ENVIRONMENTAL RESEARCH COMMUNICATIONS



**PAPER** • **OPEN ACCESS**

# Cost-effective control of air pollution in South Asia: modeling and policy applications

To cite this article: Pallav Purohit *et al* 2024 *Environ. Res. Commun.* **6** 125017

View the article online for updates and enhancements.

IOP Publishing Environ. Res. Commun. 6 (2024) 125017 https://doi.org/10.1088/2515-7620/ad9b74

Environmental Research Communications



OPEN ACCESS

RECEIVED
29 August 2024

REVISED
12 November 2024

ACCEPTED FOR PUBLICATION
6 December 2024

PUBLISHED
18 December 2024



PAPER

# Cost-effective control of air pollution in South Asia: modeling and policy applications

**Pallav Purohit**[1], **Gregor Kiesewetter**[1], **Wolfgang Schöpp**[1], **Fabian Wagner**[1], **Zbigniew Klimont**[1], **Chris Heyes**[1], **Adriana Gómez-Sanabria**[1], **Parul Srivastava**[1], **Jens Borken-Kleefeld**[1] and **Markus Amann**[2]

[1] Pollution Management Research Group, Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

[2] Formerly International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

**E-mail:** purohit@iiasa.ac.at

**Keywords:** ambient air pollution, air quality management, air pollution control policies, emission scenarios, cost-optimal strategies, clean air policies

Supplementary material for this article is available online

## Abstract

Air pollution poses a critical environmental challenge to sustainability, environmental health and public well-being in the South Asia Region (SAR). This study identifies hotspots of fine particulate matter ($PM_{2.5}$) across SAR, analyzing both concentration levels and exposure. Moreover, it aims at a comprehensive understanding of the various sources of air pollution in these critical areas and a systematic evaluation of the costs and benefits of relevant policy actions, utilizing the GAINS modeling framework. A wide variety of sources contribute to $PM_{2.5}$ levels in ambient air, and effective air quality management requires a balance of measures across these sources. Current environmental policies, while effective in decoupling emissions from economic growth in SAR, are insufficient to achieve significant reductions in ambient $PM_{2.5}$ concentrations. However, considerable scope exists for further measures beyond current policies that could help to bring the WHO Interim Targets (IT-1) for $PM_{2.5}$ closer. Finally, it is shown that cost-optimal strategies for air quality management can achieve significant cost savings compared to conventional approaches; however, they require collaboration between states, regions and countries in South Asia.

## 1. Introduction

Ambient air pollution continues to be a major public health concern, linked to increased morbidity and mortality owing to pollutant levels exceeding acceptable standards in many cities. In 2021, nearly 99% of the global population was exposed to harmful levels of fine particulate matter ($PM_{2.5}$), which is associated with serious health impacts (HEI 2024, WHO 2022). The South Asia Region (SAR) faces severe air pollution, with an estimated 60% of its population living in areas surpassing even the least stringent World Health Organization (WHO) air quality interim target (IT). This severe air pollution is estimated to contribute to two million premature deaths annually across the region, imposing substantial economic costs (World Bank 2023). Seventeen out of the world's 20 most polluted cities are situated in South Asia (IQAir 2021), with notable impacts on India, Pakistan, Bangladesh and Nepal. While air pollution in SAR caused significant welfare losses, estimated at 7.4% of the regional GDP in 2013 (World Bank 2016), there are promising solutions available that can substantially improve ambient air quality and provide additional benefits (UNEP 2019, Dimitrova *et al* 2021).

The primary origins of ambient $PM_{2.5}$ differ throughout the SAR region, influenced by a confluence of factors, including regional topography, meteorological patterns, the intensity and distribution of emissions across the area, and the size of administrative zones. For example, air pollution in Bangladesh is primarily attributed to vehicular emissions, industrial activities, and brick kilns (Saha *et al* 2024, DOE 2019, Begum *et al* 2013) while India experiences increased air pollution in cities due to burning of fossil fuels, biomass, waste and resuspended dust (Adhikary et al 2024, Bhanarkar et al 2018, Venkataraman et al 2018, Guttikunda et al 2014). In Nepal, strong population growth and inadequate pollution control have led to widespread air quality degradation, particularly in Kathmandu Valley (Regmi et al 2019, Sadavarte et al 2019), whereas Pakistan, despite low energy consumption, faces increasing air pollution from widespread biomass use and unplanned industrialization (Khwaja et al 2012).

To address these issues, policymakers have implemented various air pollution control policies (MoCC 2023, GoN 2020, MoEFCC 2019, DoE 2018, MoMDE 2016), yet more action is needed. Key policies include establishing national clean air programs, national ambient air quality standards, setting emission limits for vehicles and industry, regulating fuel quality, clean cooking initiatives, waste management, conducting public awareness campaigns, and investing in cleaner energy sources and public transportation to mitigate the crisis (Gani et al 2022, Mir et al 2022, Islam et al 2020, Majumdar et al 2020, Purohit et al 2019). The effectiveness of these policies depends on their implementation, enforcement, and regular monitoring (Ness et al 2021, Gordon et al 2018, Amann et al 2017). In addition, continuous evaluation and refinement of policies based on scientific research and technological advancements are also essential for effective air pollution control in South Asia (Mookherjee 2022).

The concentration of $PM_{2.5}$ is one of the most representative indicators of air pollution and a health risk factor for premature mortality and disease burden (WHO 2021). Particulate matter is emitted directly but also formed in the atmosphere from precursors, such as nitrogen oxides ($NO_x$), sulfur dioxide ($SO_2$), volatile organic compounds (VOCs) and ammonia ($NH_3$). Major emission sources are transport, residential combustion, industry, power, agriculture and municipal waste. Air pollution has traditionally been associated primarily with urban environments, due to concentration of industrial activities, vehicular traffic, and high population density. This focus is also due in part to the availability of monitoring data, which is primarily collected in cities. However, air pollution, including $PM_{2.5}$, can extend beyond borders and become trapped within expansive airsheds, influenced by climatic and geographic factors. With an atmospheric lifetime of about a week, $PM_{2.5}$ may have been transported a considerable distance before reaching a particular location. As a result, a substantial portion of particulate matter present at any given location originates from distant sources, often beyond the jurisdictional and regulatory control of local authorities. Amann et al (2017) demonstrate that even in megacities such as Delhi, more than half of the ambient $PM_{2.5}$ found in urban areas originates from pollution sources that are outside the immediate jurisdiction of the municipal administration. Similarly, Ravishankara et al (2020) found that outdoor particulate pollution presents comparable health risks in rural and urban areas across India. Ravindra et al (2022) further stressed the need for comprehensive air pollution management strategies that address urban, semi-urban, and rural regions alike.

Purohit et al (2019) demonstrated that in many Indian states, major sources of $PM_{2.5}$ pollution originate outside their jurisdictions. As a result, most states cannot substantially improve air quality and reduce population exposure independently, highlighting the need for regionally coordinated emission reduction strategies for effective outcomes. Even national level strategies may fall short when airsheds extend beyond national borders. Thus, this study adopts a South Asia-wide perspective, underscoring the role of regional collaboration in achieving clean air targets.

A variety of interventions exist for controlling air pollution. Previous studies have largely focused on evaluating the impact of measures within specific sectors. For example, Chowdhury et al (2019) underscored the significance of transitioning to clean household fuels in meeting state-level NAAQS standards. Similarly, Purohit et al (2019) demonstrated the potential for reducing $PM_{2.5}$ exposure through concerted efforts across multiple sectors. However, these studies did not outline cost-effective pathways to achieve clean air targets, leaving a gap in prioritizing the most impactful strategies. In this context, this study investigates the potential benefits, both in terms of environmental advantages and cost-effectiveness, of establishing collaborative agreements among specific states of SAR to tackle air quality issues on a larger regional level, encompassing both urban and rural areas. It provides detailed information on pollution sources, regional impacts, and evaluates the environmental and cost-effectiveness dimensions of various policy packages within individual jurisdictions and across diverse regions.

The paper is organized as follows: section 2 introduces the modeling tools, scenarios, and data sources employed in the study. Section 3 scrutinizes South Asia's current air quality, examining drivers, population exposure, and pollution dispersion. It also assesses pollution control scenarios between 2018 and 2030, discussing their impact on air quality and associated costs in the region. Section 4 concludes the discussion.

