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Science to Foster the WHO Air Quality Guideline Values?

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Editorial: Science to Foster the WHO Air Quality Guideline Values

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Keywords: air pollution, health, WHO air quality guidelines (AQG), policy, legislation

Editorial on the Special Issue

Science to Foster the WHO Air Quality Guideline Values

Air pollution is among the leading risk factors for poor health worldwide – in 2021, it was the second leading risk factor for premature mortality, surpassed only by high blood pressure, and resulting in 8.1 million deaths [1]. Everyone is vulnerable to its impacts, and some are more at risk than others. People's level of vulnerability is outside of individual control, as it evolves with age, health condition, socio-economic status, as well as where people live, study, or work. The impacts of poor air quality can be further exacerbated through exposure to a variety of climate hazards. Rising temperatures are worsening air pollution and its health effects, underscoring the urgent need for integrated action to simultaneously improve air quality and reduce greenhouse gas emissions [2]. Just in the last few years, wildfires, extreme heatwaves, and more frequent and severe dust storms have proven to be devastating to air quality in regions around the globe.

There is a large global body of evidence linking exposure to air pollution, especially fine particulate matter ($PM_{2.5}$), with impacts on all major human organ systems. Furthermore, epidemiological studies have now documented health effects at levels below current national ambient air quality standards. The Health Effects Institute recently completed a comprehensive research initiative to investigate the health effects of long-term exposure to low levels of air pollution in Europe, Canada and the United States [3]. Particular strengths of the studies included the large populations (7–69 million people), state-of-the-art exposure assessment methods, and thorough statistical analyses that applied novel methods. All three studies documented positive associations between mortality and exposure to $PM_{2.5}$ at levels as low as 4 μg/m^3 or even lower. Furthermore, the studies observed linear (United States), or supra-linear (Canada and Europe) exposure-response functions for $PM_{2.5}$ and mortality, with no evidence for a threshold. This research initiative provided important new evidence of the adverse effects of long-term exposures to low levels of air pollution at and below current standards, suggesting that further reductions in air pollution could yield larger benefits than previously anticipated [3].

Based on these and other studies, the World Health Organization (WHO) released new Air Quality Guidelines (AQG) in September 2021. They recommended that annual mean concentrations of $PM_{2.5}$ should not exceed 5 μg/m^3, finding that adverse health effects occur above this concentration [4]. They also recommended a set of interim targets, meant to provide a step wise pathway towards achievement of the AQG values set at 35, 25, 15, and 10 μg/m^3. Governments in the United States and Europe have recently moved toward more stringent $PM_{2.5}$ standards—9 and 10 μg/m^3, respectively—to align more closely with the 2021 WHO AQG [5, 6]. Meanwhile, the Federal Commission of Air Hygiene advised the Swiss Government to adopt the new WHO AQG values as the national standards [7]. Others such as Uganda have recently adopted National Air Quality

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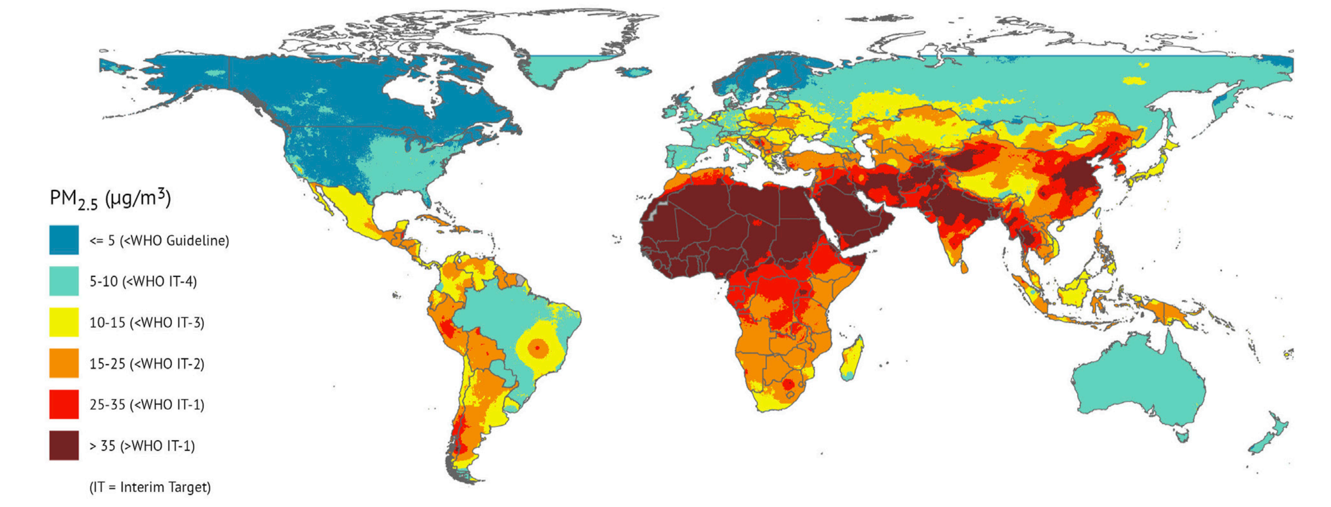

FIGURE 1 | National population-weighted annual average PM$_{2.5}$ concentrations in 2020 [1].

Standards for the first time [8], and Brazil has adopted the National Air Quality Policy with progressive air quality targets consistent with the 2021 WHO AQG [9].

This Special Issue, entitled "*Science to Foster the WHO Air Quality Guideline Values*," presents recent science that underpins the WHO AQG and offers insights into pathways for action. One issue is abundantly clear—the disease burden from air pollution is not borne equally across the world, with countries in Asia, Africa, and the Middle East experiencing the highest levels of ambient PM$_{2.5}$ and associated health impacts (**Figure 1**). Hence, there is a particular need to improve air quality in those regions (e.g., Safi et al. and Kundu et al.).

Much of what is currently known about the adverse effects of ambient air pollution and its solutions come from studies conducted in high-income regions, especially North America and Western Europe, with relatively low air pollution levels, and in more recent years, from studies in China where air pollution levels are relatively high [10, 11]. As governments around the world act to improve air quality, there is a continuing need for research to strengthen the local evidence base on disease risk at relatively high levels of air pollution, identify the air pollution sources most responsible for disease burden and assess the public health effectiveness of actions taken to improve air quality. Such studies are also invaluable for strengthening local scientific and infrastructure capacities, raising awareness of local communities, and supporting evidence-based decision making. To strengthen awareness, there is also a need to update Air Quality Index tools – used by many authorities to communicate the state of air quality on a daily basis – with the 2021 WHO AQG (Adebayo-Ojo et al.). More research is also needed to capture the direct and indirect health effects of climate change more fully, including the interactions with air pollution.

Overall, bold air quality and climate actions are needed at all levels–international, national, local–and across all sectors such as transport, energy, industry, agriculture, and residential. There is cause for optimism: there are various examples from locations across the globe that show that if action is taken to improve air quality, so does population health [12]. Scientific data and evidence such as that presented in the articles in the Special Issue, will continue to play a fundamental role in fostering evidence-based air quality and climate actions, to reduce the inequity in air quality both within and across countries, and to close the gap between national air quality standards and the 2021 WHO AQG.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

AUTHOR DISCLAIMER

The views expressed in this article are those of the authors and do not necessarily reflect the views of the Health Effects Institute or its sponsors.

CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

REFERENCES

1. Health Effects Institute (HEI). *State of Global Air 2024. Special Report*. Boston, MA: Health Effects Institute (2024).
2. Romanello M, Walawender M, Hsu SC, Moskeland A, Palmeiro-Silva Y, Scamman D, et al. The 2024 Report of the Lancet Countdown on Health and Climate Change: Facing Record-Breaking Threats From Delayed Action. *Lancet* (2024) 404:1847–96. doi:10.1016/S0140-6736(24)01822-1
3. Boogaard H, Crouse DL, Tanner E, Mantus E, van Erp AM, Vedal S, et al. Assessing Adverse Health Effects of Long-Term Exposure to Low Levels of Ambient Air Pollution: The HEI Experience and What's Next? *Environ Sci Technol* (2024) 58:12767–83. doi:10.1021/acs.est.3c09745
4. World Health Organization (WHO). *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization (2021).
5. European Union (EU). Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on Ambient Air Quality and Cleaner Air for Europe. 2024.
6. United States Environmental Protection Agency (U.S. EPA). *Reconsideration of the National Ambient Air Quality Standards for Particulate Matter. Final Rule*. Washington, DC: Rules and Regulations. Federal Register (2024), 89:45.
7. Eidgenössische Kommission für Lufthygiene (EKL) *Die Neuen WHO-Luftqualitätsrichtwerte 2021 und ihre Bedeutung für die Schweizer Luftreinhalte-Verordnung*. Bern: Federal Commission for Air Hygiene EKL. 120 (2023).
8. National Environment Management Authority (NEMA). Introduces Air Quality Regulations to Combat Pollution (2024). Available from: https://govinfohub.go.ug/index.php/2024/05/09/nema-introduces-air-quality-regulations-to-combat-pollution/ (Accessed December 10, 2024).
9. Tavella RA, de Moura FR, Miraglia SGEK, da Silva Júnior FMR. A New Dawn for Air Quality in Brazil. *Lancet Planet Health* (2024) 8:e717–e718. doi:10.1016/S2542-5196(24)00203-1
10. Orellano P, Kasdagli MI, Pérez Velasco R, Samoli E. Long-Term Exposure to Particulate Matter and Mortality: An Update of the WHO Global Air Quality Guidelines Systematic Review and Meta-Analysis. *Int J Public Health* (2024) 69:1607683. doi:10.3389/ijph.2024.1607683
11. Kasdagli MI, Orellano P, Pérez Velasco R, Samoli E. Long-Term Exposure to Nitrogen Dioxide and Ozone and Mortality: Update of the WHO Air Quality Guidelines Systematic Review and Meta-Analysis. *Int J Public Health* (2024) 69:1607676. doi:10.3389/ijph.2024.1607676
12. Schraufnagel DE, Balmes JR, De Matteis S, Hoffman B, Kim WJ, Perez-Padilla R, et al. Health Benefits of Air Pollution Reduction. *Ann Am Thorac Soc* (2019) 16:1478–87. doi:10.1513/AnnalsATS.201907-538CME

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Time-Trends in Air Pollution Impact on Health in Italy, 1990–2019: An Analysis From the Global Burden of Disease Study 2019

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Objectives: We explored temporal variations in disease burden of ambient particulate matter 2.5 µm or less in diameter ($PM_{2.5}$) and ozone in Italy using estimates from the Global Burden of Disease Study 2019.

Methods: We compared temporal changes and percent variations (95% Uncertainty Intervals [95% UI]) in rates of disability adjusted life years (DALYs), years of life lost, years lived with disability and mortality from 1990 to 2019, and variations in pollutant-attributable burden with those in the overall burden of each $PM_{2.5}$- and ozone-related disease.

Results: In 2019, 467,000 DALYs (95% UI: 371,000, 570,000) were attributable to $PM_{2.5}$ and 39,600 (95% UI: 18,300, 61,500) to ozone. The crude DALY rate attributable to $PM_{2.5}$ decreased by 47.9% (95% UI: 10.3, 65.4) from 1990 to 2019. For ozone, it declined by 37.0% (95% UI: 28.9, 44.5) during 1990–2010, but it increased by 44.8% (95% UI: 35.5, 56.3) during 2010–2019. Age-standardized rates declined more than crude ones.

Conclusion: In Italy, the burden of ambient $PM_{2.5}$ (but not of ozone) significantly decreased, even in concurrence with population ageing. Results suggest a positive impact of air quality regulations, fostering further regulatory efforts.

Keywords: air pollution, particulate matter, ozone, global burden of disease, air quality regulations

INTRODUCTION

Air pollution represents a paradigm of risk factor associated to relatively modest increases in the individual risk, but to substantial disease burden at the population level [1]. The World Health Organization (WHO) recognized air pollution as a health risk factor in 1958 [2], with effects ranging from subclinical lesions to premature death [3, 4]. Although directives have been thereafter issued, it remains a substantial public health concern owed to its mortality and disability burden [5–7]. In 2008, the European Union (EU) introduced the "Air Quality Directive", fixing target values for long-term concentrations of air pollutants [4]. As a plausible effect, a reduction of 22% in annual mean concentrations of $PM_{2.5}$ was observed across Europe from 2009 to 2018. Conversely, an increase in ozone concentrations was registered over the same period, owed to increasing in precursors emission and changes in regional climate characteristics [1, 8]. The 2021 WHO Global Air Quality Guidelines updated air quality levels, focusing on six pollutants: particulate matter with diameter equal or smaller than 2.5 and 10 µm ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide [3]. In this frame, it is compelling to understand the health impact of regulation-driven modifications in pollutant concentrations.

The Global Burden of Diseases (GBD) Study 2019 graded air pollution as fourth-ranking risk factor for mortality and disability-adjusted life years (DALYs) globally, accounting for 85.6 deaths (95% Uncertainty Interval [95% UI]: 75.7, 96.1) and 2791.1 DALYs (95% UI: 2468.8, 3141.4) per 100,000 people [7]. These estimates quantify health impacts attributable to exposure to ambient and household $PM_{2.5}$ and ambient ozone, and account for morbidity and mortality of selected diseases associated with pollution: chronic obstructive pulmonary disease (COPD), lower respiratory infections (LRI), ischemic heart disease (IHD), stroke, tracheal bronchus and lung (TBL) cancer, type 2 diabetes mellitus (T2DM), premature birth and decreased birthweight [1, 7].

Specific evidences from the GBD Study underlined that deaths and DALYs due to $PM_{2.5}$ long-term exposure globally increased from 1990 to 2015. Meanwhile, an increment of ozone-attributable COPD deaths was observed [9]. These trends might result from several phenomena that add up to the variation in pollutants concentrations, such as changes in the population age structure or variations in mortality and morbidity rates [8–13].

Using GBD estimates, we investigated temporal variations in disease burden from long-term exposure to ambient $PM_{2.5}$ and ozone from 1990 to 2019 in Italy, with the aim of disentangling the effect of the reduction in air pollution concentration from demographic (population ageing) and epidemiologic (mortality and morbidity rates) population dynamics.

METHODS

Overview

The GBD Study provides comprehensive global estimates of disease burden, such as incidence, prevalence, mortality, years of life lost (YLLs), years lived with disability (YLDs), healthy life expectancy (HALE) and DALYs, for 204 countries and territories [7]. It also applies a comprehensive and standardized method to identify risk factors and risk-outcome associations by disease cause. Risk factors are organized in five hierarchical nested levels; risk-outcome pairs are assessed for inclusion based on availability and strength of the evidence for a causal association, and on the feasibility of developing complete estimates of exposure levels [7, 14].

The burden attributable to a risk factor is estimated for each risk–outcome pair based on the overall estimate of the outcome burden, spatial and temporal exposure estimates for the risk factor, the theoretical minimum risk exposure level (TMREL) and the relative risk, or dose-response function, describing the association between risk factor and outcome [15].

Here, we focus on the burden of long-term exposure to ambient $PM_{2.5}$ (GBD level four risk factor) and ozone (GBD level three risk factor) pollution. Detailed descriptions of data sources, metrics and methods are available elsewhere [7]. The study is compliant with the Guidelines for Accurate and Transparent Health Estimates Reporting [16].

Ambient $PM_{2.5}$ Exposure and Associated Risk-Outcome Pairs

Input data used by GBD 2019 to estimate population-weighted exposure to ambient $PM_{2.5}$ included ground measurements, satellite-based estimates, chemical transport model simulations, and population estimates. GBD 2019 data sources for ground measurements of $PM_{2.5}$ consisted of updated measurements from GBD 2017 and additional measurements provided by the WHO Global Ambient Air Quality Database in 2018. A hierarchy of conversion factors ($PM_{2.5}/PM_{10}$ ratios) was used to obtain $PM_{2.5}$ values for locations containing only measurements of PM_{10}. The satellite-based estimates combined information on aerosol optical depth retrievals from multiple satellites, chemical transport model simulations and information on land use, and were available on a spatial resolution of $0.1^0 \times 0.1^0$ (which corresponds to 11×11 km at the equator) [17]. Population estimates were derived from the Gridded Population of the World database for the years 1990, 1995 (3rd version), and 2000, 2005, 2010, 2015, 2020 (4th version), and natural spline interpolation was used to calculate population estimates in intermediate years. $PM_{2.5}$ estimates in Italy were calculated using a Bayesian hierarchical calibration model, thus combining information from satellite retrievals, chemical transport model simulations and population estimates calibrated with ground monitor $PM_{2.5}$ estimates. The TMREL for ambient particulate matter was estimated on a uniform distribution with lower and upper bounds corresponding to 2.4 and 5.9 μg/m^3 based on the average of the minimum and 5th percentiles of exposure distributions to air pollution in the cohort studies used to produce the GBD estimates.

Risk-attributable disease burden for ambient $PM_{2.5}$ was computed for risk-outcome pairs validated for inclusion using the scientific literature. Such validation procedure identified the following GBD level three outcomes (causes): IHD, stroke, COPD, T2DM, LRI, TBL cancer, and neonatal disorders [7, 14].

In order to ascertain the shape of the dose-response relationship for each outcome, the GBD 2019 adopted the Meta-Regression-Bayesian Regularized Trimmed (MR-BRT) strategy, with input data from studies assessing the effect of $PM_{2.5}$ ambient and household pollution [6, 16, 18–20].

Ambient Ozone Exposure and Associated Risk-Outcome Pairs

GBD 2019 definition of ozone ambient air pollution is the highest seasonal (6 months) average of 8-h daily maximum ozone concentrations measured as parts per billion (ppb), for each $0.1^0 \times 0.1^0$ grid cell on a global scale. Ozone ground measurements obtained from the Tropospheric Ozone Assessment Report and continent-specific chemical transport models provided by the Chemistry-Climate Model Initiative were combined in a single geo-statistical modelling tool, the Bayesian Maximum Entropy, to estimate the exposure to ambient ozone pollution globally for the period 1990–2017. Subsequently, a log-linear model was run to extrapolate ambient ozone pollution exposure for the years 2018 and 2019. The TMREL for ambient ozone air pollution ranged between 29.1 and 35.7 ppb [7, 10].

In GBD Study 2019, estimation of ambient ozone pollution attributable disease burden is based on a literature review exploring long-term ozone exposure and COPD mortality including five cohort studies, followed by MR-BRT risk splines estimation [7, 14].

Analysis

We used GBD estimates for population-weighted exposure, population age structure, deaths, DALYs, YLLs and YLDs attributable to ambient $PM_{2.5}$ and ozone in Italy from 1990 to 2019 [21, 22]. We also obtained GBD estimate for the global population age structure in 2019. For ozone, estimated DALYs corresponded to YLLs, as YLDs were always null, since literature only supported the association with COPD mortality. We downloaded the same measures also for the overall burden of each disease associated with $PM_{2.5}$ and ozone. Crude and age-standardized rates per 100,000 person-years with 95% UI were considered for all estimates. Age-standardized rates were computed through a direct standardization, using GBD 2019 World Standard Population as a reference [23].

The temporal evolution of the burden attributed to ambient $PM_{2.5}$ and ozone pollution from 1990 to 2019 was analyzed both as annual rates and percent variation (95% UI) in rates from

TABLE 1 | Crude and age-standardized rates of disability-adjusted life years (DALYs) due to ambient particulate matter and ozone pollution in 2019. Temporal variation from 1990 to 2010, 2010 to 2019 and from 1990 to 2019 (Global Burden of Disease Study, Italy, 1990–2019).

	Crude DALY rate per 100,000 inhabitants				Age-standardized DALY rate per 100,000 inhabitants			
	Estimate (95% UI) for 2019	Percent variation (95% UI) 1990–2010	Percent variation (95% UI) 2010–2019	Percent variation (95% UI) 1990–2019	Estimate (95% UI) for 2019	Percent variation (95% UI) 1990–2010	Percent variation (95% UI) 2010–2019	Percent variation (95% UI) 1990–2019
Ambient $PM_{2.5}$ pollution								
Total	773.51 (614.49, 944.96)	−35.4 (−56.1, 10.6)	−19.4 (−23.8, −15.8)	−47.9 (−65.4, −10.3)	357.49 (284.57, 435.66)	−51.0 (−66.2, −18.2)	−28.7 (−32.9, −25.4)	−65.1 (−76.4,−41.9)
Sex								
Males	924.49 (734.23, 1122.18)	−37.8 (−57.5, 6.0)	−21.3 (−25.6, −17.6)	−51.0 (−67.3, −16.0)	473.69 (379.03, 574.07)	−52.3 (−67.4, −20.4)	−31.4 (−35.4, −28.0)	−67.3 (−77.8, −45.2)
Females	630.48 (492.28, 781.10)	−31.6 (−53.7, 18.2)	−16.7 (−21.4, −12.7)	−43.0 (−62.2, −1.7)	257.11 (203.30, −315.61)	−49.3 (−65.1, −15.0)	−25.3 (−30.5, −20.9)	−62.1 (−74.3, −37.4)
Age class								
Under 5	149.06 (99.88, 206.60)	−65.1 (−77.2, −47.6)	−38.6 (−61.3, −4.7)	−78.5 (−86.9, −66.9)				
5–14	0.88 (0.53, 1.37)	−71.1 (−83.3, −41.9)	−37.3 (−43.4, −30.4)	−81.9 (−89.6, −63.4)				
15–49	130.68 (101.15, 162.50)	−41.2 (−59.0, −1.5)	−21.0 (−26.9, −15.6)	−53.5 (−68.2, −21.6)				
50–74	568.38 (443.46, 709.92)	−48.3 (−64.9, −10.0)	−30.9 (−34.9, −27.7)	−64.3 (−76.3, −38.6)				
75 plus	1944.78 (1511.85, 2391.02)	−47.2 (−65.1, −5.8)	−29.2 (−32.9, −26.1)	−62.6 (−75.7, −33.3)				
Cause								
Ischemic heart disease	212.66 (166.32, 263.14)	−48.3 (−64.7, −12.1)	−21.9 (−26.2, −18.1)	−59.6 (−73.0, −30.1)	96.18 (76.55, 118.07)	−59.9 (−72.6, −31.7)	−31.3 (−35.1, −28.1)	−72.5 (−81.4, −53.0)
Type 2 diabetes mellitus	173.82 (105.80, 259.13)	29.0 (−6.5, 103.0)	−13.2 (−20.0, −7.4)	11.9 (−21.8, 77.7)	79.15 (48.50, 117.64)	−0.2 (−27.8, 56.6)	−20.6 (−27.0, −15.0)	−20.8 (−44.9, 25.6)
Stroke	146.38 (116.55, 178.93)	−51.4 (−68.4, −12.4)	−21.4 (−25.8, −17.4)	−61.8 (−75.7, −31.9)	64.08 (51.43, 77.88)	−63.2 (−75.8, −33.7)	−30.4 (−34.3, −27.1)	−74.4 (−83.5, −54.4)
Tracheal, bronchus, and lung cancer	130.40 (92.42, 176.52)	−27.3 (−51.6, 24.7)	−22.4 (−27.8, −18.0)	−43.7 (−63.0, −1.1)	61.78 (43.77, 83.57)	−41.9 (−61.2, −0.5)	−30.7 (−35.5, −26.7)	−59.7 (−73.6, −29.8)
Chronic obstructive pulmonary disease	86.06 (57.28, 119.48)	−18.8 (−51.2, 58.3)	−14.8 (−20.1, −9.8)	−30.8 (−59.1, 34.0)	32.79 (22.13, 45.53)	−42.5 (−65.5, 11.6)	−27.7 (−32.2, −23.5)	−58.5 (−75.3, −19.9)
Lower respiratory infections	18.66 (11.06, 28.97)	−40.2 (−65.1, 16.8)	−10.7 (−16.7, −5.5)	−46.6 (−69.2, 5.4)	7.94 (4.77, 12.18)	−63.4 (−78.8, −28.2)	−28.7 (−33.3, −24.8)	−73.9 (−84.7, −49.3)
Neonatal disorders	5.46 (3.57, 7.65)	−63.4 (−77.1, −43.1)	−48.7 (−68.5, −18.2)	−81.2 (−88.6, −70.0)	15.36 (10.04, 21.54)	−61.4 (−75.8, −39.8)	−35.3 (−60.4, 3.1)	−75.0 (−84.8, −60.0)
Ambient ozone pollution[a]								
Total	65.63 (30.31, 101.92)	−37.0 (−44.5, −28.9)	44.8 (35.5, 56.3)	−8.8 (−18.6, 0.4)	23.56 (10.98, 36.79)	−56.8 (−61.8, −51.3)	22.1 (14.5, 31.7)	−47.3 (−52.3, −41.1)
Sex								
Males	83.77 (38.92, 129.07)	−44.6 (−50.9, −37.8)	42.9 (32.3, 55.7)	−20.9 (−28.6, −12.5)	36.02 (16.73, 55.31)	−61.1 (−65.5, −56.3)	15.8 (7.7, 26.3)	−55.0 (−59.1, −50.4)
Females	48.44 (22.56, 76.41)	−18.0 (−29.4, −6.0)	47.8 (35.8, 61.7)	21.2 (2.9, 37.5)	14.82 (6.82, 23.66)	−45.3 (−52.2, −36.1)	26.4 (17.8, 37.9)	−30.9 (−38.4, −20.6)

(Continued on following page)

TABLE 1 | (*Continued*) Crude and age-standardized rates of disability-adjusted life years (DALYs) due to ambient particulate matter and ozone pollution in 2019. Temporal variation from 1990 to 2010, 2010 to 2019 and from 1990 to 2019 (Global Burden of Disease Study, Italy, 1990–2019).

	Crude DALY rate per 100,000 inhabitants				Age-standardized DALY rate per 100,000 inhabitants			
	Estimate (95% UI) for 2019	Percent variation (95% UI) 1990–2010	Percent variation (95% UI) 2010–2019	Percent variation (95% UI) 1990–2019	Estimate (95% UI) for 2019	Percent variation (95% UI) 1990–2010	Percent variation (95% UI) 2010–2019	Percent variation (95% UI) 1990–2019
Age class								
15–49	2.30 (1.06, 3.57)	−45.4 (−53.8, −34.0)	32.0 (19.9, 47.9)	−27.9 (−37.4, −12.2)				
50–74	28.30 (13.22, 44.01)	−62.6 (−67.5, −55.7)	20.7 (11.3, 32.3)	−54.9 (−59.9, −47.1)				
75 plus	251.35 (114.29, 389.58)	−48.4 (−54.7, −42.7)	23.4 (15.1, 33.8)	−36.4 (−43.6, −30.1)				

[a]*The burden of ozone is limited to mortality for chronic obstructive pulmonary disease among people aged 15 and more. UI, uncertainty interval.*

1990 to 2019, 1990 to 2010, 2010 to 2019. This analysis was stratified by age, sex and cause-specific disease burden.

To highlight the contribution of demographic and epidemiologic dynamics in the variation of disease burden attributable to ambient pollution, we first compared time changes of crude and age-standardized rates attributable to ambient $PM_{2.5}$ and ozone pollution, as the discrepancy in the temporal evolution of these two measures is related to population aging. Crude rates depict the real estimated variation based on the age-structure of the Italian population, while age-standardized ones report the expected variation if the population maintained a fixed age-structure equal to that of the global one. Therefore, the decrease observed for age-standardized rates can be interpreted as the expected decrease in the absence of population ageing. Then, we compared time changes in overall diseases burden to that attributable to $PM_{2.5}$ and ozone, through age-standardized rates. These comparisons were carried out both graphically and on percent variations (95% UI) over 1990–2010 and 2010–2019 periods.

RESULTS

The Burden of Ambient Air Pollution in 2019

In 2019, in Italy, ambient $PM_{2.5}$ pollution accounted for 24,700 deaths (95% UI: 19,200, 30,000) and 467,000 DALYs (95% UI: 371,000, 570,000), corresponding to 3.8% (95% UI: 3.0, 4.7) of total deaths, and 2.6% (95% UI: 2.0, 3.2) of total DALYs. The burden attributable to ambient ozone pollution was lower, with 3,490 deaths (95% UI: 1,600, 5,390) and 39,600 DALYs (95% UI: 18,300, 61,500), corresponding to 0.5% (95% UI: 0.3, 0.8) and 0.2% (95% UI: 0.1, 0.3), respectively.

