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Interplay of Climate Change and Air Pollution- Projection of the under-5 mortality attributable to ambient particulate matter (PM2.5) in South Asia

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ABSTRACT

Ambient fine particulate matter (PM2.5) pollution is a leading health risk factor for children under- 5 years, especially in developing countries. South Asia is a $PM_{2.5}$ hotspot, where climate change, a potential factor affecting PM2.5 pollution, adds a major challenge. However, limited evidence is available on under-5 mortality attributable to PM2.5 under different climate change scenarios. This study aimed to project under-5 mortality attributable to long-term exposure to ambient $PM_{2.5}$ $_u$nder seven air pollution and climate change mitigation scenarios in South Asia. We used a concentration-risk function obtained from a previous review to project under-5 mortality attributable to ambient $PM_{2.5}$. With a theoretical minimum risk exposure level of 2.4 μg/m^3, this risk function was linked to gridded annual PM2.5 concentrations from atmospheric modeling to project under-5 mortality from 2010 to 2049 under different climate change mitigation scenarios. The scenarios were developed from the Aim/Endues global model based on end-of-pipe (removing the emission of air pollutants at the source, EoP) and 2 °C target measures. Our results showed that, in 2010–2014, about 306.8 thousand under-5 deaths attributable to $PM_{2.5}$ occurred in South Asia under the Reference (business as usual) scenario. The number of deaths was projected to increase in 2045–2049 by 36.6% under the same scenario and 7.7% under the scenario where EoP measures would be partially implemented by developing countries (EoPmid), and was projected to decrease under other scenarios, with the most significant decrease (81.2%) under the scenario where EoP measures would be fully enhanced by all countries along with the measures to achieve 2 °C target (EoP-maxCCSBLD) across South Asia. Country-specific projections of under-5 mortality varied by country. The current emission control strategy would not be sufficient to reduce the number of deaths in South Asia. Robust climate change mitigation and air pollution control policy implementation is required.

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1. Introduction

Exposure to ambient fine particulate matter less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) is a leading health risk factor (Global Burden of Disease [GBD], 2020). In 2017, approximately 4.9 million premature deaths were attributed to air pollution, mostly in developing

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countries (GBD, 2018). Air pollution is also a leading health risk factor for children (WHO, 2018), with those aged under 5 years being particularly vulnerable due to their small airways, immature respiratory and immune systems, faster breathing, and higher ventilation rate than body weight (Bateson and Schwartz, 2008; Yang et al., 2020). Under-5 mortality is a key indicator of the public health and social development of a country. Quantitative goals to reduce under-5 mortality have been a part of several global agendas in the past as well as critical objectives of Sustainable Development Goal 3 (SDG3), which aims to reduce under-5 mortality to at least 25 deaths per 1000 live births and calls for a substantial reduction in deaths and illnesses from air pollution (UN-IGME, 2021).

South Asia, identified as a "Less Developed Region," by the United Nations, Department of Economic and Social Affairs (UNDESA) (UNDESA, 2022) has been recognized as a $PM_{2.5}$ hotspot, with a substantial increase in population-weighted $PM_{2.5}$ concentration in recent years (Krishna, 2017). Due to unplanned urbanization, rapid industrialization, and fossil fuel burning, roughly 620 million children in this region are exposed to polluted and toxic air (Health Effects Institute, 2020). Climate and weather have strong influences on the spatial and temporal distribution of pollutant concentrations through different pathways (Kinney, 2018; Zhang et al., 2018). Air pollution can also affect climate change, and their joint impact causes severe health outcomes (Silva et al., 2013; Orru et al., 2017). Short-lived climate pollutants (SLCPs), such as black carbon (BC), ozone, methane, and hydrofluorocarbons, exert a warming influence on climate. Recently, a reduction in SLCP emission has been recognized to have potential co-benefits of mitigating climate change and reducing adverse health effects (Hanaoka and Masui, 2020). Studies have suggested that global population-weighted $PM_{2.5}$ concentrations have increased by 5% from pre-industrial times to the present (Fang et al., 2013), and as global climate continues to change, the impact of air pollution is likely to be aggravated in the future. Air pollution-related adverse health outcomes are becoming graver in South Asia, as this area represents one of the most vulnerable regions to global climate change (IPCC, 2022).

To date, several studies have projected air pollution-related mortality in the context of climate change, with a limited focus on premature deaths among adult populations (Tagaris et al., 2010; Silva et al., 2016, Chowdhury et al., 0.2018, Xu et al., 2021; Wang et al., 2022). The impact of long-term ambient $PM_{2.5}$ exposure on under-5 mortality in South Asia under different climate change mitigation scenarios has yet to be explored. Projecting under-5 mortality attributable to ambient $PM_{2.5}$ under different climate scenarios will not only provide insights into potential health risks related to climate change in the future but also add scientific support to policies to reduce long-term particulate matter and SLCP emissions, as well as specific interventions to reduce their health burdens. To address the current research gap, the present study aimed to project under-5 mortality attributable to ambient $PM_{2.5}$ under several hypothetical air pollution and climate change mitigation scenarios for the period 2010–2049. In the current study, our approach to under-5 mortality was based on a demographic definition, specifically referring to the mortality of children under −5 years of age. Additionally, we maintained consistency with our previous study (Anita et al., 2023) by defining long-term exposure as post-birth exposure.

2. Materials and methods

2.1. Study setting

The present study was designed to project under-5 mortality attributable to future ambient $PM_{2.5}$ emission in the entire South Asia region and each constituent country under different climate change mitigation scenarios. South Asia comprises eight countries: Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka. It is a densely populated region with a population size of about 2 billion people , i.e., 25.0% of the world population (UN-DESA, 2022), with a fast-growing economy.