## 2. Materials and methods

### 2.1. The GAINS model

The Greenhouse gas Air Pollution Interactions and Synergies (GAINS) modeling framework (see figure S1) has been used to map air pollution hotspots in SAR. GAINS provides a framework that utilizes the annual average population-weighted mean exposure to ambient $PM_{2.5}$ to comprehensively assess cost-effective policy interventions (Amann *et al* 2011). The initial step in this process involves a thorough evaluation of the current air quality in the SAR region, identifying primary sources of pollution and their overall impact on the region's air quality. In this study, 31 emission source regions within the SAR were analyzed, differentiating 23 sub-national regions within India, 4 in Pakistan and 2 in Bangladesh (see figure S2), to capture the region's diverse characteristics. Table S1 provides a detailed overview of the SAR regions considered in this study. Emission inventories of the relevant air pollutants, primary $PM_{2.5}$, $SO_2$, $NO_x$, $NH_3$ and NMVOC were developed for all geographical regions. Emission scenarios of these pollutants were constructed by incorporating future projections of anthropogenic activities. For future years, GAINS considers the implementation rates of predetermined control measures and assesses the potential for additional emission reductions provided by several control measures (Amann *et al* 2020).

To evaluate the effectiveness of implemented emission control measures, estimates were generated for measures enforced up to 2015, and for additional policies and measures adopted between 2015 and 2018. This study prioritized local measurements of emission factors and supplemented data gaps with insights from global studies carried out under comparable socio-economic and technological circumstances. Spatial patterns of emissions were evaluated at a resolution of $0.1° \times 0.1°$ (approximately 10 km $\times$ 10 km) longitude–latitude, using data from both local sources and globally available datasets (i.e., fine-scale gridded population data and road maps). Additionally, satellite data were utilized to detect agricultural waste burning. In sectors without finely resolved data, spatial distributions were determined using relevant proxy variables at a resolution of 0.5° (Klimont *et al* 2017), initially developed within the framework of the Global Energy Assessment project (GEA 2012). Natural emissions were based on the data employed in the EMEP model (Simpson *et al* 2012) and the GEOSCHEM model (van Donkelaar *et al* 2019) for atmospheric chemistry and transport. To estimate annual average $PM_{2.5}$ concentrations throughout the study area, all precursor emissions are incorporated into a reduced-form atmospheric dispersion model.

The GAINS model thus provides estimates of grid-average $PM_{2.5}$ concentrations at a $0.1°\times0.1°$ (~10 km $\times$ 10 km) resolution across the domain (Amann *et al* 2020), facilitating the computation of mean population exposure within administrative regions, covering the entire SAR population. The model underwent rigorous validation against monitoring data collected from a comprehensive network of air quality monitoring stations (see figure S3). Further details are provided in the supplementary information (SI) (see section S.1).

The GAINS model also includes a stand-alone optimization module that can be used to identify cost-optimal technology portfolios, aligned with specific air quality targets or designated marginal costs for a given future year (Wagner *et al* 2012). The optimization module is formulated as a linear programming problem within the GAMS code (Brooke *et al* 1988) and is solved using the CPLEX solver (Wagner *et al* 2013). The module optimally balances end-of-pipe emission control measures across countries/regions, pollutants and economic sectors in such a way that user-defined target levels on the various environmental impacts are met at least costs. GAINS distinctly separates environmental objectives from control costs, making the valuation of various environmental benefits explicit and open to interpretation based on results. This flexibility enables GAINS to support policymakers in evaluating policy options without losing focus on cost-effectiveness. This optimization tool is utilized in the current analysis to develop cost-effective strategies for air quality management (AQM) in the SAR region. Further details including set of equations are described in Wagner *et al* (2013).

### 2.2. Baseline and alternative scenarios

The Stated Policies (STEPS) scenario published by the International Energy Agency (IEA) in its World Energy Outlook 2019 (IEA, 2019) provides the trends of emission generating socio-economic activities (i.e., population growth, economic development, energy consumption, industrial activities) adopted as a common 'baseline' in this study. Energy projections from IEA are imported into the GAINS model and downscaled to the regional and sectoral granularity of GAINS using suitable proxy data (Purohit *et al* 2019). The basic statistical data for agriculture originates from the Food and Agriculture Organization (FAO) of the United Nations (http://faostat.fao.org).

Various alternative emissions scenarios up to 2030 analyze the potential spectrum of future air quality, particularly focusing on population exposure to $PM_{2.5}$. The analysis leverages a widely accepted economic growth path that incorporates anticipated structural economic shifts. These scenarios incorporate different assumptions in key policy areas, including energy, climate, agriculture, and air pollution prevention policies, which have been critical for past air pollution trends. Table 1 presents the alternative scenarios, demonstrating the consequences of different AQM approaches. These variations include a range of ambition levels, priorities for efforts, and degrees of coordination across jurisdictions. Further details are provided in section 3 of the manuscript.

**Table 1.** Description of scenarios analyzed.

| Scenario [Acronym] | Description | Remarks |
|---|---|---|
| 1. Baseline scenario [*CLE*] | • The *CLE* scenario considers the existing legislation (until 2018) for controlling air pollution. | • Strict compliance with existing emission standards specific to individual sources and regions. |
| 2. Ad-hoc selection of measures [*ADH*] | • The *ADH* scenario explores an upscaling of measures that are currently taken in parts of SAR to the entire region. Cost-effectiveness is secondary, with measures frequently determined without considering the interplay of air quality impacts across different regions. | • Aligning with prevailing regional perspectives, the emphasis is on the power sector, major industries, and road transportation.<br>• Each region acts independently. |
| 3. Achieve WHO Interim Target (IT) 1 throughout South Asia [*IT1*] | • The *IT1* scenario aims to achieve WHO Interim Target 1 across South Asia with a focused strategy. AQM targets pollution hotspots in the SAR region, ensuring mean $PM_{2.5}$ exposure meets the WHO IT 1 of 35 $\mu g\ m^{-3}$. The long-range transport of pollution to the most polluted areas requires regional coordination for achieving the WHO IT 1, measures in other regions are selected based on their cost-effectiveness. | • Regions cooperate to the extent they are contributing to pollution hotspots |
| 4. Towards the next WHO Interim Target [*IT+*] | • The *IT+* scenario aims for cost-effective $PM_{2.5}$ exposure reductions in the SAR region via coordinated efforts. Targeting the next WHO IT, measures are chosen to cut mean population exposure disparities by 90% by 2030. | • Full coordination across regions to maximize cost-effectiveness. |
| 5. Maximum technically feasible emission reductions [*MTFR*] | • The MTFR scenario explores potential air quality improvements by 2030 through full implementation of all available emissions controls, regardless of cost. New technologies are introduced only with new investments, without replacing existing capital assets prematurely. | • Envisions a gradual and full implementation of the best available technologies.<br>• No regional coordination. |

### 2.3. Data sources

The GAINS modeling framework utilizes a range of region-specific data including official statistics on social and economic factors, fuel use, industries, agriculture, transportation, and waste management. Relevant information from global data, obtained under similar conditions, is used to fill any gaps. Table S2 details the data sources employed for energy and process related activities, which served as the foundation for developing the base-year emission inventory for the SAR regions. Moreover, table S3 presents a comprehensive summary of existing and planned air pollution control policies and regulations at the sectoral, national, regional, and state/provincial levels within SAR countries. Additional information on policies, measures, regulations at sectoral levels in SAR countries can be found in SI (see table S3).

## 3. Results and discussion

The GAINS modeling framework described above is used to evaluate SAR's current air quality (section 3.1), explore scenarios for air pollution control in SAR (section 3.2), develop tailored solutions for cost-effective regional diversity (section 3.3), and assess the implications for AQM (Section 3.4). Maps illustrate ambient annual average $PM_{2.5}$ concentrations and mean population exposure to $PM_{2.5}$ in distinct regions under 2015 and 2018 legislation scenarios. Exposure reductions, associated emission control costs for alternative scenarios, and the impact of emission control measures in SAR on mean $PM_{2.5}$ exposure in specific regions are also described.

### 3.1. Ambient $PM_{2.5}$ concentrations in 2018

Figure 1(a) presents the annual mean $PM_{2.5}$ concentration for 2018, showing a notable variation across the region. On a large scale, the Indo-Gangetic Plain (IGP) exhibits the highest levels, with annual mean concentrations surpassing the WHO's 5 $\mu g\ m^{-3}$ guideline value (WHO 2021) by a factor of 20 or more. Additional concentration peaks are evident in numerous cities and desert areas (figure 1(a)). Conversely, concentrations are considerably lower in the southern part of the SAR, although they still significantly exceed the WHO guideline value.