Crude DALY rates per 100,000 inhabitants due to ambient $PM_{2.5}$ amounted to 773.5 (95% UI: 614.5, 945.0). The burden was higher among males (924.5, 95% UI: 734.2, 1122.2) than in females (630.5, 95% UI: 492.3, 781.1). Children aged up to 5 years had higher DALY rates (149.1, 95% UI: 99.9, 206.6) than those aged 5 to 14 (0.9, 95% UI: 0.5, 1.4). Within the following age classes, an increasing trend emerged, reaching a maximum of 1944.8 (95% UI: 1511.9, 2391.0) among people aged 75 or more. The top three conditions associated to $PM_{2.5}$ exposure in relation to DALY rate per 100,000 were IHD, T2DM and stroke (**Table 1**, **Supplementary Tables S1–S3**).

As for ambient ozone pollution, the total crude DALY rate per 100,000 inhabitants was 65.6 (95% UI: 30.3, 101.9), (**Table 1**). The burden was higher among males (83.8, 95% UI: 38.9, 129.1) than in females (48.4, 95% UI: 22.6, 76.4), and it increased with age, starting from 2.3 (95% UI: 1.1, 3.6) among people aged 15–49 and rising to 251.4 (95% UI: 114.3, 389.6) among those aged 75 or more (**Table 1**).

Age-standardized DALY rates were 357.5 (95% UI: 284.6, 435.7) and 23.6 (95% UI: 11.0, 36.8), respectively for ambient $PM_{2.5}$ and ozone. The difference between males and females persisted: estimated DALY rates were respectively 473.7 (95% UI: 379.0, 574.1) and 257.1 (95% UI: 203.3, 315.6) for $PM_{2.5}$, and 36.0 (95% UI: 16.7, 55.3) and 14.8 (95% UI: 6.8, 23.7) for ozone. Furthermore, when stratifying by condition associated with $PM_{2.5}$, the pollutant burden confirmed to be highest for IHD and T2DM (**Table 1**).

A thorough description of mortality, YLLs and YLDs attributable to $PM_{2.5}$ and ozone is reported in **Supplementary Tables S1–S3**. The overall crude mortality rate was 40.9 (95% UI: 31.8, 49.8) per 100,000 inhabitants, while the age-standardized one was 14.8 (95% UI: 11.8, 17.9) (**Supplementary Table S1**). YLLs outweighed YLDs, with age-standardized rates of respectively 269.8 (95% UI: 220.0, 320.5) and 87.7 (95% UI: 56.1, 125.4) (**Supplementary Tables S2, S3**). Differences between sexes were also confirmed for mortality and YLL rates. The distribution among age classes mirrored that observed for DALYs for all other burden measures. Notably, YLDs exceeded YLLs for T2DM, and they represented a consistent share of the total DALYs for COPD and stroke.

Temporal Trends

The population-weighted average concentration of $PM_{2.5}$ decreased from 26.9 μg/m^3 in 1990 to 16.1 μg/m^3 in 2019 (**Supplementary Figure S1**). This was mirrored by a clear decreasing trend in the burden from 1990 to 2019 in terms of crude and age-standardized mortality, DALY and YLL rates,

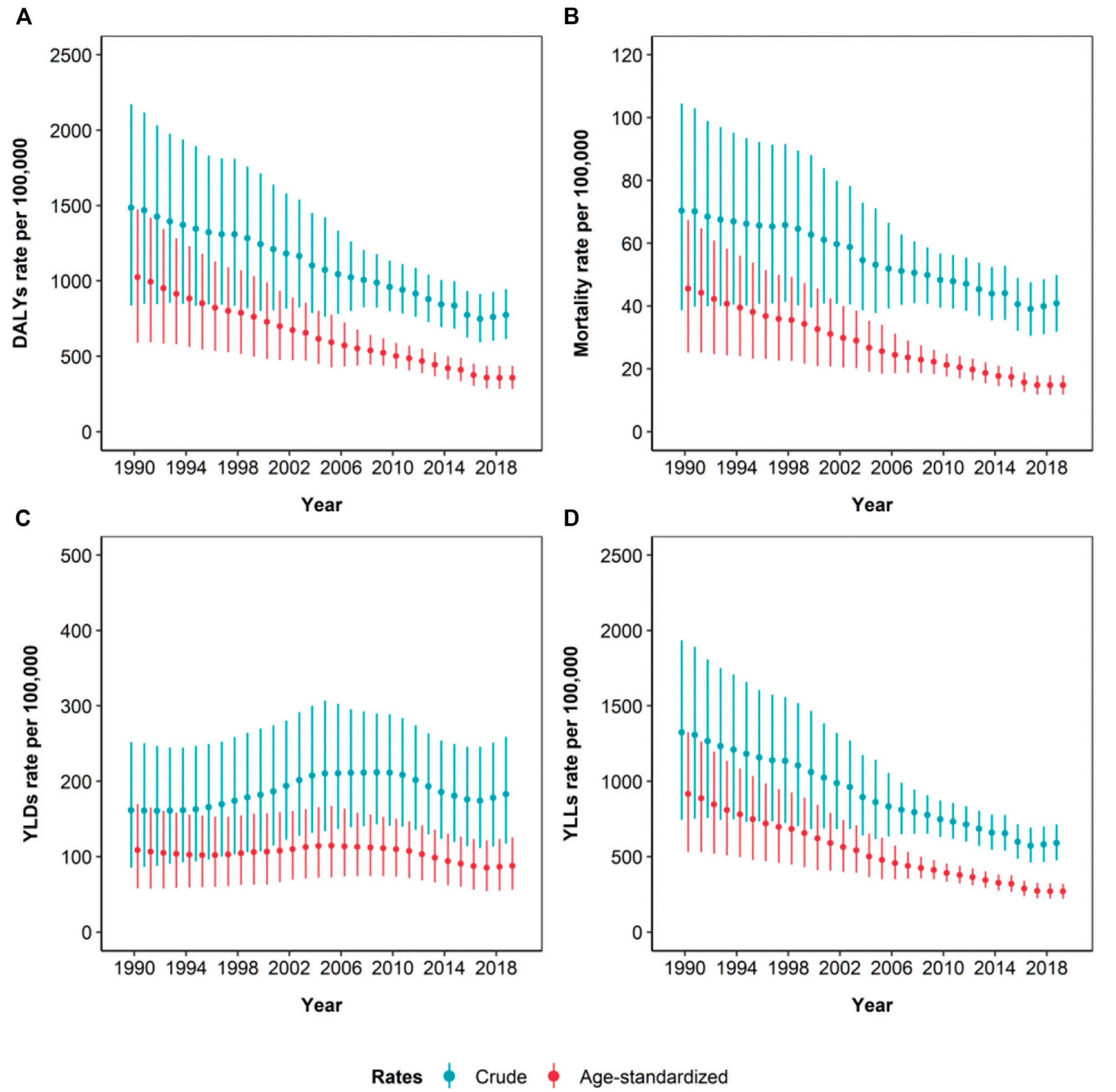

FIGURE 1 | Time-series of the estimated crude and age-standardized rates (per 100,000 inhabitants) of disability adjusted life years (DALYs) **(A)**, mortality **(B)**, years lived in disability (YLDs) **(C)**, and years of life lost (YLLs) **(D)**, due to ambient particulate matter pollution, from 1990 to 2019. Whiskers represent 95% Uncertainty Intervals (Global Burden of Disease Study, Italy, 1990–2019).

while YLD rates showed a rather stable trend (**Figure 1**). However, variations in crude rates were significantly lower than those observed for age-standardized rate. Crude DALY, mortality and YLL rates decreased by 47.9% (95% UI: 10.3, 65.4), 41.9% (95% UI: 3.2, 62.1) and 55.4% (95% UI: 22.6, 70.5), while the corresponding age-standardized rates decreased by 65.1% (95% UI: 41.9, 76.4), 67.5% (95% UI: 43.1, 78.8) and 70.5% (95% UI: 51.1, 80.1) (**Table 1**; **Supplementary Tables S1–S3**). When comparing the periods 1990–2010 and 2010–2019, significant differences in crude and age-standardized rates variations persisted only within the second period (**Table 1**; **Figure 2**). Focusing on DALYs, crude rates declined by 19.4% (95% UI: 15.8, 23.8), while the age-standardized ones decreased by 28.7% (95% UI: 25.4, 32.9). Variations observed for mortality and YLLs were similar to those of DALYs while YLDs showed slightly milder declines (**Table 1**; **Supplementary Tables S1–S3**; **Figure 2**). Focusing on age-specific rates, the decrease appeared to be slightly higher among people aged less than 14 for all the

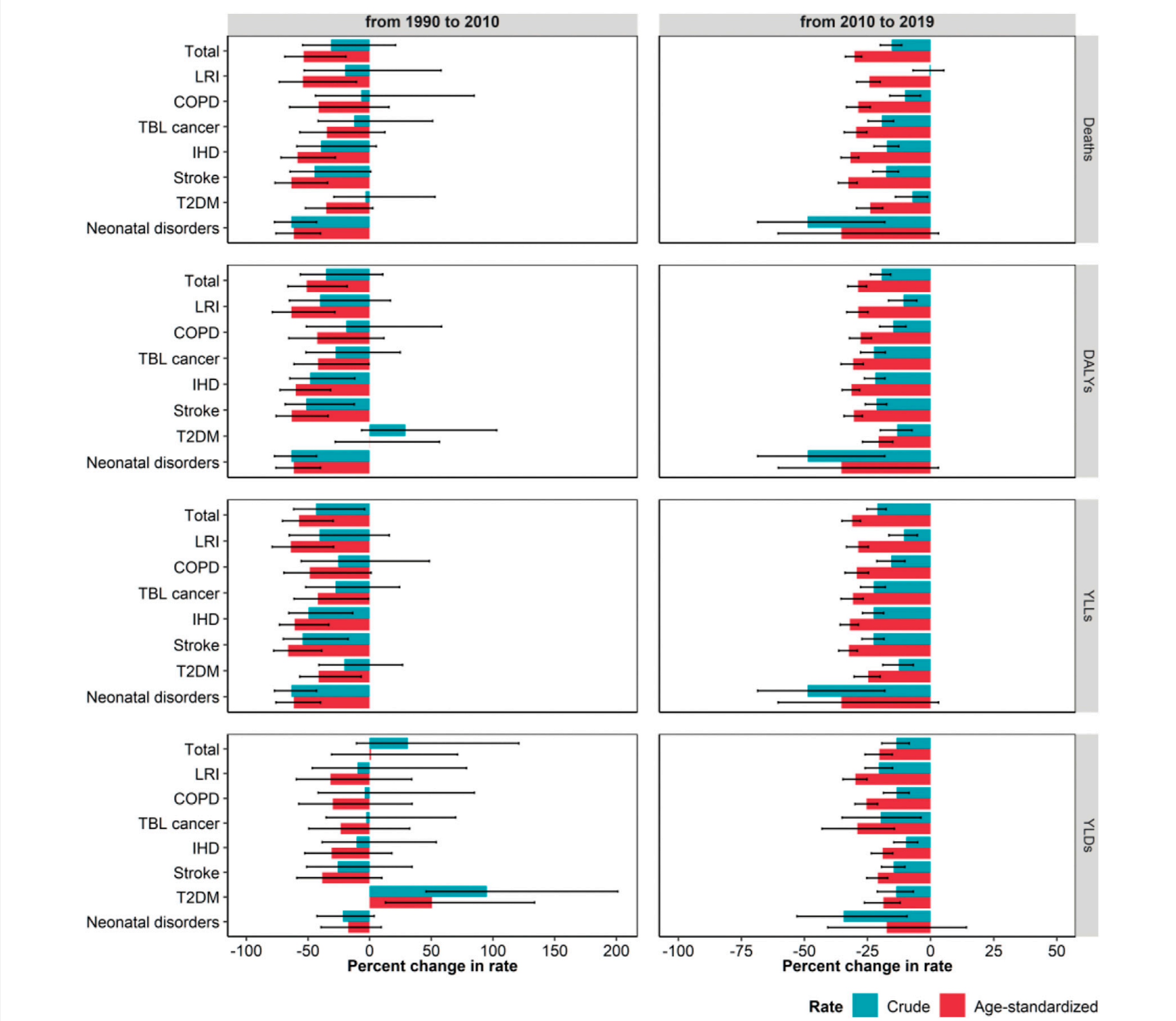

FIGURE 2 | Estimated percent change in crude and age-standardized rates (per 100,000 inhabitants) of mortality (deaths), disability adjusted life years (DALYs), years of life lost (YLLs) and years lived in disability (YLDs) due to ambient particulate matter pollution, from 1990 to 2010 and from 2010 to 2019, stratified by cause. Whiskers represent 95% Uncertainty Intervals. LRI, Lower respiratory infections; COPD, Chronic obstructive pulmonary disease; TBL, Tracheal, bronchus and lung; IHD, Ischemic heart disease; T2DM, Type 2 diabetes mellitus (Global Burden of Disease Study, Italy, 1990–2019).

measures, while the minimum decrease in terms of DALYs was observed for people aged 15–49, due to a 29.5% (95% UI: 25.7, 33.6) decrease in YLL rates that is partially counterbalanced by a 6.8% (95% UI: −5.1, 18.3) increase in YLD rates (**Table 1**; **Supplementary Tables S1–S3**). Crude 2010–2019 DALY rates decrease ranged from 10.7% (95% UI: 5.5, 16.7) for LRI to 48.7% (95% UI: 18.2, 68.5) for neonatal disorders, but when considering age-standardized rates, all decreases were close to 30%, with the exception of T2DM (20.6%, 95% UI: 15.0, 27.0). A similar consideration applied to YLLs, while differences were even more pronounced when considering mortality (**Figure 2** and **Supplementary Tables S1–S3**).

Ambient ozone pollution burden described no clear decline during the whole period 1990–2019. Indeed, crude DALY and mortality rates declined by 37.0% (95% UI: 28.9, 44.5) and 20.6% (95% UI: 11.5, 30.4) during 1990–2010, but they increased by 44.8% (95% UI: 35.5, 56.3) and 52.6% (95% UI: 42.9, 64.8) during the following period. A similar trend was observed for age-standardized rates (**Table 1**; **Supplementary Table S1**; **Figure 3**).

The decrease observed from 1990 to 2010 was more pronounced for age-standardized rates, while in the following period the increase was higher for crude rates (**Figure 4**).

Variations in the burden reflected trends in the population-weighted average ozone concentration, that oscillated from

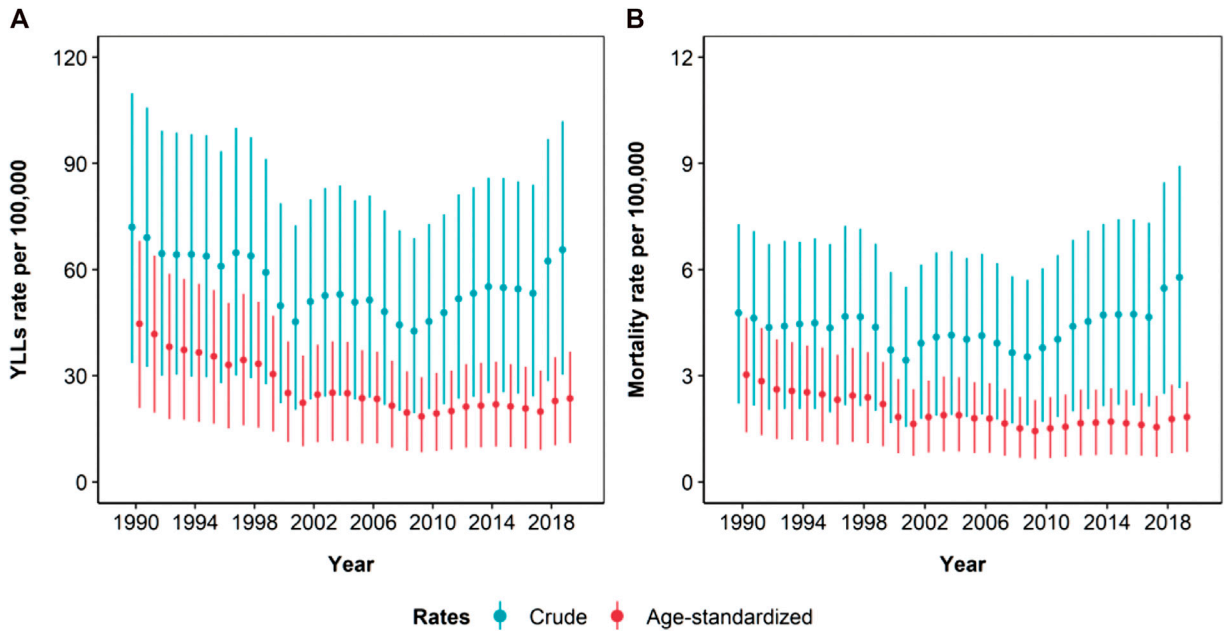

FIGURE 3 | Time-series of the estimated crude and age-standardized rates (per 100,000 inhabitants) of years of life lost (YLLs) **(A)*** and mortality **(B)** due to ambient ozone pollution, from 1990 to 2019. Whiskers represent 95% Uncertainty Intervals (Global Burden of Disease Study, Italy, 1990–2019). *YLLs account for the whole DALYs amount.

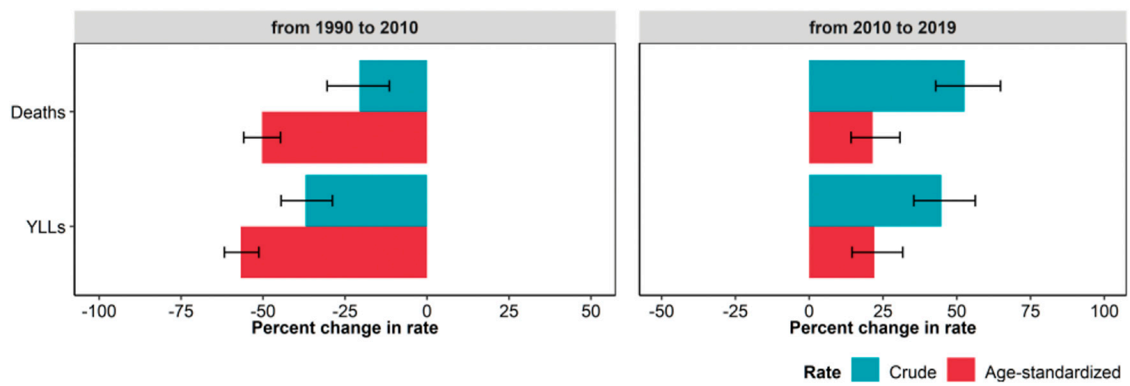

FIGURE 4 | Estimated percent change in crude and age-standardized rates (per 100,000 inhabitants) of mortality (deaths), and years of life lost (YLLs*) due to ambient ozone pollution, from 1990 to 2010 and from 2010 to 2019. Whiskers represent 95% Uncertainty Intervals (Global Burden of Disease Study, Italy, 1990–2019). *The burden of ozone is limited to chronic obstructive pulmonary disease mortality, therefore YLLs account for the whole DALYs amount.

56.6 ppb in 1990 to 48.7 ppb in 2010 to 54.1 ppb in 2019 (**Supplementary Figure S1**).

Understanding the Contribution of Exposure Variation

For all diseases, measures referred to the overall burden but YLDs displayed a significant decline during the study period, especially during 1990–2010, with the exception of T2DM (**Supplementary Figures S2–S8**). Indeed, during that period, reductions in age-standardized DALY rates ranged from 27.7% for COPD (95% UI: 23.0, 30.1) to 54.3% for stroke (95% UI: 52.5, 56.8). YLL and mortality rates showed similar declines, while YLD rates showed moderate declines, and two diseases, namely neonatal and T2DM, faced an increase of respectively 9.1% (95% UI: 0.5, 18.7) and 59.3% (95% UI: 48.5, 71.6) (**Figure 5**; **Supplementary Table S4**). For DALYs, YLLs and mortality, percent reductions were similar for the overall burden and for the burden attributable to ambient $PM_{2.5}$, while the percent reduction in ozone attributable burden was significantly higher than the overall burden of COPD (**Figure 5**).

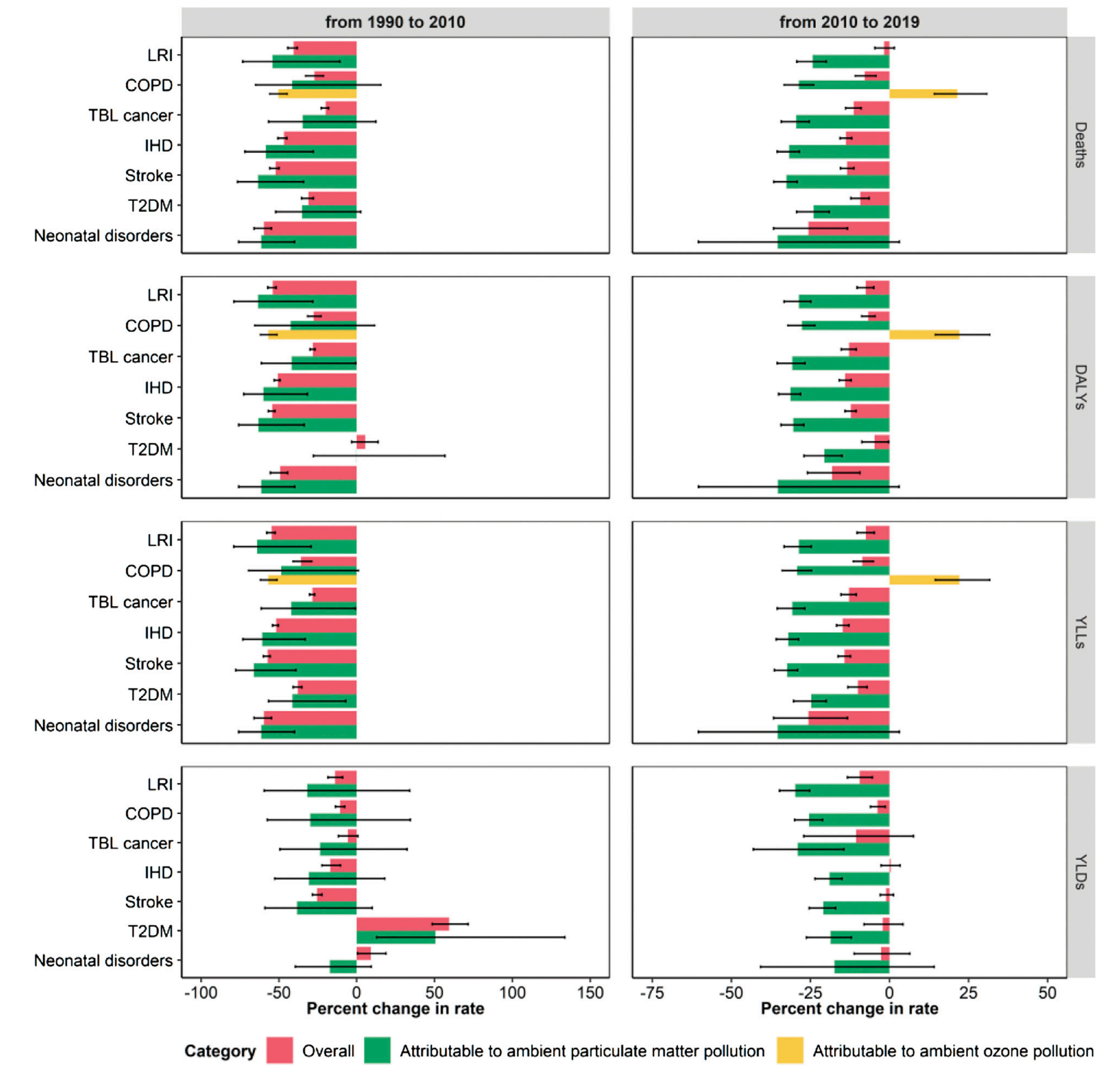

FIGURE 5 | Estimated percent change in age-standardized rates (per 100,000 inhabitants) of mortality (deaths), disability adjusted life years (DALYs), years of life lost (YLLs), and years lived in disability (YLDs) for each cause associated with ambient air pollution. Comparison among overall variations and variations in rates due to ambient particulate matter and ozone pollution, from 1990 to 2010 and from 2010 to 2019. Whiskers represent 95% Uncertainty Intervals (Global Burden of Disease Study, Italy, 1990–2019). LRI, Lower respiratory infections; COPD, Chronic obstructive pulmonary disease; TBL, Tracheal, bronchus and lung; IHD, Ischemic heart disease; T2DM, Type 2 diabetes mellitus.

The temporal dynamic changed during the following period (2010–2019): percent reductions in the overall burden measures were much lower than in the previous period for all the analyzed diseases. In some cases, age-standardized DALY rate reductions were close to 0, as for T2DM (4.7%, 95% UI: 0.2, 8.7), COPD (6.7%, 95% UI: 4.6, 8.8) and LRI (7.5%, 95% UI: 4.9, 10.3) (**Figure 5**; **Supplementary Table S4**). Similar variations were traced for YLLs and mortality rates, while for most of the diseases YLDs did not decrease significantly. Conversely, the disease burden attributable to ambient $PM_{2.5}$ consistently declined and the burden attributable to ambient ozone consistently increased (**Figure 5**).

DISCUSSION

$PM_{2.5}$ and Ozone Attributable Burden in 2019

GBD estimates for Italy in 2019 attribute 466,530 (95% UI: 370,621, 569,934) DALYs to ambient $PM_{2.5}$, which ranked eighth among risk factors of the fourth hierarchical nested level of GBD Study and yielded 24,666 (95% UI: 19,177, 30,047) deaths [24]. Ozone accounted for 39,582 (95% UI: 18,282, 61,469) DALYs, with 3,487 (95% UI: 1,597, 5,385) associated deaths [24].

For both pollutants, and all burden measures (mortality, DALYs, YLLs and YLDs), attributable crude and age-adjusted rates were higher among males than in females, and age-specific rates were higher among children under 14 and in the elderly. The burden of ambient $PM_{2.5}$, in terms of age-standardized DALY rate was unevenly stratified among exposure-related diseases: IHD and T2DM absorbed 50% of the overall burden. The gap detected between males and females is essentially explained by differences in mortality rate for these diseases [23].

The temporal variation in the burden of respiratory diseases (LRI and COPD), TBL cancer, and T2DM is due to the age-associated trends in incidence and mortality, which increase with age [25–27]. For IHD and stroke, the age-related increase comes both from age-related variations in incidence and mortality, and from the use of different exposure-response functions for each 5-year age class. This accounts for higher susceptibility to effects of air pollutants among the elderly [28, 29].

As for ozone, that is so far associated with long-term COPD mortality only, considerations mirror those related to $PM_{2.5}$ and COPD.

Temporal Variation in the Burden of Ambient $PM_{2.5}$

In the period 1990–2019, we identified a clear decreasing trend in $PM_{2.5}$-attributable burden with an overall reduction of 47.9% (95% UI: 10.3, 65.4) of the crude DALY rate. Decreases were confirmed for mortality and YLLs, but not for YLDs. Reductions in age-standardized rates were significantly higher, accounting for 65.1% (95% UI: 41.9, 76.4) in DALY rates. In the period-stratified analysis—i.e., 1990–2010 vs. 2010–2019—a significant difference between crude and age-standardized rates reductions persisted only during the second period, probably owed to the higher precision in estimates, which have narrower uncertainty intervals. These variations parallel reductions in $PM_{2.5}$ concentrations observed after the introduction of key policy interventions, starting from 1988 [30–34]. The 2008 EU directive set a target value for $PM_{2.5}$ of 25 μg/m^3 for long-term concentrations, which was subsequently lowered to 20 μg/m^3 from 1st January 2020 [31–33]. Thereafter, $PM_{2.5}$ concentrations continued to decrease with a percentage reduction of about 37% between 1990 and 2018 [35].

The observed reduction in $PM_{2.5}$ concentrations leads the decreasing trend detected in the related disease burden. However, reduction of exposure is only one of the drivers of the observed trend: temporal changes are also affected by demographic and epidemiologic dynamics of the population [8, 10].

The role of demographic dynamic was analyzed comparing variations of crude and age-standardized rates. The decrease observed for age-standardized rates was significantly higher than that for crude ones, meaning that the increasing proportion of elderly population counteracts the effects of exposure reduction. Worth noting is that the large difference between crude and age-standardized rates is partially explained by the different age structure of the Italian population as compared to the global one used for the standardization: in line with our observations regarding population ageing, the Italian population has a larger elderly fraction throughout the study period (**Supplementary Figure S9**).

