{2.5}$ frequently exceeding the safety limits established by the EU, and Campania is one of the most affected Italian regions, particularly the provinces of Naples and Caserta, which record air pollution levels among the highest in the country [63,64]. The city of Naples is among the most exposed in Europe, with annual average PM_{10} values far exceeding the 40 μg/m³ threshold, well above the 15μg/m³ indicated by the WHO Air Quality Guidelines (AQG) in 2021 (Table 3). This makes Naples one of the cities with the most polluted air in Europe, highlighting the health and environmental emergency [57,62].

Benevento, despite being a less densely populated and urbanized city, is not exempt from episodes of elevated $PM_{2.5}$, which can occur during the winter months, especially due to the intensive use of domestic heating (e.g., the use of wood-burning stoves and fossil fuels) and poor atmospheric ventilation, typical of cold days. During these periods, particulate matter levels can reach relevant values, with a particular impact on air quality. The Air Quality Index (AQI) often classifies the situation as "moderate" or "unhealthy for sensitive groups", with pollution peaks exceeding AQG, especially during periods of high concentrations of fine particles. The negative effects on the population's health, such as the risk of respiratory and cardiovascular diseases, are amplified under these conditions [56,65].

More specifically, the analysis of the 2015-2024 period highlights that, despite noteworthy progress at the national level in reducing particulate matter concentrations, Campania continues to have higher pollution levels than the national average (Table 4). In 2024, the average PM_{10} concentration in Italy was 23 μg/m³, while in Campania was 29 μg/m³, a gap of 6 μg/m³. Similarly, for $PM_{2.5}$, the national average concentration was 11 μg/m³, while in Campania was 16 μg/m³. These values frequently exceed the limits indicated by the WHO, which recommends PM_{10} values lower than 15 μg/m³ and $PM_{2.5}$ values lower than 5 μg/m³ annually [55-57].

These data confirm that, although improvements have been made in environmental policies at the national level, Campania remains one of the Italian regions most vulnerable to the harmful effects of air pollution. The persistently high concentration of fine particulate matter is an indicator of unresolved environmental challenges, linked to structural factors such as population density, intense vehicular traffic, and the use of fossil fuels in residential and industrial settings, which contribute to the region's persistent air quality problems [66,67].

Furthermore, the analysis of temporal trends shows seasonal fluctuations in pollution levels, with peaks more evident during the winter months, mainly linked to the use of domestic heating and unfavourable weather conditions that impede the dispersion of air contaminants. Despite efforts to improve air quality, the data confirm that Campania continues to suffer from persistent air pollution, requiring targeted interventions and more effective environmental policies [55-57].

Territorial differences and socioeconomic vulnerabilities in Campania

A key element of the methodological approach considered in the study is the analysis of intraregional differences, which allowed us to identify high-risk areas within Campania, in parallel with the socioeconomic and environmental conditions.

Air pollution in Campania is also characterized by an uneven geographical distribution, with varying levels of exposure across provinces, influenced by socioeconomic and territorial factors (Table 5). The provinces of Naples and Caserta, with larger urbanization and population density, have the highest concentrations of PM_{10} and $PM_{2.5}$, mainly due to vehicular traffic and intensive industrial processes. In contrast, Benevento and Avellino show intermediate values, but with frequent $PM_{2.5}$ peaks, especially in the winter months, linked to home heating methods and local atmospheric factors. The province of Salerno, despite having a lower overall exposure, still records sporadic exceedances of the legal limits for the main pollutants. These spatial differences are accentuated by socioeconomic inequalities [55-57].

The most vulnerable areas, characterized by low incomes, high population density and poor access to healthcare services, tend to be those with the highest exposure to air pollution. People living in these disadvantaged neighbourhoods are particularly susceptible to the negative effects of pollution, due both to larger exposure to pollutants such as $PM_{2.5}$ and to limited access to healthcare and air purification technologies. Epidemiological studies confirm that individuals living in precarious socioeconomic contexts are more exposed to respiratory and cardiovascular diseases, exacerbating health inequalities. Furthermore, these social groups are less able to adopt personal protective measures, such as using air purifiers, which might mitigate the harmful effects of pollution [68,69].