The diversity of SAR is a key characteristic, making it necessary to tailor clean air strategies to the specific circumstances, capacity, and context of each country, region, or city. There is no one-size-fits-all approach to air quality policies, given the wide range of local conditions. However, one common characteristic is that $PM_{2.5}$ concentrations in 2018 surpassed the WHO's air quality guideline by a considerable margin across the entire SAR. The geo-physical approach used in atmospheric calculations (see figure S1) allows for tracking emissions from specific sources. This facilitates quantifying their impact on $PM_{2.5}$ concentrations in the region's ambient air.

#### *3.1.1. Significance of secondary $PM_{2.5}$ particles in South Asia*

The fine particulate matter in ambient air consists of both primary particles, such as soot, mineral dust, smoke, dirt, etc which are emitted directly, and secondary aerosols, formed in atmospheric chemical processes from gaseous precursor emissions like $SO_2$, $NO_x$, $NH_3$, and VOCs. In vast regions of SAR, secondary aerosols constitute a significant portion of the total $PM_{2.5}$ in ambient air (Amann *et al* 2017, Pant *et al* 2016, Sharma *et al* 2007). Often, their contributions surpass those of primary particles originating from anthropogenic sources, as depicted in figures 1(b)–(c). Therefore, it is necessary to develop comprehensive strategies that address the full range of emissions, including precursor emissions that contribute to the formation of secondary aerosols.

#### *3.1.2. Diverse sources of $PM_{2.5}$ pollution in South Asia*

The total $PM_{2.5}$ in ambient air resulting from human activities can be further associated with various economic sectors and activities, encompassing both primary and secondary $PM_{2.5}$. In South Asia, as in many other regions, power plants, large industries and vehicles give rise to significant $PM_{2.5}$ concentrations, often exceeding the recommended WHO limit (WHO 2021). However, additional sources that hold less importance in other parts of the world also significantly contribute to the pollution burden (see figure S4). These include, among others, the burning of solid fuels for cooking and heating in winter (Klimont *et al* 2017, Chafe *et al* 2014), emissions from small-scale industries, including brick kilns (Tibrewal *et al* 2023, Klimont *et al* 2017, Weyant *et al* 2014), current practices of municipal waste management in the region (Singh *et al* 2024), open burning of agricultural waste (Patange *et al* 2024, Lan *et al* 2022), inefficient use of mineral fertilizers (Aryal *et al* 2021, Mujeri *et al* 2013), fireworks, cremation, etc (Pandey *et al* 2021, Bikkina *et al* 2019, Purohit *et al* 2010). Therefore, policy interventions focusing on emission sources prominent in other parts of the world (Amann *et al* 2020) can only achieve limited $PM_{2.5}$ reductions in South Asia due to the significant contributions from region-specific pollution sources. Unfortunately, due to their lesser significance in other regions, understanding of these emissions is limited. However, improving our understanding of these sources could provide valuable insights for developing cost-effective AQM strategies.

#### *3.1.3. Impact of natural sources on $PM_{2.5}$ levels in South Asia*

In addition to anthropogenic sources, the source attribution in the model shows that in certain regions of SAR, significant contributions to $PM_{2.5}$, both in relative and absolute terms, stem from natural sources, notably soil dust in arid areas (figures 1(d)–(e)). In the western parts of SAR, natural dust sources significantly overshadow the contributions from human activities, with $PM_{2.5}$ concentrations exceeding 50 $\mu g\ m^{-3}$. While the substantial impact of natural sources is acknowledged in these areas (Katiyar *et al* 2024, Singh *et al* 2017, Guttikunda *et al* 2014, Begum *et al* 2011), accurately quantifying their contribution remains a challenge. The analysis for this study takes a conservative quantitative approach by opting for the lower estimate from two independent global scientific quantifications for different parts of the domain: EMEP model estimate for Bangladesh, India, Nepal and Sri Lanka (Simpson *et al* 2012, Tsyro *et al* 2011); and van Donkelaar *et al* (2019) for Pakistan. While acknowledging inherent uncertainties, it is essential to remember that natural sources significantly impact $PM_{2.5}$ levels and cannot be immediately controlled through policy interventions. This fact must be considered when setting realistic policy targets for total $PM_{2.5}$ concentrations in ambient air.

### 3.2. Scenarios for air pollution management in the South Asia region

Leveraging the understanding of key air pollution characteristics in South Asia, this section investigates alternative AQM strategies, which aim for sustained air quality improvements, minimizing population exposure to levels closer to global air quality standards. The success of these strategies depends on factors like population growth, urbanization trends, economic development, and the strength of recent regulations. Table S4 outlines additional measures, beyond the 2018 legislation, that are currently under consideration by authorities in the SAR regions. Starting with a baseline projection for 2030, this study emphasizes the need for full implementation of current air quality legislation. It then explores four different pollution control scenarios. By assessing the

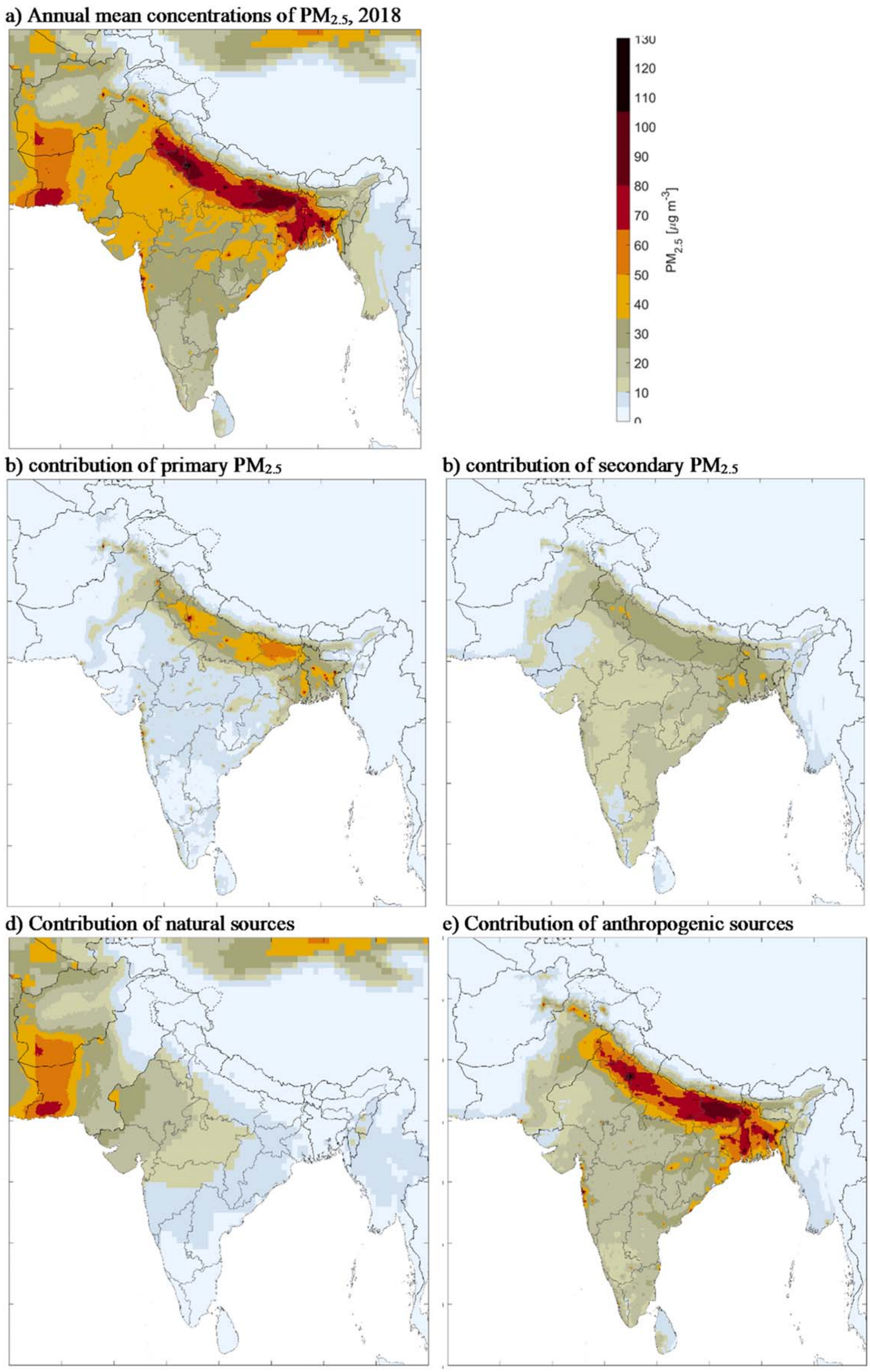


**Figure 1.** Annual $PM_{2.5}$ concentrations (a) computed for 2018; (b) concentrations of primary $PM_{2.5}$; (c) contributions of secondary $PM_{2.5}$; (d) contributions of natural sources; (e) contributions of anthropogenic emission sources[3].

cost-effectiveness of these approaches, the study aims to identify the most efficient strategies for further improving air quality in South Asia, thereby guiding AQM planning efforts.