2.2. Ambient $PM_{2.5}$ concentration projection

We used the aerosol concentration data with a grid resolution of 1.4*1.4° (~150 km × 150km) obtained from simulation with the global chemistry-aerosol transport model CHASER-V4 (Chemical reactions AGCM for the Study of Atmospheric Environment and Radiative Forcing Version4) (Sudo and Akimoto, 2007; Sekiya and Sudo, 2014; Nakajima et al., 2020; Sekiya et al., 2018, 2023). The CHASER model, based on the climate simulation framework of the Model for Interdisciplinary Research on Climate (MIROC), simulates detailed processes of atmospheric chemistry and aerosols partly in cooperation with the aerosol transport model SPRINTARS (Spectral Radiation-Transport Model for Aerosol Species) (Takemura et al., 2005, 2009). CHASER calculates the concentrations of 92 species through 280 chemical reactions (gaseous, aqueous, and heterogeneous chemical reactions) considering the chemical cycle of O_3–HOx–NOx–CH_4–CO along with oxidation of non-methane volatile organic compounds (NMVOCs) for both anthropogenic and biogenic components (Miyazaki et al., 2017). It also simulates the detailed chemistry of SO_4^{2-}-NO_3^--NH_4^+ considering gas and aqueous-phase oxidation of SO_2 with online calculation of the pH value of cloud droplets. The BC aging process due to condensation of SO_4^{2-} and semi-volatile NMVOCs onto its surface is also taken into account to represent the changes in hygroscopicity of BC in the air. The formation of Secondary organic aerosols (SOAs) is simulated in the chemical processes of oxidation of NMVOCs including aromatics, isoprene, and terpenes. The chemistry and aerosol components of the model are driven by the direct emissions of NOx, CO, NMVOCs, CH_4, SO_2, DMS (dimethyl sulfide), NH_3, BC, and OC. In this study, we use the simulated concentrations of ammonium sulfate $(NH_4)_2 SO_4$, ammonium nitrate NH_4NO_3, organic carbon (OC) of both the anthropogenic and biogenic origins, and black carbon (BC) for representing $PM_{2.5}$. Since these types of aerosols are treated mostly as fine particles (<2.5 μm) in the model, all the components of concentrations are used without any size segregation.

2.3. SLCP mitigation scenarios

The present study used $PM_{2.5}$ concentrations projected under several hypothetical mitigation scenarios categorized into the following two groups: "End-of-Pipe (EoP) only" scenarios, where devices to remove SLCPs would be installed at emission sources to directly reduce the emission of particular pollutants, and "EoP & 2 °C target" scenarios, where measures to achieve the, to limit the global average temperature rise to well below 2 °C (2 °C target)would be implemented in addition to EoP measures (Hanaoka and Masui, 2020). "EoP only" scenarios were further divided into the EoPmid and EoPmax scenarios based on the adoption and implementation of EoP measures. Here EoPmid refers to the scenario where EoP measures are expected to be implemented by all developed countries by 2050, and in developing countries by about an additional 50% compared with the current level and EoPmax refers to the maximum implementation of EoP measures all over the world. "EoP & 2 °C target" scenarios included combinations of various mitigation measures other than EoP measures, e.g., enhancement of carbon sequestration and storage (CCS), enhancement of renewable energy (RES), intensive electrification in buildings (BLD), and intensive electrification in the transport sector (TRT) (Table S1). These scenarios were simulated on the basis of a three-stage analysis, i.e., setting up socio-economic scenarios qualitatively and quantitatively with the Shared Socioeconomic Pathway (SSP) 2 as a reference (stage 1), determining the future final service demands by each sector based on socioeconomic dynamics such as future population and GDP as references (stage 2), and selecting an ideal technology using a global technology bottom-up model, named the Asia-Pacific Integrated Model-Endues AIM/Endues [Global] model (stage 3), as described previously (Hanaoka et al., 2014; Hanaoka and Masui, 2018, 2020; Nakajima et al., 2020). These scenarios would also contribute to the changes in the global temperature as a previous study showed the reference scenario will increase the global mean surface air temperature by about1.0 °C by 2050, whereas the temperature will be decreased under the EoPmidCCSBLD and EoPmaxCCSBLD scenarios by 0.31 °C and 0.33 °C by 2050, respectively (Nakajima et al., 2020).

The Reference scenario is the business-as-usual scenario, which assumes that the current trend of air pollution control and climate change mitigation policies continues. We projected under-5 mortality attributable to ambient $PM_{2.5}$ under the representative scenarios (i.e., Reference, EoPmid, EoPmax, EoPmidRESTRT, EoPmaxCCSBLD, EoPmidRESBLDTRT, and EoPmaxCCSBLD) in South Asian countries for 2010–2049, with years 2010–2014 set as the baseline period representing the current situation. We projected under-5 mortality in South Asia for both 2045–2049 and 2030–2034 (near-term future), as 2030 is considered an important year both in terms of fulfilling SDGs and being one of the milestone years for achieving long-term mitigation goals. On the other hand, with the availability of modeled data till 2049, we had considered 2045–2049 as long-term aligned with the stipulations of the Paris Agreement 2015. This agreement emphasizes limiting global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. countries must reduce their greenhouse gas emissions to 'net zero' by 2050 (UNFCCC, 2015). We also projected under-5 mortality in each of the eight countries in South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal, the Maldives, Pakistan, and Sri Lanka).

2.4. Population data

We used gridded total population projections under SSP2 from the model. To prepare gridded under-5 population data, we obtained under-5 mortality rates in the eight countries for the baseline year 2010 and national-level population data and future projections of both total population and under-5 population sizes (medium fertility variant) from the UN data repository (World Health Organization, 2018, from https://population.un.org/wpp/Download/Standard/Population/). We computed the gridded under-5 population by multiplying the gridded total population by the proportion of the national under-5 population. All-age and under-5 population data were collected from 2010 to 2050. The annual under-5 population for each corresponding grid of countries was projected using linear interpolation for the 5-year interval dataset.

We considered the under-5 mortality rate in 2010 of each country as a fixed value throughout the entire estimation, assuming no change in under-5 mortality rates from 2010 to 2049. The under-5 mortality rates per thousand live births in 2010 in South Asian countries were as follows: Bangladesh, 49.1; Bhutan, 42.4; Afghanistan, 87.8; India, 58.2; Maldives, 13.9; Nepal, 45.9; Pakistan, 87.1; and Sri Lanka, 11.4. The equations used to prepare the dataset are described in detail in the Supplementary document.