The analysis of socioeconomic inequalities linked to pollution reveals how the condition of vulnerability not only increases health risks, but also creates a vicious circle that limits social mobility. People living in environments with poor economic opportunities are more vulnerable to the harmful effects of pollution, and socioeconomic inequalities often translate into larger environmental impacts, further reducing the quality of life and well-being. In this context, air pollution is not only an environmental problem, but also a social issue that exacerbates existing inequalities [70-72].

Territorial inequalities in Campania are also evident in the distribution of monitoring and intervention policies. Urban areas such as Naples benefit from larger resources and infrastructure for air quality control, thanks to advanced monitoring systems and targeted interventions to reduce emissions. Conversely, rural and peripheral areas, although recording not negligible levels of $PM_{2.5}$, are less monitored and receive less support from local authorities. This disparity in resources and interventions creates further vulnerability for the populations residing in these areas, who are not adequately protected from the air pollution effects. Recent studies have highlighted how rural areas, despite presenting high levels of pollution, are less covered by monitoring networks, with the risk of inadequate corrective interventions [68,69].

Chronic respiratory diseases in Campania in the national and international context

In this regard, it is worth noting that numerous epidemiological studies have highlighted an association between exposure to environmental contaminants and an increase in respiratory diseases among the population living in Campania, particularly in the provinces of Naples and Caserta. The main evidence comes from the SENTIERI Project of the Italian National Institute of Health, which analyzed the health effects of Sites of National Interest (SIN), documenting excess mortality and hospital admissions for respiratory diseases in areas characterized by industrial contamination, the presence of landfills, and illegal waste management. Other epidemiological evidence confirms the association between exposure to environmental contaminants and an increased risk of respiratory diseases in areas of Campania affected by contaminated sites and illegal waste disposal. In particular, the VI SENTIERI Report updated the analyses of the Sites of National Interest (SIN), confirming excess mortality and hospitalizations for respiratory diseases among populations living in areas most exposed to industrial emissions, soil contamination, and air pollution [73,74].

A recent study, conducted in the Terra dei Fuochi area, analyzed 38 municipalities comprising nearly one million inhabitants and confirmed an increase in mortality and hospitalizations in areas with the highest density of landfills and illegal waste burning sites. The authors observed a gradient of risk associated with the intensity of environmental exposure, highlighting that the health impact affects not only oncological diseases, but also respiratory and cardiovascular diseases [75].

In parallel, a review summarizing over twenty years of epidemiological research in Campania, concluded that the available evidence supports a consistent association between chronic exposure to environmental contaminants and an increase in various pathologies, including respiratory diseases, while emphasizing the need for further analytical studies to define the contribution of individual pollutants [76].

Within the national context, Campania presents epidemiological characteristics that reflect a North-South gradient already highlighted in other healthcare settings. In particular, an apparent paradox is observed: despite a lower diagnosed prevalence compared to the northern regions, the disease burden appears higher in terms of hospitalizations, exacerbations, and avoidable mortality. This phenomenon can be interpreted in light of the social determinants of health, which are also widely recognized in WHO reports. In Campania, factors such as higher smoking prevalence, higher levels of urban pollution, poor socioeconomic conditions, and less access to prevention and early diagnosis programs contribute to greater exposure to risk and less effective management of chronic diseases [77,78].

One of the most critical aspects, in line with international findings, is underdiagnosis, particularly of COPD and pulmonary fibrosis. The GBD highlights how a significant proportion of COPD cases in high-income countries remain undiagnosed, especially in the early stages. This phenomenon is likely amplified in regional contexts such as Campania, where access to spirometry and specialized diagnostic pathways may be less uniform [21,58,77].

International comparisons highlight how healthcare systems with strong integration between primary and specialist care are able to achieve better outcomes in chronic disease. In Northern European countries, for example, structured screening and management programs for COPD have significantly reduced hospitalizations and improved patients' quality of life. Conversely, in southern Italy, including Campania, critical issues persist: fragmented care pathways, less widespread integrated management programs, and uneven access to care [78,79].

GBD and WHO data indicate that the burden of chronic respiratory diseases is expected to increase in the coming decades, primarily due to the aging population and the persistence of environmental risk factors [21,80,81]. In this context, Campania could be particularly vulnerable if effective prevention and management strategies are not implemented. In particular, priorities include improving early diagnosis (spirometry, imaging), reducing exposure to risk factors (smoking, pollution), strengthening the local management of chronic patients, and developing specialist networks for complex conditions such as pulmonary fibrosis [82-84].