#### 3.2.1. A baseline projection for 2030

The baseline projection, based on Stated Policies Scenario (STEPS) of the IEA (2019), assumes continued population and economic growth, foreseeing a doubling of per-capita income by 2030. The STEPS scenario incorporates increased adoption of renewable energy within the power sector, improvement of fuel standards across the transportation sector, integration of electric vehicles, advancement of energy efficiency initiatives, and expansion of clean fuel usage for cooking. Additional information regarding energy, climate, and air pollution prevention policies in South Asia is provided in table S3 of the supplementary section.

Economic restructuring and enhanced energy efficiency lead to a significant decrease in the energy intensity of GDP, translating to slower growth (50%) in total primary energy consumption compared to the 150% increase in GDP. The decline in poverty and the implementation of recent policies promoting access to clean fuels (Adhikary *et al* 2024, Awan *et al* 2024, Roy and Acharya 2023, CCA 2022, MoPNG 2020, MPEMR 2013, Wickramasinghe, 2011) are anticipated to decrease the percentage of households using solid biomass by 60%. Conversely, vehicle mileage closely tracks income trends (figure S5).

In the Baseline scenario, the implementation of existing emission controls, coupled with the structural economic changes in the SAR region and energy policies, will reduce the growth in $PM_{2.5}$ precursor emissions. The particular focus on enhancing access to clean fuels (MoPNG 2020, Cameron *et al* 2016) will restrict the rise in primary $PM_{2.5}$ emissions to 12%. The precursor emissions for secondary $PM_{2.5}$ are expected to experience larger increases, namely +39% for $SO_2$, +46% for $NO_x$, and +19% for $NH_3$. These increments are significantly smaller than the projected 150% increase in GDP by 2030.

To improve air quality, governments in the SAR region have implemented additional air pollution control measures since 2015 (see table S3). Nonetheless, achieving full implementation remains a challenge (Ness *et al* 2021, Peng *et al* 2020, Khwaja *et al* 2012). Effective enforcement of the measures established between 2015 and 2018 (i.e., 2018 legislation) would result in significantly reduced emissions by 2030. Primary $PM_{2.5}$ emissions would then decrease by 4% (instead of increasing by 12%), $SO_2$ emissions would decrease by 43% (instead of increasing by 39%), and the growth in $NO_x$ emissions would decrease from +46% to +10%. However, $NH_3$ levels would remain unaffected due to the absence of legislation targeting this pollutant (see figure S6). The notable disparity in air quality outcomes between the 2015 and 2018 legislation scenarios emphasizes the critical need for stricter enforcement of existing policies. Additionally, it highlights the potential advantages of effectively implementing recent legislation.

The necessity of robust enforcement of recent pollution control legislation (see table S3) is underscored by the uncertainty surrounding future air quality in the SAR region. However, the political feasibility of implementing such regulations across various sectors and regions may vary, as noted by Peng *et al* (2021). The current regulation not only has the potential to counteract the effects of the projected sharp rise in economic activities but also to achieve significant reductions in ambient $PM_{2.5}$ levels. Nevertheless, the implemented measures will fall short of attaining even the least ambitious WHO IT Level 1 (35 $\mu g\ m^{-3}$) in large parts of the SAR region (figure 2).

Figure 3(a) illustrates the mean population exposure to $PM_{2.5}$ in the regions analyzed here, with red dots representing the average exposure in 2018. The upper part of the light blue bars illustrates exposure levels expected in 2030 due to the 2015 legislation, while the lower part of the dark blue bars represents achievable exposure levels through comprehensive implementation of the supplementary 2018 policies. Additionally, contributions from natural sources are shown in grey for reference. The anticipated structural modifications in the economy, together with energy policies and existing emission controls, should prevent a notable worsening of current population exposure (as highlighted by the light blue arrows in figure 3(a)), thereby mitigating some of the pressure stemming from economic growth. Whether they will decrease current levels (as indicated by the red dots in figure 3(a)) hinges on the efficacy of implementing air pollution control policies (illustrated by the dark blue arrows). In regions currently facing elevated $PM_{2.5}$ concentrations (such as the IGP and in urban clusters in other areas), the average population exposure is expected to remain significantly higher than even the least ambitious WHO IT1. Even with the recent measures, approximately two-thirds of the population in SAR will still be exposed to $PM_{2.5}$ levels above this target level.

#### 3.2.2. Alternative air quality management scenarios

Four alternative AQM strategies (see table 1) showcase different approaches, varying in level of ambition and the extent of regional collaboration. In addition to the CLE measures outlined in the 2018 legislation, additional

[3] All maps are presented in longitude-latitude grid, with the bounding box defined by the coordinates (60°E, 5°N) and (100°E, 40°E), representing the lower-left and upper-right corners, respectively.

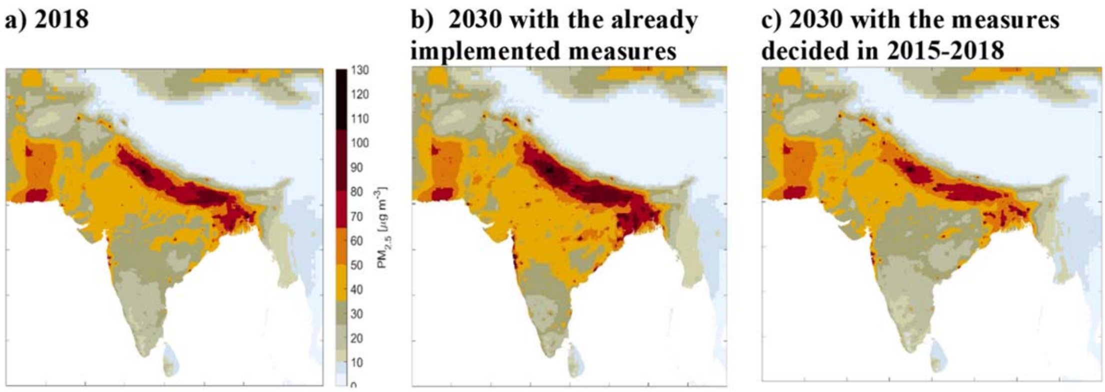


**Figure 2.** Ambient $PM_{2.5}$ concentrations in (a) 2018, (b) 2030, with existing measures, and (c) 2030, with full measures implemented from 2015 to 2018.

emission control measures for 2030 (beyond the 2018 legislation) that are currently considered by SAR administrations are listed in table S4. The substantial potential for further enhancing air quality through additional measures is illustrated in figure 3(b). Starting from the exposure levels resulting from compliance with the 2018 air quality legislation, the dark-yellow bars represent potential improvements achievable through measures implemented within the same region (referred to as 'local' MTFR). The light-yellow bars depict the additional effects of measures taken in other regions. It is evident from figure 3(b) that adopting the MTFR controls across SAR could reduce the mean population exposure to $PM_{2.5}$ in each region below the WHO IT1 by 2030. In the MTFR case (lower end of the yellow bars), the average population exposure in SAR could decrease from around 50 $\mu g\ m^{-3}$ in 2018 to 17 $\mu g\ m^{-3}$ in 2030. The remaining exposure arises from natural sources (the grey bars in figure 3(b)) and emissions not eliminable by currently available technical measures by 2030 due to deployment constraints. Reductions in concentrations are attributed to sources within the same region (dark yellow bars) and inflow from other regions (light yellow bars). Importantly, several regions, particularly in the IGP region and urban areas, may not individually achieve the WHO IT1 even with full implementation of technically feasible measures, as pollution inflow from external regions and natural sources already exceeds 35 $\mu g\ m^{-3}$.

Owing to the transportation of pollution over long distances, actual improvements in air quality within a region rely not just on local actions but also on measures implemented in other locations, necessitating regional coordination of AQM efforts, particularly in regions where the influence of local emissions is minimal. The benefits achieved through local measures only account for a small fraction of the total potential and fall significantly short of meeting WHO IT1 by a substantial margin in many regions. Nevertheless, these regions will reap spill-over benefits from actions taken abroad (grey bars in figure S7), although the magnitude of these benefits will remain uncertain in the absence of regional coordination. As shown in various regions worldwide, airshed-wide coordination of measures is crucial for improving the effectiveness and economic efficiency of AQM strategies, despite the governance challenges involved.