2.5. Projection of under-5 mortality attributable to ambient $PM_{2.5}$

To project under-5 mortality attributable to ambient $PM_{2.5}$ for each grid i (Mi), we multiplied the under-5 population of each grid (Pop_u5_i) by the mortality rate of under-5 children (m_0) in 2010 for the country and the population attributable fraction of the corresponding grid i (PAF_i), as follows:

$$M_i = Pop\_u5_i \times m_0 \times PAF_i$$

PAF_i was estimated for each grid i as

$$PAF_i = (RR_i - 1) / \ RR_i$$

where RR_i is the relative risk of each grid i for the $PM_{2.5}$ concentration (C_x) greater than the reference concentration (C_f). We calculated the relative risk using the log-linear equation (Anenberg et al., 2010), where

$$RR_i = exp\left[\beta\left(C_x - C_f\right)\right] \quad if \ \ C_x > C_f$$

$$RR_i = 1 \quad if \ \ C_x \leq C_f$$

We used 2.4 μg/m^3 as C_f based on previous reports (Burnett et al., 2018; Wang et al., 2022). We intended to adopt a more localized and region-specific approach to capture the nuanced health burden, requiring parameters tailored to the South Asian context. Due to the lack of sufficient epidemiological evidence on the association of long-term (post-birth ambient $PM_{2.5}$ exposure with under-5 mortality, we conducted a review (Anita et al., 2023) to generate the risk function used for this projection and found only one study, which made a log-linear function., The value of the coefficient beta (β)was obtained from one included previous cohort study of under-5 child survival in India (Liao et al., 2022) of the review mentioned above.

We summed up the number of M_i for each year for each country. This analysis was performed for all seven mitigation scenarios. All statistical analyses and calculations were performed, and all figures were produced, using R version 4.0.5.

3. Results

3.1. Projection of ambient $PM_{2.5}$ concentration from modeled data

The annual mean $PM_{2.5}$ concentration during the baseline period in South Asia was 16.2 μg/m^3. This value was projected to increase in the 2040s across the region under the Reference (25.0 μg/m^3) and EoPmid (19.9 μg/m^3) scenarios and decrease under the other scenarios (Fig. 1). In 2045–2049, mean $PM_{2.5}$ concentrations ranged from 5.5 μg/m^3 under the EoPmaxCCSBLD scenario to 14.5 μg/m^3 under the EoPmax scenario.

Fig. 2 shows the spatial distribution of $PM_{2.5}$ concentrations (A) and changes in ambient $PM_{2.5}$ concentration under different scenarios in the late 2040s (B). Under the Reference scenario, $PM_{2.5}$ concentrations were projected to increase in 2045–49 in most parts of South Asia, especially in the central and northwestern parts. This increasing trend was mostly expected to continue under the EoPmid scenario. However, the distribution of $PM_{2.5}$ concentrations showed a gradual decreasing trend under the EoPmax scenario across the entire region, with notable decreases under the EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios (Fig. 2).

There were also individual trends in annual $PM_{2.5}$ concentrations in each South Asian country. In all countries, ambient $PM_{2.5}$ concentrations were projected to increase in 2045–2049 relative to the baseline period under the Reference scenario. Under the EoPmid scenario, however, $PM_{2.5}$ concentrations were projected to increase in the late 2040s in six countries (Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka) relative to the baseline period, although there was no steady trend. Each of these six countries showed a different pattern of increasing/decreasing $PM_{2.5}$ concentrations in 2010–2049. On the other hand, under the EoPmax scenario, $PM_{2.5}$ concentrations were projected to decrease in 2044–2049 relative to the baseline period in all countries, with Afghanistan and Pakistan showing the largest decline around 2030–2034. As for the other scenarios, a steadily decreasing trend was observed for all eight countries over the period 2010–2049, with the smallest value observed under the EoPmaxCCSBLD scenario. However, under the EoPmidCCSBLD scenario, while most countries showed the lowest $PM_{2.5}$ concentration in 2045–2049, Afghanistan, Pakistan, Sri Lanka, and the Maldives showed the lowest concentration in 2040–2044. Under all scenarios, changes in $PM_{2.5}$ concentration were most significant in Bangladesh, India, Pakistan, and Nepal (Fig. S1).

3.2. Under-5 mortality attributable to ambient $PM_{2.5}$

The number of under-5 deaths attributable to $PM_{2.5}$ during the baseline period was 306.8 thousand and was projected to increase to

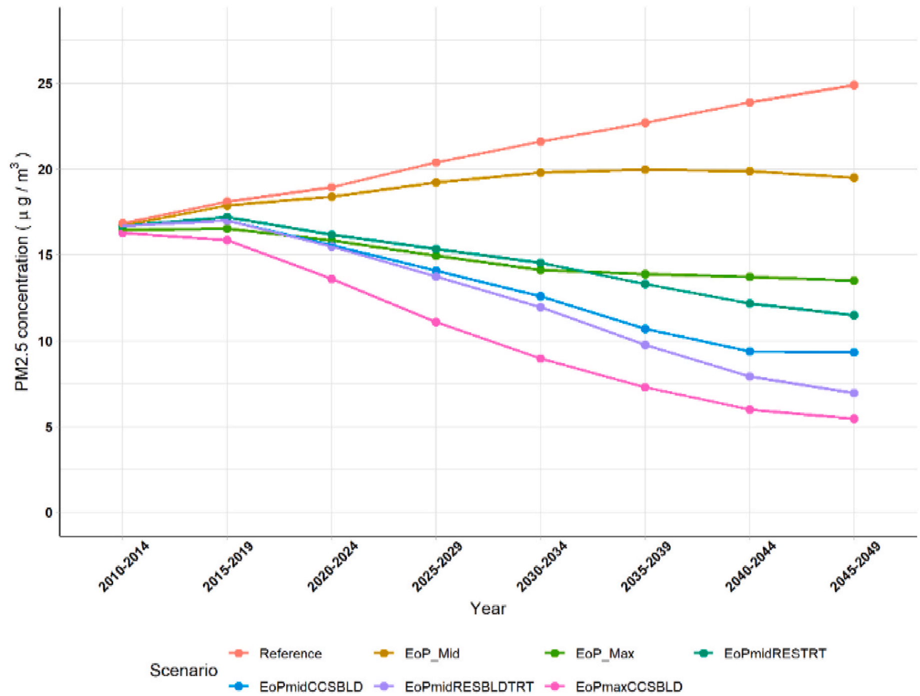

Fig. 1. Annual mean concentration of PM2.5 (μg/m3) across South Asia from 2010 to 2049 in five-year interval under Reference, EoPmid, EoPmax, EoPmidRESTRT, EoPmidCCSBLD, EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios.

