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Original Research

Health system resilience and the health impacts of environmental degradation: A global analysis

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ABSTRACT

Objectives: This study examines the impact of environmental degradation, focusing on air pollution and CO_2 emissions, as key climate stressors on health outcomes, specifically pollution-related mortality and disability-adjusted life years (DALYs). The research explores how healthcare infrastructure, accessibility, quality, and policies contribute to climate resilience by mitigating pollution-related mortality and supporting adaptation to environmental stressors.
Study design: Using panel data from 145 countries between 2009 and 2017, the study assesses both the direct effects of environmental factors on health outcomes and the mitigating role of healthcare systems. The design incorporates variation across countries and time to better understand these relationships.
Methods: Panel analysis models estimate the relationship between air pollution, CO_2 emissions, and health outcomes. Interaction terms between CO_2 emissions and healthcare system indicators are tested to determine if stronger healthcare systems can reduce pollution-induced mortality and DALYs.
Results: The study confirms that air pollution exposure is significantly linked to increased mortality and DALYs. While improved healthcare infrastructure, accessibility, and quality help mitigate some pollution-related health risks, they are insufficient to offset the long-term negative effects of CO_2 emissions. The interaction terms between CO_2 emissions and healthcare resilience are statistically insignificant, suggesting that even well-functioning healthcare systems cannot fully counteract the harmful consequences of environmental degradation.
Conclusion: While strengthening healthcare systems is vital for enhancing resilience to air pollution, the persistent adverse effects of CO_2 emissions stress the need for integrated environmental and health policies. Emission reduction strategies and stricter environmental regulations must complement healthcare improvements to effectively safeguard public health.

1. Introduction

Climate change and environmental degradation, including particulate matter (PM2.5) and carbon dioxide (CO_2), are major public health threats, contributing to morbidity and mortality worldwide.[1,2] PM2.5 and CO_2 emissions are linked to respiratory and cardiovascular diseases, premature death, and hospitalizations.[3,4] While PM2.5 is a direct inhalable pollutant generated through combustion, CO_2 is a non-toxic greenhouse gas. However, both are highly correlated at the country level, as they are primarily driven by the same fossil-fuel sources. Moreover, rising CO_2 levels contribute to climate warming, which can intensify the health impacts of PM2.5 by increasing the frequency of heatwaves and atmospheric stagnation events that trap fine particulates closer to the ground.[5,6]

A growing body of literature has explored the impact of air pollution on health, most studies either focus exclusively on PM2.5 exposure or do not consider the broader health system capacity in mitigating its effects. This study adds to the literature by integrating both PM2.5 and CO_2 emissions into the analysis—allowing for the distinction between direct pollutant exposure and broader environmental degradation.[7] The capacity of health systems to adapt and respond to these challenges is crucial for health resilience.[7,8] Climate-resilient health systems can anticipate, respond to, and recover from climate-induced health burdens while maintaining core functions.[7,8]

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The study applies a health system resilience framework to investigate how infrastructure, accessibility, quality, and policy orientation moderate these health effects across 145 countries. This multidimensional and integrative approach remains underexplored and offers important policy implications.[9–12] Weak health systems, with limited resources, are less equipped to manage climate-induced emergencies, leading to higher mortality and morbidity.[5,13] While the direct effects of air pollution on health are well-documented,[14–16] fewer studies examine how health system resilience moderates these effects.[17–19] The indirect consequences of CO_2 emissions—such as rising temperatures and food insecurity—are often overlooked.[20–22] These pressures are particularly severe in low- and middle-income countries, where healthcare resources are strained. This study addresses this gap by analysing how health system resilience moderates the relationship between environmental degradation and pollution-related mortality across different income levels.

Therefore, the study tests three hypotheses.

H1. (Direct pathway) Higher exposure to PM2.5 is associated with increased pollution-related mortality

H2. (Indirect pathway) Higher CO_2 levels—used here as a proxy for climate-related environmental stress—remain positively associated with environment-related mortality even after controlling for PM2.5.

H3. (Moderation pathway) Greater health-system capacity in terms of infrastructure, access, quality and policy attenuates the mortality effects of CO_2-driven environmental stress.

2. Methods

2.1. Data

The data is a panel set of country-level data from 2009 to 2017 for 188 countries. This makes up a sample size of a maximum of 1159 observations. Data are collated from different sources including the World Health Organisation (WHO), the World Development Indicators (WDI), the UN Population and Health Statistics, Global Health Estimates for the burden of disease, the Global Carbon Budget and CO_2 and Greenhouse Gas Emissions database by Our World in Data. Table A1 in the appendix shows the definition of all variables and the source of variables. Table 1 below shows descriptive statistics for all variables grouped by level of economic development of countries including low, lower middle-income, upper middle-income and high-income countries. Table A2 in the appendix provides descriptive statistics divided by country grouping by economic development into low-income countries, lower-middle income, upper-middle income and high-income countries based on the World Bank classification. Our data set has 70 low-income, 49 middle-income and 55 high-income countries.