We finally considered the role of the epidemiologic dynamic, which is synthesized by temporal variations in the overall burden of diseases associated with $PM_{2.5}$. From 1990 to 2010, the overall mortality, DALY and YLL rates of the diseases of interest decreased significantly, except for T2DM. YLD rates showed a moderate decline, except for neonatal disorders and T2DM. These trends are mainly driven by improvement in case management of those conditions from the 1990s [36]. For instance, the advances in care of cardiovascular diseases and the reductions in their major risk factors, some progresses in diagnosis and management of TBL cancers, as well as novel therapeutic approaches for lower respiratory diseases effectively impacted on patient outcomes and quality of life [37–41]. As regards T2DM, there was an increase of medical check-ups and laboratory tests for early detection of T2DM and systematic glycemic control in the population at risk. Likewise, the use of novel treatments impacted on the prognosis and survival of diabetic patients [42, 43].

Proportional reductions in ambient $PM_{2.5}$ burden closely resembled those of each investigated disease, highlighting that the reduction of $PM_{2.5}$ burden was likely unrelated to a significant decrease in the exposure to the risk factor itself. This reflects the absence of an air quality standard for $PM_{2.5}$, that was enforced only in late 2010 [33]. Thereafter, the overall burden of T2DM, COPD and LRI displayed only moderate reductions, and YLDs remained constant for all diseases except for LRI and COPD. $PM_{2.5}$ burden proportional decrease was significantly higher than the overall one, suggesting that the reduction in exposure concentration had a significant role in decreasing the burden attributable to the pollutant.

If we interpret our results in the framework of an accountability study that aims at evaluating the impact of air quality regulations on public health [44], our results suggest that the national regulations introduced in Italy in 2010, establishing that the average annual concentration of $PM_{2.5}$ should be ≤25 μg/m^3 by 2015 [33], lead to a decrease in the average $PM_{2.5}$ concentration (**Supplementary Figure S1**), that was in turn associated with a decrease in the attributable burden of air pollution-associated diseases between 2010 and 2019. These considerations encourage the enforcement of new and more stringent regulations, in line with the recently issued WHO air quality guidelines, which recommend a yearly target value of 5 μg/m^3 for $PM_{2.5}$ [3]. However, a proper assessment of the future impact of such interventions should carefully account for future population dynamics and their impact on air pollution-associated outcomes [45].

Temporal Variation in the Burden of Ambient Ozone

Temporal dynamics in ozone burden differed across periods: crude and age-standardized DALY rates declined by 37.0% (95% UI: 28.9, 44.5) from 1990 to 2010, but increased by 44.8% (95% UI: 35.5, 56.3) during the following period.

This mirrors the trends in ozone concentrations, that have been increasing since 2009, despite EU Directives 2002/3/EC and 2008/50/EC set a threshold of 120 μg O_3/m^3 as daily maximum 8-h average not to be exceeded for more than 25 times in a year [46, 47].

When comparing the variations of crude and age-standardized DALYs and mortality rates attributable to ozone, crude rates displayed a less pronounced variation. From 1990 to 2010, the decrease in age-standardized burden was close to 50% for both DALYs and mortality, but the decrease in the crude one did not exceed 30%. The increase in age-standardized burden from 2010 to 2019 was close to 25%, but the increase in the crude one exceeded 50%. This confirms the impact of population ageing.

When comparing the variations in the overall age-standardized mortality, DALYs and YLLs of COPD, with those in ozone-attributable burden, we observed a clear indication of a beneficial impact of exposure reduction during the period 1990–2010 and an opposite detrimental effect of exposure increase in the following period. As mentioned, COPD burden was characterized by a significant reduction in both time-windows of interest. During 1990–2010, such reduction was less pronounced than the reduction in ozone-attributable burden. In 2010–2019, we observed that ozone-attributable burden consistently increased, suggesting that ozone concentrations were rising counteracting the mortality decrease.

Strengths and Limitations

GBD estimates provide a unique opportunity to assess how air pollution has changed its impact on the health of the Italian population. Nonetheless, some limitations to our study should be mentioned. First, risk-outcome pairs identified for $PM_{2.5}$ and ozone exclude some diseases for which evidence, although mounting, is still not strong enough, including cardiological conditions (e.g., hypertension) and neurological diseases (e.g., dementia, intellectual disability, hypertension, asthma) [8]. Worth mentioning that a preliminary global analysis on the linkage between exposures to $PM_{2.5}$ and dementia estimated that the highest dementia-related burden attributable to air pollution was found in developed countries with aging population and moderate-to-high levels of $PM_{2.5}$ [48]. Ostro et al. pointed out how GBD estimates are affected by variations in exposure assessment strategies and counterfactual scenarios [49], while Burnett and Cohen described how the choice of the of relative risk functions strongly impacts on the population attributable risk estimation [50]. The magnitude of risk is assumed to depend on $PM_{2.5}$ mass alone, without considering its composition [8, 51]. Furthermore, there is no distinction between sexes, and for respiratory outcomes there is no distinction among age-classes, although susceptibility to air pollution might vary by sex and age [14]. In addition, the choice of TMREL is critical, as it significantly affects the estimated burden [51]: recent results confirm that adverse health effects of $PM_{2.5}$ and ozone persist at levels below the current EU $PM_{2.5}$ limits [52].

Our considerations regarding the significant role of exposure reduction are based on comparisons between estimated variations and their 95% UI, therefore they retain a high level of uncertainty, that would be reduced by carrying out a decomposition analysis, actually quantifying the estimated contributions of trends in mortality and in pollutant concentration [9]. This might be a future development of our analysis. Also, our conclusions regarding the impact of future regulatory efforts should be supported by an accountability study, that allows to infer the causal relationship between interventions and the burden of air pollution [53].

Moreover, estimates of pollutants concentrations were less reliable up to 2005, due to the lack of a monitoring system for $PM_{2.5}$: in Italy the first monitoring stations were introduced in 2005–2006. Finally, methods used to estimate the burden did not consider the huge variations in regional concentrations of air pollutants nor the different demographic and epidemiologic dynamics of the Italian territory.

Conclusion

In Italy, the overall decrease in the estimated burden of ambient $PM_{2.5}$ and ozone between 1990 and 2019 suggests a beneficial effect of air quality regulations. However, while after 2010 these regulations continued to be followed by reductions in $PM_{2.5}$ concentrations, and consequently on its attributable burden, ozone concentration is on the rise. Also, population ageing leads to an increase in susceptible population, which partially counterbalances the beneficial effects of exposure reduction. Air pollution remains a major public health concern, and new regulations are essential to mitigate its future impact. Regulatory efforts should be directed towards improving the quality of the air and protecting health, as well as to tackling climate change, which is closely interlinked with air pollution and, in particular, with ground-level ozone. Likewise, further research focusing on subnational areas and country comparisons is crucial to inform future policies and strategies to mitigate the burden.

DATA AVAILABILITY STATEMENT

Availability of input data varies by source. Select data are available in a public, open-access repository. Select data are available on reasonable request. Select data may be obtained from a third party and are not publicly available. All results from the study are included in the article or uploaded as **Supplementary Material** or are available online.

AUTHOR CONTRIBUTIONS

Providing data or critical feedback on data sources: ALC, GD, PF, GI, and CL. Developing methods or computational machinery: SC, PC, PF, CF, SH, FM, and JV. Providing critical feedback on methods or results: SC, CF, PF, CA, DB, EC, MC, GoC, ALC, BC, PC, GmC, GD, SD, FE, DGo, DGu, SH, GI, CLV, PL, ML, FM, LM, LGM, SM, PP, FS, RS, ET, MVe, JV, and FV. Drafting the work or revising it critically for important intellectual content: SC, CF, PF, CA, LA, IA, FB-A, AB, CB, NB, DB, GaC, MC, GoC, ALC, MSC, AC, PC, GD, BA, FE, SG, DGo, DGu, SH, II, SI, GI, CLV, PL, CL, ML, FM, LGM, PM, LM, SM, PP, UP, NP, GR, FS, SS, BS, MS, ET, BU, MVa, MVe, and FV. Managing the estimation or publications process: PF. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2023.1605959/full#supplementary-material

REFERENCES

1. Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, Cromar K, et al. A Joint ERS/ATS Policy Statement: what Constitutes an Adverse Health Effect of Air Pollution? an Analytical Framework. *Eur Respir J* (2017) 49(1): 1600419. doi:10.1183/13993003.00419-2016
2. World Health Organization. Expert Committee on Environmental Sanitation & World Health Organization. In: Air Pollution: Fifth Report of the Expert Committee on Environmental Sanitation. Geneva, Switzerland: World Health Organization (1958).
3. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva, Switzerland: World Health Organization (2021).
4. World Health Organization – Regional Office for Europe. *Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project: Technical Report*. Copenhagen, Denmark: WHO Europa (2013).
5. European Environment Agency. *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe*. Copenaghen: European Union (2008).
6. United States Environmental Protection Agency. *National Ambient Air Quality Standards* (2020). Available from: https://www.epa.gov/criteria-air-pollutants/naaqs-table (Accessed February 22, 2023).
7. GBD 2019 Risk Factors Collaborators. Global burden of 87 Risk Factors in 204 Countries and Territories, 1990-2019: a Systematic Analysis for the Global Burden of Disease Study 2019. *Lancet* (2020) 396(10258):1223–49. doi:10.1016/S0140-6736(20)30752-2
8. European Environment Agency. *Air Pollution Due to Ozone: Health Impacts and Effects of Climate Change*. European Environment Agency. (2023). Available from: https://www.eea.europa.eu/data-and-maps/indicators/air-pollution-by-ozone-2/assessment (last accessed on Feb 22, 2023).
9. Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, 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. *Lancet* (2017) 389(10082):1907–18. doi:10.1016/S0140-6736(17)30505-6
10. Yin P, Brauer M, Cohen AJ, Wang H, Li J, Burnett RT, 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) 4(9):e386–e98. doi:10.1016/S2542-5196(20)30161-3
11. Istituto Nazionale di Statistica (ISTAT). *Invecchiamento attivo e condizioni di vita degli anziani in Italia*. Roma: ISTAT (2020).
12. Istituto Nazionale di Statistica (ISTAT). *Rapporto annuale 2019: la situazione del Paese*. Roma: ISTAT (2019).
13. EUROSTAT. *Ageing Europe: Looking at the Lives of Older People Inthe EU – 2019 Edition*. Luxembourg: Publications Office of the European Union (2019).
14. Yazdi MD, Wang Y, Di Q, Requia WJ, Wei Y, Shi L, et al. Long-term Effect of Exposure to Lower Concentrations of Air Pollution on Mortality Among US Medicare Participants and Vulnerable Subgroups: a Doubly-Robust Approach. *Lancet Planet Health* (2021) 5(10):e689–e697. doi:10.1016/S2542-5196(21)00204-7
15. Shaffer RM, Sellers SP, Baker MG, de Buen Kalman R, Frostad J, Suter MK, et al. Improving and Expanding Estimates of the Global burden of Disease Due to Environmental Health Risk Factors. *Environ Health Perspect* (2019) 127(10):105001. doi:10.1289/EHP5496
16. Stevens GA, Alkema L, Black RE, Boerma JT, Collins GS, Ezzati M, et al. Guidelines for Accurate and Transparent Health Estimates Reporting: the GATHER Statement. *Lancet* (2016) 388(10062):e19–e23. doi:10.1016/S0140-6736(16)30388-9
17. van Donkelaar A, Martin RV, Brauer M, Hsu NC, Kahn RA, Levy RC, et al. Global Estimates of Fine Particulate Matter Using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors. *Environ Sci Technol* (2016) 50(7):3762–72. doi:10.1021/acs.est.5b05833
18. Istituto Nazionale di Statistica (ISTAT). *Health for All - Italia 2020* (2023). Available from: https://www.istat.it/it/archivio/14562 (last accessed on Feb 22, 2023).
19. Zheng P, Barber R, Sorensen RJD, Murray CJL, Aravkin AY. Trimmed Constrained Mixed Effects Models: Formulations and Algorithms. *J Comput Graphical Stat* (2021) 30(3):544–56. doi:10.1080/10618600.2020.1868303

20. Global Burden of Disease Collaborative Network. *Global Burden of Disease Study 2019 (GBD 2019) Particulate Matter Risk Curves*. Seattle, United States of America: Institute for Health Metrics and Evaluation (2021). doi:10.6069/KHWH-2703
21. Global Burden of Disease Project. *Global Health Data Exchange - GBD Results Tool* (2023). Available from: http://ghdx.healthdata.org/gbd-results-tool (last accessed on Feb 22, 2023).
22. State of Global Air. *State of Global Air* (2020). Available from: https://www.stateofglobalair.org/data/#/air/plot ((last accessed on Mar 8, 2022).
23. GBD 2019 Diseases and Injuries Collaborators. Global burden of 369 Diseases and Injuries in 204 Countries and Territories, 1990-2019: a Systematic Analysis for the Global Burden of Disease Study 2019. *Lancet* (2020) 396(10258):1204–22. doi:10.1016/S0140-6736(20)30925-9
24. Global Burden of Disease Project. *Global Health Data Exchange - GBD Compare* (2023). Available from: https://vizhub.healthdata.org/gbd-compare/ (last accessed on Feb 22, 2023).
25. GBD 2016 Lower Respiratory Infections Collaborators. Estimates of the Global, Regional, and National Morbidity, Mortality, and Aetiologies of Lower Respiratory Infections in 195 Countries, 1990–2016: a Systematic Analysis for the Global Burden of Disease Study 2016. *Lancet Infect Dis* (2018) 18(11):1191–210. doi:10.1016/S1473-3099(18)30310-4
26. Global Burden of Disease Cancer CollaborationFitzmaurice C, Abate D, Abbasi N, Abbastabar H, Abd-Allah F, et al. Global, Regional, and National Cancer Incidence, Mortality, Years of Life Lost, Years Lived with Disability, and Disability-Adjusted Life-Years for 29 Cancer Groups, 1990 to 2017. A Systematic Analysis for the Global Burden of Disease Study. *JAMA Oncol* (2019) 5(12):1749–68. doi:10.1001/jamaoncol.2019.2996
27. Munshi MN, Meneilly GS, Rodríguez-Mañas L, Close KL, Conlin PR, Cukierman-Yaffe T, et al. Diabetes in Ageing: Pathways for Developing the Evidence Base for Clinical Guidance. *Lancet Diabetes Endocrinol* (2020) 8(10): 855–67. doi:10.1016/S2213-8587(20)30230-8
28. Boezen HM, Vonk JM, van der Zee SC, Gerritsen J, Hoek G, Brunekreef B, et al. Susceptibility to Air Pollution in Elderly Males and Females. *Eur Respir J* (2005) 25:1018–24. doi:10.1183/09031936.05.00076104
29. Aga E, Samoli E, Touloumi G, Anderson HR, Cadum E, Forsberg B, et al. Short-term Effects of Ambient Particles on Mortality in the Elderly: Results from 28 Cities in the APHEA2 Project. *Eur Respir J Suppl* (2003) 40:28s–33s. doi:10.1183/09031936.03.00402803
30. European Environment Agency. *Urban PM2.5 Concentrations Presented as Multi-Annual Average in the EU, 2008–2010*. EEA (2012). Available from: https://www.eea.europa.eu/data-and-maps/figures/urban-pm2.5-concentrations-presented-as (last accessed on Feb 22, 2022).
31. Organisation for Economic Co-operation and Development (OECD). *Air Pollution Exposure*. OECD: OECD data (2020). Available from: https://data.oecd.org/air/air-pollution-exposure.htm ((last accessed on Feb 22, 2023).
32. Istituto superiore per la protezione e la ricerca ambientale (ISPRA). *Analisi dei trend dei principali inquinanti atmosferici in Italia (2008 – 2017)*. Roma: ISPRA (2018). Available from: https://www.isprambiente.gov.it/files2019/pubblicazioni/rapporti/R_302_18_TREND_ARIA.pdf ((last accessed on Feb 22, 2023).
33. Gazzetta Ufficiale. *Decreto Legislativo 13 agosto 2010, n.155 "Attuazione della direttiva 2008/50/CE relativa alla qualità dell'aria ambiente e per un'aria più pulita in Europa"* (2010). Gazzetta Ufficiale della Repubblica Italiana n. 216 del 15. Rome: stituto Poligrafico e Zecca dello Stato.
34. Viviano G, Settimo G. Normativa sulla qualità dell'aria e recepimento delle direttive della Unione Europea. *Ann Ist Super Sanità* (2003) 39(3):343–50.
35. Istituto superiore per la protezione e la ricerca ambientale (ISPRA). *Italian Emission Inventory 1990-2018. Informative Inventory Report 2020*. Roma: ISPRA (2020). Available from: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/inventario-nazionale-delle-emissioni-in-atmosfera-1990-2018.-informative-inventory-report-2020 ((last accessed on Feb 22, 2022).
36. GBD 2017 Italy Collaborators. Italy's Health Performance, 1990-2017: Findings from the Global Burden of Disease Study 2017. *Lancet Public Health* (2019) 4(12):e645–e657. doi:10.1016/S2468-2667(19)30189-6
37. Cortesi PA, Fornari C, Madotto F, Conti S, Naghavi M, Bikbov B, et al. Trends in Cardiovascular Diseases burden and Vascular Risk Factors in Italy: The Global Burden of Disease Study 1990-2017. *Eur J Prev Cardiol* (2020) 28: 385–96. doi:10.1177/2047487320949414
38. Palmieri L, Bennett K, Giampaoli S, Capewell S. Explaining the Decrease in Coronary Heart Disease Mortality in Italy between 1980 and 2000. *Am J Public Health* (2010) 100(4):684–92. doi:10.2105/AJPH.2008.147173
39. Santalucia P, Baviera M, Cortesi L, Tettamanti M, Marzona I, Nobili A, et al. Epidemiologic Trends in Hospitalized Ischemic Stroke from 2002 to 2010: Results from a Large Italian Population-Based Study. *J Stroke Cerebrovasc Dis* (2015) 24(8):1917–23. doi:10.1016/j.jstrokecerebrovasdis.2015.05.008
40. Associazione Italiana di Oncologia Medica. *I Numeri del Cancro in Italia 2020*. Milano: AIOM (2020). Available from: https://www.aiom.it/wp-content/uploads/2020/10/2020_Numeri_Cancro-operatori_web.pdf ((last accessed on Feb 22, 2023).
41. Pesce G. Mortality Rates for Chronic Lower Respiratory Diseases in Italy from 1979 to 2010: an Age–Period–Cohort Analysis. *ERJ Open Res* (2016) 2: 00093–2015. doi:10.1183/23120541.00093-2015
42. Istituto nazionale di statistica (ISTAT). *Il Diabete in Italia – Anni 2000-2011*. Rome: ISTAT (2012). Available from: https://www.istat.it/it/files//2012/09/Il-diabete-in-Italia.pdf ((last accessed on Feb 22, 2023).
43. Istituto nazionale di statistica (ISTAT). *Il Diabete in Italia – Anni 2000-2016*. Rome: ISTAT (2017). Available from: https://www.istat.it/it/files/2017/07/REPORT_DIABETE.pdf ((last accessed on Feb 22, 2023).
44. Boogaard H, van Erp AM, Walker KD, Shaikh R. Accountability Studies on Air Pollution and Health: the HEI Experience. *Curr Environ Health Rep* (2017) 4(4):514–22. doi:10.1007/s40572-017-0161-0
45. GBD MAPS Working Group. *Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China. Special Report 20*. Boston, MA: Health Effects Institute (2016).
46. European Environment Agency. *Air Quality in Europe - 2020 Report*. Luxembourg: Publications Office of the European Union (2020).
47. Gazzetta Ufficiale. *Decreto Legislativo 21 Maggio 2004, n. 183 "Attuazione Della Direttiva 2002/3/CE Relativa All'ozono Nell'aria"* (2004). Gazzetta Ufficiale della Repubblica Italiana n. 171 del 23. Rome: stituto Poligrafico e Zecca dello Stato.
48. Ru M, Brauer M, Lamarque JF, Shindell D. Exploration of the Global Burden of Dementia Attributable to PM2.5: What Do We Know Based on Current Evidence? *Geohealth* (2021) 5(5):e2020GH000356. doi:10.1029/2020GH000356
49. Ostro B, Spadaro JV, Gumy S, Mudu P, Awe Y, Forastiere F, et al. Assessing the Recent Estimates of the Global burden of Disease for Ambient Air Pollution: Methodological Changes and Implications for Low- and Middle-Income Countries. *Environ Res* (2018) 166:713–25. doi:10.1016/j.envres.2018.03.001
50. Burnett R, Cohen A. Relative Risk Functions for Estimating Excess Mortality Attributable to Outdoor PM2.5 Air Pollution: Evolution and State-Of-The-Art. *Atmosphere* (2020) 11(6):589. doi:10.3390/atmos11060589
51. Boogaard H, Walker K, Cohen AJ. Air Pollution: the Emergence of a Major Global Health Risk Factor. *Int Health* (2019) 11(6):417–21. doi:10.1093/inthealth/ihz078
52. Di Q, Wang Y, Zanobetti A, Koutrakis P, Choirat C, Dominici F, et al. Air Pollution and Mortality in the Medicare Population. *N Engl J Med* (2017) 376(26):2513–22. doi:10.1056/NEJMoa1702747
53. Zigler CM, Kim C, Choirat C, Hansen JB, Wang Y, Hund L, et al. *Causal Inference Methods for Estimating Long-Term Health Effects of Air Quality Regulations. Research Report 187*. Boston, MA: Health Effects Institute (2016).

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A New Global Air Quality Health Index Based on the WHO Air Quality Guideline Values With Application in Cape Town

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Objectives: This study developed an Air Quality Health Index (AQHI) based on global scientific evidence and applied it to data from Cape Town, South Africa.

Methods: Effect estimates from two global systematic reviews and meta-analyses were used to derive the excess risk (ER) for $PM_{2.5}$, PM_{10}, NO_2, SO_2 and O_3. Single pollutant AQHIs were developed and scaled using the ERs at the WHO 2021 long-term Air Quality Guideline (AQG) values to define the upper level of the “low risk” range. An overall daily AQHI was defined as weighted average of the single AQHIs.

Results: Between 2006 and 2015, 87% of the days posed “moderate to high risk” to Cape Town’s population, mainly due to PM_{10} and NO_2 levels. The seasonal pattern of air quality shows “high risk” occurring mostly during the colder months of July–September.

Conclusion: The AQHI, with its reference to the WHO 2021 long-term AQG provides a global application and can assist countries in communicating risks in relation to their daily air quality.

Keywords: air pollution, air quality guidelines, health effects, globalized air quality health index, air quality regulations

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INTRODUCTION

In 2012, approximately 50 million South Africans (95%) were exposed to harmful concentrations of ambient particulate matter with aerodynamic diameter <2.5 µm ($PM_{2.5}$) and ozone (O_3) with measurements above the national ambient air quality standards (NAAQS) of 10 µg/m^3 and 120 µg/m^3, respectively [1]. In South Africa, the total burden of disease attributable to $PM_{2.5}$ was estimated at 19,507 premature deaths, with 463,028 (95% Uncertainty interval (UI): 273,422–632,937) disability-adjusted life years (DALYs); while 1734 premature deaths due to COPD were attributed to O_3 with 61,130 DALYs (95% UI: 25,634–84,605) [1].

The daily communication of air quality to the public has been in practice since the late nineties with the use of Air Quality Index (AQI) and lately in the early 2000s, the Air Quality Health Index (AQHI).

The AQI is conventionally developed using criteria pollutants of which the short-term average concentrations are compared to the short-term limit values set by the national ambient air quality standards (NAAQS). The pollutant with the highest value relative to its limit value determines the short-term AQI value [2]. This means the AQI is based on reporting the most offending pollutant, while ignoring the "lower levels" of the other pollutants. This is one of the core reasons why the index has received criticism. As countries adopt different NAAQS, air quality indices are not comparable across countries, which is a confusing feature of a tool adopted to communicate the risks related to daily levels of air pollution. In particular, the lowest index values are usually labeled as "green" or "healthy air". Thus, with discrepant AQI scales, the same level of pollution may be communicated as "green" in one city or country but "hazardous" elsewhere. Other limitations of AQIs include their inability to reflect additive or combined effects of multiple pollutants, to capture effects below thresholds and that they are rarely updated when the NAAQS are reviewed or amended [3–5].

In South Africa, the NAAQS of the pollutants are less stringent than those proposed by WHO in 2005 and, thus, far less stringent than the new 2021 WHO air quality guideline (AQG) values. This has major implications on the way South Africa communicates short-term air quality to the public. South Africa's AQI has five bands on a scale of 1–10 indicating "low," "moderate," "high" "very high" and "hazardous" risk levels of air quality [6]. The bands defining "good" air quality or "low" pollution are enormous, with hourly concentration of $PM_{2.5}$, PM_{10}, NO_2, SO_2 and O_3 varying from 0–103 μg/m^3, 0–190 μg/m^3, 0–200 ppb (376 μg/m^3), 0–350 ppb (916.7 μg/m^3) and 0–80 ppb (157 μg/m^3), respectively. Thus, concentrations within these ranges are declared to be "safe" or healthy although they may be far higher than the 2005 WHO Air Quality Guideline values [7]. Therefore, the misclassification of the air quality levels in this index leads to an underestimation of the true risks. In fact, only extreme episodes of unusually high levels of air pollution above NAAQS can be captured, which, in most parts of the country, are rare as seen on the South African Air Quality Information System (SAAQIS) [8].

In contrast, the health-based multipollutant indices commonly known as AQHI have the primary objective of comprehensively accounting for the short-term health effects of multiple air pollutants. The AQHI reflects the overall influence of different mixtures of air pollutants and the presence of effects at low levels of exposure, which by design is a limitation of the AQI. Cairncross et.al. constructed a health-based multipollutant index a decade before South Africa implemented the AQI. They used relative risks for daily mortality from a WHO health impact assessment conducted in Europe to illustrate the method for developing the index [3]. A well-constructed AQHI must have a few attributes as highlighted by Hewings [2]. These involve the inclusion of criteria pollutants and their synergies, expandable for other pollutants and averaging times; comparability among communities; understandability to the public; and usability as an information and alert system.

We add two other criteria that an AQI or AQHI index should fulfill. First, a health oriented index should consistently weigh the health impact of each pollutant. Second, the long-term WHO AQG values rather than the short-term values should be a point of reference to properly reflect the scientific evidence in the interpretation of short-term concentrations. WHO does not consider the short-term AQG values as a "healthy" reference but as a concentration that should not be exceeded more than three times a year. Instead, AQI ignore this statistical definition of short-term limit values but consider these concentrations as "healthy" irrespective of the number of exceedances. This results in the paradox that daily compliance with the short-term guideline values will define air quality as "healthy" although the annual mean may still be far above the long-term WHO AQG value.

In the 2021 WHO AQG update it has been emphasized, that the effect of ambient air pollution on mortality, cardiovascular and respiratory disease hospital admissions can be observed at levels lower than WHO 2005 air quality guidelines and South Africa's NAAQS [9–15], thus, AQG values have been lowered. This calls for a revision of the AQI and we take this as an opportunity to develop a globally generalizable index that addresses the limitations and paradox of current AQI discussed above.

Therefore, this study proposes a revised methodology for the AQI to be of direct relevance for South Africa and beyond. We describe the numeric formulation of the index and its health standardized scaling, which uses the WHO 2021 long-term AQG values as point of reference to define "healthy" air quality. We also propose the translation of the scale into a traffic-color-based scheme (green-yellow–red). Finally, the constructed index is applied to daily air pollution data from Cape Town, 2006–2015.

METHODS

The development of our health-based multiple pollutant index which will be referred to as AQHI for simplicity requires five steps as illustrated in **Figure 1**. Each step is described in more detail in the method section of the **Supplementary Material**. In summary, the numeric formulation of the AQHI starts with using existing epidemiological concentration-response functions (CRF) for four ambient pollutants, generally a relative risk estimate (RR) per unit increase in the ambient concentrations. These RR from large reviews are used for the derivation of the new WHO AQG (2021) [16, 17]. In the second step we used these CRF's to derive the daily excess mortality risks for each of the four pollutants. Third, we scaled the distribution of each pollutant's excess risk (ER) to index values with linear categories from 1 to 10+ in a way that the index value of 3 corresponds to the ER derived for the concentrations where the WHO long-term AQG values are met. Fourth, the overall AQHI is calculated by taking the weighted average of the four index values. In the last step, we

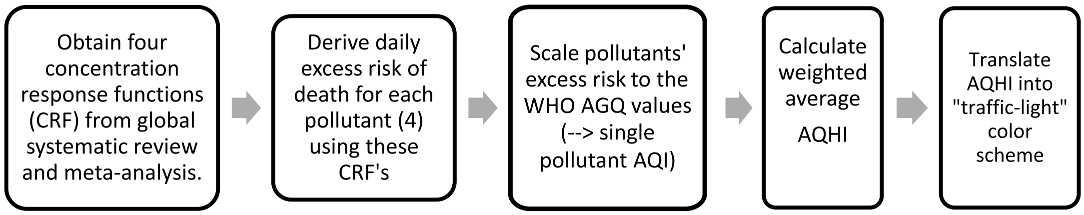

FIGURE 1 | A four-step guide for constructing an Global Air Quality Health Index (AQHI) Cape Town, South Africa 2006 and 2015.