419.1 thousand in 2045–2049 under the Reference scenario (Fig. S2). Fig. 3 shows the changes in the number of under-5 deaths in 2045–2049 under all seven scenarios. Under the Reference scenario, the number of deaths was projected to increase by 112.4 thousand (36.6%) in 2045–2049. A gradual increase in the number of under-5 deaths in 2045–2049 was observed under the EoPmid scenario, by approximately 23.7 thousand (7.7%). The projected under-5 mortality showed a decrease in 2045–2049 under the other scenarios, with the EoPmaxCCSBLD scenario giving the highest reduction of 248.9 thousand (81.1%), followed by the EoPmidRESBLDTRT scenario giving a reduction of roughly 222.9 thousand (72.5%). Under the EoPmax, EoPmidRESTRT, and EoPmidCCSBLD scenarios, under-5 mortality was projected to decrease by 79.21 thousand (25.8%), 122.8 thousand (40.0%), and 183.4 thousand (59.8%), respectively, in 2045–2049 (Fig. 3). A similar trend of change was observed in near-term future projections for 2030–2034 (Table 1), with an increase of 84.6 thousand (27.6%) under the Reference scenario and 52.5 thousand (17.1 %) under the EoPmid scenario. On the other hand, the attributable mortality is likely to be reduced under other scenarios with the highest reduction of 163.1 thousand (53.1%) under the EoPmaxCCSBLD scenario, followed by 107.8 thousand (35.1%) under the EoPmidRESBLDTRT scenario, and 96.4 thousand (31.4%) under the EoPmidCCSBLD scenario.

In country-specific projections, the under-5 mortality was expected to increase in 2045–2049 relative to that in the baseline period in Bangladesh (4.5%), India (29.3%), Bhutan (31.7%), Nepal (33.5%), Afghanistan (99.5%), and Pakistan (99.7%) under the Reference scenario, whereas the under-5 mortality was expected to decrease in 2045–2049 in Sri Lanka (8.5%) and the Maldives (4.1%) under the same scenario (Fig. S3). Changes in the burden of under-5 mortality varied by country under different scenarios (Fig. 4). Under the EoPmid scenario, under-5 mortality was expected to increase in 2045–2049 relative to that in the baseline period in Afghanistan (47.5%), Bhutan (4.6%), India (0.6%), Nepal (4.5%), and Pakistan (62.3%), and decrease in Bangladesh (12.5%) and Sri Lanka (21.2%). Under the EoPmax scenario, the under-5 mortality was expected to decrease in 2045–2049 relative to that in the baseline period in Afghanistan (3.6%), Bangladesh (34.2%), Bhutan (28.3%), India (32.9%), Nepal (28.0%), and Sri Lanka (21.2%), but was expected to increase in Pakistan (20.5%). In the Maldives, under-5 mortality was expected to decrease in 2045–2049 under all scenarios, it is likely to be almost zero under the EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios. In the entire region of South Asia, under-5 mortality was expected to decrease steadily under all "EoP & 2 °C target" scenarios, with the most significant decrease expected under the EoPmaxCCSBLD scenario, followed by the EoPmidRESBLDTRT and EoPmidCCSBLD scenarios.

In near-term future projections for 2030–2034, countries in South Asia generally showed a decreasing trend in under-5 mortality under most scenarios relative to the baseline period (Table S2), although country-by-country variations were noted. Under the Reference and EoPmid scenarios, most counties showed an elevated number of under-5 deaths, with Pakistan showing the most significant increase (57.0% and 46.9%, respectively), followed by Nepal (30.1% and 19.9%, respectively), Afghanistan (43.6% and 28.4%, respectively), and India (24.3% and 13.3%, respectively). On the other hand, Sri Lanka and the Maldives showed decreases by 2.1% and 98.5% under the Reference scenario, respectively, and by 8.5% and 98.7% under the EoPmid scenario, respectively. Under the other scenarios, all countries showed decreases, except in Pakistan where increases were observed under the EoPmax (11.5%) and EoPmidRESTRT (7.0%) scenarios. Among these results, the most significant decrease was observed under the EoPmaxCCSBLD scenario in three countries (Bangladesh, 13695; India, 127492; Pakistan, 18462) in 2030–2034 and in four countries (Bangladesh, 21633; India, 118396; Pakistan, 33898; and Nepal, 3198) in 2045–2049, while moderate changes were observed in other countries.

4. Discussion

In the present study, we have projected the burden of under-5 mortality attributable to ambient $PM_{2.5}$ under seven hypothetical air pollution and climate change mitigation scenarios. To our knowledge, this is the first study that has attempted to link air pollution and climate change with under-5 mortality in South Asia. Our results provide an overview of the current and future situation of under-5 mortality in South Asia, revealing that the mortality burden is likely to increase