2.1.1. Dependent variables

This study examines pollution-related mortality and disability-adjusted life years (DALYs) due to air pollution, with health system indicators as moderators. Pollution's impact on mortality includes respiratory diseases, cardiovascular conditions, and premature deaths, with exposure to PM2.5 and CO_2 emissions linked to increased risk.[3,23] Mortality data includes deaths from lower respiratory infections, strokes, ischaemic heart disease, COPD, and lung cancer in adults (25+ years). Age-standardised rates, as defined by WHO,[24] help compare health impacts across countries by controlling for age structure differences. DALYs, which account for both premature mortality and the burden of disease, provide a broader assessment of public health beyond fatalities.[25]

The mean rate of population-weighted pollution mortality is 110 deaths per 100,000, with substantial variation across countries. High-income countries report an average of 30 deaths per 100,000, while low-income countries report 223 deaths per 100,000 due to higher PM2.5 concentrations and weaker regulations.[15,16] Fig. A1 and A2 in the appendix show exposure to PM2.5 levels exceeding WHO guidelines for low and middle-income countries versus high-income countries. Statistical matching techniques estimate the effects of high PM2.5 exposure ($\geq$38.145 $\mu g/m^3$) and high CO_2 emissions ($\geq$0.273 metric tons per GDP), revealing a significant increase in mortality by 32 and 533 deaths per 100,000, respectively (Appendix A4).

The mean PM2.5 concentration in our sample from 2009 to 2017 is 44, 37, 25 and 19 $\mu g/m^3$ for low, lower-middle, upper-middle and high-income countries, respectively, with a range 5–95 $\mu g/m^3$ as shown in Table 1. These figures are more four times greater than the WHO guideline for annual average PM2.5 (10 $\mu g/m^3$). In our study, health outcomes are affected by the environmental efficiency of economic activity between countries where a lower value of CO_2 emissions (metric tons per GDP) indicates a less carbon-intensive economy and less environmental impact. The descriptive statistics indicate a clear inverse relationship between income levels and CO_2 emissions per unit of GDP. High-income countries exhibit the lowest mean CO_2 emissions intensity (0.30 metric tons per GDP), while low-income countries have the highest (1.53). This trend suggests that wealthier nations tend to have more energy-efficient economies, benefiting from advanced technologies,

Table 1
Descriptive statistics.

Variable	Variable Group	Obs.	Mean	Std. dev.	Min	Max
Air pollution mortality rate (per 100,000 population)	DEPENDENT	1324	110	84.95	7.57	356.9
DALYs (per 100,000 population, age-standardised)	DEPENDENT	1348	1369	930.20	137	4689
PM2.5 air pollution mean annual exposure (micrograms per cubic meter)	ENVIRONMENTAL DEGRADATION	1396	29.07	17.81	5.26	95.24
CO2 emissions (metric tons per GDP)	ENVIRONMENTAL DEGRADATION	1392	0.59	1.31	0.141	19.82
Health spending (% of GDP)	INFRASTRUCTURE	1521	6.39	2.58	1.22	20.41
Medical doctors (per 10,000 population)	INFRASTRUCTURE	1070	20.31	15.30	0.128	82.95
Hospital beds (per 1000 population)	INFRASTRUCTURE	627	3.36	2.39	0.1	16.46
UHC index	ACCESSIBILITY	339	64.02	15.59	22	89
Primary healthcare per capita	ACCESSIBILITY	147	674.30	862.81	11	3799
Healthy life expectancy at 60 yrs	QUALITY	509	14.97	2.62	8.1	21
Policy target for chronic respiratory diseases (dummy variable)	POLICY	656	0.55	0.49	0	1
Policy target for cardiovascular diseases (dummy variable)	POLICY	661	0.66	0.47	0	1
GDP per capita (constant 2010 100US$)	CONTROL	1539	146.08	223.71	2.141	1941.88
Trade (% of GDP)	CONTROL	1464	88.93	51.80	0.17	408.36

Notes: (1) The number of observations for each variable reflects data availability across a balanced panel of 188 countries from 2009 to 2017. Due to the use of multiple data sources and differences in national reporting capacities—particularly among low-income countries—some variables have fewer observations. This variation is primarily due to inconsistencies in annual reporting and data completeness across countries and indicators. (2) UHC index is Universal Health Coverage (UHC) index, which is a composite measure developed by the World Health Organization (WHO) to assess the extent to which people receive the health services they need without suffering financial hardship. It ranges from 0 to 100, with higher values indicating better coverage of essential health services. [42] *(3) Detailed definitions and sources for variables are provided in Table A1 in the appendix.Environmental degradation variables.*

cleaner energy sources, and stronger environmental regulations.[26] In contrast, low-income countries often rely on carbon-intensive energy sources, such as coal and biomass, and have less access to energy-efficient infrastructure, contributing to their higher emissions intensity.[27,28]

2.1.2. Health system variables

We are using three indicators to examine healthcare system infrastructure on a global sample, which are healthcare spending share of GDP, number of medical doctors per population, and hospital beds per population. Healthcare system infrastructure is a crucial determinant of a population's health outcomes, particularly in mitigating the effects of environmental and economic shocks. Healthcare spending, the availability of medical staff, and hospital beds per population are widely used indicators in assessing the infrastructure, resilience, and effectiveness of healthcare provision.[1,2,18,29,30] These metrics are essential for evaluating a health system's resources available for inpatient services and ability to deliver quality care, respond to patient needs, and manage unexpected health crises. While previous studies have used these indicators individually to explore health outcomes, they often do so within national or regional case studies, or without explicitly connecting them to environmental degradation. This study extends existing work by analysing these indicators together within a unified resilience framework, and assessing their moderating role on pollution-related mortality in a large cross-country sample. Several studies have explored the role of these indicators in evaluating the role of physical and human capital investments in the healthcare system, highlighting their direct impact on health outcomes, especially during climate-induced shocks like heatwaves.[10,31–34] Key indicators like healthcare infrastructure, staffing levels, and system efficiency significantly impact patient care and outcomes.[19,21,35–37] Collectively, these indicators proxy the core structural components of health system capacity—financing, workforce availability, and inpatient care infrastructure—and are routinely used in cross-country resilience and mortality studies.[31,47,52,60–62] The term 'infrastructure' is used here as a conceptual category only; each indicator is analysed separately in its own model specification and not combined into a single index. Low- and middle-income countries, with inadequate healthcare infrastructure, struggle with the growing burden of heat-related illnesses and respiratory diseases from air pollution.[4,12,38,39] Poor infrastructure leads to delays in medical interventions, resulting in higher mortality from conditions like heatstroke, asthma, COPD, and lung infections.[4,12,13,40]