TABLE 1 | Derivation of the weighted average AQHI indices: the single pollutant concentration-response functions (CRF), the related beta coefficient, the chosen WHO AQG reference value, [16, 17] the related daily excess risk (ER) (Eq. **1**). In addition, the daily ER%s of the pollutants ER% per index unit are shown. Thus, by design, the single pollutant index value of 3 corresponds to PM_{10}, NO_2, SO_2 and O_3 concentrations of 15 μg/m^3, 10 μg/m^3, 20 μg/m^3, and 60 μg/m^3, respectively. The weights for the average index value are shown for both, the $PM_{2.5}$ and the PM_{10} based AQHI. Cape Town, South Africa 2006 and 2015.

Pollutant p	CRF published in WHO AQG (per 10 μg/m^3)	Beta coefficient per 1 μg/m^3	WHO AQG reference value [1] in μg/m^3 for index value = 3	ER (%) at index value = 3	Average ER (%) per index unit	Inverse weight for $PM_{2.5}$ based AQHI	Inverse weight for PM_{10} based AQHI
$PM_{2.5}$	1.0065	0.00065	5	0.326	0.109	1	—
PM_{10}	1.0041	0.00041	15	0.617	0.206	—	1
NO_2	1.0072	0.00072	10	0.723	0.241	0.451	0.853
SO_2	1.0059	0.00059	20[2]	1.187	0.396	0.275	0.519
O_3	1.0043	0.00043	60	2.614	0.871	0.125	0.236

categorize the 10 index units into the color scheme of traffic lights where "green" will be up to level 3 of the scale, thus in compliance with the excess risk occurring at concentrations up to the long-term WHO AQG values of each pollutant. Therefore, if concentrations of all pollutants remain on all days within the "green" levels, air quality will also be compliant with the long-term AQG values. Concentrations above the index value of 10 all fall into the unbounded upper category of "10+".

In the last section, we will apply the new AQHI to the time series of Cape Town used in the first step to demonstrate the features of the AQHI and the level of compliance of the past air quality in Cape Town with the proposed index.

Due to the high correlation between PM_{10} and $PM_{2.5}$, and given that some authorities restrict the monitoring of PM to only one fraction, we propose to derive the AQHI with either one of the two size fractions of PM. Thus, each of the two AQHI will include four pollutants, namely the three gaseous pollutants but only one of the two particulate mass fractions. In our case study, we will apply the PM_{10} based AQHI to our 2006–2015 Cape Town data.

The daily ERs were calculated using Eq. **1**, therefore, the excess risk associated with the long-term WHO AQG-value c_i of pollutant i becomes $100\left(e^{\beta_i c_i} - 1\right)$.

$$pollutant\ i\ excess\ risk\ on\ day\ t = 100\left(e^{\beta_i x_i(t)} - 1\right) \qquad (1)$$
$$\beta_i = coeffcient\ per\ 1\,\tfrac{ug}{m3}\,increase\ of\ pollutant\ i, x_i(t) = concentration\ of\ pollutant\ i\ on\ day\ t)$$

We used the ERs associated with an index of 1 (**Table 1**) to define the weights of the pollutant-specific AQHIs in the overall AQHI. For each pollutant i, the weight W_i is defined as the ratio between the ER of PM_{10} (or $PM_{2.5}$) and the ER of the pollutant i. Thus, the weight of PM_{10} (or $PM_{2.5}$) is defined to be 1. The daily average AQHI value is the weighted mean of the index values of the different pollutants using Eq. **2**, rounded to the nearest integer.

$$Weighted\ Average\ AQHI(t) = \frac{1}{\sum W_i}\sum_{i=1\ldots n} W_i * AQHI_i(t) \quad (2)$$
$$where\ n = number\ of\ pollutants\ used\ in\ AQHI, i = pollutant, AQHI_i(t) = derived\ index\ value\ for\ pollutant\ i\ on\ day\ t\ and\ W_i = weight\ of\ AQHI_i(t)$$

Given that monitoring stations may occasionally not be functional, authorities will face the challenge of missing data. We propose a simple imputation in the **Supplementary Material**. Otherwise, the weighted average AQHI may be based on less than four index values.

Using the result from **Table 1** we present the final AQHI in **Table 2** below:

Application of the Proposed Method to Cape Town

In this section we used the daily air pollution monitoring data from Cape Town from 2006–2015 which was aggregated to city level from all available stations and analyzed for previous publications [10, 11]. We described the distribution of daily concentrations of each pollutant and of the daily ER% in this long-term time-series.

In addition, the total daily ER% was translated into the pollutant-specific daily index values. In the last step, we derived the daily weighted average AQHI, based on PM_{10} and the three gaseous pollutants, as described in the Methods.

RESULTS

The daily averages (standard deviation) of PM_{10}, NO_2, SO_2 and O_3 were 30.4 μg/m^3 (13.6 μg/m^3), 17 μg/m^3 (8.8 μg/m^3), 11 μg/m^3 (5.5 μg/m^3) and 33 μg/m^3 (12.3 μg/m^3), respectively. These data have been previously described in detail [10]. The 2021 WHO short-term air quality guideline values were exceeded on 497 (13.6%) days of the 3,652 day study period for PM_{10} (>45 μg/m^3), 501 (13.7%) days for NO_2 (>25 μg/m^3), and 196 (5.4%) days for SO_2 (>40 μg/m^3); however we did not observe any exceedance for Ozone (>100 μg/m^3). The daily concentrations of PM_{10} and NO_2 exceeded the WHO AQG 2021 long-term values on 93% (n = 3,399) and 70% (n = 2,533) of the days of the study period. The daily means of each pollutant during the study period of 2006–2015 are shown in (**Supplementary Figure S2**). Ozone levels after 2010 were below the WHO AQG long-term value while PM_{10} shows a decreasing trend. NO_2 and SO_2 do not show a discernible trend.

The highest average daily excess risk (ER%) was observed for PM_{10} with an ER% of 1.25%, while SO_2 had the lowest ER% with a daily average of 0.6%; NO_2 and O_3 averaged 1.08% and 1.05% respectively. The number of days on which the individual AQHIs were in agreement with the long-term values of the WHO 2021 AQG, i.e. with an AQHI of 1, 2 or 3 and a "green" color code, was 277 (7.58%), 741 (20%), 3,366 (92.17%) and 2,613 (71.55%) for PM_{10}, NO_2, SO_2 and O_3, respectively. The distribution of the individual pollutants and their AQHIs is shown in **Table 3**.

AQHI level 3 indicates PM_{10} exceeds on average the WHO long-term value (15 μg/m^3 vs. 19 μg/m^3) while the means of the other pollutants are below their long-term WHO AQG values. PM10, with the lowest number of missing days (0.2%) and contributing more weight to the combined index, likely compensated for missing measurements of other pollutants.

Figure 2 shows the air quality in Cape Town. The weighted average AQHI for the combination of all four pollutants during the study period of 3,652 days was "low risk" on 482 days (13%), "moderate risk" on 2,565 days (70%) and"high risk" on 605 days (17%). In the first 2 years, there were 6 "low risk" days each and the last year (2015) had the highest number of "low risk" days (123 days, i.e.33%). There appears to be an improvement in air quality when comparing the beginning and the end of the study period, but there was no clear trend, as the number of "low risk" days varied in the intervening years. In addition, the first 3 years had more "moderate-high risk" days between April and September. After 2009, however, the seasonal pattern became more pronounced with "high risk" days occuring mostly in the colder months of June–September. We provide an interactive plot showing the single pollutant AQHIs and the weighted average AQHI for the study period in Cape Town, South Africa 2006 and 2015.

DISCUSSION

This study constructed a globally applicable Air Quality Health index using concentration-response functions (CRF) obtained from recent global systematic reviews on the short-term effects of air pollutants on daily mortality [16, 17]. It is the first index to incorporate the newly published long-term WHO Air Quality Guideline values as a reference point to define "healthy" or "low risk" days. Thus, judgments about daily air quality will not contradict current evidence of health effects occurring at concentrations exceeding the long-term AQG values. Indeed, all AQI currently in use can lead to the paradox that all daily means may be labeled "green" or healthy although the annual mean may substantially exceed the WHO reference values.

TABLE 2 | The constructed AQHI showing the range of excess mortality risk per pollutant, levels of risk and the corresponding health messages. Cape Town, South Africa 2006 and 2015.

	Single pollutant ER% range					Health messages	
AQHI	PM_{10}	NO_2	SO_2	O_3	Risk levels	General population	Susceptible population
1	<0.21	<0.24	<0.4	<0.87	Low risk (AQHI 1–3)	Ideal conditions for regular outdoor activities	Enjoy your usual outdoor activities
2	>0.21–0.42	>0.24–0.48	>0.4–0.8	>0.89–1.74			
3	>0.42–0.63	>0.48–0.72	>0.8–1.2	>1.74–2.61			Follow your doctor's advice for exercise
4	>0.63–0.84	>0.72–0.96	>1.2–1.6	>2.61–3.48	Moderate risk (AQHI 4–6)	No need to modify your usual outdoor activities	If you have heart or breathing problems, and experience symptoms, consider reducing physical exertion outdoors or rescheduling activities to times when the index is lower
5	>0.84–1.05	>0.96–1.20	>1.6–2	>3.48–4.35			Contact your doctor and follow their advice
6	>1.05–1.26	>1.20–1.44	>2–2.4	>4.35–5.22			
7	>1.26–1.47	>1.44–1.68	>2.4–2.8	>5.22–6.09	High risk (AQHI 7–10+)	Consider reducing or rescheduling strenuous outdoor activities to periods when the index is lower, especially if you experience symptoms	Children, the elderly and people with breathing or heart problems should avoid physical exertion outdoors
8	>1.47–1.68	>1.68–1.92	>2.8–3.2	>6.09–6.96			
9	>1.68–1.89	>1.92–2.16	>3.2–3.6	>6.96–7.83			If you have heart or breathing problems, follow your doctor's advice about managing your condition
10+	>1.89–2.10+	>2.16–2.40+	>3.6–4.0+	>7.83–8.70+			

TABLE 3 | Distribution of daily mean (standard deviation) concentration of pollutants and number of days per weighted average-AQHI value in Cape Town for the period from 2006 to 2015 (in total, 3,652 days) Cape Town, South Africa 2006 and 2015.

Single -AQHI	PM_{10}		NO_2		SO_2		O_3	
	μg/m^3	Days	μg/m^3	Days	μg/m^3	Days	μg/m^3	Days
1[3]	—	—	—	—	8.3 (4.7)	3 (0.1%)	—	—
2	15.1 (3.2)	33 (0.9%)	3.9 (1.4)	4 (0.1%)	7.2 (2.9)	30 (0.8%)	30.8 (10.3)	24 (0.7%)
3	19.3 (5.6)	419 (11.4%)	7.2 (2.8)	265 (7.3%)	8.0 (4.1)	398 (10.9%)	32.4 (10.9)	308 (8.4%)
4	22.5 (7.8)	1,015 (27.8%)	11.0 (3.8)	916 (25.1%)	8.9 (4.3)	984 (26.9%)	30.9 (12.6)	715 (19.6%)
5	29.1 (10.2)	954 (26.1%)	15.3 (5.1)	875 (24.0%)	10.0 (4.6)	945 (25.9%)	33.9 (12.5)	720 (19.7%)
6	36.2 (10.9)	602 (16.5%)	18.7 (6.1)	601 (16.5%)	11.5 (5.3)	598 (16.4%)	35.2 (12.3)	440 (12.0%)
7	42.8 (11.3)	345 (9.4%)	24.6 (6.6)	345 (9.4%)	12.6 (4.7)	337 (9.2%)	34.7 (12.4)	249 (6.8%)
8	51.6 (11.0)	241 (6.6%)	32.8 (7.1)	214 (6.6%)	16.6 (6.3)	241 (6.6%)	32.5 (11.4)	181 (5.0%)
9	65.1 (13.2)	37 (1.0%)	41.8 (8.3)	37 (1.0%)	26.8 (5.3)	37 (1.0%)	30.7 (11.3)	35 (1.0%)
Missing	—	9(0.3%)	—	368 (10.1%)	—	79(2.2%)	—	980 (26.8%)

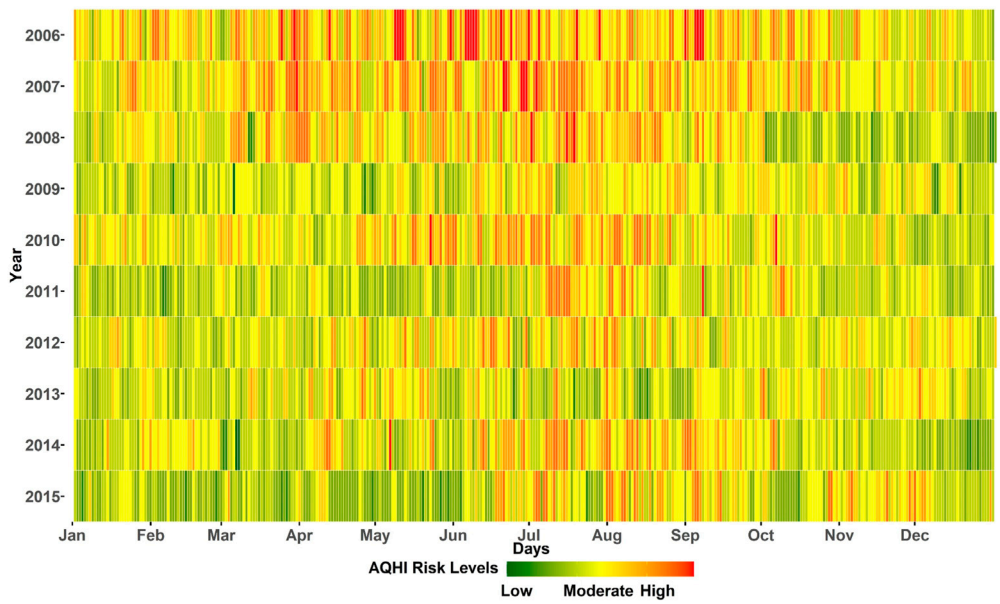

FIGURE 2 | Daily global air quality health index. Colors correspond to the proposed "traffic light categories" of the AQHI. Cape Town, South Africa 2006 and 2015.

Our novel index keeps a methodological similarity with the Canadian AQHI. The latter index was constructed with an assumption of linear, no-threshold associations between the exposure to air pollutants and daily excess mortality. The appropriateness of this approach was also demonstrated in recent systematic reviews, including a particularly large multicity study on particulate matter and daily mortality also used in the derivation of the new WHO AQG values [18].

The application of our index to data from Cape Town showed that the proposed AQHI would qualify 87% of the days in our study period as "moderate" or "high risk". This strongly contradicts the risk levels communicated via the current South African AQI where the past years would mostly be labeled as "good". A large body of literature endorses the revised qualification of Cape Town's air quality. Previous studies of short-term effects of air pollution on cardiorespiratory health in the study area reported that PM_{10} and NO_2 were positively associated with hospital admissions and at levels far below the average daily concentrations observed in Cape Town during the study period. An interquartile range (IQR) increase of 12 μg/m^3 for PM_{10} and 7.3 μg/m^3 for NO_2 were associated with a 2% (95% confidence interval (CI): 0.5%–3.2%) and 2.3% (95% CI: 0.6%–4%) increased risk of respiratory disease hospitalizations, respectively [11]. In addition, the same increment in PM_{10} was associated with a 2.1% increased risk in cardiovascular hospitalization [11]. Another study on CVD and RD mortality showed a 4.5% increased risk of CVD mortality (95% CI: 1.4%–7.6%) for an IQR change of 10.7 μg/m^3 in NO_2. In addition, an IQR change of 16 μg/m^3, 11 μg/m^3, and 16 μg/m^3 in PM_{10}, NO_2 and O_3 was associated with an increased risk of 2.4% (95% CI: 0.9%–2.2%), 2.2% (95% CI: 0.4%–4.1%) and 2.5% (95% CI: 0.2%–4.8%) in RD mortality, respectively [10]. During our study period, the ER% for the average PM_{10} (30.3 μg/m^3) and NO_2 (16.6 μg/m^3) levels would correspond to 1.25 ER% (AQHI 10) and 1.2ER% (AQHI 6) of death, respectively. Thus, it is appropriate to label the air quality to which the population of Cape Town was exposed to as poor rather than as "low risk".

There is no universal method for constructing an AQHI; most authors have developed their index using the methods of Cairncross and Stieb, but the indices differ in the number of pollutants, averaging times and breakpoints for risk classification [3, 5]. Our use of established effect estimates is similar to Cairncross' air pollution index, but these authors used estimates from a European study whereas ours are from a global systematic review. Ideally, an AQHI would communicate the combined effects of the pollution mixture. The approach of Stieb et.al. [5] to develop an AQHI based on multi-pollutant time-series analyses, was indeed an intriguing proposal along these lines. However, the number of multi-pollutant studies is very limited, thus, the derivation of mutually adjusted effect estimates would rely on thin data, usually from high income countries. Moreover, most multipollutant studies evaluated only two-pollutant models whereas mutually adjusted models with three or even all four pollutants used in our AQHI are not available [16]. Thus, we consider our approach based on single-pollutant CRFs as adequate.

Our approach challenges though the derivation of a combined AQHI summary measure. If the four AQHI were based on mutually adjusted CRF's, the sum of the four estimates would be an adequate measure of the overall AQHI. However, the sum of single-pollutant ERs would clearly overestimate the true total ER given the substantial correlation between single pollutants such as PM and NO_2 or SO_2. Without proper knowledge of the degree of overlap it is impossible to properly adjust the sum of single-pollutant based ERs. Thus, to nevertheless integrate information of four pollutants into one single AQHI, we derived a weighted average AQHI. Inevitably, this will underestimate the total risk to the extent that at least part of the effects of single pollutants are additive, i.e. independent of those estimated for the other pollutants. Indeed, for PM and ozone, risk assessors agreed to treat those as independent effects, thus, the Global Burden of Disease integrates the sum of both into the assessment of the total air pollution related burden [19]. Instead for the other three pollutants, combined models are not yet available. In fact, a recent study made valuable first efforts to integrate mutually adjusted risk estimates for two pollutants, namely, $PM_{2.5}$ and NO_2 [20].

As mentioned, a novelty of our AQHI is the full alignment with the WHO AQG values. AQHI values 1 to 3 (green) all comply with daily concentrations up to the long-term mean guideline values. Our method reveals an interesting feature of the AQG values, which plays a key role in the derivation of the overall average index value. As emphasized in the WHO AQG (2021) [9], the Guideline Development Group did not define any "acceptable" health burden to derive the guideline values. Instead the lowest concentration for which effects could be observed with sufficient confidence were taken to define the long-term AQG values. This contrasts with the prevailing risk management concept for carcinogens where "acceptable risks"—e.g., 1 case per 1 Million lives—are defined as "acceptable" policy target [21]. The WHO AQG emphasize also the lack of evidence for any "thresholds of no effect" for the pollutants used in the AQHI, thus, concentration below the guideline values are not considered "healthy" but the shape of the CRF is not yet defined below those levels. If one estimates the excess risk for the concentrations proposed by WHO as the guideline values as compared to zero pollution, one obtains in essence the implicitly defined "acceptable risks" as shown in **Table 1**. Those ER vary substantially across the four pollutants. E.g. the ER% at the limit value of ozone is 4.23 times higher than the ER% at the new guideline value of PM_{10}. In other words, the WHO AQG has the inherent inconsistency of tolerating a much higher health burden due to ozone than due to PM_{10}. Thus, taken at the same index level (e.g. 3), the arithmetic mean of four ER% would be dominated by the burden due to ozone.

As a consequence of the dominance of the ER% scaling of ozone and of the much more likely compliance of ozone with the AQG values the arithmetic mean of the four index values would often mask "high risk" days of PM_{10} (and NO_2) as "low risk" days. Such bias jeopardizes the intention of the AQHI, namely to coherently communicate the daily health risks due to air pollution. Thus, instead of using the arithmetic mean we derive the weighted mean AQHI using the inverses of the ER % at the WHO AQG reference values as the weights. As shown in **Table 3**, as a consequence of this weighting, the measured concentrations of the four pollutants are mostly below the long-term AQG values on days when the derived overall AQHI results at level 1, 2 or 3. However, in case of PM10 the long-term AQG value is exceeded on 296 days (8%) of the study period partly due to its weight.

Our proposal for a globally adopted AQHI is an innovative approach as it offers a fresh perspective on the long-standing issues of AQIs. It fully standardizes the science based communication of risk levels irrespective of the local policies and pollution. It endorses the "right to know" on a global scale, in an equitable manner. On the other side, it forces authorities in regions with very high levels of air pollution to label air quality on most if not all days as "red" or "high risk." Globally harmonized AQHI facilitate the comparison of air quality across geographical locations (within or between countries). A standardized index could provide additional value in tracking air quality trends over time, which can help authorities to evaluate their efforts and policies to achieve clean air.

For the reporting of the AQHI, authorities may adopt various approaches. The index could be reported for each monitoring station or for the mean values of each pollutant across all stations of a geographical location. Such regional mean AQHI could also help to reduce exposure misclassification as people are exposed at different levels of air pollution as they move within the region (e.g. for work). Authorities may also opt for the reporting of all four single-pollutant AQHI and the related weighted average. This would transparently disclose problematic pollutants. However, for the users of the AQHI, it may be confusing to deal with five different values. Thus, the reporting of the weighted average AQHI might be the preferable choice. In addition, sensitivity analysis of PM_{10}-and $PM_{2.5}$-based indices and simple imputation for missing pollutants are discussed in the **Supplementary Material**.

We propose to replace currently used AQI with our new scheme. The communication messages of current AQI are, however, still adequate (see **Table 2**). As shown in the literature [5], the communication of AQI values and related health information assists the general population to keep track of the air quality and possibly subscribe to receiving notifications for when the risk level exceeds a certain threshold, e.g., when it goes beyond green for people at risk. A study in Canada showed that air quality alert programs led to a 25% (95%CI 1%–47%) reduction in asthma-related emergency department visits [22]. Another study in Chile, reported a reduction in deaths among the elderly (age >64 years) following the announcement of above-average pollution episodes; the Chilean authorities accompanied their announcements with mandatory measures such as driving restrictions to reduce car emissions, shutting down of certain large stationary emitters, and other protocols, which resulted in a further 20% reduction in air pollution compared to days without alerts [23]. This shows that mandatory measures, such as those implemented in Chile, could be more effective in reducing pollution and protecting human health if accompanied by air quality alert at a certain threshold—for example, when the AQHI risk level approaches "high risk." We recognize though, that making people aware of their air quality and the associated risks may not be sufficient to change their behaviour. At the very least, it could help susceptible people to self-calibrate if they understand the levels of the index at which they experience symptoms and discomfort.

Conclusion

This study has constructed a global air quality health index as an effective tool for communicating air quality to the public on a daily basis. The alignment of our index scale with the science based excess risks attributable to the daily concentrations of the four pollutants used in our index guarantees global comparability of local air quality levels and fosters a coherent understanding of the related health effects. This, in turn, may foster public support for the adoption of stringent clean air policies.

AUTHOR CONTRIBUTIONS

Conceptualization TA-O, JW, and NK; Methodology TA-O and NK; Data collection, TA-O and JW; Analysis TA-O and NK; Writing TA-O; all authors including OA, CS, and NP-H contributed and reviewed the article prior to submission. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2023.1606349/full#supplementary-material

REFERENCES

1. Roomaney RA, Cairncross E, Tesfaye M, Kapwata T, Abdelatif N, Olivier C, et al. Estimating the Burden of Disease Attributable to Ambient Air Pollution (Ambient PM2.5 and Ambient Ozone) in South Africa for 2000, 2006 and 2012. *South Afr Med J* (2022) 112(8B):705–17. doi:10.7196/SAMJ.2022.v112i8b.16483
2. Hewings J. *Air Quality Indices: A Review*. Toronto, ON: Pollution Probe Foundation (2001).
3. Cairncross EK, John J, Zunckel M. A Novel Air Pollution Index Based on the Relative Risk of Daily Mortality Associated With Short-Term Exposure to Common Air Pollutants. *Atmos Environ* (2007) 41(38):8442–54. doi:10.1016/j.atmosenv.2007.07.003
4. Perlmutt LD, Cromar KR. Comparing Associations of Respiratory Risk for the EPA Air Quality Index and Health-Based Air Quality Indices. *Atmos Environ* (2019) 202:1–7. doi:10.1016/j.atmosenv.2019.01.011
5. Stieb DM, Burnett RT, Smith-Doiron M, Brion O, Shin HH, Economou V. A New Multipollutant, No-Threshold Air Quality Health Index Based on Short-Term Associations Observed in Daily Time-Series Analyses. *J Air Waste Manag Assoc* (2008) 58(3):435–50. doi:10.3155/1047-3289.58.3.435
6. Gwaze P, Mashele SH. South African Air Quality Information System (SAAQIS) Mobile Application Tool: Bringing Real Time State of Air Quality to South Africans. *Clean Air J* (2018) 28(1):3. doi:10.17159/2410-972x/2018/v28n1a1
7. World Health Organization. *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005: Summary of Risk Assessment*. Geneva: World Health Organization (2006).
8. South African Air Quality Information System. *Air Quality Index Map* (2022). Available From: https://saaqis.environment.gov.za/ (Accessed September 28, 2022).
9. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization (2021).
10. Adebayo-Ojo TC, Wichmann J, Arowosegbe OO, Probst-Hensch N, Schindler C, Künzli N. Short-Term Effects of PM(10), NO(2), SO(2) and O(3) on Cardio-Respiratory Mortality in Cape Town, South Africa, 2006-2015. *Int J Environ Res Public Health* (2022) 19(13):8078. doi:10.3390/ijerph19138078
11. Adebayo-Ojo TC, Wichmann J, Arowosegbe OO, Probst-Hensch N, Schindler C, Künzli N. Short-Term Joint Effects of PM(10), NO(2) and SO(2) on Cardio-Respiratory Disease Hospital Admissions in Cape Town, South Africa. *Int J Environ Res Public Health* (2022) 19(1):495. doi:10.3390/ijerph19010495
12. Wichmann J, Voyi K. Ambient Air Pollution Exposure and Respiratory, Cardiovascular and Cerebrovascular Mortality in Cape Town, South Africa: 2001-2006. *Int J Environ Res Public Health* (2012) 9(11):3978–4016. doi:10.3390/ijerph9113978
13. Lokotola CL, Wright CY, Wichmann J. Temperature as a Modifier of the Effects of Air Pollution on Cardiovascular Disease Hospital Admissions in Cape Town, South Africa. *Environ Sci Pollut Res Int* (2020) 27(14):16677–85. doi:10.1007/s11356-020-07938-7
14. Thabethe NDL, Voyi K, Wichmann J. Association Between Ambient Air Pollution and Cause-Specific Mortality in Cape Town, Durban, and Johannesburg, South Africa: Any Susceptible Groups? *Environ Sci Pollut Res* (2021) 28:42868–76. doi:10.1007/s11356-021-13778-w
15. Olutola BG, Wichmann J. Does Apparent Temperature Modify the Effects of Air Pollution on Respiratory Disease Hospital Admissions in an Industrial

Area of South Africa? *Clean Air J* (2021) 31(2):1–11. doi:10.17159/caj/2021/31/2.11366
16. Orellano P, Reynoso J, Quaranta N, Bardach A, Ciapponi A. Short-Term Exposure to Particulate Matter (PM10 and PM2.5), Nitrogen Dioxide (NO2), and Ozone (O3) and All-Cause and Cause-Specific Mortality: Systematic Review and Meta-Analysis. *Environ Int* (2020) 142:105876. doi:10.1016/j.envint.2020.105876
17. Orellano P, Reynoso J, Quaranta N. Short-Term Exposure to Sulphur Dioxide (SO(2)) and All-Cause and Respiratory Mortality: A Systematic Review and Meta-Analysis. *Environ Int* (2021) 150:106434. doi:10.1016/j.envint.2021.106434
18. Liu C, Chen R, Sera F, Vicedo-Cabrera AM, Guo Y, Tong S, et al. Ambient Particulate Air Pollution and Daily Mortality in 652 Cities. *N Engl J Med* (2019) 381(8):705–15. doi:10.1056/NEJMoa1817364
19. GBD 2019 Risk Factors Collaborators. Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990-2019: A Systematic Analysis for the Global Burden of Disease Study 2019. *Lancet (London, England)* (2020) 396(10258): 1223–49. doi:10.1016/S0140-6736(20)30752-2
20. Castro A, Künzli N, de Hoogh K, Kappeler R, Kutlar Joss M, Vienneau D, et al. Mortality Attributable to Ambient Fine Particulate Matter and Nitrogen Dioxide in Switzerland in 2019: Use of Two-Pollutant Effect Estimates. *Environ Res* (2023) 231:116029. doi:10.1016/j.envres.2023.116029
21. Castro A, Götschi T, Achermann B, Baltensperger U, Buchmann B, Felber Dietrich D, et al. Comparing the Lung Cancer Burden of Ambient Particulate Matter Using Scenarios of Air Quality Standards Versus Acceptable Risk Levels. *Int J Public Health* (2020) 65(2):139–48. doi:10.1007/s00038-019-01324-y
22. Chen H, Li Q, Kaufman JS, Wang J, Copes R, Su Y, et al. Effect of Air Quality Alerts on Human Health: A Regression Discontinuity Analysis in Toronto, Canada. *Lancet Planet Health* (2018) 2(1):e19–e26. doi:10.1016/S2542-5196(17)30185-7
23. Mullins J, Bharadwaj P. Effects of Short-Term Measures to Curb Air Pollution: Evidence From Santiago, Chile. *Am J Agric Econ* (2015) 97(4):1107–34. doi:10.1093/ajae/aau081

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Urgent Call to Ensure Clean Air For All in Europe, Fight Health Inequalities and Oppose Delays in Action

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INTRODUCTION

As part of the Green Deal, the European Union's (EU) ambitious plan to be the first climate neutral continent by 2050, EU launched the Zero Pollution Action Plan in 2021. One of the key elements of this plan is an update of the current air quality legislation, the EU Ambient Air Quality Directive (AAQD) with air pollution limit values of 25 μg/m^3 for particulate matter with diameter <2.5 μm ($PM_{2.5}$) and 40 μg/m^3 for nitrogen dioxide (NO_2). The need for a revision became clearer upon release of the World Health Organization Air Quality Guidelines (WHO AQG) in 2021, which recommends limit values (annual mean) of 5 μg/m^3 for $PM_{2.5}$ and 10 μg/m^3 for NO_2, based on a comprehensive global review of the key scientific evidence on health effects of ambient air pollution [1]. The difference between these values exposes the large gap between science-based standards aimed at protecting health and the current, outdated EU AAQD.