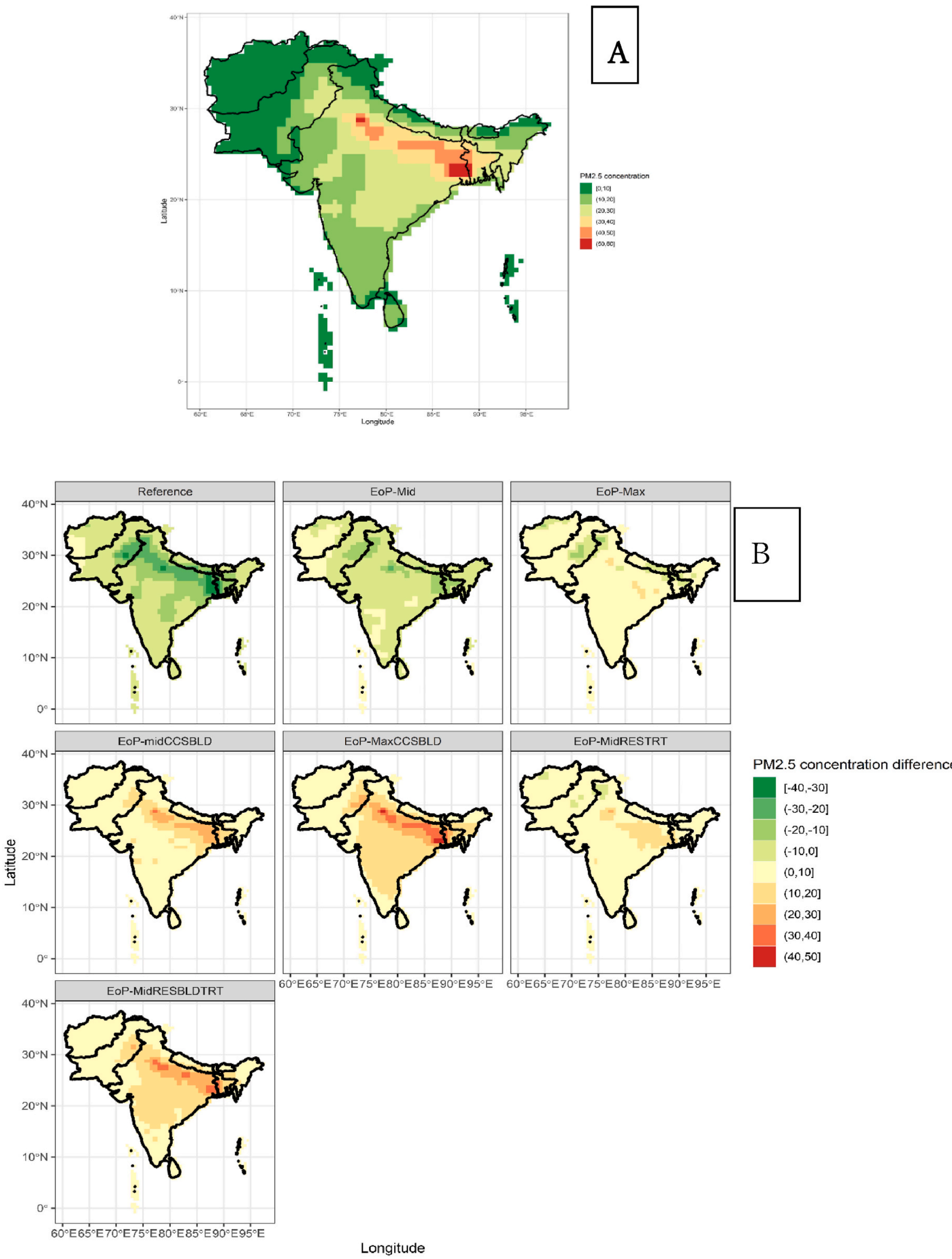

Fig. 2. Spatial distribution of ambient PM2.5 in South Asia at the baseline period (2010–2014) (A) and the changes in ambient $PM_{2.5}$ concentration in 2045-49 under Reference, EoPmid, EoPmax, EoPmidRESTRT, EoPmidCCSBLD, EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios compared to PM2.5 concentration of the baseline period (B).

under the Reference scenario as well as the EoPmid scenario across all of South Asia. To reduce avoidable under-5 deaths from air pollution, it is essential to not only minimize air pollutant emissions but also implement mitigation measures to achieve the 2 °C target.

Our analysis revealed that ambient $PM_{2.5}$ concentrations in South Asia are likely to increase in the near and far future under the Reference scenario in the context of rapid industrial development and urbanization in this region, consistent with previous studies reporting an increase in global annual mean $PM_{2.5}$ concentration attributable to GHG-induced warming in most regions in the world, including South Asia, by the end of the 21st century (Silva et al., 2017; Park et al., 2020).

The results of the present study also suggest that the burden of under-

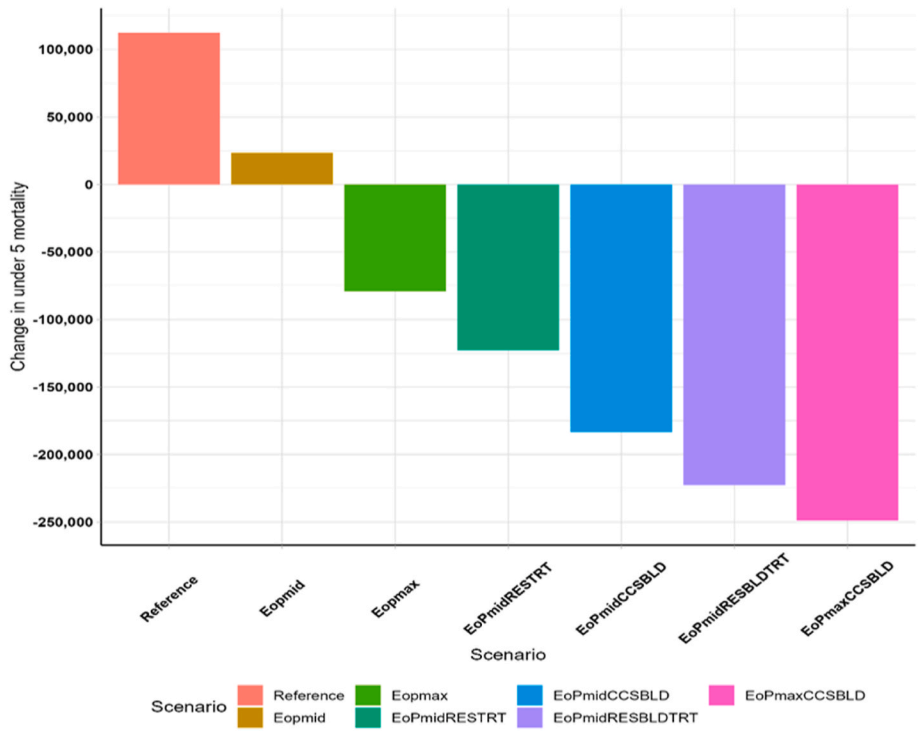

Fig. 3. Changes in the number of ambient PM2.5 attributable deaths among children below 5 years of age to in 2045–2049 from the baseline period (2010–2014) in South Asia under Reference, EoPmid, EoPmax, EoPmidRESTRT, EoPmidCCSBLD, EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios.

Table 1
Changes in under-5 mortality (U5M) in 2030–2034 under seven different scenarios.