Two scenarios - *achieve WHO Interim Target 1 everywhere in South Asia [IT1]* and *toward the next lower WHO Interim Target [IT+]* - demonstrate the effectiveness of coordinated strategies (see table 1). In each scenario, regions would collaborate as needed to reach shared goals of enhancing air quality through customized interventions. This guarantees that overall financial investments in pollution mitigation are minimized, maximizing cost-effectiveness. The two scenarios target distinct air quality objectives, leading to varying distributions of benefits and costs related to air quality. Adhering to traditional methods, the *IT1* scenario focuses on addressing pollution in the most heavily affected areas by enforcing a uniform target to be achieved across all SAR regions. For simplicity, the WHO IT1 of 35 $\mu g\ m^{-3}$ has been applied for the year 2030. Under this scenario, ambient $PM_{2.5}$ levels are frequently lower than those of the *IT+* scenario, particularly over the IGP region. In the *IT+* scenario, each region progressively decreases its average exposure levels across the four WHO IT of 35, 25, 15, and 10 $\mu g\ m^{-3}$, moving towards the WHO guideline of 5 $\mu g\ m^{-3}$. This novel approach ensures that progress in less-polluted areas is not delayed until air quality targets are met in more-polluted places. A more equitable dispersion of air quality improvements yields substantially higher health benefits for communities while capitalizing on gains from cost-effective measures.

The four scenarios produce different distributions of air quality improvements due to their varied target-setting approaches, as depicted in figure 4. Notably, WHO IT1 could be achievable across the SAR region by 2030, except in areas heavily influenced by natural sources. However, despite mean exposure levels dropping

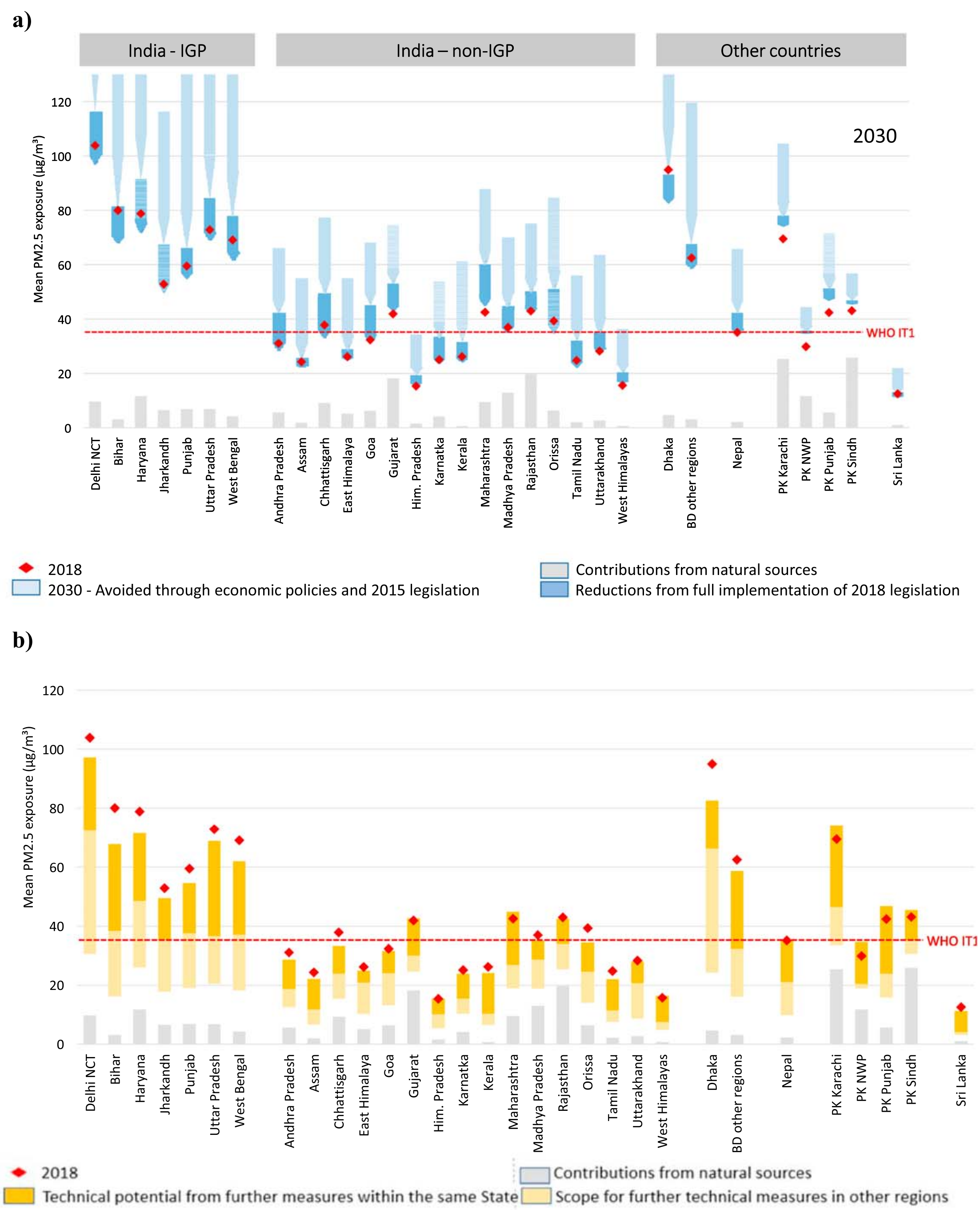


**Figure 3.** Baseline $PM_{2.5}$ concentration and mitigation potential (a) mean population exposure to $PM_{2.5}$; and (b) potential for improvements in $PM_{2.5}$ mean exposure in 2030 resulting from the complete implementation of the maximum feasible emission reductions in the regions distinguished in this analysis [Note: the scale is truncated at 130 $\mu g\ m^{-3}$].

below this threshold in specific regions, local hotspots exceeding 35 $\mu g\ m^{-3}$ persist in the less ambitious scenarios.

### *3.2.3. Evaluating cost-effectiveness in alternative scenarios*

The four AQM strategies not only vary in the extent and geographical spread of exposure enhancements but also differ in their cost-effectiveness. Full compliance with the 2015 legislation costs approximately US\$35 billion annually through 2030, or 0.7% of GDP, while mean $PM_{2.5}$ exposure in South Asia is projected to be 57.9 $\mu g\ m^{-3}$ by 2030. Adhering to the 2018 legislation will cost approximately US\$74 billion annually by 2030, resulting in a 2030 $PM_{2.5}$ exposure of 47 $\mu g\ m^{-3}$. Compared to the 2015 legislation, the 2018 legislation results in additional costs of US\$3.6 billion per $\mu g\ m^{-3}$ reduced by 2030. Figure 5 depicts the reductions in exposure and the associated costs of emission control for the four AQM approaches outlined earlier. All costs presented in figure 5 are relative to the cost under the 2018 legislation.