The health community position is clear: follow the science and fully align the new EU limit values with the WHO AQD by 2030. This is a historic opportunity towards clean air in Europe for all that could prevent hundreds of thousands of premature deaths and millions of new cases of non-communicable diseases (NCDs) every year [2], as well as improve health of all European citizens. Full alignment with WHO AQG would enhance children health in Europe by improving lung function [3] and reducing asthma and respiratory infections burden. Achieving the WHO AQG would also reduce healthcare costs, social, environmental and health inequalities, boost economic growth, and help mitigate the adverse effects of climate change [4].

In October 2022 the European Commission presented its proposal for a revised AAQD with limit values of 10 ug/m^3 for $PM_{2.5}$ and 20 μg/m^3 for NO_2 to be met by 2030. While the Commission's proposal is an important step in the right direction, it provided no clear pathway on full alignement with WHO AQG [5]. In September 2023, the European Parliament went a step further, and voted to adopt the WHO AQGs with full implementation by 2035. Parliament's historical vote to endorse science-based air quality standards was applauded for by the health community. However, in November 2023, the European Council adopted its negotiating mandate (the Council version of the AAQD proposal), which endorsed the Commission proposal, leaving out full alignment with WHO AQGs. Furthermore, the Council proposed another serious relaxation of the AAQD ambition, allowing delays in achieving limit values up to the 2040 for countries whose gross domestic product (GDP) *per capita* is below EU average, 17 of 27 EU countries, mainly in Eastern Europe and Italy [6].

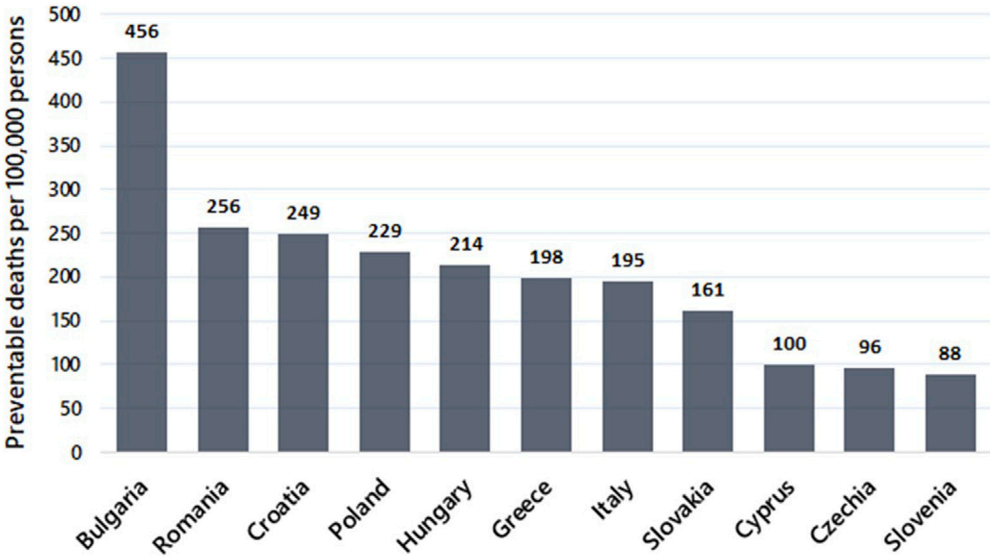

FIGURE 1 | Number of preventable premature deaths (per 100,000 persons) for avoiding a 10-year delay in reaching a $PM_{2.5}$ target concentration of 10 μg/m^3 in Member States with a mean population-weighted $PM_{2.5}$ exposure above 10 μg/m^3 in 2020.

The delay in cleaning up air pollution would widen the social, economic and health inequality between East and West. The Council's proposal also allows for a ten-year delay for all countries that could demonstrate that they will not reach the limit values by 2030.

Currently (January 2024), the European Council, Parliament, and Commission are engaged in trilateral discussions of the revision of the AAQD. The lack of pathway to full alignment with WHO AQGs and potential delays are of great concern to the health professional's community, patients, and general public.

DELAYS MEAN LOST LIVES AND POOR HEALTH

$PM_{2.5}$ caused 432,000 premature deaths in Europe in 2021, of which 253,000 were at levels above the recommended WHO AQG of 5 μg/m^3 [2]. These numbers are likely underestimated, as newest research from Europe points at even stronger impacts of air pollution on mortality. Furthermore, there are millions of air pollution-related new cases of asthma, chronic obstructive respiratory diseases (COPD), acute respiratory infections, lung cancer, stroke, myocardial infarction, hypertension, diabetes, dementia and mental health disorders, as well as aggravations of these diseases in already ill persons each year.

Delays in cleaning up the air in Europe are highly problematic, as they would result in preventable loss of life and exacerbate inequities across Europe. For example, for EU Member States with a mean population-weighted $PM_{2.5}$ exposure above 10 μg/m^3 in 2020 [7], a 10-year delay in reaching 10 μg/m^3 (i.e. 2040 instead of 2030) would result in an excess of 327,600 premature deaths. This calculation assumes a linear decrease of $PM_{2.5}$ levels from 2020 to 10 μg/m^3 in either 2030 or 2040 and uses the relative risk estimate from the meta-analyses on $PM_{2.5}$ and all-cause mortality WHO [8]. It is notable that two-thirds of the preventable health burden affects the poorer countries in Eastern Europe, and about one-third in Italy (**Figure 1**). These numbers make it clear that allowing delays will impose a substantial, unjust, and unacceptable loss of human lives in Europe. It is important to stress that delays will mean failure to protect those who are most susceptible to harmful effects of air pollution: children, pregnant women, elderly, already sick, and people in low socio-economic groups.

DELAYS WILL WIDEN THE INEQUALITY GAP BETWEEN EAST AND WEST EUROPE

The proposed delay by the Council would mean that by 2030, residents of the 11 most affluent EU states could legally demand to be protected from the dangers of air pollution, while over 240 million people in 17 lower-income EU countries would still be exposed to harmful air pollution for another 10 years [6]. Eastern European countries are those that have the highest levels of air pollution and related health costs in Europe. The emissions come from coal-based energy production and outdated industry sectors, followed by use of wood and coal for residential heating and cooking, and old vehicle fleets [9]. Council proposal would increase these inequalities. Using poverty as an excuse to fail to act, is the exact opposite of what these countries need. It would be more beneficial for health with a fair and clear legislative framework and financial support targeted to accelerate (and not delay) urgently needed clean air actions and policies in all relevant sectors. This would allow the EU citizens from the most affected countries to catch up with in reaching clean air targets and enjoy health benefits as citizens of Western Europe. There are currently EUR 147 billion, or 8.3% of the multiannual financial framework for the 2021–2027 period of the EU budget dedicated to the clean air objective [10].

DELAYS ON URGENT ACTION ON AIR POLLUTION MEAN DELAYS IN ADDITIONAL HEALTH BENEFITS

As the healthcare systems around Europe struggle with increasing costs related to ageing and multi-morbidities, saving costs by preventing air pollution related NCDs and enhancing healthy ageing, is an opportunity that must not be missed. Finally, strict air pollution policies and initiatives would provide additional health co-benefits by enhancing physical activity (e.g., supporting a shift to active travel such as cycling, walking, and public transport in cities), reducing road traffic noise, increasing greening of the cities, and help mitigate climate change impacts on our societies and our health.

CONCLUSION

Trialogue negotiations between the EU Council, Commission and Parliament have started. A deal must soon be reached. We strongly urge the EU environment ministers to put European health and environmental justice at the core of their political aspirations. This is a unique public health opportunity for EU Member States to follow the scientific evidence and listen to the concerns of citizens.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

REFERENCES

1. World Health Organization. *WHO Global Air Quality Guidelines. Particulate Matter (PM 2.5 and PM 10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: WHO (2021). Contract No.: ISBN: 9789240034228.
2. EEA. *Harm to Human Health From Air Pollution in Europe: Burden of Disease 2023*. Copenhagen: EEA (2023). Report No.: 2467-3196.
3. Yu Z, Merid SK, Bellander T, Bergström A, Eneroth K, Georgelis A, et al. Associations of Improved Air Quality With Lung Function Growth From Childhood to Adulthood: The BAMSE Study. *Eur Respir J* (2023) 61(5): 2201783. doi:10.1183/13993003.01783-2022
4. Turner MC, Andersen ZJ, Neira M, Krzyzanowski M, Malmqvist E, González Ortiz A, et al. Clean Air in Europe for All! Taking Stock of the Proposed Revision to the Ambient Air Quality Directives: A Joint ERS, HEI and ISEE Workshop Report. *Eur Respir J* (2023) 62(4):2301380. doi:10.1183/13993003.01380-2023
5. Boogaard H, Andersen ZJ, Brunekreef B, Forastiere F, Forsberg B, Hoek G, et al. Clean Air in Europe for All: A Call for More Ambitious Action. *Environ Epidemiol* (2023) 7(2):e245. doi:10.1097/EE9.0000000000000245
6. EU. *Eurostat* (2024). Available from: https://ec.europa.eu/eurostat/databrowser/view/sdg_08_10/default/table (Accessed December 2, 2023).
7. EEA. *Air Quality in Europe 2022*. Copenhagen, Denmark (2022). Report No.: 05/2022.
8. Chen J, Hoek G. Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis. *Environ Int* (2020) 143:105974. doi:10.1016/j.envint.2020.105974
9. Health Effects Institute. *Trends in Air Quality and Health in Southeast Europe*. Boston, USA (2022).
10. European Commission. *Clean-Air Tracking* (2023). Available from: https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/horizontal-priorities/green-budgeting/clean-air-tracking_en#:~:text=Projected%20clean%20air%20contribution%20from%202021%20to%202027multiannual%20financial%20framework%2C%20to%20the%20clean%20air%20objective (Accessed December 2, 2023).

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Urgent Call to Ensure Clean Air in South Asia – A Growing But Neglected Public Health Emergency

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INTRODUCTION

Across its eight countries, South Asia is home to one-fourth of the world's population. The expansion of this highly populated area is being pursued at the expense of the health and welfare of its residents, particularly the most vulnerable, due to environmental degradation. Globally air pollution is thought to be the primary cause of increased morbidity and death from cardiorespiratory disorders [1]. In south Asia, the scenario is devastating, where 29 out of 30 most polluted cities are from Bangladesh, India, and Pakistan [2]. As a results, the World Meteorological Organization has issued a "red alert" for Bangladesh, India, and Pakistan about global warming indicators [3]. The risk to the lives and health of over a billion people is demonstrated by the extended exposure to harmful air quality in various parts of this regions [3]. Due to several factors, such as home and place of employment, larger populations, high exposures, and increasing numbers of people affected by chronic diseases, people in lower socioeconomic classes in South Asia are more vulnerable to the negative effects of air pollution exposure [4]. In every nation in South Asia, air pollution is a major problem. However, the fact that things are deteriorating and weakening from the inside is frequently overlooked.

Despite being a worldwide issue, air pollution disproportionately affects people in developing countries, especially the most vulnerable groups like women, children, and the elderly [5]. In South Asia, air pollution is the second most significant risk factor for negative health consequences [5]. Rapid urbanization and industrialization are key factors behind the substantially higher air pollution levels, including particulate matter (PM) concentration, in developing countries compared to developed ones [6]. In 2019, less than 1% of the global population resided in areas that complied with the air quality guidelines 2021 of the World Health Organization (WHO) [7]. According to the guideline, the annual mean $PM_{2.5}$ concentration for clean air quality should be at or below 5 μg/m^3 and NO_2 level should be at or below 10 μg/m^3 [8]. But in South Asian countries, the values are extremely higher than the normal level as presented in **Figure 1**. As a most polluted country in the region, Bangladesh had almost 80 μg/m^3 $PM_{2.5}$ annual mean concentrations which are 16 times higher than the standard average suggested by the WHO Air Quality Guidelines (AQG) and conversely Maldives a sea girt country accounts for more than 15 μg/m^3 $PM_{2.5}$ annual mean concentration (**Figure 1**).

Recent studies and extensive research programs repeatedly demonstrate that the negative impacts of air pollution are not restricted to high levels of exposure. Detrimental health consequences can occur even at extremely low concentrations of pollutants [9]. The increased $PM_{2.5}$ concentrations in South Asian air is supposed to cause millions of new cases of asthma, chronic obstructive pulmonary disease (COPD), acute respiratory infections, lung cancer, stroke, myocardial infarction, hypertension, diabetes, dementia, and mental health disorders [10]. Exposure to fine particle

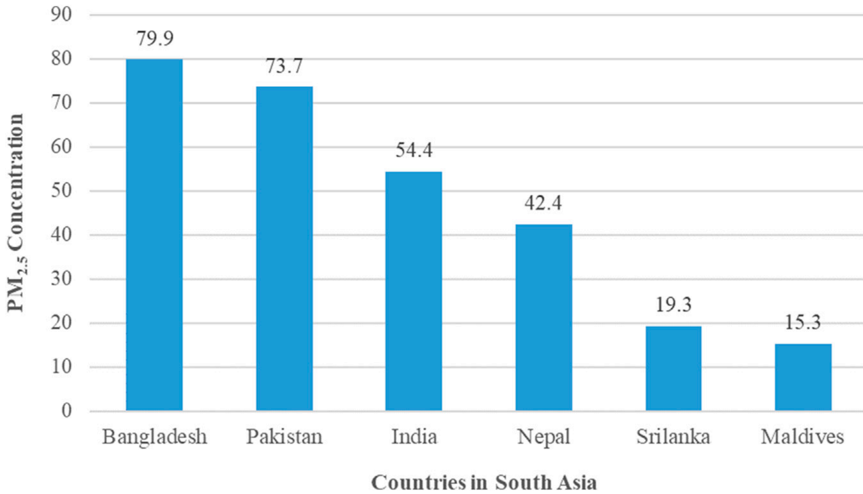

FIGURE 1 | Population weighted annual average $PM_{2.5}$ concentration in the countries of South Asia in 2023. The data reported in **Figure 1** were extracted from the website of IQAir [2].

outdoor air pollution is the most significant environmental risk factor for premature death worldwide [8]. In Europe in 2021, $PM_{2.5}$ was responsible for 432,000 premature deaths, of which 253,000 occurred at levels over the recommended WHO AQG of 5 $\mu g/m^3$ [1]. By contrast, 91% of premature deaths due to air pollution-induced environmental effects occur in low- and middle-income countries in South-East Asia [5]. Many children under the age of five in underdeveloped countries are exposed to elevated levels of $PM_{2.5}$, which impede their cognitive development, harm lung development, increase mortality from respiratory infections, and negatively impact their mental health [6, 11, 12]. Bangladeshis would enjoy a 5.4-year longer life expectancy if World Health Organization (WHO) guidelines were followed [10].

DELAYS WILL THROUGH TO THE POINT OF NO RETURN

A recent report highlights that 42 of the 50 cities with the worst air quality are in South Asia [10]. It predicts that by 2050, altered weather patterns will impact over 800 million people and strain the economy. South Asia's topography, economy, and population patterns make it particularly vulnerable to air pollution challenges. The economy traditionally relies heavily on agriculture, and thermal energy is the primary energy source in the region [10]. Given that air pollution is a regional issue, a regional strategy is necessary. By adopting the strategy, nations can allocate their funds more effectively, collaborate on combating climate change, and share this collective knowledge with the public, private, non-governmental, and government sectors [10]. Cross-border collaboration is urgently needed to address this challenge. The governments in South Asia must allocate budgets and adopt eco-friendly development policies to mitigate this potential public health emergency. Additionally, wealthy nations are expected to provide promised financial assistance to low-income nations to help implement essential adaptation and mitigation measures.

Conclusion

Air pollution in South Asia engenders a public health emergency that remains inadequately addressed. Addressing this crisis necessitates heightened attention to enhance awareness and advocate for efficacious interventions. Achieving sustainable mitigation of air pollution mandates regional cooperation. Policymakers across various echelons in these nations, spanning from local to national and regional levels, must formulate tailored policies that consider pivotal factors including economic status, local meteorological conditions, industrial activities, societal behaviors, and national literacy rates.

AUTHOR CONTRIBUTIONS

SKK and ZF extracted the data, performed statistical analysis, interpreted and drafted the manuscript. AAK was involved in validation of the study, writing, and editing the draft. MMR conceived the idea of the study, writing the draft and supervised. All authors contributed to the article and approved the submitted version.

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REFERENCES

1. Malmqvist E, Andersen ZJ, Spadaro J, Nieuwenhuijsen M, Katsouyanni K, Forsberg B, et al. Urgent Call to Ensure Clean Air for All in Europe, Fight Health Inequalities and Oppose Delays in Action. *Int J Public Health* (2024) 69: 1606958. doi:10.3389/ijph.2024.1606958
2. IQAir. *World's Most Polluted Countries and Regions* (2024). Available from: https://www.iqair.com/world-most-polluted-countries (Accessed May 17, 2024).
3. Amnesty International. *Global: Widening Impact of Climate Change on Air Pollution in South Asia Requires Urgent International Cooperation and Assistance* (2024). Available from: https://www.amnesty.org/en/latest/news/2024/03/global-widening-impact-of-climate-change-on-air-pollution-in-south-asia-requires-urgent-international-cooperation-and-assistance/ (Accessed May 11, 2024).
4. Hamanaka RB, Mutlu GM. Particulate Matter Air Pollution: Effects on the Cardiovascular System. *Front Endocrinol (Lausanne)* (2018) 9:680. doi:10.3389/fendo.2018.00680
5. Abdul Jabbar S, Tul Qadar L, Ghafoor S, Rasheed L, Sarfraz Z, Sarfraz A, et al. Air Quality, Pollution and Sustainability Trends in South Asia: A Population-Based Study. *Int J Environ Res Public Health* (2022) 19:7534. doi:10.3390/ijerph19127534
6. Anwar MN, Shabbir M, Tahir E, Iftikhar M, Saif H, Tahir A, et al. Emerging Challenges of Air Pollution and Particulate Matter in China, India, and Pakistan and Mitigating Solutions. *J Hazard Mater* (2021) 416:125851. doi:10.1016/j.jhazmat.2021.125851
7. United Nation Environmental Programme. *Pollution Action Note- Data You Need to Know* (2023). Available from: https://www.unep.org/interactives/air-pollution-note/ (Accessed May 11, 2024).
8. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization (2021). Available from: https://iris.who.int/handle/10665/345329 (Accessed May 17, 2024).
9. Hoffmann B, Boogaard H, de Nazelle A, Andersen ZJ, Abramson M, Brauer M, et al. WHO Air Quality Guidelines 2021–Aiming for Healthier Air for All: A Joint Statement by Medical, Public Health, Scientific Societies and Patient Representative Organisations. *Int J Public Health* (2021) 66:1604465. doi:10.3389/ijph.2021.1604465
10. Climate Action Network South Asia (CANSA), Doctors For Clean Air and Climate Action, Health Care Without Harm (HCWH). *Regional Collaboration of Health Professionals for Resolving South Asia's Air Pollution and Climate Crisis* (2021).
11. Anwar A, Ullah I, Younis M, Flahault A. Impact of Air Pollution (PM2.5) on Child Mortality: Evidence From Sixteen Asian Countries. *Int J Environ Res Public Health* (2021) 18:6375. doi:10.3390/ijerph18126375
12. Hossain MS, Tasnim S, Chowdhury MA, Chowdhury FIF, Hossain D, Rahman MM. Under-Five Children's Acute Respiratory Infection Dropped Significantly in Bangladesh: An Evidence From Bangladesh Demographic and Health Survey, 1996–2018. *Acta Paediatr Int J Paediatrics* (2022) 111: 1981–94. doi:10.1111/apa.16447

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Health and Economic Benefits of Complying With the World Health Organization Air Quality Guidelines for Particulate Matter in Nine Major Latin American Cities

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Objectives: This study aims to estimate the short-term preventable mortality and associated economic costs of complying with the World Health Organization (WHO) air quality guidelines (AQGs) limit values for PM_{10} and $PM_{2.5}$ in nine major Latin American cities.

Methods: We estimated city-specific PM-mortality associations using time-series regression models and calculated the attributable mortality fraction. Next, we used the value of statistical life to calculate the economic benefits of complying with the WHO AQGs limit values.

Results: In most cities, PM concentrations exceeded the WHO AQGs limit values more than 90% of the days. PM_{10} was found to be associated with an average excess mortality of 1.88% with concentrations above WHO AQGs limit values, while for $PM_{2.5}$ it was 1.05%. The associated annual economic costs varied widely, between US$ 19.5 million to 3,386.9 million for PM_{10}, and US$ 196.3 million to 2,209.6 million for $PM_{2.5}$.

Conclusion: Our findings suggest that there is an urgent need for policymakers to develop interventions to achieve sustainable air quality improvements in Latin America. Complying with the WHO AQGs limit values for PM_{10} and $PM_{2.5}$ in Latin American cities would substantially benefits for urban populations.

Keywords: air pollution, particulate matter, mortality, Latin America, air quality regulation, economic benefits

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INTRODUCTION

In recent decades, Latin American urban centers have witnessed rapid urbanization and industrialization, leading to a surge in air pollution levels [1]. Among the various pollutants, particulate matter (PM) has emerged as a critical public health concern, given its harmful impact on respiratory and cardiovascular systems [2–4]. The World Health Organization (WHO) has established air quality guidelines (AQGs) for particulate matter (PM), aiming to safeguard human health and well-being [5]. In particular, the WHO AQGs recently updated the annual limit values for particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) to 15 $\mu g/m^3$, and for particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) to 5 $\mu g/m^3$. However, compliance with these stringent standards remains a significant challenge for major Latin American cities, where factors such as population density, traffic congestion, industrial emissions, and limited resources for environmental management converge.

Understanding the multifaceted implications of non-compliance with WHO AQGs is essential for designing effective mitigation strategies [6]. One crucial aspect of this assessment is the short-term preventable mortality associated with elevated PM levels, especially in Latin American urban centers. While the total burden attributed to long-term exposure far exceeds that of short-term exposure, the immediacy of the latter presents a distinct contrast. Unlike the gradual realization of benefits associated with improved air quality over months and years due to long-term exposure, short-term effects can be mitigated "immediately." Consequently, policies targeting the reduction of daily concentrations will promptly yield benefits in terms of short-term effects, whereas the broader advantages of enhanced air quality will materialize only over an extended and less precisely

FIGURE 1 | Geographical location of the cities in the study (Latin America, 2009–2018). Note: PM_{10}: Particulate matter with an aerodynamic diameter of 10 μm or less. $PM_{2.5}$: Particulate matter with an aerodynamic diameter of 2.5 μm or less.

defined period. Moreover, the economic ramifications of failing to comply with WHO AQGs demand rigorous investigation. The cost burden extends across various sectors, including healthcare expenditures, loss of labor productivity, and diminished quality of life [7]. By quantifying the economic burden of air pollution, policymakers can make informed decisions regarding resource allocation and prioritize interventions to achieve sustainable air quality improvements.

This study aims to present a comprehensive analysis of short-term preventable mortality and associated economic costs of complying with the WHO AQGs for PM_{10} and $PM_{2.5}$ in nine major Latin American cities. These health and economic consequences of PM pollution offer a foundation for evidence-based policy formulation to enhance air quality and preserve the wellbeing of urban populations in Latin America.

METHODS

Data Collection

We collected daily time series data on environment and health from nine capital cities or the most populated cities in Central and South American countries (**Figure 1**), namely, Bogota in Colombia, Buenos Aires in Argentina, Guatemala City in Guatemala, Lima in Peru, Mexico City in Mexico, Montevideo in Uruguay, Quito in Ecuador, Santiago in Chile, and Sao Paulo in Brazil. The dataset covers an overlapping period from 2009 to 2018. Mortality data were obtained from local authorities within each country, represented by daily counts of deaths due to non-external causes (International Classification of Diseases, 9th revision (ICD-9) codes 0 to 799 and ICD-10 codes A0 to R99). In cases where non-external mortality data were unavailable, we collected daily counts of deaths from all causes. We obtained daily concentrations of PM_{10} in nine cities, and on $PM_{2.5}$ from five of these cities. Data on both pollutants were available in Mexico City, Montevideo, Quito, Santiago, and Sao Paulo. We also collected data on the daily mean temperature for each city. Data on PM and temperature were all collected from local monitoring stations and networks in each city.

Statistical Analysis

The analysis included three steps. First, we estimated the PM-mortality association, and then derived the health impact. Finally, we calculated the economic benefits of complying with WHO AQGs limit values for PM concentrations. The analysis was conducted for PM_{10} and $PM_{2.5}$ separately using R (version 4.3.1; R Development Core Team).

PM-Mortality Association

We performed city-specific time-series analyses using generalized linear models with quasi-Poisson family [8]. We developed the model based on a previous study [9]. The regression model included a natural cubic spline function with 7 degrees of freedom (*df*) per year to control for the long-term trends and seasonality and an indicator for the day of the week to account for within-week variation. We used a natural cubic spline function with 6 *df* for the 4-day moving average of daily mean temperature to account for its confounding effect on PM-mortality associations. We assumed a linear exposure-response association of mortality with PM. To identify the optimal lag days (i.e., the number of days the effect of PM could persist), we used distributed linear models with a natural cubic spline with 3 *df* for the lag-response association for the same day (lag 0) to four days after the exposure (lag 4). Then we pooled the city-specific estimates for the association by using a random-effects meta-analysis by considering city as a random effect. We reported relative risk (RR) of mortality, and the related 95% confidence interval (95%CI), for a 10 $\mu g/m^3$ increase of PM_{10} and $PM_{2.5}$.

Attributable Mortality

Although we focus on the short-term association between PM and mortality, we utilized the WHO AQGs annual limit value rather than the daily limit value to estimate the attributable mortality. The 2021 WHO AQGs were specifically determined to ensure compliance with the more crucial long-term limit values and the regulations governing daily levels [5]. Essentially, areas that meet the annual AQG limit value are likely also to meet the requirement of not surpassing the daily limit values more than three times a year and *vice versa* [10]. Therefore, any impact assessment must recognize this consistency: if every day of the year, on average, adheres to the long-term limit value, both the long-term and the short-term AQG values will be met; conversely, if every day was, on average, aligns with the short-term daily mean limit values, the AQG annual mean limits would be significantly violated. Hence, the only appropriate reference values to derive the burden for "non-compliance" with WHO AQGs are the long-term mean limit values (5 and 15 μg/m^3, respectively for $PM_{2.5}$ and PM_{10}), not the short-term limit values [10].