Scenario	U5M (in thousands) in the baseline period	U5M (in thousands) in 2030–2034	Change (%) in U5M in 2030–2034 from the baseline period
Reference	306.7	391.3	27.6
EoPmid		359.2	17.1
EoPmax		256.1	−16.4
EoPmidRESTRT		260.1	−15.2
EoPmidCCSBLD		210.3	−31.4
EoPmidRESBLDTRT		198.9	−35.1
EoPmaxCCSBLD		143.6	−53.1

5 mortality will increase as the level of $PM_{2.5}$ increases in the coming years. In recent years, several studies have provided compelling evidence about an elevated risk of adult mortality due to increased exposure to higher $PM_{2.5}$ concentrations in the current time (Cohen et al., 2017; Li et al., 2018, GBD,2018, GBD,2020) and also in the future (Goto et al., 2016). Furthermore, studies have also shown evidence of an increase in child mortality ifor acute lower respiratory infections (ALRI) resulting from exposure to air pollution (Lelieveld et al., 2018). Our findings align with the results of the aforementioned studies regarding the increase in attributable mortality for higher $PM_{2.5}$ concentrations.

In the present study, under-5 mortality was projected to decrease under scenarios involving 2 °C target measures across all of South Asia as well as in individual countries in 2045–2049 and 2030–2034 relative to that projected under the Reference scenario. Specifically, under-5 mortality declined drastically across South Asia under the EoPmaxCCSBLD scenario, which is an ideal scenario where coal-fired power generation with CCS is to be enhanced and full acceleration in the intensiveness of the electrification rate, especially in the residential and commercial sector takes place both in developed and developing countries. These findings support evidence from previous studies in China (Xu et al., 2021) and India (Chowdhury et al., 2018) regarding the decrease in premature mortality in representative concentration pathway (RCP) 4.5, in which new and effective strict climate policies would be enforced among other interventions. In addition, our results are in line with the findings of an earlier study regarding the link between GHG control initiatives and a substantial reduction in child morbidity in the United States (Perera et al., 2020), and also indicate that SLCP mitigation measures can control the impact of climate change and reduce air pollutant emission, subsequently leading to a reduction in associated adverse health outcomes.

The present study revealed that, in the context of global climate change, a higher concentration of ambient $PM_{2.5}$ will eventually increase the burden of under-5 mortality over the years, unless proper air pollution control and SLCP mitigation measures are jointly implemented across South Asia. The country-specific analysis revealed a significant increase in the number of under-5 deaths in countries with a large population (India, Pakistan), a higher ambient $PM_{2.5}$ concentration (India, Pakistan, Nepal), and in some cases a high child mortality rate (India, Pakistan). On the other hand, under-5 mortality would remain relatively low in countries with a smaller population (Sri Lanka, Maldives) and less air pollution (Bhutan, Maldives) under the Reference and EoPmid scenarios.

We observed variations by country in the pattern of reduction in the projected under-5 mortality attributable to ambient $PM_{2.5}$ under different mitigation scenarios. The most significant reduction in under-5 mortality attributable to long-term ambient $PM_{2.5}$ exposure was observed under the EoPmaxCCSBLD scenario in three countries (Bangladesh, 47.9%; India, 54.9%; Pakistan, 45.9%) in 2030–2034 and in four countries (Bangladesh, 75.7%; India, 81.1%; Nepal, 83.6%; Pakistan, 84.3%) in 2045–2049, while moderate changes were observed in the other countries. Bangladesh, India, and Pakistan are among the topmost polluted countries as well as the most densely populated countries in the region, and their economies are fast-growing, especially in Bangladesh and India. Despite that, specific policies and actions aimed at improving air quality and combatting the impacts of climate change in the coming decades, which have been implemented or are in the planning stage in both India (IEA, 2021) and Bangladesh (MOEFCC,

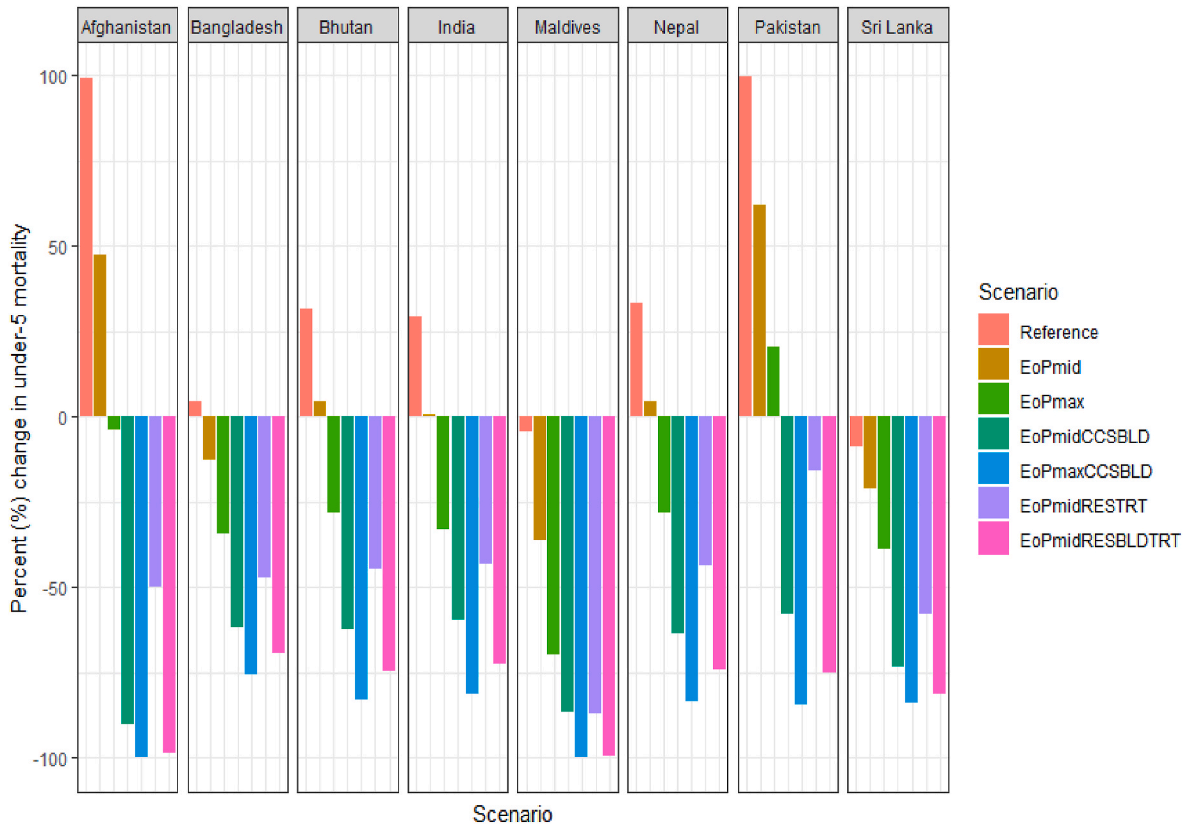

Fig. 4. Percent (%) Changes in the number of $PM_{2.5}$ attributable deaths among children below 5 years of age in 2045–2049 under Reference EoPmid, EoPmax, EoPmidRESTRT, EoPmidCCSBLD, EoPmidRESBLDTRT and EoPmaxCCSBLD scenarios compared to that at the baseline period in 8 countries in South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal, Maldives, Pakistan, and Sri Lanka).