Using universal healthcare coverage and primary healthcare spending per capita as indicators, we found that healthcare accessibility helps manage chronic diseases and improve health outcomes.[41–43] Accessible primary care reduces hospitalizations and fatalities from heat and air pollution by providing timely interventions such as bronchodilators and oxygen therapy.[41,42,44–48] Life expectancy at age 60, reflecting health system quality, is a critical indicator of resilience against pollution-induced mortality.[49] Healthy life expectancy at age 60 is widely used in cross-country health systems research as a summary indicator of healthcare quality and long-term system performance, as it reflects the effectiveness of chronic disease management and access to care in older age.[13,48–50] Strong healthcare systems, especially in high-income countries, mitigate air pollution's impact on mortality through early diagnosis and better chronic disease management.[50] In contrast, low- and lower-middle-income countries often have lower life expectancy at 60, leading to higher pollution-related mortality.[49,51]

Effective public healthcare policies that prioritize access and funding significantly enhance health system resilience.[52–54] We have integrated two proxies for national strategies targeting respiratory and cardiovascular diseases that have been shown to reduce morbidity and mortality linked to air pollution.[c] [12,44,45] This is to reflect health system policies. This study also moves beyond prior analyses by incorporating both system-level performance metrics (e.g. life expectancy) and policy orientation (e.g. primary care spending) into a single analytical model. This allows us to evaluate how the interplay between infrastructure, accessibility, and quality moderates health risks under environmental stress. We build on this evidence by quantitatively assessing how health systems mediate the relationship between environmental degradation and health outcomes across diverse socioeconomic settings. Countries featuring robust healthcare systems and strong environmental regulations report fewer pollution-related deaths.[52,53,55,56] Each health system dimension—representing infrastructure, accessibility, quality, and policy—is estimated in separate model specifications to preserve conceptual distinction and avoid multicollinearity. Moreover, data availability varies substantially across indicators and years; combining them into a single specification would substantially reduce the sample size and compromise cross-country comparability.

2.1.3. Control variables

We have used GDP per capita and trade openness indicators as control variables. GDP per capita serves as an indicator of a country's economic development and is closely linked to environmental quality, economic structure, and access to cleaner technology.[26,28,57,58] Trade openness helps account for the environmental and health implications of trade activities, as increased economic integration can lead to both pollution-intensive industrialisation and the diffusion of cleaner technologies.[27,41,55,56]

2.2. Empirical strategy

The study employs multivariate statistical techniques using a Random Effects panel specification estimated through the Generalized Least Squares Method (GLSM) to examine the role of health system infrastructure, accessibility, quality, and policy in moderating the health effects of air pollution (PM2.5 exposure) and CO_2 emissions. A log-likelihood ratio test was conducted to choose between fixed and random effects models, and the results did not support the fixed effects specification; therefore, the random effects model was selected. Standard errors are clustered at the country level to address heteroskedasticity and serial correlation. By utilising a longitudinal dataset covering 188 countries from 2009 to 2017, the analysis captures both cross-sectional and time-series variation, allowing for more robust estimation of the associations between environmental degradation and health outcomes.[d]

The correlation matrix (Table A3 at the appendix) shows that all the independent variables have low correlation, and multicollinearity is not the source of bias and/or inconsistency for our estimators. Eq. (1) shows the two health outcomes used as dependent variables in our model

[c] Among all non-communicable disease (NCD) policy indicators tracked by the WHO NCD Progress Monitor, targets for cardiovascular and respiratory diseases are the most directly related to air pollution mortality. These conditions account for a large share of premature deaths linked to PM2.5 and other pollutants. As such, we include these two policy targets as proxies for institutional responsiveness to pollution-related NCD burdens.

[d] We followed White's (1980) estimators for the variance to control for heteroskedasticity that could result in inefficient coefficient estimates and inconsistent standard errors. Our model is linear in parameters where the intercept, the estimated coefficients, the country-specific effects and the idiosyncratic error term are all linear and the country observations are independent and identically distributed (*i.i.d*) which means that observations are independent across countries.