We calculated the attributable mortality associated with the short-term exposure to PM_{10} and $PM_{2.5}$ in each city for days above the WHO AQGs annual limit values as $(1 - exp\,(-\beta_i \cdot (x_{it} - c)^+)) \times d_{it}$. Here, β_i is the log-RR for a unit increase in PM concentration in city i, x_{it} represents the daily PM concentration in city i on day t, c is the WHO AQGs limit value ($c = 15\,\mu/m^3$ for PM_{10}, and $c = 5\,\mu/m^3$ for $PM_{2.5}$), and d_{it} is the daily deaths in city i on day t. Finally, we computed the mortality fraction (%) by summing of the city-specific daily attributable deaths and dividing by the total mortality in each city, allowing for the comparison across cities, jointly with the 95% empirical CIs (eCIs) [11].

Economic Cost

We employed the concept of the value of a statistical life (VSL) to calculate the economic benefits associated with the reduction of PM_{10} and $PM_{2.5}$ levels in each city. The VSL serves as a widely used measure in cost-benefit analyses, assessing the health cost related to both environment and healthcare programs that influence social wellbeing, such as the health cost of deaths attributable to PM pollution. Essentially, VSL represents an individual's willingness to pay to reduce a unit of mortality risk [12]. To quantify the economic benefits of PM reduction, we multiplied the VSL by the number of attributable deaths in each city and calculated the average cost per year.

Ideally, the VSL obtained from the local empirical studies should be used for the calculation. However, such information was not available for the current study. Therefore, to ensure

TABLE 1 | Descriptive summary by city (Latin America, 2009–2018).

City (country)	Study period	Deaths	Mean (standard Deviation)			Percentage of days PM_{10} > 15 $\mu g/m^3$ (%)	Percentage of days $PM_{2.5}$ > 5 $\mu g/m^3$ (%)
			Temperature (°C)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)		
Bogota (Colombia)	2009–2013	142,151	14.1 (0.9)	53.2 (15.8)	-	100	-
Buenos Aires (Argentina)	2009–2018	399,592	18.3 (5.8)	29.6 (15.3)	-	94.3	-
Guatemala City (Guatemala)	2010–2015	48,170	19.3 (1.5)	48.0 (26.3)	-	98.2	-
Lima (Peru)	2010–2014	183,105	19.2 (2.4)	77.9 (26.1)	-	100	-
Mexico City (Mexico)	2009–2014	610,387	16.5 (2.5)	51.2 (20.4)	24.0 (9.9)	99.3	100
Montevideo (Uruguay)	2014–2016	92,252	18.6 (5.4)	27.4 (11.2)	8.6 (8.0)	91.4	67.1
Quito (Ecuador)	2014–2018	44,533	15.5 (1.1)	47.7 (17.3)	16.7 (5.3)	98.7	100
Santiago (Chile)	2009–2018	380,102	15.0 (5.1)	69.8 (32.1)	27.4 (15.5)	99.0	99.6
Sao Paulo (Brazil)	2010–2018	682,147	21.5 (3.5)	36.3 (18.0)	20.8 (10.9)	95.2	99.6

PM_{10}: Particulate matter with an aerodynamic diameter of 10 µm or less.
$PM_{2.5}$: Particulate matter with an aerodynamic diameter of 2.5 µm or less.

comparability between countries, we relied on international income-adjusted estimates of the country specific VSL [12] as a proxy for the economic cost in each city. The city-specific estimates were reported as annual average number of excess deaths and annual average economic benefits, allowing for a proper comparison between cities with different lengths of study period.

RESULTS

The analysis included 2,582,439 deaths across nine major cities in Latin America, with the period ranging from three to ten years. **Table 1** shows the descriptive summary of PM_{10} and $PM_{2.5}$ concentrations, average temperature, and daily mortality in each city. On average, the annual mean concentrations of PM_{10} ranged from 27.4 $\mu g/m^3$ in Montevideo to 77.9 $\mu g/m^3$ in Lima, while $PM_{2.5}$ concentrations ranged from 8.6 $\mu g/m^3$ in Montevideo to 27.4 $\mu g/m^3$ in Santiago. Across the cities and study periods, 97.4% and 97.0% of days showed concentrations of PM_{10} and $PM_{2.5}$ above the WHO AQGs daily limit values of 15 $\mu g/m^3$ and 5 $\mu g/m^3$, respectively. Majority of the days (>90%) in most cities recorded concentrations of PM higher than the WHO AQGs limit values, except for $PM_{2.5}$ in Montevideo (**Supplementary Figure S1**).

The lag-response association for most of the cities suggested a consistent delayed effect of PM on the current day (lag 0) and 1 day before (lag 1) (**Supplementary Figures S2–S3**). Therefore, we fitted a linear exposure-response association of mortality with the 2-day moving average of daily concentration of PM (lag 0–1 day) and observed a positive association between PM and mortality in all cities (**Supplementary Figures S4–S5**).

The pooled estimate showed that an increase of 10 $\mu g/m^3$ in PM_{10} was associated with a RR of 1.007 (95%CI= [1.004, 1.010]), while $PM_{2.5}$ was associated with a RR of 1.010 (95%CI= [1.007%, 1.013%]) (**Figure 2; Supplementary Table S1**). The city-specific RRs varied among cities, ranging from 1.001 (95%CI= [0.995, 1.008]) in Guatemala City to 1.018 (95%CI= [1.009, 1.028]) in Montevideo for PM_{10} and from 1.008 (95%CI= [1.004, 1.012]) in Santiago to 1.021 (95%CI= [1.008, 1.035]) in Montevideo for $PM_{2.5}$.

Overall, PM_{10} and $PM_{2.5}$ were found to be associated with an excess mortality of 1.88% (95% eCI = [1.02, 2.76]) and 1.05% (95% eCI = [0.42, 1.70]) with levels above the WHO AQGs limit values, respectively (**Figure 3**; **Supplementary Table S2**). For PM_{10}, city-specific excess mortality ranged from 0.39% (95%eCI = [−1.30, 2.13]) in Guatemala to 2.62% (95%eCI = [−0.17, 5.46]) in Quito, while for $PM_{2.5}$, city-specific excess mortality ranged from 0.42% (95%eCI = [0.08, 0.76]) in Sao Paulo to 2.13% (95%eCI = [−0.99, 5.29]) in Quito. It should be noted that the estimates in Bogota, Guatemala City, and Quito exhibit some uncertainties.

Table 2 shows the city-specific annual average estimates on excess deaths and economic cost associated with PM concentrations above the WHO AQGs limit values. The annual average economic costs of PM_{10} varied widely from US $19.5 million (95%eCI = [−64.4, 105.4]) in Guatemala City to US$ 3,386.9 million (95%eCI = [2,728.7, 4,076.2]) in Sao Paulo. Similarly, for $PM_{2.5}$, costs ranged from US$ 196.3 million (95%eCI = [−91.7, 488.8]) in Quito to US$ 2,209.6 million (95%eCI = [1,072.3, 3,396.1]) in Mexico City. Notably, Mexico City, Santiago, and Sao Paulo showed the heaviest economic burden, exceeding both PM_{10} and $PM_{2.5}$ WHO AGQs limit values.

DISCUSSION

This study analyzes data on PM and daily mortality in nine major cities in Latin America, providing evidence of the health and economic impact of daily PM concentrations above the WHO AQGs recently updated limit values for PM_{10} and $PM_{2.5}$.

In the analysis, we observed a risk increase of 0.7% in all-cause mortality per 10 $\mu g/m^3$ increase in PM_{10} and 1% for $PM_{2.5}$. These risk estimates are similar to those reported in previous studies in Latin American countries. The ESCALA study reported a mortality risk of 0.77% for PM_{10} [13], while a systematic review estimated a pooled mortality risk of 1% for $PM_{2.5}$ [2].

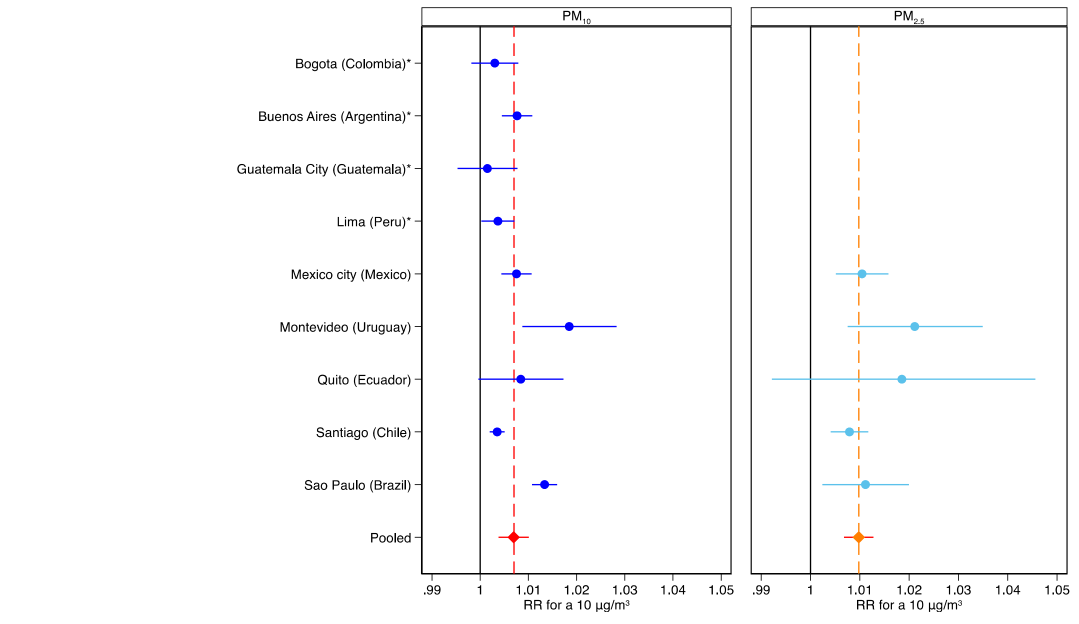

FIGURE 2 | Pooled and city-specific short-term association of mortality with 2-day moving average concentration of particulate matter, as relative risk (RR, and 95% confidence interval) for a 10 $\mu g/m^3$ increase (Latin America, 2009–2018). Note: PM_{10}: Particulate matter with an aerodynamic diameter of 10 μm or less. $PM_{2.5}$: Particulate matter with an aerodynamic diameter of 2.5 μm or less. *Cities with only PM10 data available.

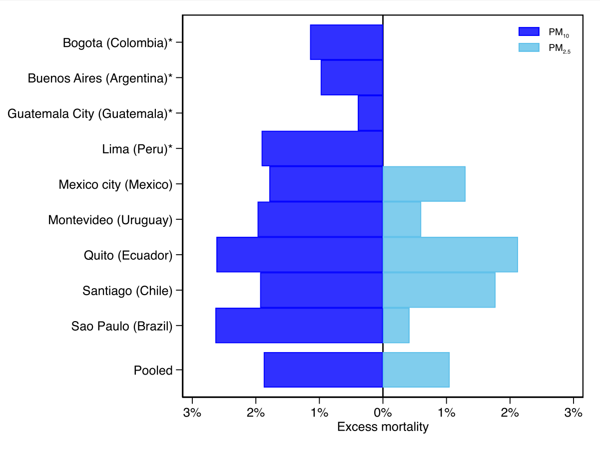

FIGURE 3 | Pooled and city-specific excess mortality associated with particulate matter concentrations above the World Health Organization air quality guidelines limit (Latin America, 2009–2018). Note: The World Health Organization air quality guidelines limit values are 15 $\mu g/m^3$ for particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) and 5 $\mu g/m^3$ for particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). *Cities with only PM10 data available.

However, the short-term effects of PM in Latin America are somewhat larger than those described in studies at the global scale. For example, Liu et al. [9] reported risk increases of 0.44% and 0.68% for PM_{10} and $PM_{2.5}$, respectively, in a study from 652 cities in 24 countries. Similarly, a WHO systematic review reported risk increases of 0.41% for PM_{10} and 0.65% for $PM_{2.5}$ [3]. However, the city-specific risk estimates showed geographical variability, ranging between 0.1% and 1.8% for a 10 $\mu g/m^3$ increase of PM_{10}, and 0.8% to 2.1% for $PM_{2.5}$. These may be related to city-specific demographics, such as variations in age distribution, socio-economic development, PM sources, and climate conditions. However, further studies are warranted to investigate these variations.

Nevertheless, our study offers a new perspective on the impact of short-term exposure to PM pollution in Latin America by estimating the health burden and its economic consequences at the city level, an investigation lacking in previous studies. In most cities studied, PM concentration exceeded WHO AQGs limit values on over 90% of days. In several cities, daily average PM_{10} and $PM_{2.5}$ concentration consistently surpassed WHO AQG limit values.

In addition, PM_{10} and $PM_{2.5}$ are associated with a short-term excess mortality of 0.39% and 0.43%, respectively, with levels above the current WHO AQGs limit values. This implies an estimated annual economic cost, which varies widely between US $19.5 to 3386.9 million for PM_{10}, and US $196 to 2209.6 million for $PM_{2.5}$. However, comparisons with previous studies are not straightforward since previous studies estimating deaths attributable to ambient PM mainly focused on the long-term effects, which are much larger than our estimation of the short-term effects. A regional multi-city study including 366 Latin American cities revealed that 58% of the population lived in the areas where annual $PM_{2.5}$ concentrations surpassed the 2005 WHO AQG of 10 $\mu g/m^3$ [14]. Moreover, the State of Global Air estimated the number of deaths attributable to long-term exposure to $PM_{2.5}$ in the Latin American countries considered in our study ranged between 733 in Uruguay to 43,600 in Brazil [15]. Similarly, different methods have been used to estimate economic impact. For example, Trejo-González et al. [16]

TABLE 2 | City-specific average annual excess deaths and annual economic cost associated with particulate matter concentrations above the World Health Organization air quality guidelines limit (Latin America, 2009–2018).

City (country)	VSL (US$ million)	PM_{10}		$PM_{2.5}$	
		Excess deaths (n, (95%eCI))	Economic cost (US$ million, (95%eCI))	Excess deaths (n, (95%eCI))	Economic cost (US$ million, (95%eCI))
Bogota (Colombia)[a]	1.228	326 (–210; 880)	400.5 (–257.5; 1,080.8)		
Buenos Aires (Argentina)[a]	2.144	391 (228; 563)	839.4 (488.4; 1,206.9)		
Guatemala City (Guatemala)[a]	0.618	32 (–105; 171)	19.5 (–64.6; 105.4)		
Lima (Peru)[a]	1.055	699 (33; 1,386)	737.7 (34.8; 1,461.7)		
Mexico City (Mexico)	1.671	1,818 (1,056; 2,610)	3,037.3 (1,765.1; 4,361.8)	1,322 (642; 2032)	2,209.6 (1,072.3; 3,396.1)
Montevideo (Uruguay)	2.705	607 (285; 940)	1,641.2 (770.6; 2,541.4)	185 (65; 309)	501.6 (175.9; 836.7)
Quito (Ecuador)	1.037	233 (–16; 487)	241.9 (–16.1; 504.7)	189 (–88; 471)	196.3 (–91.7; 488.8)
Santiago (Chile)	2.426	735 (407; 1,078)	1,782.6 (986.9; 2,614.1)	673 (345; 1,016)	1,633.6 (838.0; 2,463.8)
Sao Paulo (Brazil)	1.695	1,998 (1,610; 2,405)	3,386.9 (2,728.7; 4,076.2)	316 (64; 577)	535.5 (108.7; 977.4)

Note: The WHO AQGs limit values are 15 μg/m³ for particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) and 5 μg/m³ for particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$).

[a]*Cities with only PM10 data available.*

estimated that an average reduction of 10 $\mu g/m^3$ in the annual $PM_{2.5}$ in fifteen cities in Mexico during 2015 would have prevented 14,666 deaths and 150,771 potential years of life lost in 2015, with estimated costs of US $64,164 and $5,434 million, respectively. A recent study reported US$ 148.3 billion could be attributed to productivity lost due to $PM_{2.5}$ above the 2021 WHO AQGs in Brazil between 2000 and 2019 [17]. Moreover, Bell et al. [18] estimated the economic benefits of PM pollution reduction under two emission scenarios in Mexico City, Santiago, and Sao Paulo using willingness-to-pay and cost-of-illness from 2000 to 2020 for two emission scenarios based on current emissions patterns and regulatory trends and a control policy aimed at lowering air pollution, which was roughly US $21 to $165 billion.

Despite methodological disparities, our findings, coupled with previous studies, underline the substantial health burden and the associated economic cost posed by air pollution in Latin American urban centers, underscoring the significant benefits of lowering the PM concentrations to the current WHO AQGs limit values [6]. However, the urbanization process continues to increase in Latin American countries [1]. The primary factors leading to the deteriorating air quality in the region are the vehicle fleet, industrial sources, and biomass burning [14]. The combustion of solid fuels for cooking or heating within households adds to the overall air pollution in urban areas of certain countries, particularly where a significant portion of the population relies on solid fuels as their primary energy source [1]. These may lead governments to consider that updating their national ambient air quality standards to achieve the newly updated WHO AGQs limit values may not be feasible in their local context at the short term. Here, the interim targets proposed by WHO may be useful steps toward a progressive reduction of PM concentrations [5].

It is necessary for the countries in the region to update the regulatory framework for air quality, especially for PM, to protect public health and the environment. This should include sustainable solutions for public transportation and mobility, as well as the promotion of sustainable clean energy [1]. In this context, countries like Mexico, Colombia, and Brazil have approached their air quality standards to the WHO guidelines. However, the regulatory framework should also include the emission standards, which have a considerable delay for the countries in the region, as well as regulations related to the specifications of the fuels used.

Several limitations should be acknowledged. Single-pollutant models were fitted because data for gaseous pollutants (i.e., nitrogen and sulfur dioxides) were unavailable. In a global study, Liu et al. [9] found that the magnitude of the PM_{10} and $PM_{2.5}$ associations with all-cause mortality, although they remained statistically significant, decreased after adjusting for gaseous pollutants. Moreover, we used time-series analysis to derive the concentration-response associations of short-term exposure to PM. It is important to note that this approach may lead to an underestimation of the potential health and economic impact associated with reducing PM concentrations. Time-series studies capture only cases in which death has been triggered by air pollution exposure incurred shortly before death [19]. For instance, we observed a risk of 1% in all-cause mortality per 10 $\mu g/m^3$ increase in $PM_{2.5}$ which is notably smaller compared to the 9% estimated for the long-term exposure [20]. Furthermore, the short-term effect of PM on all-cause mortality is merely the tip of the iceberg, ignoring numerous other acute health outcomes and diseases, such as myocardial infarctions and cardiorespiratory acute hospitalizations, that are also linked to PM exposure. Therefore, we recommend future studies include other acute health outcomes and extend the current analysis to assess the long-term effects of air quality improvement related to PM in Latin America.

In conclusion, the findings reported in this study show noteworthy evidence that there is an urgent need for policymakers to develop more ambitious policies aimed at achieving sustainable air quality improvements in Latin America. Complying with the WHO AQGs daily limit values for PM_{10} and $PM_{2.5}$ would provide substantial benefits for the urban populations in Latin American cities.

AUTHOR CONTRIBUTIONS

AT and LM conceptualized the study and directed the study's implementation. JA conducted the data curation and statistical analysis with substantial contribution from LM and AT. LAC, HR-R, MHD, MdSZSC, RA, SO, GCE, NVO, VC, and DR contributed to the acquisition and interpretation of data. LM, JA, and AT drafted the manuscript with substantial contributions from LAC, HR-R, MHD, MdSZSC, RA, SO, GCE, NVO, VC, and DR. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2024.1606909/full#supplementary-material

REFERENCES

1. Riojas-Rodriguez H, da Silva AS, Texcalac-Sangrador JL, Moreno-Banda GL. Air Pollution Management and Control in Latin America and the Caribbean: Implications for Climate Change. *Rev Panam Salud Publica* (2016) 40(3):150–9.
2. Fajersztajn L, Saldiva P, Pereira LAA, Leite VF, Buehler AM. Short-Term Effects of Fine Particulate Matter Pollution on Daily Health Events in Latin America: A Systematic Review and Meta-Analysis. *Int J Public Health* (2017) 62(7):729–38. doi:10.1007/s00038-017-0960-y
3. Orellano P, Reynoso J, Quaranta N, Bardach A, Ciapponi A. Short-Term Exposure to Particulate Matter (PM(10) and PM(2.5)), Nitrogen Dioxide (NO(2)), and Ozone (O(3)) and All-Cause and Cause-Specific Mortality: Systematic Review and Meta-Analysis. *Environ Int* (2020) 142:105876. doi:10.1016/j.envint.2020.105876
4. WHO Regional Office for Europe. *Health Risks of Air Pollution in Europe-HRAPIE Project: Recommendations for Concentration-Response Functions for Cost–Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide*. Copenhagen: World Health Organization (2013). Available from: http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project-recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide (Accessed February 21, 2024).
5. World Health Orgnization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization (2021).
6. Hoffmann B, Boogaard H, de Nazelle A, Andersen ZJ, Abramson M, Brauer M, et al. WHO Air Quality Guidelines 2021-Aiming for Healthier Air for All: A Joint Statement by Medical, Public Health, Scientific Societies and Patient Representative Organisations. *Int J Public Health* (2021) 66:1604465. doi:10.3389/ijph.2021.1604465
7. OECD. *The Economic Consequences of Outdoor Air Pollution*. Paris: OECD Publishing (2016).
8. Bhaskaran K, Gasparrini A, Hajat S, Smeeth L, Armstrong B. Time Series Regression Studies in Environmental Epidemiology. *Int J Epidemiol* (2013) 42(4):1187–95. doi:10.1093/ije/dyt092
9. Liu C, Chen R, Sera F, Vicedo-Cabrera AM, Guo Y, Tong S, et al. Ambient Particulate Air Pollution and Daily Mortality in 652 Cities. *N Engl J Med* (2019) 381(8):705–15. doi:10.1056/NEJMoa1817364
10. Adebayo-Ojo TC, Wichmann J, Arowosegbe OO, Probst-Hensch N, Schindler C, Künzli N. A New Global Air Quality Health Index Based on the WHO Air Quality Guideline Values With Application in Cape Town. *Int J Public Health* (2023) 68:1606349. doi:10.3389/ijph.2023.1606349
11. Gasparrini A, Leone M. Attributable Risk From Distributed Lag Models. *BMC Med Res Methodol* (2014) 14:55. doi:10.1186/1471-2288-14-55
12. Viscusi WK, Masterman CJ. Income Elasticities and Global Values of a Statistical Life. *J Benefit-Cost Anal* (2017) 8(2):226–50. doi:10.1017/bca.2017.12
13. Romieu I, Gouveia N, Cifuentes LA, de Leon AP, Junger W, Vera J, et al. Multicity Study of Air Pollution and Mortality in Latin America (The ESCALA Study). *Res Rep Health Eff Inst* (2012) 171(171):5–86.
14. Gouveia N, Kephart JL, Dronova I, McClure L, Granados JT, Betancourt RM, et al. Ambient Fine Particulate Matter in Latin American Cities: Levels, Population Exposure, and Associated Urban Factors. *Sci Total Environ* (2021) 772:145035. doi:10.1016/j.scitotenv.2021.145035
15. Health Effects Institute. *State of Global Air 2020. Special Report*. Boston, MA: Health Effects Institute (2020).
16. Trejo-González AG, Riojas-Rodriguez H, Texcalac-Sangrador JL, Guerrero-López JL, Cervantes-Martínez K, Hurtado-Diaz M, et al. Quantifying Health Impacts and Economic Costs of PM2.5 Exposure in Mexican Cities of the National Urban System. *Int J Public Health* (2019) 64(4):561–72. doi:10.1007/s00038-019-01216-1
17. Wen B, Ademi Z, Wu Y, Xu R, Yu P, Ye T, et al. Ambient PM2.5 and Productivity-Adjusted Life Years Lost in Brazil: A National Population-Based Study. *J Haz Mat* (2024) 467:133676. doi:10.1016/j.jhazmat.2024.133676
18. Bell ML, Davis DL, Gouveia N, Borja-Aburto VH, Cifuentes LA. The Avoidable Health Effects of Air Pollution in Three Latin American Cities: Santiago, Sao Paulo, and Mexico City. *Environ Res* (2006) 100(3):431–40. doi:10.1016/j.envres.2005.08.002
19. Kunzli N, Medina S, Kaiser R, Quenel P, Horak F, Studnicka M. Assessment of Deaths Attributable to Air Pollution: Should We Use Risk Estimates Based on Time Series or on Cohort Studies? *Am J Epidemiol* (2001) 153(11):1050–5. doi:10.1093/aje/153.11.1050
20. Pope CA, Coleman N, Pond ZA, Burnett RT. Fine Particulate Air Pollution and Human Mortality: 25+ Years of Cohort Studies. *Environ Res* (2020) 183: 108924. doi:10.1016/j.envres.2019.108924

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The Impact of Air Pollution Controls on Health and Health Inequity Among Middle-Aged and Older Chinese: Evidence From Panel Data

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Objectives: We evaluated the long-term effects of air pollution controls on health and health inequity among Chinese >45 years of age.

Methods: Data were derived from the China Health Aging and Retirement Longitudinal Survey and the China National Environmental Monitoring Centre. Decreases in $PM_{2.5}$ and PM_{10} were scaled to measure air quality controls. We used a quasi-experimental design to estimate the impact of air quality controls on self-reported health and health inequity. Health disparities were estimated using the concentration index and the horizontal index.

Results: Air pollution controls significantly improved self-reported health by 20% (OR 1.20, 95% *CI*, 1.02–1.42). The poorest group had a 40% (OR 1.41, 95% *CI*, 0.96–2.08) higher probability of having excellent self-reported health after air pollution controls. A pro-rich health inequity was observed, and the horizontal index decreased after air pollution controls.

Conclusion: Air pollution controls have a long-term positive effect on health and health equity. The poorest population are the main beneficiaries of air pollution controls, which suggests policymakers should make efforts to reduce health inequity in air pollution controls.

Keywords: air pollution controls, health, health inequality, China, difference-in-differences

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INTRODUCTION

Reducing the adverse effects of pollution is a critical component of several United Nations Sustainable Development Goals (SDGs), including but not limited to the goal of ensuring healthy lives and promoting wellbeing for all at all ages (Goal 3), reducing inequalities within and between countries (Goal 10) and promoting climate action (Goal 13) [1]. The World Health Organization (WHO) released the new Global Air Quality Guidelines (AQG) in 2021 to promote

Abbreviations: SDGs: Sustainable Development Goals; WHO: World Health Organization; AQG: Air Quality Guidelines; $PM_{2.5}$: fine particulate matter ≤2.5; PM_{10}: inhalable particulate matter with a diameter of 10 μm; GDP: gross domestic product; CHARLS: China Health and Retirement Longitudinal Study; DID: Difference-in-differences; CI: Concentration index; HI: horizontal inequity.

incremental improvements in air quality. The health effects and disease burden of air pollution are serious, and air pollution has been identified as one of the most urgent issues facing China [2–8].

A series of pollution control regulations and policies have been put in place to improve air quality [4, 8, 9], emphasizing environmental controls as a central component of the overall control plan in 2013, etc. These regulations and policies are both informal or formal [4], and command-and-control or market-based [10, 11]. In 2013, air pollution controls underwent significant changes on multiple fronts [12], and the government issued the most stringent Air Pollution Prevention and Control Action Plan in history to improve air quality by strengthening comprehensive controls [2, 7, 8, 13]. Evaluating the potential impact of air pollution control policies on health is of increasing interest to policymakers as they track progress toward achieving these SDGs and their respective impacts on health and health inequities.

There is substantial evidence that air pollution controls also have health benefits. Markandya et al. concluded that substantial health gains can be achieved by taking action to prevent climate change [14]. Yang and Chou found that shutting down a power plant in New Jersey reduced the likelihood of having a low-birth-weight baby by 15% [15]. Xie et al. proposed a cooperative reduction model that encourages neighboring areas to jointly control air pollution, saving 437 more lives than the non-cooperative reduction model [16]. Chamberlain concluded that low-emission zones have positive effects on air pollution-related health outcomes, especially cardiovascular disease [17]. Tonne found that the Congestion Charging Scheme can reduce levels of traffic pollutants, and has benefits in terms of increasing life expectancy and reducing socio-economic inequalities [18]. Although efforts have been made to take inequality into account when considering air pollution control interventions, studies about the impacts of air pollution controls on health inequality and health inequities among middle-aged and older populations in China are limited [19].