The critical analysis highlights how chronic respiratory diseases in Campania represent a significant health problem, set within a global context characterized by a growing disease burden. Compared to the international scenario outlined by WHO and GBD, the region displays elements of vulnerability related to the social and organizational determinants of health. Overcoming the critical issues highlighted requires an integrated approach that combines public health interventions, improved service organization, and strengthening early diagnosis, in line with international recommendations [78,85].

Public health implications, mitigation strategies and closing remarks

Air pollution represents a crucial risk factor for respiratory health, with documented effects on inflammation, oxidative stress, and airway remodelling, which underlie chronic diseases such as asthma and COPD [3,12,19]. The pathophysiological mechanisms associated with exposure to PM_{10}, $PM_{2.5}$, and NO_2 are now well understood, but their interaction with social and regional inequalities poses further challenges for public health. Campania, with its persistent exceedances of air quality limits, is one of the most vulnerable regions in Italy, with evident disparities between different provinces [22,35,58].

Geographical and socioeconomic inequalities amplify exposure to risk, especially in densely populated and congested urban areas, creating a vicious cycle that not only exacerbates respiratory diseases but also increases their health burden. Limited access to healthcare resources and the low adaptive capacity of vulnerable populations require targeted interventions that consider not only air quality but also local socioeconomic conditions [86,87].

This scenario calls for an environmental justice approach that not only focuses on reducing air pollution but also addresses socioeconomic inequalities. Environmental policies must be designed not only to reduce emissions but also to equitably redistribute resources and opportunities, ensuring adequate access to health and environmental protection for all populations. The implementation of inclusive policies should aim to address the needs of the most vulnerable areas, such as rural areas, which are too often excluded from the benefits of the most advanced environmental policies [69,79,88].

An integrated methodological approach that combines environmental, socioeconomic, and epidemiological data is essential to accurately map the most vulnerable areas and define effective public policies, that can allow to identify priorities for health and environmental interventions, reducing exposure to pollutants and improving access to healthcare in the most affected areas [89] (Figure 2). Moreover, mitigation policies should include long-term structural solutions, such as improving public transport, adopting sustainable energy policies, and creating green spaces, to reduce the pollution load in the most critical areas and improve the quality of life [79,85,~~89~~ 90].

In this context, it is urgent to develop specific mitigation strategies for Campania, including more precise and timely monitoring of air pollution levels.

At the global level, the United Nations 2030 Agenda and its Sustainable Development Goals (SDGs) offer strategic guidance for addressing environmental and health challenges, promoting a concrete commitment from all countries to reduce air pollution and improve the quality of life in the most vulnerable areas. Integrating the SDGs with national and local environmental policies represents a unique opportunity to develop more sustainable and inclusive solutions that simultaneously address environmental problems and social inequalities [91-93].

The collection of environmental, epidemiological, and socioeconomic data must be strengthened, including the use advanced technologies such as artificial intelligence (AI), to improve air quality forecasting and exposure estimation. Machine learning techniques, for example, can analyse satellite data and enhance the accuracy of $PM_{2.5}$ concentration estimates, providing essential support for the adoption of more effective health and environmental policies. Furthermore, AI can contribute to the simulation of mitigation policies and environmental justice analyses, facilitating the identification of the most vulnerable areas and the most appropriate solutions [94,95] ~~(Figure 2)~~.

In this regard, the Health Chapter of the National Recovery and Resilience Plan (NRRP) offers a fundamental opportunity to address air pollution and public health issues in Campania and other vulnerable regions. The NRRP provides relevant funding for strengthening the national health system and promoting integrated environmental and health policies. Investing in health infrastructure, environmental research and public health policies in particularly exposed areas, such as Campania, could contribute substantially to the reduction of the health burden of air pollution and improving the resilience of vulnerable communities [96].

In conclusion, air pollution in Campania also represents a complex challenge that requires a multidisciplinary approach, integrating environmental data with socioeconomic analyses and medical research. Only through a coordinated response between institutions, scientific research, and local communities it will be possible to improve air quality and reduce the health burden associated with respiratory and cardiovascular diseases. Artificial intelligence and emerging technologies will offer valuable tools to optimize monitoring, forecasting, and environmental policy management, accelerating the achievement of a healthier and more sustainable future for the population of Campania and the entire planet.