which are mortality and DALYs due to air pollution for every country (*i*) and time (*t*). The coefficient estimate of air pollution (B1) captures the direct effect of air pollution on health outcomes, as exposure to pollutants like PM2.5 has been widely linked to increased mortality and morbidity.[3] B2 estimates the average effect of the environmental degradation caused by emissions, which can contribute to deteriorating air quality and climate-related health risks.[10] B3 is a vector of coefficient estimates for the health system resilience variables. These coefficient estimates measure the ability of a country's healthcare system to mitigate the adverse health effects of pollution through medical interventions and infrastructure.[33] B4 is a vector of all interaction terms between CO_2 emissions and health system resilience which assess whether stronger health systems can mitigate the negative health effects of environmental degradation.[6,7] Interaction effects are not specified for PM2.5, as the moderating role of health systems is conceptualised through the indirect climate pathway represented by CO_2 rather than direct particulate exposure. Stronger health systems are expected to dampen the pollution–mortality gradient by enabling better prevention, early detection, and treatment of pollution-related illnesses. Drawing on the risk-buffering framework developed by the WHO and others, we hypothesise that the positive association between CO_2 emissions and pollution-related mortality will be weaker in countries with more resilient health systems.[8] More resilient systems—via improved infrastructure, access, and quality—are better equipped to manage both the direct effects of pollutant exposure (e.g. PM2.5) and the indirect environmental consequences of CO_2 emissions (e.g. heat stress, vector-borne diseases, food insecurity). We therefore anticipate a negative interaction term ($B_4 < 0$), meaning that the slope linking CO_2 to mortality flattens as health system capacity improves. A statistically significant negative interaction would support the view that strong healthcare systems can moderate the health burden of environmental degradation.[11,12] B5 are the coefficient estimates for control variables that include GDP per capita and trade openness that may influence health outcomes beyond pollution levels.

$$\begin{aligned} &\textit{Health outcomes } (\textit{Mortality}, \textit{DALYs})_{it} = \beta_0 + \beta_1\ (\textit{Air pollution})_{it} \\ &+ \beta_2\ (\textit{CO2 emissions})_{it} + \beta_3\ (\textit{Health system reslience})_{it} \\ &+ \beta_4\ (\textit{CO2 emissions* Health system reslience})_{it} + \beta_5\ (\textit{controls})_{it} + \varepsilon_{it} \end{aligned} \quad \text{Eq. (1)}$$

3. Results

Table 2 shows the results for the effects of environmental degradation and the role of the resilience of health systems on air pollution mortality rate. Similar results were obtained using DALYs attributable to air pollution as seen in Table A5 in the Appendix. The base model at model (1) examines the direct effects of PM2.5 air pollution mean annual exposure (H1) and CO_2 emissions on air pollution-related mortality rates (H2). Notably, CO_2 is not treated as a direct local pollutant nor assumed to be causally responsible for premature mortality in itself. Instead, we include CO_2 as a proxy for broader, long-term environmental degradation and climate-related stressors—including increased temperatures and heatwaves — all of which can indirectly influence mortality patterns.[23,24] The results of this study reveal a strong and statistically significant relationship between air pollution exposure and adverse health outcomes. Specifically, PM2.5 concentration is positively associated with air pollution-related mortality, corroborating extensive literature that links fine particulate matter exposure to increased respiratory and cardiovascular morbidity and mortality.[3,23]

The significance of PM2.5 suggests that air pollution is a major driver

Table 2
The role of health system resilience (infrastructure, accessibility, quality and policies) in moderating the health effects of air pollution and CO_2 emissions: Panel analysis using Generalized Least Square Method (GLSM).

Dependent variable: Air pollution mortality rate (per 100,000 population)	Infrastructure				Accessibility	Quality	Policies
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)
PM2.5 air pollution mean annual exposure (μg/m3)	0.34** (0.15)	0.51*** (0.17)	0.48*** (0.17)	0.13 (0.13)	0.80*** (0.13)	−0.11 (0.19)	0.51*** (0.17)
CO_2 emissions (metric tons per GDP)	5.28*** (1.74)	8.99** (4.05)	8.27** (3.98)	9.65* (5.21)	−30.34 (26.5)	14.10** (6.81)	8.99** (4.05)
Healthcare spending (% of GDP)		−2.69*** (1.04)					
CO_2 emissions_ Healthcare spending		−0.32 (0.76)					
Medical doctors (per 10,000 population)			−2.45** (1.00)				
CO_2 emissions_ Medical doctors			−0.55 (0.82)				
Hospital beds (per 1000 population)				−13.31*** (1.65)			
CO_2 emissions_ Hospital beds				−2.71 (2.82)			
UHC index					−1.033*** (0.28)		
CO_2 emissions_ UHC index					0.75 (0.65)		
Healthy life expectancy at 60 yrs						−13.98** (3.31)	
CO_2 emissions_ Healthy life expectancy at 60 yrs						−0.86 (0.18)	
Policy target for respiratory diseases							−2.45** (1.00)
CO_2 emissions_ Policy target for respiratory diseases							−0.55 (0.82)
R2 (overall variation)	0.749	0.768	0.767	0.755	0.79	0.83	0.767
No of Observations	1138.00	540.00	538.00	1159.00	285	438	538.00
Wald Chi-square	580.45	599.24	610.28	733.88	181.31	866.46	610.88
P-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of Years	8	4	4	8	2	3	4
Number of Countries	145	145	145	145	145	145	145

Notes: (1) The dependent variable is the air pollution mortality rate (per 100,000 population, age-standardised) (2) We have used DALYs due to air pollution (per 100,000 population, age-standardised) as dependent variable as a robustness check and similar results are obtained. This is reported in appendix. (3) We have tested health policies for cardiovascular and respiratory diseases. Both yield similar results and we reported only health policies for respiratory diseases. (4) One of our indicators for healthcare accessibility is primary healthcare spending per capita, the results are similar to these reported in all other indicators. We reported all results at appendix. (4) Full list of control variables and robustness checks are reported in appendix. (5) Significance level *** is < 0.01, ** is < 0.05 and * is < 0.10.

of negative health outcomes, in line with prior research indicating that fine particulate matter penetrates deep into the respiratory system, exacerbating chronic illnesses such as chronic obstructive pulmonary disease (COPD), asthma, and cardiovascular disorders.[15,16] We have controlled for relevant economic and social indicators variables for economic development, GDP per capita, and level of trade openness. The coefficient estimates for PM2.5 range from 0.34 to 0.51 across all models, with statistical significance ranging between five and one percent. These findings suggest a positive and significant relationship between PM2.5 exposure and adverse health outcomes. For every unit increase in mean annual PM2.5 exposure, there is an associated increase in air pollution-related mortality, with the effect sizes varying slightly across models.