As the world's most populous country, China plays a crucial role in current scientific and policy debates on the impact of air pollution controls on health inequities [20]. There is an urgent need to assess the long-term impacts of air pollution controls on health and health inequities in the context of improving air quality in China. Our study contributes to the extant research in three ways: first, we adopted a new way to measure air pollution controls In terms of whether or not they achieve the interval value between three targets assigned by the WHO, providing a new measurement for other developing countries that are also trying to achieve the targets listed by the WHO; second, we explored the long-term impact of air pollution controls on health outcomes by using the difference-in-differences approach to solving endogenous problems in policy evaluation; and finally, we estimated health inequality before and after air pollution controls by concentrate index and horizontal index to provide quantitative support for other low- and middle-income countries to reduce inequity in air pollution controls.

METHODS

Study Design

Air pollution is caused by the presence of many different small substances in the air. In this study, we focus on two main pollutants: inhalable particulate matter with a diameter of 10 μm (PM_{10}) (panel A) and fine particulate matter≤2.5 ($PM_{2.5}$) (panel B). PM_{10} and $PM_{2.5}$ are the primary air pollutants in the vast majority of cities in China, which are also the major air pollutants in the Global AQG released by the WHO. The health risks associated with particulate matter (PM_{10} and $PM_{2.5}$) are particularly important to public health. Both $PM_{2.5}$ and PM_{10} are capable of penetrating deep into the lungs. PM_{10} is often derived from resuspension and combustion products and causes damage to the human respiratory system and immune systems. $PM_{2.5}$ is the primary air pollutant and has the most severe effects on human health.

The Chinese government has turned its attention to $PM_{2.5}$ and PM_{10} and introduced a series of strict environmental policies to regulate air pollution. The standard concentration indicators for $PM_{2.5}$ and ozone that China added to the Environmental Air Quality Standards (GB3095-2012) released in 2012 were based on the WHO 2005 AQG. Among them, $PM_{2.5}$ is equivalent to the WHO-recommended first-stage transition target, which is an active attempt for China to align with international standards in air governance and plays a key role in China's air pollution controls, promoting a significant improvement in air quality levels. Due to the increasingly prominent regional atmospheric environmental issues caused by PM_{10} and $PM_{2.5}$ pollutants in China, the Chinese government issued the "Action Plan for Air Pollution Prevention and Control" in 2013, with the main goal of reducing PM_{10} and $PM_{2.5}$ levels. According to the plan, PM_{10} levels in prefecture-level and above cities nationwide should have been reduced by more than 10% compared to 2012; $PM_{2.5}$ in regions such as Beijing Tianjin Hebei, the Yangtze River Delta, and the Pearl River Delta should have been reduced by approximately 25%, 20%, and 15%, respectively, by 2017. Air pollution in China was severe before 2013, and some studies found that $PM_{2.5}$ concentrations decreased in China's major areas after 2013 [21]. Moreover, the Chinese government implemented the "Winning the Blue Sky Defense War Three-Year Action Plan" from 2018 to 2020, which required a further significant reduction of $PM_{2.5}$. The air pollution regulations released in 2013 set the conditions for the design of the difference-in-differences technique.

For developing countries, WHO developed three transitional criteria for PM_{10} and $PM_{2.5}$ in 2005 and added the four-stage targets in 2021 (see **Supplementary Tables S1, S2**). The interval between the three stages for annual PM_{10} and $PM_{2.5}$ was 20 ug/m^3 and 10 ug/m^3, respectively. Therefore, we used the decrease of 20 ug/m^3 to measure the control of air pollution identified by PM_{10} (panel A), and the decrease of 10 ug/m^3 to measure the control of air pollution identified by $PM_{2.5}$ (panel B). If the city's annual average concentration of PM_{10} and $PM_{2.5}$ decreased by 20 ug/m^3 and 10 ug/m^3 above during the entire study period, it means that subjects living at this city treated by air pollution

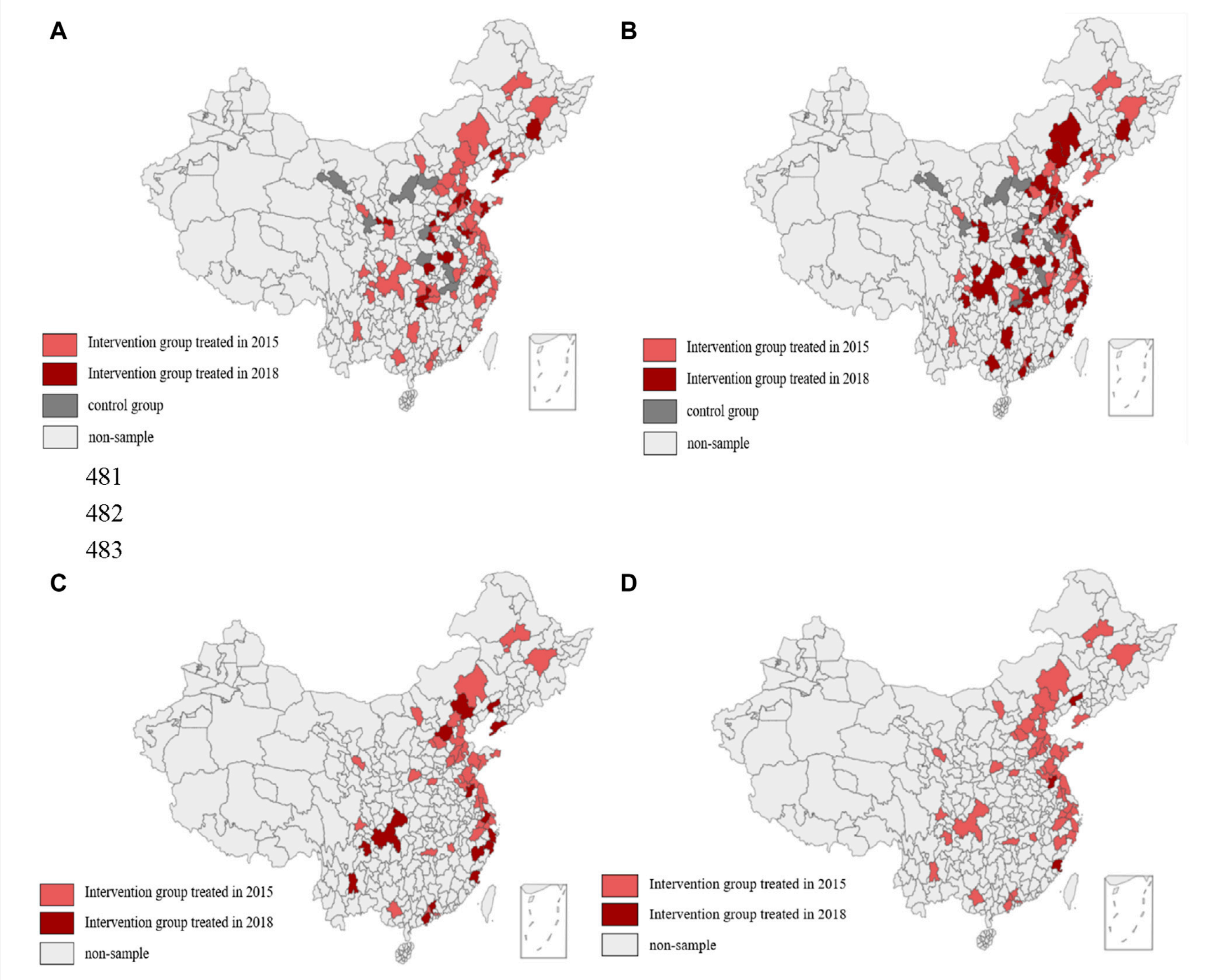

FIGURE 1 | Geographical distribution of the cities in which the subjects were located for different air pollution control groups and different control times identified by PM_{10} and $PM_{2.5}$ (Impact of Air Pollution Controls, Shaanxi, China, 2024). Note: **(A)** Shows the spatial distribution of cities for different groups and different times identified by PM_{10}. **(B)** Shows the spatial distribution of cities for different groups and different times with a one-year lag identified by PM_{10}. **(C)** Shows the spatial distribution of cities for different times identified by $PM_{2.5}$. **(D)** Shows the spatial distribution of cities for different times with a one-year lag identified by $PM_{2.5}$.

controls (treatment group). If the city's annual average concentration of PM_{10} and $PM_{2.5}$ increased or decreased slightly during the whole study period, it means that subjects living at this city have not been treated by air pollution controls (control group). There are different treatment groups and times for air pollution controls between panel A and panel B. The geographical distribution of the cities where the subjects were located for different air pollution control groups and different air pollution control times identified by PM_{10} and $PM_{2.5}$ is shown in **Figure 1**.

Data Sources

The individual-level health data come from the 2013, 2015, and 2018 China Health and Retirement Longitudinal Study (CHARLS), published by the National School of Development of Peking University. The CHARLS is a nationally representative longitudinal survey of individuals in China and their spouses, aged 45 years or older, covering 28 provinces, cities, and municipalities in the country and collecting assessments of the social, income, and health circumstances of community residents [22]. Air pollution data for each city between 2013 and 2018 were provided by the China National Environmental Monitoring Centre, the China Statistical Yearbook on the Environment, and a bulletin on the ecological environment of each province or city. The selection process is as follows: first, we delete the cities that missng the data of PM_{10} and $PM_{2.5}$; and second, we delete subjects living in the cities that have met the WHO target with a low concentration during 2013–2018 and the cities that decreased in 2015 but increased in 2018 according to the difference-in-differences design; third, we delete the missing value for economic status and self-reported health; and finally, we drop the subjects that were not followed up in 2015 and 2018. After selection, we eventually obtained panel data A, including 19,446 participants in 82 cities who were followed up over the three waves of the surveys, and panel data B, including 12,171 participants in 51 cities.

Variables

Dependent variables: self-reported health status. The answers are very good, good, fair, poor, and very poor. This reflects the overall subjective experience of mental and physical wellbeing and is closer to the WHO's definition of health [5]. Moreover, self-reported health can be used as a valid predictor of mortality and other functional limitations in many countries and regions [14, 23, 24], We set the dependent variable as a binary variable. In this study, the description of the variable was taken as having a value of 1 if a subject chose very good or good. On the contrary, fair, poor, and very poor are classified as having a value of 0.

Independent variables: the dummy variable (Treat) indicates whether the city where the subjects lived is on the air quality control list. If the city where the subjects lived was on the air pollution control list between 2013 and 2018, its value was set as 1; otherwise, its value was set as 0. The dummy variable (Post) was set to 1 for the year of air pollution controls and the year after air pollution controls, and 0 for the year before air pollution controls. The core independent variable we were concerned with was the interaction term (Did and Did_{t-1}) between the air pollution controls and the year dummy variables. Did is the net effect of air pollution control on health, and Did_{t-1} is the net effect of air pollution control with a one-year lag on health. Because we considered the effects of health lags and the time required to become aware of air quality, we used the annual average concentration of $PM_{2.5}$ in the previous year as a proxy for the concentration in the current year.

Controls: the logarithm of gross domestic product (GDP) *per capita* for each city to represent the city-level indicator; we also controlled for individual-level indicators such as sex, age, work status, economic status, educational status, and health insurance.

Statistical Analysis

The Difference-in-differences (DID) model with multiple periods and the two-way fixed-effects logistic regression model were used to estimate the causal effects of air pollution controls on self-reported health [25]. The use of quasi-experimental designs to evaluate the effects of policy treatments has gained wide acceptance in empirical research in the social sciences [26]. The DID method, which is widely accepted as the most common and best method for studying quasi-natural experiments [27] can control for temporal variation in the outcome that is not due to treatment exposure and the selection effect and has significant advantages in solving endogenous problems caused by causal identification and variable omission [28]. We compared average changes in health before and after the air pollution controls intervention between treatment and control cities [1]. It is well known that the DID analysis relies on the "common trend assumption," which means that the DID estimator requires that the average outcomes for the treatment and control groups follow parallel paths in the pre-intervention periods. Moreover, robust analyses can be performed to evaluate whether the effect measured can be attributed to the introduction of air pollution controls. All analyses were conducted using the Stata software, version 14. The regression model is shown in the following equation:

$$y_{i,t} = \alpha + \mu_i + \lambda_t + \theta treat_i \times post_{i,t} + \beta x_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$y_{i,t} = \alpha + \mu_i + \lambda_t + \theta Did + \beta x_{i,t} + \varepsilon_{i,t} \quad (2)$$

$$y_{i,t-1} = \alpha + \mu_i + \lambda_{t-1} + \theta treat_i \times post_{i,t-1} + \beta x_{i,t-1} + \varepsilon_{i,t-1} \quad (3)$$

$$y_{i,t-1} = \alpha + \mu_i + \lambda_{t-1} + \theta Did_{t-1} + \beta x_{i,t-1} + \varepsilon_{i,t-1} \quad (4)$$

In Eq. **1**, $y_{i,t}$ is the dependent variable referring to the self-reported health of subject i in period t; $x_{i,t}$ represents a set of confounding factors including city level and individual level; $treat_i \times post_{i,t}$ is the product term of the treatment dummy variable group and the time dummy variable; θ is the net effect of air control on health; μ_i represents the individual fixed effect; λ_t represents the time fixed effect; $\varepsilon_{i,t}$ is the random error term. We used Did replace $treat_i \times post_{i,t}$ in Eq. **2**. In Eq. **3**, the definition is the same as in Eq. **1**. We used Did_{t-1} to replace $treat_i \times post_{i,t-1}$ in Eq. **4**. However, we used the PM_{10} and $PM_{2.5}$ in the forward year to replace the current year, meaning that we could estimate the effect of air pollution control on health with a one-year lag.

The degree of income-related health inequality was calculated using the concentration index (CI). The CI was first introduced by Wagstaff et al., and has been widely applied as a standard method to describe and measure the degree of income-related inequality in various measures of health and healthcare utilization [3, 16, 29–33] The CI value ranges from −1 to 1. The positive value of the CI represents that good health is more concentrated in higher-income groups and *vice versa*. A formula for computing the concentration index is:

$$C = \frac{2}{\mu} \operatorname{cov}(y_i, R_i) \quad (5)$$

where C is the concentration index, y_i refers to self-reported health, μ is the mean health of the entire population, and R_i symbolizes the relative fractional rank of the economic status distribution.

The degree of income-related health inequity was calculated using the horizontal inequity index. Income-related inequality in health does not imply health inequity [34]. The horizontal inequity (HI) of health indicates the inequality in health by subtracting the contribution of need variables. The HI index is obtained by subtracting the contribution of unavoidable variables (e.g., sex and age) from the concentration index [35]. The HI index is positive, which signifies the existence of a pro-rich inequity (and *vice versa* in the case of a negative HI index).

RESULTS

The study population included 12,171 respondents (9,210 [47.36%] women; 10,236 [52.64%] men) in panel A (Air pollution controls measured by PM_{10}), and 19,446 respondents (5,787 [47.55%] women; 6,384 [52.45%]

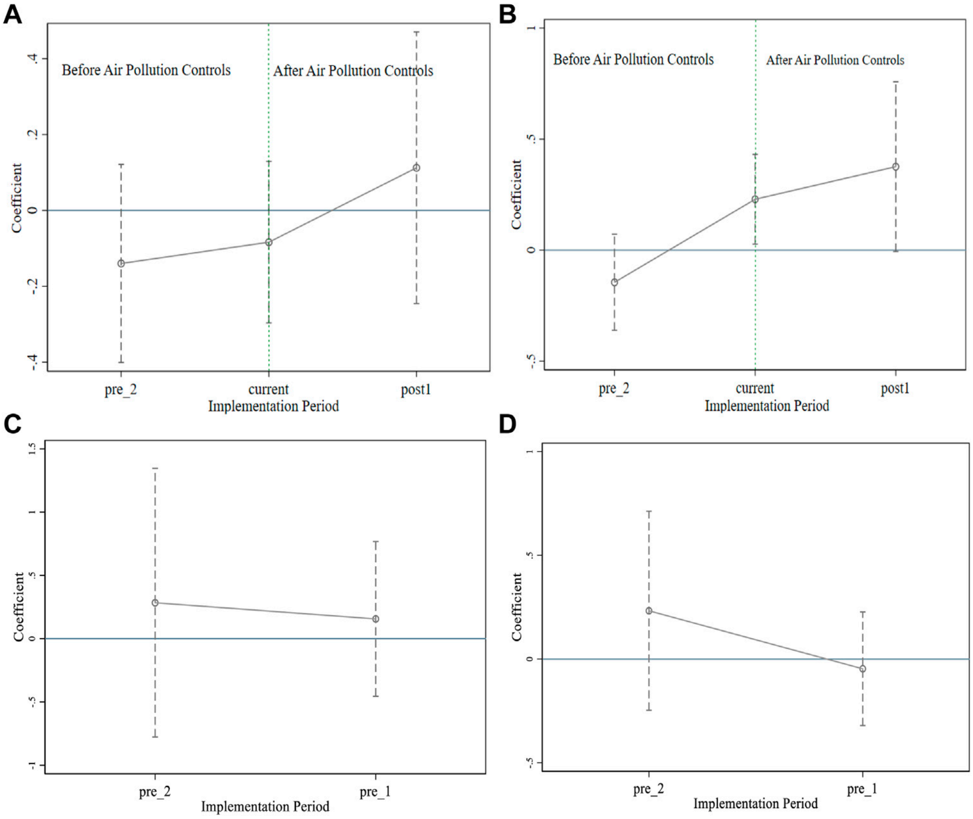

FIGURE 2 | Common trend analysis with the effect of air pollution controls identified by PM_{10} and $PM_{2.5}$ on health (Impact of Air Pollution Controls, Shaanxi, China, 2024). Note: **(A)** shows the common trend of the effect of air pollution controls identified by PM_{10} on health. **(B)** Shows the common trend of the effect of air pollution controls with a one-year lag identified by PM_{10} on health. **(C)** Shows the common trend of the effect of air pollution controls identified by $PM_{2.5}$ on health. **(D)** Shows the common trend of the effect of air pollution controls with a one-year lag identified by $PM_{2.5}$.

men) in panel B (environmental controls identified by $PM_{2.5}$). The majority of respondents were >64 years old, married, educated to the primary school level, employed, had basic health insurance, and reported a diagnosed chronic disease. Most residents had fair, poor, and very poor self-reported health (**Supplementary Table S3**).

Figure 2 shows the common trends before the intervention of air pollution controls identified by PM_{10} and $PM_{2.5}$. All the pre-intervention period estimates in panels A and B are not statistically significant. Plotting the self-reported health trajectories of the control and treatment groups for the pre-intervention periods revealed no substantial differences between the two groups (**Supplementary Table S4**). For the subjects with a one-year intervention lag, there were significant upward trends after the introduction of air pollution control. Overall, the results are consistent with the common trend hypothesis.

The results of the DID analysis are summarized in **Table 1**. For panel A and panel B, all the estimates for air pollution control without a one-year lag are not statistically significant, while the estimates for the subjects with a one-year lag are significantly positive (**Table 1**). Compared with the control group, respondents are 20% (OR 1.20, 95% *CI*, 1.02–1.42) and 24% (OR 1.24, 95% *CI*, 1.03–1.58) more likely to have very good and good health after air pollution controls in panels A and B, respectively. **Table 1** shows that air pollution controls had a positive effect on self-reported health. The DID results indicate that the odds of respondents reporting very good and good health are 26% (95% *CI*, 1.03–1.54) and 38% (95% *CI*, 1.10–1.83) in the current year of the intervention with a one-year lag in panels A and B, respectively. The DID results indicate that the odds of respondents reporting very good and good health are 46% (95% *CI*, 1.04–2.13) and 83% (95% *CI*, 1.13–2.97) after 3 years of intervention with a one-year lag in panels A and B, respectively. Overall, the positive effect of air pollution controls on health presents an upward trend.

Table 2 shows the effects and time-trend effects of economic status. We noted no significant effects on the health of the poorer and middle groups in the intervention group compared to the control group. Air pollution controls significantly improved the health of the poorest group. The DID trend effects analysis indicates that the poorest respondents are 41% more likely to report very good and good health in the current intervention period (OR 1.41, 95% *CI*, 1.01 to 2.08 in panel A). Air pollution controls improve the health of the richest group in panel B, but have insignificant effects in panel A. Thus, air pollution controls have a positive and lasting upward effect on the poorest group.

TABLE 1 | The effect of environmental controls on health and time trend analysis (Impact of Air Pollution Controls, Shaanxi, China, 2024).

	Model 1	Model 2
Panel A		
Did	0.92 (0.77–1.10)	0.86 (0.71–1.03)
Current year of air pollution control	0.99 (0.81–1.21)	0.92 (0.74–1.14)
3 years after air pollution control	1.23 (0.87–1.73)	1.12 (0.78–1.60)
Did_{t-1}	1.21 (1.02–1.42)**	1.20 (1.02–1.42)**
Current year of air pollution control	1.30 (1.07–1.58)***	1.26 (1.03–1.54)**
3 years after air pollution control	1.51 (1.05–2.17)**	1.46 (1.04–2.13)**
Control variables	No	Yes
Time-fixed effect	Yes	Yes
Individual fixed effect	Yes	Yes
Observation	19,446	19,446
Panel B		
Did	0.96 (0.58–1.59)	0.92 (0.54–1.53)
Current year of air pollution control	0.96 (0.72–1.29)	0.93 (0.69–1.26)
3 years after air pollution control	1.08 (0.65–1.78)	1.13 (0.67–1.90)
Did_{t-1}	1.22 (0.99–1.53)*	1.24 (1.03–1.58)**
Current year of air pollution control	1.43 (1.11–1.86)***	1.38 (1.10–1.83)***
3 years after air pollution control	1.99 (1.27–3.10)***	1.83 (1.13–2.97)***
Control variables	No	Yes
Time-fixed effect	Yes	Yes
Individual fixed effect	Yes	Yes
Observation	12,171	12,171

*Note: Model 1 means the results without control variables, and Model 2 means the results with control variables. Panel A means air pollution controls identified by PM_{10}, and Panel B means air pollution controls identified by $PM_{2.5}$. Did means the interaction term (Treat*post) between the air pollution controls and year dummy variables. Did_{t-1}, means the interaction term (Treat*post $_{t-1}$) between the air pollution controls and one-year lag dummy variables. Did is the net effect of air pollution control on health, and Did_{t-1}, means the net effect of air pollution control with a one-year lag on health.* *p< *0.1;* **p< *0.05;* ***p< *0.01.*

We performed a counterfactual analysis to test the robustness of the results. We assumed that the air pollution controls were implemented ahead of schedule. **Supplementary Table S5** shows that none of the estimates from the counterfactual analysis are significant for all participants and different economic status groups, illustrating that the results we obtained earlier are robust. We only used 2013 and 2015 data to estimate the effect (see **Supplementary Table S6**), and the results indicate that our findings are robust. We selected some subjects in the control group as the treatment group (see **Supplementary Table S7**), and the estimate is insignificant, illustrating that the results are robust. We also changed the control group and randomly dropped three cities from it. The estimate is similar to the main results, which demonstrates that the results are reliable.

The CIs and HIs of different groups in different years are presented in **Table 3**. All the CIs were positive, meaning that there is a statistically pro-rich health inequity and that excellent health is more concentrated in the rich economic class. The CIs increased with the years in the control group, while those for the intervention groups decreased after the air pollution controls. After subtracting the contributions of health need variables from the CIs, all HIs were positive, which means that there is a pro-rich health inequity. After the air pollution controls, the HI index in the intervention group decreased from 0.101 to 0.090 in 2013 and 2018, respectively (panel A). The HI index in the intervention group treated in 2015 decreased from 0.090 to 0.085 in 2013 and 2018, respectively (panel B). The HI index increased from 0.020 to 0.096 in the control group. The increase in pro-rich inequity in the intervention group treated in 2018 (0.089, 0.098, and 0.099) was reduced after air pollution controls (panel A). The HI index decreased after air pollution controls in the intervention group treated in 2018.

DISCUSSION

Our study examined the impact of air pollution controls on health and health inequity in China using the concentration index and the horizontal index for the first time. Our findings have shown that the control of air pollution is effective for health, and there is a lagged and lasting positive effect on health. Another interesting point is that air pollution controls generate the largest effect on the poorest population. We also noted that there are pro-rich health inequities in air pollution controls. Health inequity was reduced after air pollution controls, which means that the AQG set by the WHO can encourage China to reduce health risks and inequity from air pollution.

Although substantial studies focus on the relationship between air pollution and health outcomes, very few studies focus on air quality controls and the long-term impact of air pollution controls on health through longitudinal surveys, especially in older people. Our research offers new inspiration for other developing countries to manage air quality and achieve health equity. The current study found that air pollution controls contribute to improved health and that the positive effect is delayed by 1 year, which is consistent with earlier studies conducted in other countries like the United Kingdom. Previous studies have found that people exposed to green spaces may have health benefits by engaging in beneficial physical activity and ameliorating their stress response. This study is also consistent with the previous research in Europe [36], which indicated that the implementation of emission abatement strategies produces positive effects on the reduction of multiple-pollutant concentrations and that air quality improvement policies have beneficial effects on health. We also found that the impact of air pollution controls increases with the time of implementation. The implications of the study are clear: environmental controls could be crucial in the fight to improve health over the long term. AQG has a positive impact on air pollution controls and improves health.

The greatest health benefits from improvements in PM_{10} and $PM_{2.5}$ levels are obtained by people with the lowest socioeconomic status. This is in line with published work exploring the relationship between socioeconomic status, air pollution, and health. The possible reason is that poor individuals are more vulnerable to air pollution and have the highest exposure due to work environments such as outdoor work and more contaminated occupations [3], and they are more likely to be exposed to pollutants from indoor heating and cooking. Another possible mechanism is that they have limited options for self-protection against air pollution, such as wearing masks and buying air purifiers. So, the poorest people are more sensitive to environmental changes and air pollution controls

TABLE 2 | The effect of air pollution controls on health for subjects with different economic statuses (Impact of Air Pollution Controls, Shaanxi, China, 2024).

	Economic status				
	Poorest group	**Poorer group**	**Medium group**	**Richer group**	**Richest group**
Panel A					
Did	1.23 (0.51–2.95)	0.32 (0.15–0.70)***	0.89 (0.40–1.98)	0.31 (0.16–0.63)***	0.76 (0.44–1.32)
Current year of air pollution control	1.08 (0.31–3.75)	0.34 (0.14–0.81)**	1.06 (0.42–2.64)	0.22 (0.08–0.54)***	0.76 (0.40–1.43)
3 years after air pollution control	3.11 (0.31–30.91)	0.45 (0.10–2.03)	1.01 (0.20–5.15)	0.10 (0.02–0.49)***	0.73 (0.25–2.13)
Did_{t-1}	1.41 (1.01–2.08)**	0.88 (0.42–1.84)	0.52 (0.23–1.12)*	0.98 (0.53–1.84)	1.36 (0.85–2.20)
Current year of air pollution control	1.44 (0.98–2.12)*	0.83 (0.38–1.80)	0.53 (0.24–1.18)	0.89 (0.45–1.76)	1.43 (0.82–2.53)
3 years after air pollution control	2.45 (1.02–7.07)**	0.66 (0.16–2.65)	0.62 (0.16–2.42)	0.68 (0.20–2.25)	1.58 (0.58–4.31)
Controls	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes
Observation	3,885	3,886	3,886	3,886	3,885
Panel B					
Did	2.02 (0.43–9.56)	0.65 (0.16–2.50)	0.14 (0.04–0.45)**	0.85 (0.32–2.27)	1.16 (0.53–2.53)
Current year of air pollution control	1.50 (0.65–3.45)	0.57 (0.27–1.21)	0.47 (0.26–0.85)**	0.95 (0.58–1.56)	1.10 (0.74–1.63)
3 years after air pollution control	0.45 (0.08–2.35)	4.18 (1.02–17.14)**	2.09 (0.14–11.58)	1.01 (0.38–2.66)	0.81 (0.37–1.75)
Did_{t-1}	4.48 (1.32–15.18)**	0.50 (0.16–1.53)	0.78 (0.30–2.07)	1.86 (0.82–4.22)	2.12 (1.09–4.13)**
Current year of air pollution control	5.07 (1.45–17.73)***	0.60 (0.17–2.11)	0.75 (0.26–2.23)	2.15 (0.26–2.23)	3.76 (1.09–4.13)***
3 years after air pollution control	16.65 (1.01–278.22)**	0.93 (0.11–7.82)	0.68 (0.11–4.28)	2.91 (0.26–2.23)	9.83 (2.0–48.28)***
Controls	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes
Observation	2,432	2,432	2,433	2,432	2,432

*Note: Panel A means air pollution controls identified by PM_{10}, and Panel B means air pollution controls identified by $PM_{2.5}$. Did means the interaction term (Treat*post) between the air pollution controls and year dummy variables. Did_{t-1}, means the interaction term (Treat*post $_{t-1}$) between the air pollution controls and one-year lag dummy variables. Did is the net effect of air pollution control on health, and did_{t-1}, indicates the net effect of air pollution control with a one-year lag on health.* *p< 0.1; **p< 0.05; ***p< 0.01.