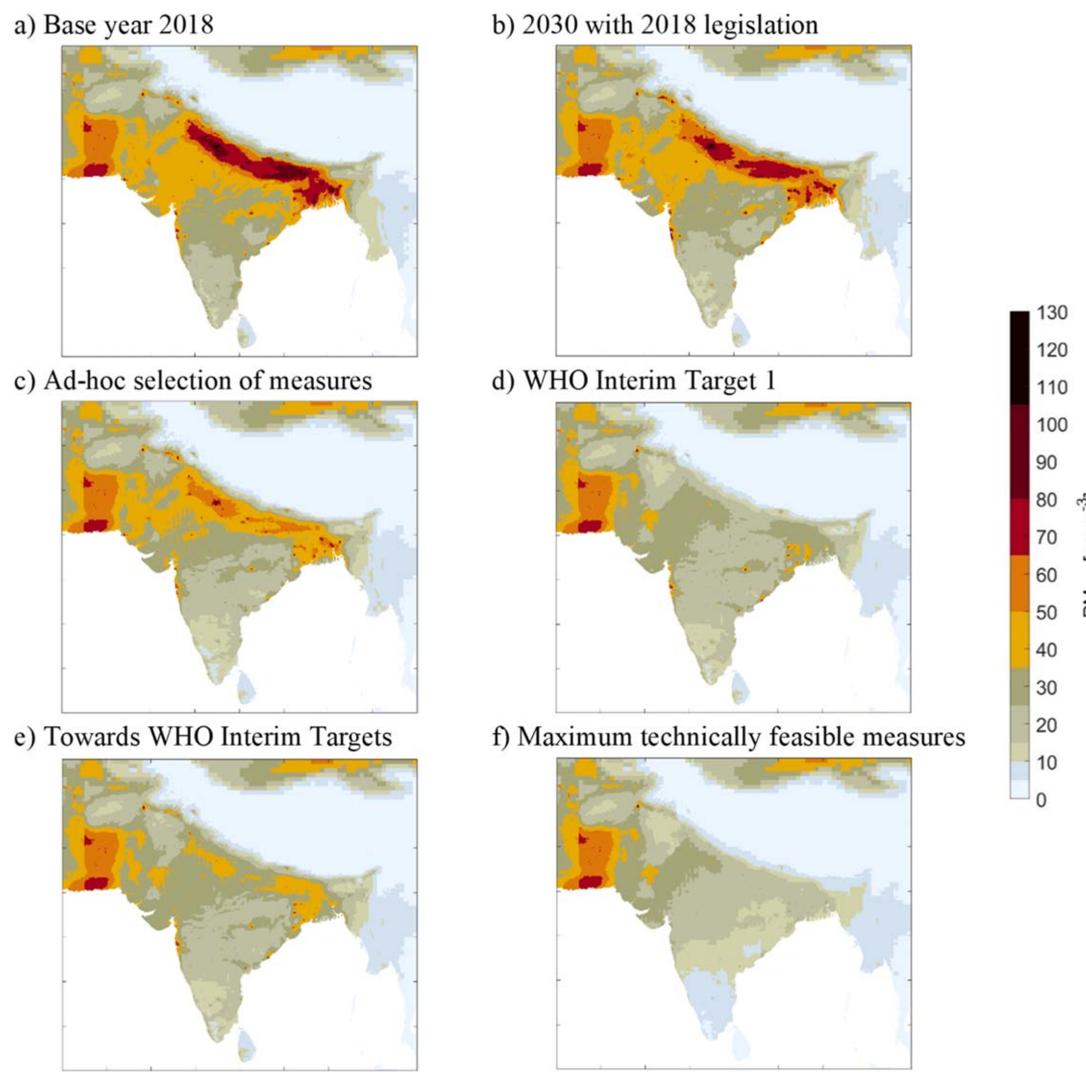


**Figure 4.** Ambient concentrations of $PM_{2.5}$ for 2018 and the scenarios for 2030.

Scaling up the current end-of-pipe emissions controls, as in the *ADH* scenario, would lower the average exposure to 37 $\mu g\, m^{-3}$, costing an additional US$10.6 billion per year, or 0.20% of GDP annually until 2030. Focusing on the most heavily polluted regions by aiming to reduce exposure below the WHO IT1 of 35 $\mu g\, m^{-3}$ everywhere in South Asia, as in the scenario '*achieve WHO Interim Target 1 everywhere in South Asia*,' cuts the average exposure by half to 26 $\mu g\, m^{-3}$. This reduction is attributed to the co-benefits derived from implementing measures in other areas upwind. The additional costs increased to US$19 billion per year, or 0.35% of GDP annually through 2030. Interestingly, the cost-effectiveness of these two last approaches is roughly comparable, with a cost of US$780 million per $\mu g\, m^{-3}$ of reduced exposure.

The most cost-effective approach applies a collective but differentiated shift toward the WHO interim targets, as outlined in the *IT+* scenario. If each region were to cut exposure to below the next lower interim target, mean exposure in SAR would decline to 30 $\mu g\, m^{-3}$, a reduction of 40% of 2018 levels. Additional annual costs amount to US$5.7 billion per year, or 0.11% of GDP annually through 2030. Notably, the costs of such an approach are 45% lower than those of the *ADH* scenario, while it would deliver 70% higher reductions in total exposure in South Asia. At US$278 million per $\mu g\, m^{-3}$ of reduced exposure, this approach is the most cost-effective. Full implementation of all technically feasible emissions controls (*MTFR*) would cut exposure in 2030 to 17 $\mu g\, m^{-3}$.

### 3.3. Tailored solutions for cost-effective regional diversity

The *IT+* scenario optimizes cost-effectiveness by identifying end-of-pipe measures in each region that achieve specific exposure targets at minimal cost. Across South Asia, the selected measures vary significantly,

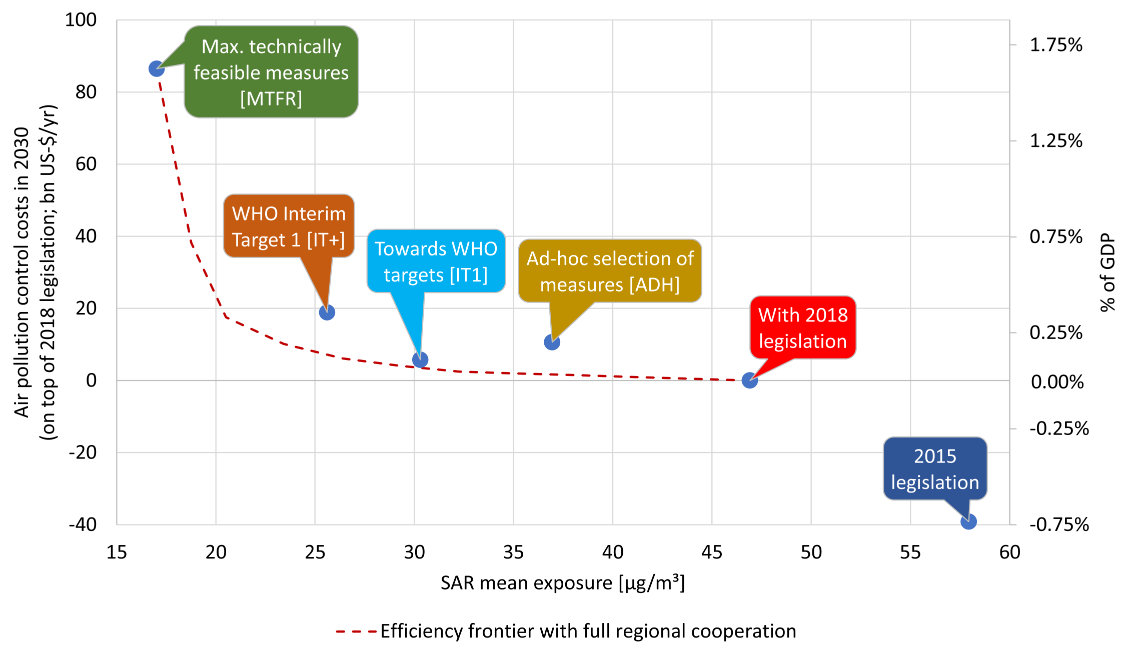


**Figure 5.** The reductions in exposure and the costs associated with emission control across the four alternative emission control scenarios.

reflecting diverse factors such as economic structures, emission sources, topography, population density, meteorological conditions, existing emission controls, and potential for additional measures within each area. While the analysis was performed separately for each of the 31 study regions, figure 6 demonstrates the impact of individual measures on average exposure levels across six aggregated areas: the IGP and other regions encompassing India, Bangladesh, Nepal, Pakistan, and Sri Lanka. The blue bars represent the exposure improvements of the 2018 legislation, while the yellow bars denote exposure reductions achievable through cost-effective measures in the *IT+* scenario. The grey ranges delineate the potential for additional improvements from measures not deemed cost-effective within the region under this scenario, such as technologically advanced emission controls for vehicles. A comparison between the effects of the 2018 legislation (blue bars in figure 6) and the additional potential for cost-effective exposure reductions (the yellow bars) distinctly illustrates that achieving more ambitious air quality targets necessitates addressing emission sources that have not previously been the primary focus.

The change in AQM strategies is also mirrored by the costs associated with control measures across different sectors. The estimated total costs for implementing the 2018 legislation throughout South Asia amount to US$ 74 billion per year. Most of these costs, totaling US$ 55 billion, are attributed to road transport, with an additional US$ 12 billion allocated for emission controls in the power sector (figure S8). In contrast, in the *IT1* scenario, additional costs total only US$ 5.7 billion per year, with approximately half attributed to measures in the household sector. Around 40% of these additional costs are associated with further controls in sectors already addressed in the 2018 legislation, such as mobile sources, power generation, and industry, while the remaining 10% is associated with the agricultural sector.

The significant movement of pollution across city, state, and even international boundaries is crucial in assessing cost-effective policy interventions for improving air quality while minimizing economic burdens. This study emphasizes the importance of regional coordination, particularly highlighted in the *IT+* scenario, where approximately 40% of exposure reductions in the IGP and Bangladesh result from emission controls implemented in other regions (figure S9). This collaborative approach not only enhances cost-effectiveness but also yields significant economic benefits in areas heavily affected by pollution.