Across all model specifications, CO_2 emissions per unit of GDP remain a strong and significant predictor of pollution-related mortality, even after controlling for PM2.5 exposure. This reflects the indirect health effects of CO_2 through climate-linked pathways—such as rising temperatures, more frequent heatwaves, wildfire activity, and secondary pollutant formation—rather than CO_2 toxicity itself.[22,39] These results align with evidence that climate change amplifies existing health risks and compounds respiratory, cardiovascular, and heat-related illnesses.[16,17,21] The coefficients for CO_2 emissions range from 5.28 to 9.65, with statistical significance levels ranging from one to five percent. While resilient health systems can buffer the short-term effects of air pollution, they are insufficient to offset the cumulative, long-term impacts of emissions-driven environmental change. This underscores the need for integrated public health and climate strategies, where emission reduction and adaptation policies are treated as core components of health protection.

3.1. Moderating effect of health system infrastructure, accessibility, quality and policies on air pollution mortality

To assess how healthcare system infrastructure moderates air pollution's impact on mortality, Models (2), (3), and (4) incorporate healthcare spending, medical doctors per population, and hospital beds per population. The results indicate that stronger healthcare infrastructure significantly reduces the adverse effects of PM2.5 exposure on mortality, aligning with previous studies emphasizing the importance of resilient healthcare systems in mitigating environmental health risks.[15,21]

Model (2) shows that higher healthcare spending is linked to lower mortality, supporting the role of financial investment in improving public health and mitigating pollution-related risks.[18,31,34] Model (3) demonstrates that a higher density of medical doctors reduces air pollution-related mortality, in line with studies showing that adequate medical workforce availability is crucial for managing pollution-induced diseases.[15,17] Model (4) confirms that greater hospital bed availability is associated with lower pollution-related mortality, supporting findings that robust healthcare infrastructure improves health outcomes in pollution-affected areas.[16,17]

Model (5) explores health system accessibility through Universal Healthcare Coverage (UHC), showing that countries with better access to healthcare experience lower air pollution mortality, consistent with prior research.[17,23] Additionally, Model (6) finds that higher life expectancy at age 60, a proxy for healthcare quality, is negatively associated with pollution-related mortality, suggesting that quality healthcare reduces the adverse effects of air pollution.[3,45]

Model (7) examines health system policies, revealing that national strategies for managing respiratory and cardiovascular diseases reduce pollution-related mortality. Proactive health policies targeting pollution-induced diseases contribute to better health outcomes.[17,23] However, the interaction term between CO_2 emissions and health system resilience indicators in Models (2) to (7) is statistically insignificant, suggesting that even strong health systems may not fully counteract the harmful effects of CO_2 emissions. This implies that while health systems can mitigate pollution-related mortality, their capacity to address the long-term impacts of CO_2 emissions is limited. These findings align with existing literature on the limitations of healthcare interventions in addressing environmental mortality.[39,40] The lack of significance suggests that health system improvements may be more effective for short-term health crises than for long-term environmental stressors, reinforcing the need for integrated policies combining healthcare with environmental regulation.[49,51]

4. Discussion

This study integrates health system resilience within the broader discourse on climate adaptation and public health governance, contributing to the WHO's Operational Framework for Climate-Resilient and Low-Carbon Health Systems.[8,59] Our findings provide evidence for policymakers to design integrated health and environmental policies that strengthen health system resilience while advancing climate mitigation efforts.[22,59,60] Given the escalating public health threats posed by environmental degradation, understanding how healthcare systems can act as buffers against climate-induced health risks is essential for achieving sustainable, equitable, and climate-resilient health outcomes globally.[1,6,23,61] This study highlights the significant and persistent impact of environmental degradation—particularly PM2.5 exposure and CO_2 emissions—on air pollution-related mortality.[5–8,18,23]

Notably, CO_2 emissions per unit of GDP are also found to be positively and significantly associated with mortality outcome across most model specifications. The persistence of this effect, even when controlling for PM2.5 exposure, highlights an important but often overlooked dimension of environmental health research: the indirect health consequences of CO_2 emissions. While CO_2 itself is not directly toxic at ambient levels, it contributes to climate change, which in turn exacerbates health risks through mechanisms such as rising temperatures, increased frequency and intensity of wildfires, and higher ozone and secondary pollutant formation.[22,39] These indirect pathways can lead to worsening respiratory health, heat-related illnesses, and vector-borne diseases, underscoring the complex interplay between climate change and public health.[21] This result lends empirical support to prior studies that emphasise the broader health burdens associated with climate change, beyond just conventional air pollutants.[16,17] These results demonstrate a robust positive relationship between CO_2 emissions and poor health outcomes. The findings imply that while PM2.5 pollution remains a critical determinant of respiratory and cardiovascular diseases, policy interventions that solely focus on controlling fine particulate matter may be insufficient to fully mitigate the adverse health impacts of environmental degradation. Instead, addressing the indirect health effects of CO_2 emissions—through climate mitigation policies, emission reductions, and adaptation strategies—should be an integral component of public health planning and environmental policy. Together, these findings emphasise the direct and indirect significant effects of environmental resource depletion in driving adverse health outcomes across countries.