TABLE 3 | Horizontal inequity of self-reported health for the different groups at different times with a one-year lag (Impact of Air Pollution Controls, Shaanxi, China, 2024).

	Control group			Intervention group treated in 2015			Intervention group treated in 2018		
	2013	**2015**	**2018**	**2013**	**2015**	**2018**	**2013**	**2015**	**2018**
Panel A									
Contribution of need variables (age-sex)	0.050	0.019	0.027	0.024	0.011	0.030	0.020	0.033	0.032
Contribution of control variables	0.197	0.425	0.479	0.364	0.344	0.370	0.354	0.418	0.428
Residual	–0.177	–0.320	0.384	–0.263	–0.244	–0.280	–0.265	–0.320	–0.329
CI	0.071***	0.125***	0.124***	0.124***	0.111***	0.120***	0.109***	0.130***	0.131***
HI	0.020	0.106	0.096	0.101	0.099	0.090	0.089	0.098	0.099
Observation	713	713	713	1,983	1,983	1,983	3,786	3,786	3,786
Panel B									
Contribution of need variables (age-gender)				0.030	0.026	0.025	–0.016	0.028	0.044
Contribution of control variables				0.348	0.363	0.335	0.327	0.335	0.364
Residual				–0.258	–0.268	–0.249	–0.215	–0.254	–0.294
CI				0.120***	0.121***	0.110***	0.096***	0.109***	0.113***
HI				0.090	0.095	0.085	0.112	0.088	0.069
Observation				2,473	2,473	2,473	1,584	1,584	1,584

Note: Control group means that the subjects of the city's annual average concentration of PM_{10} did not meet the interval released by the WHO. Intervention group in 2015 means that subjects living in the cities that implemented the air pollution controls in 2015 (annual average concentration of PM_{10} or $PM_{2.5}$ decreased by 20 ug/m^3 and 10 ug/m^3 in 2015). Intervention group in 2018 means that subjects living in the cities that implemented the air pollution controls in 2018 (annual average concentration of PM_{10} or $PM_{2.5}$ decreased by 20 ug/m^3 and 10 ug/m^3 in 2018). Because all the cities' annual average concentration of $PM_{2.5}$ decreased by 10 ug/m^3 during 2013–2018, there was no control group and the values of the control group in panel B were missing. ***p< 0.01.

than the rich group. On the other hand, the health of the poorest groups is relatively bad, making them more vulnerable to health damage from air pollution than the general population.

The notion in our study that interventions at the societal level, such as improving the air quality where people live, could impact health inequalities is novel. We estimated trends in health inequities before and after air pollution controls and noted that the pro-rich health inequity decreased with the improvement in air pollution. Conversely, populations living in areas without improvements in air quality might observe an increase in income-related health inequity, which could have implications for those developing countries where environmental change remains a major challenge to achieving the SDGs. In the United Kingdom, Richard et al. conducted a cross-sectional survey and found that people living in green areas had lower inequality in mortality from all causes and circulatory diseases than those living in areas with less exposure to green spaces [37]. Greater exposure to air pollution is a driver of health inequalities found among people of low socioeconomic status [21]. The reason is that if we reduce the same amount of exposure to environmental hazards through air quality controls, the differences in vulnerability and avoidance of air pollution among populations of different socioeconomic statuses will be reduced.

This study has several limitations. First, due to the limited air quality data in China, we only used city-level data to perform the analysis. Second, the dependent variable used in this study is subjective, and we need to extend the study to objective health indicators. Third, we did not include indoor air pollution controls. Fourth, our conclusion may not be generalizable to the general population, as our sample is limited. Finally, the present study was subject to possible unobserved confounding factors, such as disability status, indoor air pollution, and so on.

Air pollution controls improved Chinese self-reported health and health equity, and the positive impacts increased year by year, which is in line with the achievement of SDG goals and AQG. The largest effects of air pollution controls were observed among the poorest population. After the air pollution controls, the concentration index and the horizontal inequity index decreased. Therefore, it is imperative for air-polluted regions to urgently foster AQG, increase government investment in air pollution controls, and scale up environmental actions to reduce the population's exposure to air pollution by reducing the health damage and health inequity caused by air pollution. In addition, promoting equal access to basic public services, focusing on environmental protection, and improving the ability of vulnerable groups to prevent health risks are also key policies to improve health equity [35].

DATA AVAILABILITY STATEMENT

Data can be obtained from the China Health and Retirement Longitudinal Study website.

ETHICS STATEMENT

The studies involving humans were approved by the Ethical Review Committee (IRB) at Peking University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization YZ, SG, and CS; Methodology XZ, ZZ, and TZ; Analysis YZ, DZ, and DC; Writing YZ and ZP; All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2024.1606956/full#supplementary-material

REFERENCES

1. In: Rosa W, editor. Goal 2. End Hunger, Achieve Food Security and Improved Nutrition, and Promote Sustainable Agriculture. *A New Era in Global Health*. New York, NY: Springer Publishing Company (2017).
2. Chen Z, Wang JN, Ma GX, Zhang YS. China Tackles the Health Effects of Air Pollution. *Lancet* (2013) 382(9909):1959–60. doi:10.1016/S0140-6736(13)62064-4
3. Jiao K, Xu M, Liu M. Health Status and Air Pollution Related Socioeconomic Concerns in Urban China. *Int J Equity Health* (2018) 17(1):18. doi:10.1186/s12939-018-0719-y
4. Li G, He Q, Shao S, Cao J. Environmental Non-Governmental Organizations and Urban Environmental Governance: Evidence From China. *J Environ Manage* (2018) 206:1296–307. doi:10.1016/j.jenvman.2017.09.076
5. Meng C, Tang Q, Yang Z, Cheng H, Li Z, Li K. Collaborative Control of Air Pollution in the Beijing–Tianjin–Hebei Region. *Environ Technol Inno* (2021) 23(2):101557. doi:10.1016/j.eti.2021.101557
6. Miao Z, Baležentis T, Shao S, Chang D. Energy Use, Industrial Soot and Vehicle Exhaust Pollution—China's Regional Air Pollution Recognition, Performance Decomposition and Governance. *Energ Econ* (2019) 83:501–14. doi:10.1016/j.eneco.2019.07.002
7. Wang T, Peng J, Wu L. Heterogeneous Effects of Environmental Regulation on Air Pollution: Evidence From China's Prefecture-Level Cities. *Environ Sci Pollut Res* (2021) 28(20):25782–97. doi:10.1007/s11356-021-12434-7
8. Zhang M, Liu X, Ding Y, Wang W. How Does Environmental Regulation Affect Haze Pollution Governance? — An Empirical Test Based on Chinese Provincial Panel Data. *Sci Total Environ* (2019) 695:133905. doi:10.1016/j.scitotenv.2019.133905

9. Guo S, Lu J. Jurisdictional Air Pollution Regulation in China: A Tragedy of the Regulatory Anti-Commons. *J Clean Prod* (2019) 212:1054–61. doi:10.1016/j.jclepro.2018.12.068
10. Chu Z, Bian C, Yang J. Joint Prevention and Control Mechanism for Air Pollution Regulations in China: A Policy Simulation Approach With Evolutionary Game. *Environ Impact Asses* (2021) 91:106668. doi:10.1016/j.eiar.2021.106668
11. Yan Y, Zhang X, Zhang J, Li K. Emissions Trading System (ETS) Implementation and its Collaborative Governance Effects on Air Pollution: The China Story. *Energ Policy* (2020) 138:111282. doi:10.1016/j.enpol.2020.111282
12. Jin Y, Andersson H, Zhang S. Air Pollution Control Policies in China: A Retrospective and Prospects. *Int J Env Res Pub He* (2016) 13(12):1219. doi:10.3390/ijerph13121219
13. Song Y, Li M, Zhang M, Sun X. Study on the Impact of Air Pollution Control on Urban Residents' Happiness From Microscopic Perspective. *J Clean Prod* (2019) 229:1307–18. doi:10.1016/j.jclepro.2019.05.070
14. Markandya A, Sampedro J, Smith SJ, Van Dingenen R, Pizarro-Irizar C, Arto I, et al. Health Co-Benefits From Air Pollution and Mitigation Costs of the Paris Agreement: A Modelling Study. *Lancet Planet Health* (2018) 2(3):e126–33. doi:10.1016/S2542-5196(18)30029-9
15. Yang M, Chou SY. The Impact of Environmental Regulation on Fetal Health: Evidence From the Shutdown of a Coal-Fired Power Plant Located Upwind of New Jersey. *J Environ Econ Manage* (2018) 89:95. doi:10.1016/j.jeem.2017.11.005
16. Xie Y, Zhao L, Xue J, Hu Q, Xu X, Wang H. A Cooperative Reduction Model for Regional Air Pollution Control in China That Considers Adverse Health Effects and Pollutant Reduction Costs. *Sci Total Environ* (2016) 573:458–69. doi:10.1016/j.scitotenv.2016.08.077
17. Chamberlain RC, Fecht D, Davies B, Laverty AA. Health Effects of Low Emission and Congestion Charging Zones: A Systematic Review. *Lancet Public Health* (2023) 8(7):e559–e574. PMID: 37393094. doi:10.1016/S2468-2667(23)00120-2
18. Tonne C, Beevers S, Armstrong B, Kelly F, Wilkinson P. Air Pollution and Mortality Benefits of the London Congestion Charge: Spatial and Socioeconomic Inequalities. *Occup Environ Med* (2008) 65(9):620–7. Epub 2008 Feb 28. PMID: 18308748. doi:10.1136/oem.2007.036533
19. Brulle RJ, Pellow DN. Environmental Justice: Human Health and Environmental Inequalities. *Annu Rev Public Health* (2006) 27(1):103–24. doi:10.1146/annurev.publhealth.27.021405.102124
20. Tilt B. China's Air Pollution Crisis: Science and Policy Perspectives. *Environ Sci Pol* (2019) 92:275–80. doi:10.1016/j.envsci.2018.11.020
21. Chuai X, Lu Y, Xie F, Yang F, Zhao R, Pang B. A New Approach to Evaluate Regional Inequity Determined by PM2.5 Emissions and Concentrations. *J Environ Manage* (2021) 277:111335. doi:10.1016/j.jenvman.2020.111335
22. Zhao Y, Hu Y, Smith JP, Strauss J, Yang G. Cohort Profile: The China Health and Retirement Longitudinal Study (CHARLS). *Int J Epidemiol* (2014) 43(1):61–8. doi:10.1093/ije/dys203
23. Gao H, Yang W, Yang Y, Yuan G. Analysis of the Air Quality and the Effect of Governance Policies in China's Pearl River Delta, 2015–2018. *Atmosphere* (2019) 10(7):412. doi:10.3390/atmos10070412
24. Idler EL, Benyamini Y. Self-Rated Health and Mortality: A Review of Twenty-Seven Community Studies. *J Health Soc Behav* (1997) 38(1):21–37. doi:10.2307/2955359
25. Callaway B, Sant'Anna PHC. Difference-in-Differences With Multiple Time Periods. *J Econom* (2021) 225(2):200–30. doi:10.1016/J.JECONOM.2020.12.001
26. Zhou Z, Zhao Y, Shen C, Lai S, Nawaz R, Gao J. Evaluating the Effect of Hierarchical Medical System on Health Seeking Behavior: A Difference-in-Differences Analysis in China. *Soc Sci Med* (2021) 268:113372. doi:10.1016/j.socscimed.2020.113372
27. Slaughter MJ. Trade Liberalization and Per Capita Income Convergence: A Difference-in-Differences Analysis. *J Int Econ* (2001) 55(1):203–28. doi:10.1016/S0022-1996(00)00087-8
28. Liu GG, Tang C, Liu Y, Bu T, Tang D. Will High-Speed Railway Influence the Healthcare Seeking Behaviour of Patients? Quasi-Experimental Evidence From China. *Health Policy Plan* (2021) 36(1 0):1633–43. doi:10.1093/heapol/czab018
29. Doorslaer E, Wagstaff A, Paci P. Equity in the Finance and Delivery of Health Care: Some Tentative Cross-Country Comparisons. *Oxford Rev Econ Pol* (1989) 5:89–112. doi:10.1093/oxrep/5.1.89
30. Van Doorslaer E, Wagstaff A, van der Burg H, Christiansen T, De Graeve D, Duchesne I, et al. Equity in the Delivery of Health Care in Europe and the US. *J Health Econ* (2000) 19(5):553–83. doi:10.1016/S0167-6296(00)00050-3
31. Van Doorslaer E, Wagstaff A, Bleichrodt H, Calonge S, Gerdtham UG, Gerfin M, et al. Income-Related Inequalities in Health: Some International Comparisons. *J Health Econ* (1997) 16(1):93–112. doi:10.1016/S0167-6296(96)00532-2
32. Wagstaff A, van Doorslaer E, van der Burg H, Calonge S, Christiansen T, Citoni G, et al. Equity in the Finance of Health Care: Some Further International Comparisons. *J Health Econ* (1999) 18(3):263–90. doi:10.1016/S0167-6296(98)00044-7
33. Wagstaff A, van Doorslaer E. Equity in Health Care Finance and Delivery. *Handbook Health Econ* (2000) 1:1803–62. doi:10.1016/S1574-0064(00)80047-5
34. Bago d'Uva T, Jones AM, van Doorslaer E. Measurement of Horizontal Inequity in Health Care Utilisation Using European Panel Data. *J Health Econ* (2009) 28(2):280–9. doi:10.1016/j.jhealeco.2008.09.008
35. Zhao Y, Zhou Z, Fan X, Nawaz R, Zhao D, Xu T, et al. Comparison of Inequity in Health-Related Quality of Life Among Unemployed and Employed Individuals in China. *BMC Public Health* (2021) 21(1):52. doi:10.1186/s12889-020-10038-3
36. Costa S, Ferreira J, Silveira C, Costa C, Lopes D, Relvas H, et al. Integrating Health on Air Quality Assessment-Review Report on Health Risks of Two Major European Outdoor Air Pollutants: PM and NO_2. *J Toxicol Env Health-pt B-crit Rev* (2014) 17(6):307–40. doi:10.1080/10937404.2014.946164
37. Mitchell R, Popham F. Effect of Exposure to Natural Environment on Health Inequalities: An Observational Population Study. *Lancet* (2008) 372(9650):1655–60. doi:10.1016/S0140-6736(08)61689-X

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COMMENTARY
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Time to Act for Clean Air for All in the WHO Eastern Mediterranean Region; Strategic Actions for the Health Sector

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Keywords: air pollution, health, WHO air quality guidelines (AQG), particulate matter, air pollutants

INTRODUCTION

The WHO Eastern Mediterranean Region (EMR), encompassing nearly 745 million people across 22 countries, faces significant environmental health challenges [1, 2]. Every year, environmental health risks cause more than one million premature deaths across the Region. Air pollution alone accounts for more than 560,000 premature deaths, with 370,000 attributed to ambient air pollution [3]. These deaths are due to five main health outcomes, including ischemic heart disease (IHD), stroke, chronic obstructive pulmonary diseases (COPD), lung cancer (LC), and acute lower respiratory infections (ALRI) [4]. There is a strong belief that these figures are underestimated due to insufficient epidemiological studies on other health outcomes, for which the causality and evidence are still evolving.

In 2019, the region recorded the second highest annual population-weighted exposure of particulate matter with aerodynamic equal to or less than 2.5 µm ($PM_{2.5}$), with an average concentration of 43.3 µg/m^3 - nine times higher than WHO Air Quality Guideline (AQG) values [3]. In addition, the region had the highest annual concentrations of nitrogen dioxide (NO_2), with an average of 47.5 µg/m^3, among WHO regions, surpassing WHO AQG values by nearly five times [5]. The region's air quality is extremely affected by natural sources, i.e., sand and dust storms (SDS), which contribute 30%–60% of the total PM levels across various EM countries [6, 7]. However, anthropogenic sources such as unsustainable development, continued urbanization, industrialization, transportation, open burning of municipal and agricultural waste, and specific sources, i.e., diesel generators, are considerable and should be addressed.

The WHO AQG 2021 indicates that air pollution has detrimental health impacts at all exposure levels, even at the lowest concentrations. A critical message of the guidelines is that each reduction in outdoor concentrations of key air pollutants yields health benefits for the exposed population [4]. This is a wake-up call to reconsider current air quality management strategies for health protection.

AIR QUALITY AND HEALTH IN THE REGION

The region is off-track; the air pollution-attributable death rate increased from 72.8 per 100,000 inhabitants in 2016 to 77.6 per 100,000 in 2019 [3]. In 15 countries in the region, the age-standardized mortality rate worsened in 2019 compared to 2016 (**Figure 1**). In only five countries the age-standardized mortality rate had slightly improved. Although 17 out of 22 countries in the region have national ambient air quality standards (NAAQS) for the key air pollutants, $PM_{2.5}$ levels were steady with no significant reduction between 2016 and 2019 (**Figure 2**) [3, 8]. This

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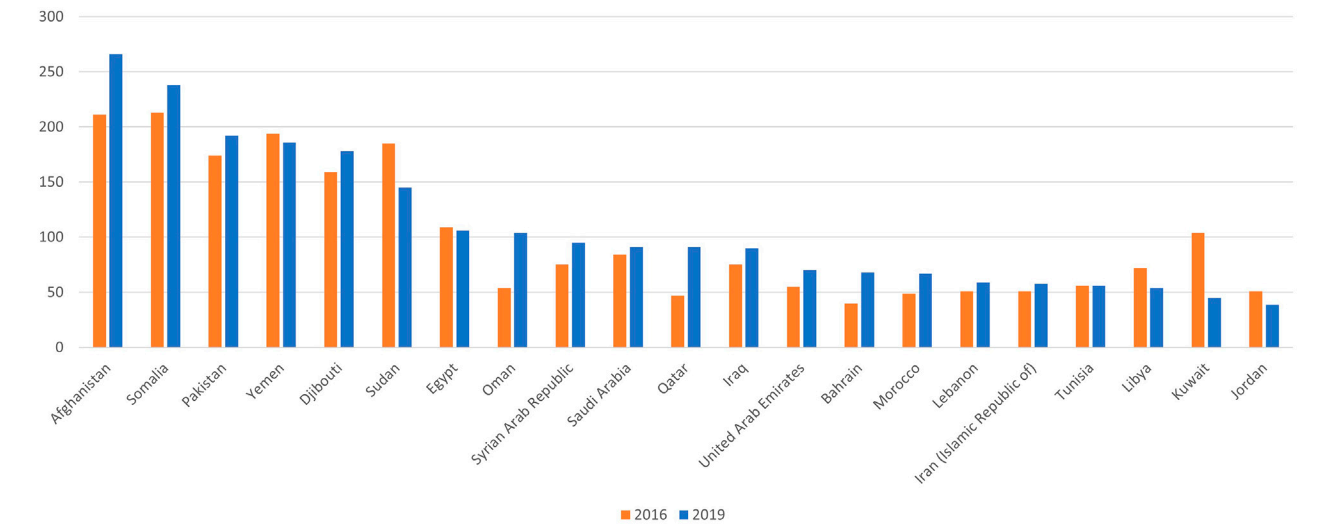

FIGURE 1 | Age-standardized death rate attributable to air pollution for each Eastern Mediterranean (EM) country in 2016 and 2019 (Eastern Mediterranean Region, 2024).

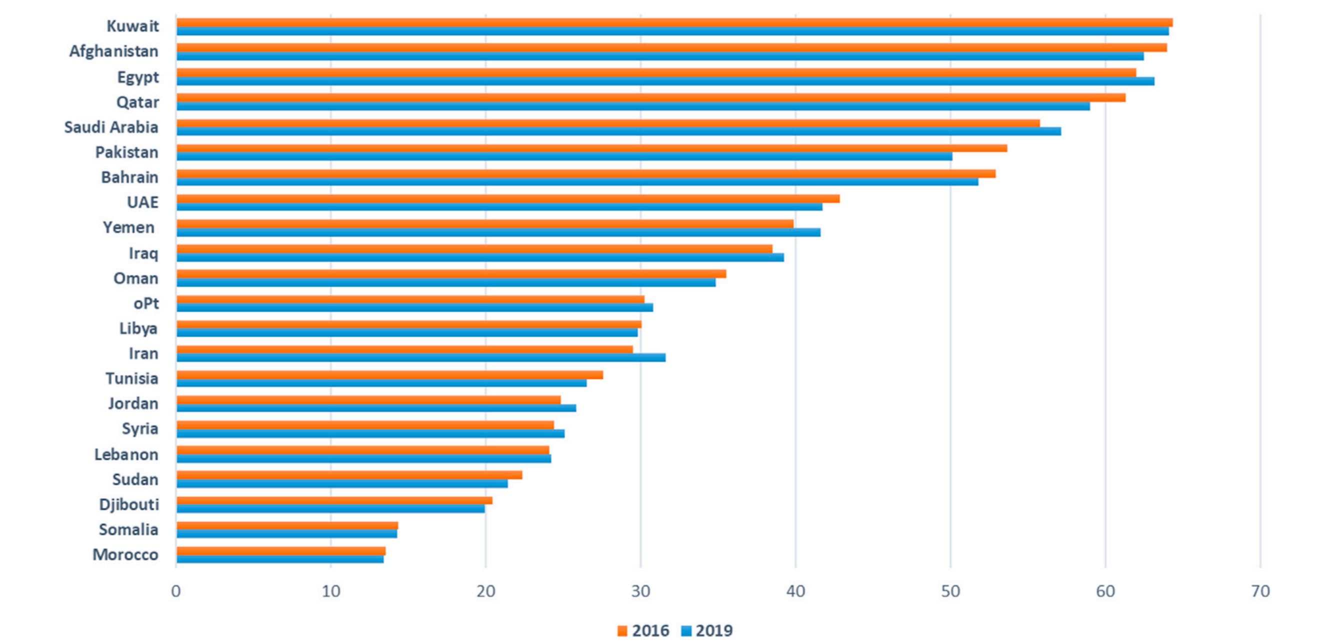

FIGURE 2 | Population-weighted exposure to Particulate Matter (PM2.5) in 2016 and 2019 by Eastern Mediterranean (EM) country (Eastern Mediterranean Region, 2024).

stagnation indicates inadequate non-health-based air quality management strategies, plans, and regulatory enforcement.

AIR QUALITY MANAGEMENT IN THE REGION

A regional survey to assess the countries' capacities in air quality monitoring and management systems in the Region was conducted through the WHO/EMR/HPD/CHE. Responses to survey were received from 16 out of 22 EM countries [Afghanistan, Egypt, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Morocco, Pakistan, Occupied Palestinian Territory (oPt), Saudi Arabia, Somalia, Sudan, Syria, Tunisia and Yemen]. According to the survey, 11 countries recognize the right to clean air, and have national or subnational air quality action plans (AQAPs). In eight countries (Egypt, Iran, Jordan, Kuwait, Lebanon, Morocco, Saudi Arabia, and Tunisia) the health component is included into the national AQAPs, and its implementation is a shared responsibility between ministries of environment and health. In Afghanistan, Iraq, and Pakistan only environmental authorities are responsible for AQAPs implementation. In Somalia, Syria, and Yemen where are no AQAPs, there are some fragmented efforts to tackle air pollution. Even though air quality management is a multi-stakeholder multi-sectoral public health issue, health sector involvement in air quality management remains limited across the Region.

STRATEGIC ACTIONS FOR HEALTH SECTOR

The health sector through leadership and intersectoral governance, evidence-based advocacy, operational programmes, surveillance, and monitoring can drive progress in tackling air pollution and obtaining short- and long-term health benefits. This includes:

Advocate for Action by Other Sectors to Reduce Air Pollution [Adopt Health in All Policies (HiAP) Approach]

While the health sector works to minimize its own emissions of key air pollutants, it is crucial to advocate for actions aimed at improving air quality beyond the health sector, such as energy, transport, housing, labor, industry, food systems and agriculture, power generation, waste management, water and sanitation, and urban planning. The health sector plays an important role in integrating health considerations into air quality policies by assessing the associated health and economic impacts of action and inaction. In addition to defining and promoting national indicators to measure progress in air quality management policies, interventions, and strategies.

Address the Root Causes of Disease

Reducing the annual number of 560,000 premature deaths associated with air pollution requires the efficient scale-up of a primary prevention strategy. Integrating air quality measures into disease prevention programmes, especially those targeting non-communicable diseases (NCDs) is essential. According to the global strategy to prevent non-communicable diseases, healthy environments, such as clean air, healthy and safe work environments, and chemical safety, are key elements in NCDs prevention, and relevant action is being called for.

Building the Capacities of the Health Sector

The health workforce needs regular training to better understand the health risks of exposure to indoor and outdoor air pollution, communicate health risks, and advise patients and vulnerable populations on personal measures to mitigate health risks from air pollution. In addition, health workforce needs skills to leverage the “health argument” for scaling up actions, engage in high-level discussions and intersectoral dialogues, monitor economic and environmental investments, and communicate health impacts with all concerned stakeholders and community.

Enhancing Surveillance and Early Warning and Alerting Systems

A robust health surveillance system is crucial for conducting health impact assessment, advancing air pollution and health research, and developing an impact-based people-centered early warning and alert system. A well-established early warning and alert system ensures that timely and actionable health messages are delivered directly to the public. Through this, the health sector empowers individuals to take proactive measures to reduce public exposure to air pollution and its health impacts while shaping policy decisions.

Conclusion

Reducing air pollution levels in the WHO EMR hinges on a robust response from the health sector. This includes advocating for actions beyond the health sectors through integrating and prioritizing associated health implications, scaling up primary prevention strategies, empowering the health workforce, and strengthening health surveillance and early warning and alert systems. By driving these strategic actions, the health sector can play a crucial role in mitigating air pollution’s impact and advancing public health across the Region.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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REFERENCES

1. World Health Organization. *WHO Eastern Mediterranean Region*. Cairo: World Health Organization (2024). Available from: https://www.emro.who.int/entity/about-us/index.html#:~:text=The%20WHO%20Regional%20Office%20for,of%20nearly%20745%20million%20people (Accessed September 26, 2024).
2. World Health Organization. *Progress on the Health-Related Sustainable Development Goals and Targets in the Eastern Mediterranean Region*. Cairo: WHO Regional Office for the Eastern Mediterranean (2023). Available from: https://applications.emro.who.int/docs/Progress-health-related-SDGs-targets-EMR-2023-eng.pdf (Accessed September 20, 2024).
3. WHO Global Health Observatory (GHO). *Air Pollution Indicators*. Geneva: World Health Organization (2024). Available from: https://www.who.int/data/gho/data/themes/air-pollution/ambient-air-pollution (Accessed September 10, 2024).
4. WHO global air quality guidelines. *Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization (2021). Licence: CC BY-NC-SA 3.0 IGO.
5. World Health Organization. *WHO Ambient Air Quality Database, 2022 Update: Status Report*. Geneva: World Health Organization; 2023. Licence: CC BY-NC-SA 3.0 IGO.
6. Faridi S, Yousefian F, Roostaei V, Harrison RM, Azimi F, Niazi S, et al. Source Apportionment, Identification and Characterization, and Emission Inventory of Ambient Particulate Matter in 22 Eastern Mediterranean Region Countries: A Systematic Review and Recommendations for Good Practice. *Environ Pollut* (2022) 310:119889. doi:10.1016/j.envpol.2022.119889
7. Hopke PK, Dai Q, Li L, Feng Y. Global Review of Recent Source Apportionments for Airborne Particulate Matter. *Sci Total Environ* (2020) 740:140091. doi:10.1016/j.scitotenv.2020.140091
8. Faridi S, Krzyzanowski M, Cohen AJ, Malkawi M, Moh'd Safi HA, Yousefian F, et al. Ambient Air Quality Standards and Policies in Eastern Mediterranean Countries: A Review. *Int J Public Health* (2023) 68:1605352. doi:10.3389/ijph.2023.1605352

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Corrigendum: Time-Trends in Air Pollution Impact on Health in Italy, 1990–2019: An Analysis from the Global Burden of Disease Study 2019

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There was an error regarding the affiliation for Paolo Lauriola. The affiliation 17 "International Society Doctors for the Environment, Milan, Italy," should be replaced with "International Network of Public Health and Environment Tracking (INPHET)."

The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way. The first published incorrect version of the article has been updated.