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Table 1. Pathway of pollution-induced lung damage.

Air pollutants
($PM_{2.5}$, PM_{10}, NO_2, O_3)
↓
Chronic airway inflammation
↓
Oxidative stress (ROS)
↓
Impaired mucociliary clearance
↓
Airway remodeling
↓
Bronchial obstruction
(↓FEV_1, ↓FEV_1/FVC)
↓
Chronic respiratory diseases

Table 2. Clinical-functional pattern associated with environmental pollution. Chronic exposure to air pollutants, particularly fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) is associated with a significant reduction in FEV_1 and the FEV_1/FVC ratio, resulting in an obstructive spirometric pattern and contributing to the development and progression of diseases such as COPD and asthma. Developed from: Schraufnagel *et al.* [14], Landrigan *et al.* [17], Agusti A *et al.* [43] - Pellegrino et al. [49] - ATS/ERS [50].

Spirometric parameter	*Functional assessments*	*Evidence of exposure to pollution*	*Clinical implications*
FEV1	↓	Reduction associated with chronic exposure to $PM_{2.5}$, NO_2	Airway damage
FVC	Normal or ↓ mild	Less affected than FEV1	Relatively preserved volume
FEV1/FVC	↓	Indicative of pollutant-related obstruction	Diagnosis of obstructive pattern
Expiratory flow rates	↓	Bronchial inflammation and remodeling	Flow limitation
Clinical risk	↑ exacerbations	Exacerbations in Asthma and COPD	Worsening prognosis

Table 3. Air quality intensity in the provinces of the Campania region (Italy) [55-57].

Napoli		**Very high exposure**
Caserta		**High exposure**
Benevento		**Medium exposure**
Avellino		**Medium exposure**
Salerno		**Low exposure**

Table 4. Trend of average annual concentrations of PM10 and PM2.5 respectively, in Italy and in the Campania region, from 2015 to 2024 [55-57].

Year	***Italy (µg/m³)***	***Campania (µg/m³)***	***Italy (µg/m³)***	***Campania (µg/m³)***
	PM_{10}		**$PM_{2.5}$**	
2015	32	38	20	25
2016	31	37	19	24
2017	30	36	18	23
2018	29	35	17	22
2019	28	34	16	21
2020	27	33	15	20
2021	26	32	14	19
2022	25	31	13	18
2023	24	30	12	17
2024	23	29	11	16

Table 5. Overlap between exposure and socioeconomic vulnerability in the provinces of the Campania region (Italy) [55-57].

High exposure + high vulnerability	**Napoli**
	Caserta
Medium exposure + medium vulnerability	**Benevento**
	Avellino
Lower exposure + medium vulnerability	**Salerno**