## 4. Conclusions and policy recommendations

South Asia has become a critical global hotspot for air pollution. Fine particulate matter ($PM_{2.5}$) concentrations can be as much as 20 times higher than the WHO's recommended levels (5 $\mu g\ m^{-3}$) in some of the region's most densely populated and impoverished areas. Exposure to such extreme air pollution inflicts various detrimental consequences, including hindered growth and impaired cognitive

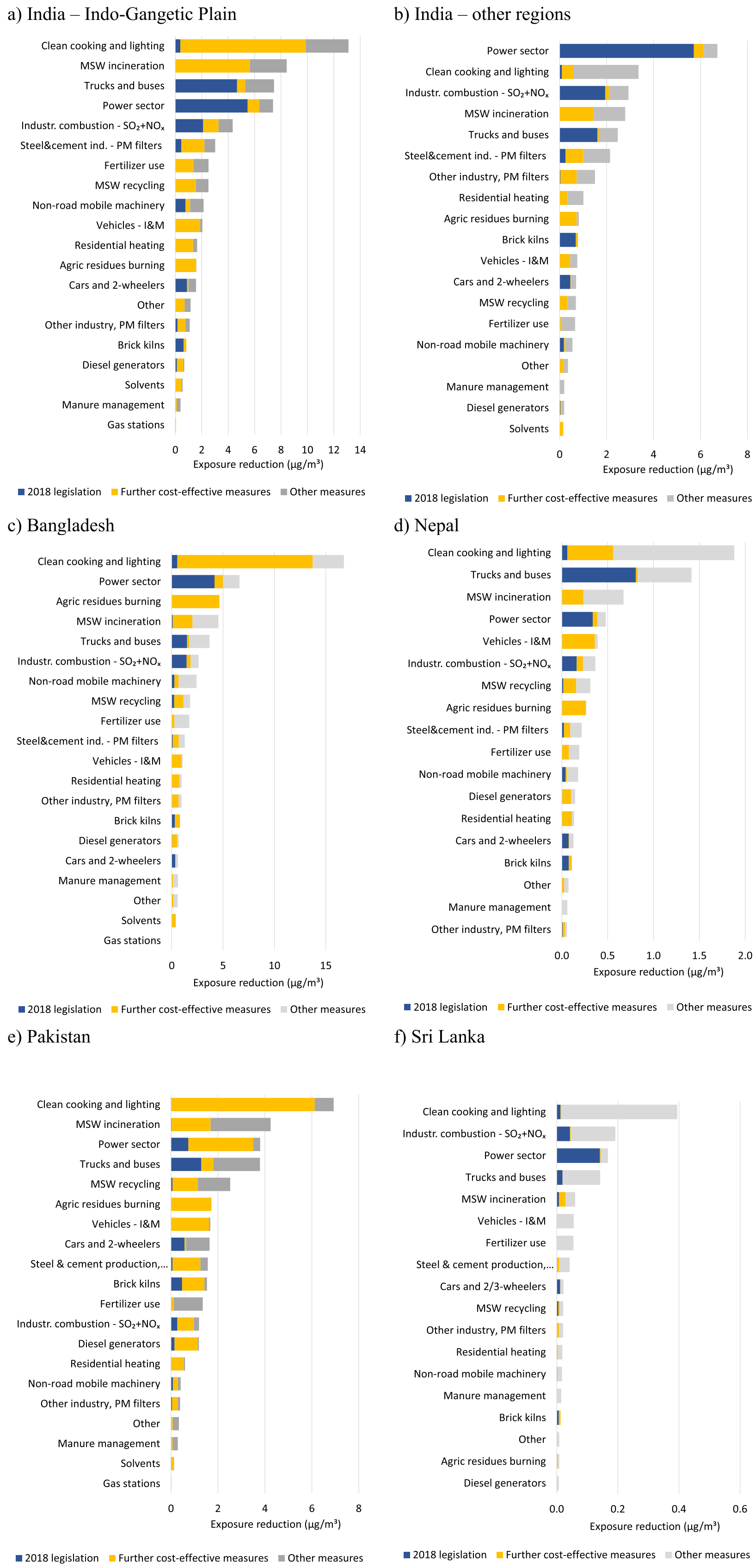


**Figure 6.** Assessing the effects of emission control measures in South Asia on average $PM_{2.5}$ exposure in specific regions. The yellow bars represent the cost-effective reductions resulting from measures implemented in the 'Towards WHO Interim Targets' scenario.

development in children, respiratory infections, and the onset of chronic, debilitating diseases. Even if fully executed, existing policy measures will only offer partial relief in diminishing $PM_{2.5}$ concentrations in South Asia.

Addressing this pressing challenge with fragmented approaches is unlikely to yield satisfactory results since air pollution transcends geographical boundaries. In South Asia, diverse sources contribute to air pollution, including large industries, power plants, vehicles, as well as the burning of solid fuel for cooking and heating, emissions from small industries like brick kilns, waste incineration, and human cremation. Addressing air pollution requires not only targeting specific sources but also fostering cooperation among countries to implement cost-effective collaborative strategies that leverage the interconnected nature of air quality.

Monitoring the chemical composition of $PM_{2.5}$ indicates that a significant portion of the overall $PM_{2.5}$ in the ambient air across the SAR region consists of secondary particles. Effective AQM requires addressing precursor emissions of secondary particles in a cost-efficient manner. While existing legislation addresses $SO_2$ and $NO_x$ emissions to some extent, including $NH_3$ emissions, primarily from agricultural activities, in regulatory frameworks can significantly enhance effectiveness, given their critical role in secondary particle formation in many situations.

The study explores four scenarios for reducing air pollution, differing in terms of policy implementation and international collaboration. The most economically efficient scenario, which involves full coordination between regions, would decrease the average $PM_{2.5}$ exposure in South Asia to 30 $\mu g\ m^{-3}$, at a cost of US$278 million per $\mu g\ m^{-3}$ reduction.

## Acknowledgments

The modeling work conducted by IIASA was funded by the World Bank (7191106) as part of its Flagship Study on South Asia.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/ppurohit76/Cost-effective-control-of-air-pollution-in-South-Asia. Data will be available from 31 December 2024.

## ORCID iDs

Pallav Purohit https://orcid.org/0000-0002-7265-6960
Gregor Kiesewetter https://orcid.org/0000-0002-9369-9812
Chris Heyes https://orcid.org/0000-0001-5254-493X
Adriana Gómez-Sanabria https://orcid.org/0000-0002-2317-3946

## References

Adhikary M *et al* 2024 Air pollution and mortality in india: investigating the nexus of ambient and household pollution across life stages *GeoHealth* **8** e2023GH000968
Amann M *et al* 2011 Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications *Environ. Modell. Softw.* **26** 1489–501
Amann M *et al* 2020 Reducing global air pollution: the scope for further policy interventions *Philos. Transact. A Math. Phys. Eng. Sci.* **378** 20190331
Amann M *et al* 2017 Managing future air quality in megacities: a case study for Delhi *Atmos. Environ.* **161** 99–111
Aryal J P *et al* 2021 Factors affecting farmers' use of organic and inorganic fertilizers in South Asia *Environ. Sci. Pollut. Res.* **28** 51480–96
Awan A *et al* 2024 Drivers of clean fuel adoption and consumption intensity at the household level in Pakistan *Energ. Effic.* **17** 24
Begum B A *et al* 2011 Long–range transport of soil dust and smoke pollution in the South Asian region *Atmos. Pollut. Res.* **2** 151–7
Begum B A *et al* 2013 Air pollution by fine particulate matter in Bangladesh *Atmos. Pollut. Res.* **4** 75–86
Bhanarkar A D *et al* 2018 Managing future air quality in megacities: co-benefit assessment for Delhi *Atmos. Environ.* **186** 158–77
Bikkina S *et al* 2019 Air quality in megacity Delhi affected by countryside biomass burning *Nat. Sustain.* **2** 200–5
Brooke A *et al* 1988 *Generalized Algebraic Modelling System (GAMS)—A User's Guide.* (The Scientific Press)
Cameron C *et al* 2016 Policy trade-offs between climate mitigation and clean cook-stove access in South Asia *Nat. Energy* **1** 15010
CCA 2022 *Country Action Plan (CAP) for Transforming the Cookstoves and Fuels Market in Nepal.* (Clean Cooking Alliance (CCA))
Chowdhury S *et al* 2019 Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources *Proc. Natl. Acad. Sci. USA* **116** 10711–6
Chafe Z A *et al* 2014 Household cooking with solid fuels contributes to ambient $PM_{2.5}$ air pollution and the burden of disease *Environ. Health Perspect.* **122** 1314–20
Dimitrova A *et al* 2021 Health impacts of fine particles under climate change mitigation, air quality control, and demographic change in India *Environ. Res. Lett.* **16** 054025
DoE 2019 *Sources of Air Pollution in Bangladesh - Brick Kiln and Vehicle Emission Scenario. Department of Environment (DoE), Ministry of Environment, Forest and Climate Change, Dhaka*