The results also underscore that while strong healthcare systems can mitigate some of the immediate health effects of air pollution, they are not sufficient to counteract the long-term adverse health consequences of environmental degradation, particularly those driven by CO_2 emissions and climate change.[15,19,20,23] The insignificant interaction terms between CO_2 emissions and healthcare system resilience indicators suggest that investments in health infrastructure, accessibility, quality, and policies, while beneficial for overall health outcomes, do not fully neutralize the harmful effects of environmental degradation.[59–61] This reinforces the urgent need for a multidimensional policy approach that integrates healthcare improvements with robust environmental policies.[6,23] While health system capacity plays an important role in reducing pollution-related mortality, many of the pathways linking CO_2 emissions to health operate outside the health sector, through energy systems, environmental regulation, labour conditions, and urban infrastructure. This reinforces that effective mitigation of climate-related health risks requires cross-sectoral policies that extend beyond healthcare provision alone.Previous studies have examined the health impacts of air pollution while accounting for temperature variation or testing temperature–pollution interaction effects, particularly in relation to heat-related mortality.[33,34,36,38] However, this literature typically focuses on short-term climatic fluctuations or episodic heat exposure, treating temperature as a transient stressor rather than a structural driver of long-run environmental change. In contrast, this study adopts a cumulative climate risk perspective by using CO_2 emissions as a proxy for sustained climatic stress, consistent with research emphasizing the long-term health implications of global warming, ecosystem disruption, and chronic disease pathways.[4,23,24] This approach enables joint analysis of direct pollution exposure (PM2.5) and indirect climate-mediated risks within a unified cross-country framework, extending prior work that has examined temperature, heat variation, or particulate pollution in isolation.[6,15,16]

While prior research has explored the health effects of air pollution or climate change, these studies typically analyse single pollutants (e.g. PM2.5) or assess health impacts without considering the moderating role of health systems.[12,14,19,22,29] This study contributes to the literature by adopting a multidimensional framework that integrates both direct pollutants (PM2.5) and broader indicators of environmental degradation (CO_2), and by systematically analysing how different aspects of health system resilience—namely infrastructure, accessibility, quality, and policy—mediate these effects in a global cross-country setting. This approach enables a more comprehensive understanding of how health systems can buffer environmental health risks, particularly in low-resource contexts.

Strong national health policies targeting respiratory and cardiovascular diseases can significantly reduce pollution-related mortality, as shown in this study.[53,54] Countries with well-developed public health strategies—such as air pollution monitoring programs, early warning systems for pollution spikes, and national disease management plans—exhibit greater resilience to environmental health crises.[14,15] While healthcare system resilience improvements play a crucial role in reducing the mortality burden of air pollution, they cannot fully counteract the adverse health effects of environmental degradation on their own.[9–12,14,20] The findings emphasise that addressing air pollution mortality requires an integrated approach that combines healthcare system strengthening with proactive environmental policies.[18,50,53] Governments and international organisations should work collaboratively to implement cross-sectoral strategies that align public health goals with environmental sustainability efforts.[50] Strengthening healthcare infrastructure, ensuring universal access to quality care, and implementing targeted health policies are critical steps in reducing pollution-related health risks.[25,31] However, these efforts must be complemented by aggressive climate action, including emissions reduction strategies, investments in renewable energy, and urban planning policies that promote cleaner air and healthier environments.[22,23,59] Without such comprehensive and coordinated policies, the long-term health risks of environmental degradation will continue to challenge even the most well-developed healthcare systems.[59,61,62]

This study offers an innovative contribution by empirically examining how multiple dimensions of health system resilience moderate the relationship between environmental degradation and mortality across a large, global sample—an area that remains underexplored despite its growing policy relevance, particularly for low- and middle-income countries. Despite its contributions, this study has some limitations. First, the use of country-level aggregate data may obscure within-country inequalities in health system access and pollution exposure. Second, while the study includes a wide set of resilience indicators, data availability limited the inclusion of variables such as emergency preparedness or climate-specific health adaptation strategies. Third, causal inference is limited by the observational nature of the data, and while the associations are robust, endogeneity concerns, such as reverse causality between health outcomes and system investments, remain. Finally, differences in data quality and reporting standards across countries may affect comparability.

Ethical statement

Ethical approval was not required for this study as it is based solely on the secondary analysis of publicly available, aggregate country-level data. No individual-level or sensitive data were used.

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Declaration of use of generative AI

Generative AI tools (Grammarly) were used to assist with text clarity, grammar checks and proofreading during the drafting and revision process. All content, data interpretation, and conclusions are the responsibility of the authors, and the manuscript has been carefully reviewed to ensure accuracy and integrity. The authors take full responsibility for the content of the publication.

Declaration of competing interests

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2025.106048.