2021), could have a significant impact on reducing under-5 mortality. Meanwhile, we found smaller number of under-5 deaths from our projections for Afghanistan, Bhutan, and Sri Lanka under various scenarios, although the current under-5 mortality rate is extremely high in Afghanistan and relatively high in Bhutan. This is possibly due to low simulated $PM_{2.5}$ concentrations in these countries. Sri Lanka has a lower under-5 mortality rate compared with its neighbors and has a relatively lower $PM_{2.5}$ concentration. As for the Maldives, the ambient mean $PM_{2.5}$ concentration is the lowest in the region, and it has a small population size; as the results suggest, excess under-5 mortality due to exposure to ambient $PM_{2.5}$ will likely be avoided in the Maldives under ambitious scenarios to achieve the 2 °C target. Only a few studies have projected under-5 mortality in changing $PM_{2.5}$ concentrations under different climate change mitigation scenarios. Our findings support a previous report that premature mortality attributed to $PM_{2.5}$ would decrease under the scenarios of small population size and relatively lower concentration of air pollution (Wang et al., 2022).

The present study also showed that, if the current trend of policies continued with no measures taken to achieve the 2 °C target, South Asian countries would have an increased number of under-5 deaths, especially in countries with a larger population and elevated $PM_{2.5}$ concentration. However, the increase in the number of under-5 deaths in Bangladesh (4.5%), where under-5 mortality and $PM_{2.5}$ concentration are both high, was not higher than that in India (29.3%) or Pakistan (99.7%) in 2045–2049 under the Reference scenario. The reason that causes this discrepancy might not be evident from this analysis, however, this can probably be explained by the several assumptions of SSP2 which were considered during the model construction, and also from the prolonged effect of other determinants of under-5 mortality found in several studies; such as prenatal and antenatal health care, births in a health facility, and other coverage (Rubayet et al., 2012; Murad et al., 2023), combined effects of birth order, maternal age at birth, parental education, and other social determinants (Khan and Awan, 2017), and nationwide vaccination and immunization programs (Shahid et al., 2023). Nonetheless, to explain trends and variations in the projected mortality in different countries under different scenarios, extensive research on situation analysis regarding current and future energy demands, economic development, and combined effects of air pollution control measures, mitigation policies, future interventions aimed at mitigation, and access to finance and technologies will be necessary. Moreover, how much of these measures are translated into real actions for curbing emissions in each country would significantly impact the achievement of co-benefits.

The present study has several strengths. First, this is the first study to link under-5 mortality with SLCP mitigation measures across the entire South Asian region, where issues pertaining to air pollution pose a significant threat to people, particularly children. These issues are more severe among children living in densely populated, low- and middle-income countries, such as South Asian countries, due to the lack of resources for maintaining good air quality and the continuous pressure of economic development by rapid industrialization and urbanization, which often undermine impacts on health during the growth process. Second, we used a coefficient reported by a cohort study in India on the association between long-term $PM_{2.5}$ exposure and child survival, in which results were obtained using a substantial number of individual, country-level, and socioeconomic variables. The use of this coefficient likely reduced the uncertainty of mortality estimation in the same region. Third, we focused on under-5 mortality attributable to ambient $PM_{2.5}$ under various climate change mitigation scenarios in South Asia. Only a few studies have analyzed the impact of climate change on air pollution and health burden, with most studies conducted in adult populations (Tagaris et al., 2010; Chowdhury et al., 2018 Park et al., 2020; Wang et al., 2022) or with different study settings (Tagaris et al., 2010; Park et al., 2020; Wang et al., 2022). The present study is novel because the future projections of under-5 mortality were done under different air pollution and climate change mitigation scenarios, which, to our knowledge, have yet to be explored in South Asia. Fourth, the present study described country-specific variations in under-5 mortality under different air pollution and climate change mitigation scenarios, with a focus on long-term all-cause mortality attributable to ambient $PM_{2.5}$. This is important from both scientific and policy perspectives in South Asia. South Asian countries are committed to curbing carbon emissions by 2030 and onwards; however, these countries are already experiencing several collective and individual challenges, including the contradiction between economic development and energy demand, population overpopulation, climate vulnerability, finance and technology constraints, agriculture and land use, rapid urbanization and heavy transportation, and policy and institutional framework. Finance and technology commitments from developed countries, regional cooperation, and country-specific policies are required to overcome these challenges and ensure a sustainable environment to reduce health impacts. The present study is particularly important in this context, as it revealed that air pollution control measures to introduce the maximum EoP technology alone will not be sufficient: air pollution control and modern mitigation technologies will need to be combined to attain the goal of reducing under-5 mortality. To this end, the findings of the present study could be used as guidance to develop a sustainable environment in the coming future. Moreover, to identify appropriate current and future interventions to address under-5 mortality, a broad understanding of the causes of mortality in this vulnerable age group is required. The results of the present study may provide policymakers with a solid base for understanding the need to formulate robust mitigation policies, enforce air quality control measures in domestic, industrial, and transport sectors, and enhance regional cooperation to combat the impacts of climate change to reduce under-5 mortality.

The present study also has a few limitations inherent to any projection study. First, we used simulated global concentration data of the components of $PM_{2.5}$ dispersed over a grid area of approximately 150 km × 150 km, and $PM_{2.5}$ concentration data for the baseline period were also obtained by simulation modeling. This spatial resolution might not have covered local-scale variations in air pollution in South Asia. Second, although several studies have reported that high temperatures can enhance the number of non-accidental, specific-cause mortality or morbidities attributable to particulate matter (Zhang et al., 2018; Sun et al., 2015), future temperature changes were not considered when simulating air pollution data used in the present study; this might have led to an underestimation of exposure. Third, we assumed that under-5 mortality would be similar to that in 2010 across the entire study period. These projections may have led to an overestimation of the size of the under-5 population as well as the mortality burden since the under-5 mortality rate might decrease in the future due to factors such as improved healthcare, better resource mobilization, and technological advances.