DoE 2018 *Bangladesh - National Action Plan for Reducing Short-Lived Climate Pollutants (SLCPs). Bangladesh: Department of Environment (DoE), Ministry of Environment, Forest and Climate Change*

Gani S *et al* 2022 Systematizing the approach to air quality measurement and analysis in low- and middle-income countries *Environ. Res. Lett.* **17** 021004

GEA 2012 *Global Energy Assessment - Toward a Sustainable Future* (Cambridge University Press) Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

GoN 2020 *Air Quality Management Action Plan for Kathmandu Valley. Government of Nepal (GoN)*

Gordon T *et al* 2018 Air pollution health research priorities for India: perspectives of the Indo-U.S. communities of researchers *Environ. Int.* **119** 100–8

Guttikunda S K *et al* 2014 Nature of air pollution, emission sources, and management in the Indian cities *Atmos. Environ.* **95** 501–10

HEI 2024 *State of Global Air 2024: Special Report.* (Health Effects Institute (HEI))

IQAir 2021 *World Air Quality Study 2021: Region and City $PM_{2.5}$ Ranking.* Available at: https://iqair.com/in-en/world-air-quality-study accessed on 20/03/2023.

Islam M R *et al* 2020 Ambient air quality in the Kathmandu Valley, Nepal, during the pre-monsoon: concentrations and sources of particulate matter and trace gases *Atmos. Chem. Phys.* **20** 2927–51

Katiyar A *et al* 2024 Fugitive road dust particulate matter emission inventory for India: a field campaign in 32 Indian cities *Sci. Total Environ.* **912** 169232

Khwaja M A *et al* 2012 *Air Pollution Reduction and Control in South Asia. Working paper Series 121, Sustainable Development Policy Institute (SDPI), Islamabad*

Klimont Z *et al* 2017 Global anthropogenic emissions of particulate matter including black carbon *Atmospheric Chem. Phys.* **17** 8681–723

Lan R *et al* 2022 Air quality impacts of crop residue burning in India and mitigation alternatives *Nat. Commun.* **13** 6537

Majumdar D *et al* 2020 Emission inventory and scenario analysis for the Kolkata Metropolitan City, India *Atmos. Environ.* **222** 117135

Mir K A *et al* 2022 Co-benefits of addressing climate change and air pollution simultaneously in Pakistan *Environ. Sci. Policy* **133** 31–43

MoCC 2023 *National Clean Air Policy (NCAP). Ministry of Climate Change (MoCC)* (Government of Pakistan)

MoEFCC 2019 *National Clean Air Programme (NCAP). Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, New Delhi.*

MoMDE 2016 *Clean Air 2025: An Action Plan for Air quality Management. Ministry of Mahaweli Development & Environment (MoMDE), Colombo*

Mookherjee P 2022 *India's Air Pollution Challenge: Translating Policies into Effective Action.* (Observer Research Foundation)

MoPNG 2020 *Prathan Mantri Ujjwala Yojana (PMUY). Ministry of Petroleum and National Gas (MoPNG), Government of India, New Delhi.*

MPEMR 2013 *Country Action Plan for Clean Cookstoves. Power Division, Ministry of Power, Energy and Mineral Resources (MPEMR), Government of the People's Republic of Bangladesh, Dhaka.*

Mujeri M K *et al* 2013 *Improving the Effectiveness, Efficiency and Sustainability of Fertilizer Use in South Asia. Global Development Network (GDN) Working paper Series, New Delhi*

Ness J E *et al* 2021 *An Overview of Policies Influencing Air Pollution from the Electricity Sector in South Asia. National Renewable Energy Laboratory, Golden, CO.*

Pandey A *et al* 2021 Health and economic impact of air pollution in the states of India: the Global Burden of Disease Study 2019 *Lancet Planet Health* **5** e25–38

Pant P *et al* 2016 Exposure to particulate matter in India: a synthesis of findings and future directions *Environ. Res.* **147** 480–96

Patange O *et al* 2024 Mitigation of non-$CO_2$ greenhouse gases from Indian agriculture sector *Environ. Res. Lett.* **19** e074020

Peng W *et al* 2020 The critical role of policy enforcement in achieving health, air quality, and climate benefits from India's clean electricity transition *Environ. Sci. Technol.* **54** 11720–31

Peng W *et al* 2021 Incorporating political feasibility concerns into India's clean air policies for addressing air quality and climate objectives *One Earth* **4** 1–12

Purohit P *et al* 2019 Mitigation pathways towards national ambient air quality standards in India *Environ. Int.* **133** 105147

Purohit P *et al* 2010 *GAINS-Asia. Scenarios for cost-effective control of air pollution and greenhouse gases in India. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

Ravindra K *et al* 2022 Preventable mortality attributable to exposure to air pollution at the rural district of Punjab, India *Environ. Sci. Pollut. Res.* **29** 32271–8

Ravishankara A R *et al* 2020 Outdoor air pollution in India is not only an urban problem *Proc. Natl. Acad. Sci. U.S.A.* **117** 28640–4

Regmi R P *et al* 2019 Wintertime boundary layer evolution and air pollution potential over the Kathmandu valley, Nepal *J. Geophys. Res. Atmos.* **124** 4299–325

Roy A and Acharya P 2023 Energy inequality and air pollution nexus in India *Sci. Total Environ.* **876** 162805

Sadavarte P *et al* 2019 Nepal emission inventory—I: Technologies and combustion sources (NEEMI-Tech) for 2001–2016 *Atmos. Chem. Phys.* **19** 12953–73

Saha P K *et al* 2024 In-vehicle ultrafine and fine particulate matter exposures during commuting in a South Asian megacity: Dhaka, Bangladesh *Atmos. Environ.* **321** 120340

Sharma M *et al* 2007 Role of atmospheric ammonia in the formation of inorganic secondary particulate matter: a study at Kanpur, India *J. Atmos. Chem.* **58** 1–17

Simpson D *et al* 2012 The EMEP MSC-W chemical transport model—technical description *Atmos. Chem. Phys.* **12** 7825–65

Singh M *et al* 2024 Tackling municipal solid waste crisis in India: insights into cutting-edge technologies and risk assessment *Sci. Total Environ.* **917** 170453

Singh N *et al* 2017 Fine particulates over South Asia: review and meta-analysis of $PM_{2.5}$ source apportionment through receptor model *Environ. Pollut.* **223** 121–36

Tibrewal K *et al* 2023 Reconciliation of energy use disparities in brick production in India *Nat. Sustain.* **6** 1248–57

Tsyro S *et al* 2011 Modelling of sea salt concentrations over Europe: key uncertainties and comparison with observations *Atmos. Chem. Phys.* **11** 10367–88

UNEP 2019 *Air Pollution in Asia and the Pacific: Science-based Solutions* (United Nations Environment Programme (UNEP))

van Donkelaar A *et al* 2019 Regional estimates of chemical composition of fine particulate matter using a combined geoscience-statistical method with information from satellites, models, and monitors *Environ. Sci. Technol.* **53** 2595–611

Venkataraman C *et al* 2018 Source influence on emission pathways and ambient PM2.5 pollution over India (2015–2050) *Atmos. Chem. Phys.* **18** 8017–39

Wagner F *et al* 2012 Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries *Sustain. Sci.* **7** 169–84

Wagner F *et al* 2013 *The GAINS Optimization Module: Identifying Cost-effective Measures for Improving Air Quality and Short-term Climate Forcing. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

Weyant C *et al* 2014 Emissions from South Asian Brick Production *Environ. Sci. Technol.* **48** 6477–83

WHO 2021 *Global Air Quality Guidelines. Particulate Matter ($PM_{2.5}$ and $PM_{10}$), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide* (World Health Organization (WHO))

WHO 2022 *Ambient (outdoor) Air Pollution* (World Health Organization)

Wickramasinghe A 2011 Energy access and transition to cleaner cooking fuels and technologies in Sri Lanka: Issues and policy limitations *Energy Policy* **39** 7567–74

World Bank 2016 *The Cost of Air Pollution: Strengthening the Economic Case for Action* (The World Bank)

World Bank 2023 *Striving for Clean Air: Air Pollution and Public Health in South Asia* (The World Bank)