References

1. Romanello M, Di Napoli C, Green C, et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet*. 2023 Dec 16;402(10419):2346–2394.
2. Landrigan PJ, Fuller R, Acosta NJ, et al. The Lancet Commission on pollution and health. *The lancet*. 2018 Feb 3;391(10119):462–512.
3. Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*. 2015 Sep 17; 525(7569):367–371.
4. Smith KR, Chafe Z, Woodward A, et al. *Human health: impacts, adaptation, and co-benefits. InClimate Change 2014 impacts. Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*. 2015:709–754.
5. Rogelj J, den Elzen M, Höhne N, et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*. 2016;534(7609):631–639.
6. Fiore AM, Naik V, Leibensperger EM. Air quality and climate connections. *J Air Waste Manag Assoc*. 2015;65(6):645–685.
7. Ansah EW, Amoadu M, Obeng P, Sarfo JO. Health systems response to climate change adaptation: a scoping review of global evidence. *BMC Public Health*. 2024 Jul 29;24(1):2015.
8. Keim ME. Building human resilience: the role of public health preparedness and response as an adaptation to climate change. *Am J Prev Med*. 2008 Nov 1;35(5): 508–516.
9. Nunes AR. Resilience: conceptualisations and challenges for effective heatwave public health planning. *Public Health*. 2024 May 1;230:113–121.
10. World Health Organization. *WHO Guidance for climate-resilient and Environmentally Sustainable Health Care Facilities*. World Health Organization; 2020 Oct 31.
11. Burnett R, Chen H, Szyszkowicz M, et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proc Natl Acad Sci*. 2018 Sep 18;115(38):9592–9597.
12. Balakrishnan K, Dey S, Gupta T, et al. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. *Lancet Planet Health*. 2019 Jan 1;3(1):e26–e39.