Fourth, while projecting under-5 mortality, the impacts of indoor air pollution measured by personal monitors, and the nutritional conditions of both mother and children were not considered although personal exposure to indoor air pollution can significantly contribute to overall $PM_{2.5}$ exposure, and indoor exposure and nutritional conditions play a pivotal role in the health outcomes of children under 5. However, due to data limitations and our study design, we concentrated on ambient $PM_{2.5}$ exposure only with the underlying assumption that nutritional conditions and indoor air pollution would be unchanged. Fifth, we did not use Integrated Exposure-Response (IER) or Global Exposure Mortality Model (GEMM) functions for projecting under-5 mortality attributable to ambient $PM_{2.5}$ because the GEMM function was developed based on the cohorts of the adult population. Although IER for Incidence of acute lower respiratory infections (ALRI) could be applied to under-5 mortality estimation, it combined the studies of air pollution and second-hand smoke, most of them came from high-income countries and we aimed to focus specifically on the parameters generated from the South Asian context. Sixth, while we acknowledge the existence of broader health burdens and several maternal, child, and socioeconomic determinants for children under five years of age in South Asia, we could not consider this aspect as there was no data on stipulated future health conditions available and it was beyond the predefined scope of our study. Future studies could include these parameters to generate the concentration-response function from a well-designed cohort study in South Asia. Lastly, we had not considered the interaction between $PM_{2.5}$ and other pollutants like O_3, SO_2, and NO_2 while doing this analysis. While we acknowledge the importance of incorporating parameters like ozone and other air pollutants and the effect of temperature change in future studies, our current analysis was focused on the specific implications of $PM_{2.5}$ on the burden of child mortality in South Asia.

Effectively addressing the uncertainties surrounding air pollution and climate change mitigation demands a meticulously crafted and interconnected strategy. This necessitates a profound acknowledgment of multifaceted issues related to policy implementation, technological advancements, financial considerations, and other pivotal factors that are instrumental in mitigating the challenges posed by climate change. Simultaneously, the reduction of under-5 mortality rates requires a comprehensive and multifaceted approach. This encompasses critical elements such as improving healthcare access, implementing immunization initiatives, intervening in nutrition, advancing infrastructure development, implementing preventive measures, and empowering communities, among other strategies.

The success of climate mitigation efforts is intricately linked to the precise execution of policies. While governments and international bodies may articulate ambitious plans, translating them into tangible actions depends on factors like political will, public support, and the ability to navigate complex bureaucratic processes. Moreover, the role of technological advancements is paramount. While researchers strive for cleaner technologies, the unpredictable pace of technological progress necessitates policies that align with state-of-the-art advancements. In this context, the flow of finance is a critical facilitator in the successful implementation of such policies. Technological progress and finance also hold significant promise for enhancing public healthcare systems, particularly for vulnerable populations like children under the age of 5. However, the landscape of child health is intricately shaped by socioeconomic factors, maternal and household indicators, and environmental influences, particularly in developing regions.

A collaborative approach is indispensable for success in both climate mitigation and child health. Partnerships with diverse sectors, including the commercial sector, non-governmental groups, and community-based organizations, offer a synergistic platform for maximizing resource utilization. The significance of comprehensive monitoring and evaluation mechanisms cannot be overstated, providing accurate assessments of the impact of interventions on child mortality and climate outcomes. This data-driven approach ensures informed decision-making and promotes the effectiveness of strategies in both domains".

5. Conclusion

The noteworthy finding of this study is the potential child health consequences of massive economic development activities in the future on which the model was constructed, which could further deteriorate air quality and exacerbate the already pronounced effects of climate change. This emphasizes the crucial importance of adopting a practical approach that aligns economic growth with sustainable environmental practices. Besides, despite sincere efforts, child mortality rates remain alarmingly high in specific South Asian countries, presenting challenges in meeting the Sustainable Development Goals (SDGs). The intricate relationship between climate change, air quality, and child health, underscores the need for collaboration among academia, policymakers, and leaders to work toward solutions that strike a balance between socio-economic progress and environmental sustainability. We believe that the results of the present study can help South Asian countries identify the need for robust policies, and instrumental interventions aimed at mitigation, and collaborate further to realize the co-benefits of combating climate change and air pollution and reducing associated health burdens for generations to come.

Transparency statement

The authors affirm that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted.

What is already known on this topic?

Exposure to ambient $PM_{2.5}$ and other air pollutants adversely affects birth outcomes and the health of children below 5 years of age. Children in low- and middle-income countries are particularly vulnerable to the effects of toxic air, which has been linked to an increased risk of childhood illnesses including lower respiratory tract infections, asthma, wheezing, and middle ear infections leading to death. South Asia is a $PM_{2.5}$ hotspot, where exposure to ambient $PM_{2.5}$ is one of the leading causes of premature death. Extreme vulnerability to climate change also might aggravate health risks associated with air pollution in this region.

What does this study add?

Despite the vulnerability of children to ambient $PM_{2.5}$, evidence to date is scarce regarding the impact of long-term ambient $PM_{2.5}$ exposure on under-5 mortality. This is the first study that has attempted to project under-5 mortality attributable to long-term ambient $PM_{2.5}$ exposure in South Asia and constituent countries under various air pollution control and climate change mitigation scenarios. The results showed that the current emission control strategy would not be sufficient for reducing the number of avoidable deaths in South Asia. Robust climate change mitigation and air pollution control policy implementation is warranted.

CRediT authorship contribution statement

Wahida Musarrat Anita: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Athicha Uttajug:** Conceptualization, Writing – review & editing. **Xerxes Tesoro Seposo:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Kengo Sudo:** Methodology, Writing – review & editing, Data curation. **Makiko Nakata:** Conceptualization, Writing – review & editing. **Toshihiko Takemura:** Conceptualization, Validation, Data curation. **Hirohisa Takano:** Software, Supervision, Writing – review & editing. **Taku Fujiwara:** Supervision, Writing – review & editing. **Kayo Ueda:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118292.

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