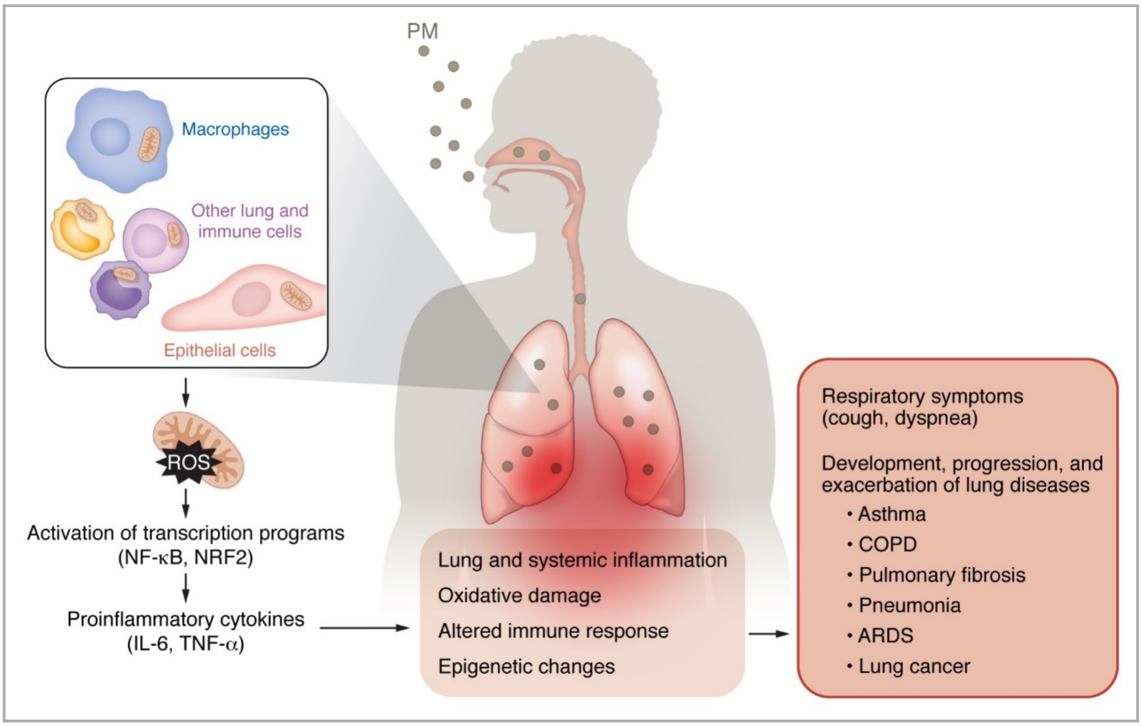

Figure 1. Mechanisms by which PM air pollution affects the respiratory system. Reproduced from: Hamanaka *et al.* [12].

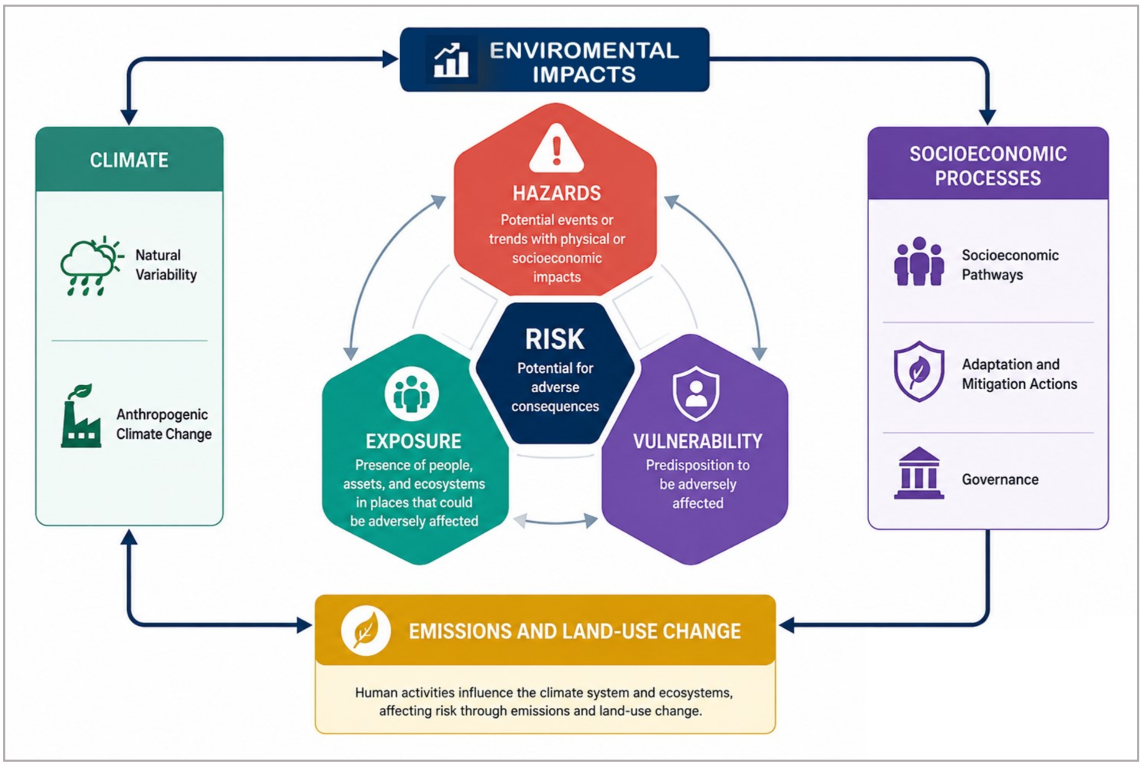

Figure 2. Diagram showing the interactions among climate change–related hazards, vulnerability, and exposure and how they are related to climate and socioeconomic impacts. Modified from: IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [89].