13. Yin P, Brauer M, Cohen AJ, et al. The effect of air pollution on deaths, disease burden, and life expectancy across China and its provinces, 1990–2017: an analysis for the Global Burden of Disease Study 2017. *Lancet Planet Health*. 2020 Sep 1;4(9): e386–e398.
14. Guan WJ, Zheng XY, Chung KF, Zhong NS. Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. *Lancet*. 2016 Oct 15; 388(10054):1939–1951.
15. Mannucci PM, Harari S, Franchini M. Novel evidence for a greater burden of ambient air pollution on cardiovascular disease. *Haematologica*. 2019 Oct 31;104 (12):2349.
16. Tong S. Air pollution and disease burden. *Lancet Planet Health*. 2019 Feb 1;3(2): e49–e50.
17. Paul VK, Rastogi A, Dua S, Basu C. *Healthcare Infrastructure, Resilience and Climate Change: Preparing for Extreme Weather Events*. Routledge; 2023 Jul 20.
18. Corvalan C, Villalobos Prats E, Sena A, et al. Towards climate resilient and environmentally sustainable health care facilities. *Int J Environ Res Publ Health*. 2020 Dec;17(23):8849.
19. Or Z, Seppänen AV. The role of the health sector in tackling climate change: a narrative review. *Health Policy*. 2024 Mar 20, 105053.
20. Paterson J, Berry P, Ebi K, Varangu L. Health care facilities resilient to climate change impacts. *Int J Environ Res Publ Health*. 2014 Dec;11(12):13097–13116.
21. Cohen AJ, Brauer M, Burnett R, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The lancet*. 2017 May 13;389(10082): 1907–1918.
22. Di Q, Wang Y, Zanobetti A, et al. Air pollution and mortality in the Medicare population. *N Engl J Med*. 2017 Jun 29;376(26):2513–2522.
23. Costello A, Romanello M, Hartinger S, et al. Climate change threatens our health and survival within decades. *Lancet*. 2023 Jan 14;401(10371):85–87.
24. Romanello M, Walawender M, Hsu SC, et al. The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action. *Lancet*. 2024 Nov 9;404(10465):1847–1896.
25. World Health Organization. *Age-Standardized Mortality Rate (Per 100 000 Population)*. Geneva: WHO; 2021. https://www.who.int/data/gho/indicator-metadata-registry/imr-details/78.
26. World Health Organization. *Disability-Adjusted Life Years (Dalys)*. Geneva: WHO; 2021. https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158.
27. El Anshasy AA, Katsaiti MS. Energy intensity and the energy mix: what works for the environment? *J Environ Manag*. 2014 Apr 1;136:85–93.
28. Solarin SA, Al-Mulali U, Gan GG, Shahbaz M. The impact of biomass energy consumption on pollution: evidence from 80 developed and developing countries. *Environ Sci Pollut Control Ser*. 2018 Aug;25:22641–22657.
29. Yao X, Yasmeen R, Padda IU, Shah WU, Kamal MA. Inequalities by energy sources: an assessment of environmental quality. *PLoS One*. 2020 Mar 20;15(3), e0230503.
30. Watts N, Amann M, Arnell N, et al. The 2019 report of the Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. *Lancet*. 2019 Nov 16;394(10211):1836–1878.
31. OECD. *Health at a Glance 2023: OECD Indicators*. Paris: OECD Publishing; 2023. https://www.oecd.org/health/health-at-a-glance/.
32. Kruk ME, Gage AD, Arsenault C, et al. High-quality health systems in the Sustainable Development Goals era: time for a revolution. *Lancet Global Health*. 2018 Nov 1;6 (11):e1196–e1252.
33. Bunker A, Wildenhain J, Vandenbergh A, et al. Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence. *EBioMedicine*. 2016 Apr 1;6:258–268.
34. Phung D, Thai PK, Guo Y, Morawska L, Rutherford S, Chu C. Ambient temperature and risk of cardiovascular hospitalization: an updated systematic review and meta-analysis. *Sci Total Environ*. 2016 Apr 15;550:1084–1102.
35. Sun Z, Chen C, Xu D, Li T. Effects of ambient temperature on myocardial infarction: a systematic review and meta-analysis. *Environmental Pollution*. 2018 Oct 1;241: 1106–1114.
36. Hajat S, Vardoulakis S, Heaviside C, Eggen B. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. *J Epidemiol Community Health*. 2014 Jul 1;68(7):641–648.
37. Díaz J, Carmona R, Mirón IJ, Ortiz C, León I, Linares C. Geographical variation in relative risks associated with heat: update of Spain's heat wave prevention plan. *Environ Int*. 2015 Dec 1;85:273–283.
38. Kovats RS, Hajat S. Heat stress and public health: a critical review. *Annu Rev Publ Health*. 2008;29:41–55, 2008 Apr 1.
39. Anderson GF, Frogner BK, Johns RA, Reinhardt UE. Health care spending and use of information technology in OECD countries. *Health Aff*. 2006 May;25(3):819–831.
40. Alders P, Costa-Font J, de Klerk M, Frank R. What is the impact of policy differences on nursing home utilization? The cases of Germany and the Netherlands. *Health Policy*. 2015 Jun 1;119(6):814–820.
41. Amoadu M, Ansah EW, Sarfo JO, Hormenu T. Impact of climate change and heat stress on workers' health and productivity: a scoping review. *The Journal of Climate Change and Health*. 2023 Jul 1;12, 100249.
42. World Health Organization. *Universal Health Coverage (UHC)*. Geneva: WHO; 2023. https://www.who.int/news-room/fact-sheets/detail/universal-health-coverage-uhc.
43. World Health Organization. *Primary Health Care on the Road to Universal Health Coverage: 2019 Monitoring Report*. Geneva: WHO; 2019. https://www.who.int/docs/default-source/documents/2019-uhc-report.pdf.
44. Kringos DS, Boerma WG, Hutchinson A, et al. The breadth of primary care: a systematic literature review of its core dimensions. *BMC Health Service Research*. 2010;10:65.
45. López-Campos JL, Tan W, Soriano JB. Global burden of COPD. *Respirology*. 2016;21 (1):14–23.
46. Bousquet J, Kiley J, Bateman ED, et al. Prioritised research agenda for prevention and control of chronic respiratory diseases. *Eur Respir J*. 2010 Oct 31;36(5): 995–1001.
47. World Health Organization. *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*. Geneva: WHO; 2016. https://www.who.int/publications/i/item/9789241511353.
48. Khan KS, Jawaid S, Memon UA, et al. Management of chronic obstructive pulmonary disease (COPD) exacerbations in hospitalized patients from admission to discharge: a comprehensive review of therapeutic interventions. *Cureus*. 2023 Aug 18;15(8).
49. Pope IIICA, Ezzati M, Dockery DW. Fine-particulate air pollution and life expectancy in the United States. *N Engl J Med*. 2009 Jan 22;360(4):376–386.
50. Lelieveld J, Pozzer A, Pöschl U, Fnais M, Haines A, Münzel T. Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective. *Cardiovasc Res*. 2020 Sep 1;116(11):1910–1917.
51. Debie A, Nigusie A, Gedle D, Khatri RB, Assefa Y. Building a resilient health system for universal health coverage and health security: a systematic review. *Global Health Research and Policy*. 2024 Jan 4;9(1):2.
52. Thomas S, Sagan A, Larkin J, Cylus J, Figueras J, Karanikolos M. *Strengthening Health Systems Resilience: Key Concepts and Strategies*. vol. 29. Copenhagen: WHO Regional Office for Europe; 2020.
53. Elkomy S, Jackson T. Health resilience and the global pandemic: the effect of social conditions on the COVID-19 mortality rate. *J Int Dev*. 2024 Jul;36(5):2342–2371.
54. Elkomy S, Jackson T. WHO non-communicable diseases Global Monitoring Framework: pandemic resilience in Sub-Saharan Africa and low-income countries. *Soc Econ Plann Sci*. 2024 Oct 1;95, 102043.
55. James C, Colombo F, Morgan D, Vammalle C. Finance and health dialogue needed to build resilient health systems. *Bull World Health Organ*. 2024 Apr 17;102(5):368.
56. Barkat K, Alsamara M, Al Kwifi OS, Jarallah S. Does trade openness mitigate environmental degradation in Organisation for Economic Co-operation and Development (OECD) countries? Implications for achieving sustainable development. In: *InNatural Resources Forum*. vol. 49. Oxford, UK: Blackwell Publishing Ltd; 2025 Feb:677–698, 1.
57. Lu Z, Jiang L, Wang X. Exploring the role of environmental pollution and trade openness in human health in the context of sustainable development. *PLoS One*. 2025 Mar 10;20(3), e0312246.
58. Awan AM, Azam M. Evaluating the impact of GDP per capita on environmental degradation for G-20 economies: does N-shaped environmental Kuznets curve exist? *Environ Dev Sustain*. 2022 Sep;24(9):11103–11126.
59. Zhang JD, Cheng XF, He YT, et al. Environmental pollution, trade openness and the health of middle-aged and elderly people: an analysis of threshold effect based on data from 111 prefecture-level cities in China. *Arch Public Health*. 2024 Nov 5;82(1): 202.
60. World Health Organization (WHO). *Operational Framework for Building Climate Resilient and Low Carbon Health Systems*. Geneva: WHO; 2023. https://www.who.int/publications/i/item/9789240081888.
61. Mosadeghrad AM, Isfahani P, Eslambolchi L, Zahmatkesh M, Afshari M. Strategies to strengthen a climate-resilient health system: a scoping review. *Glob Health*. 2023 Aug 28;19(1):62.
62. Braithwaite J, Tran Y, Fisher G, Ellis LA, Smith CL, Zurynski Y. Health system performance on greenhouse gas emissions, climate change and development status in 38 OECD countries. *Sci Rep*. 2025 Feb 11;15(1):5101.