AIR QUALITY IN ASIA

Air Pollution Trends and Mitigation Policy Options

UNITED NATIONS
ESCAP
Economic and Social Commission for Asia and the Pacific

The shaded areas of the map indicate ESCAP members and associate members.*

The Economic and Social Commission for Asia and the Pacific (ESCAP) is the most inclusive intergovernmental platform in the Asia-Pacific region. The Commission promotes cooperation among its 53 member States and 9 associate members in pursuit of solutions to sustainable development challenges. ESCAP is one of the five regional commissions of the United Nations.

The ESCAP secretariat supports inclusive, resilient and sustainable development in the region by generating action-oriented knowledge, and by providing technical assistance and capacity-building services in support of national development objectives, regional agreements and the implementation of the 2030 Agenda for Sustainable Development.

** The designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.*

AIR QUALITY IN ASIA

Air Pollution Trends and Mitigation Policy Options

Photo credits
Cover: Unsplash
Page 12: Unsplash
Page 20: Unsplash
Page 22: Unsplash
Page 25: Unsplash
Page26: Unsplash
Page 27: Unsplash
Page 28: Unsplash
Page 31: Unsplash
Page 35: Valuing Waste, Transforming Cities, ESCAP Report
Page 36: Unsplash
Page 37: Air Pollution and Greenhouse Gas Emissions from the Agricultural Sector in South and Southeast Asia, ESCAP Report
Page 39: Unsplash
Page 40: Unsplash
Page 43: Unsplash
Page 44: 25 Clean Air Measures for Asia and the Pacific, UNEP Report
Page 45: Unsplash

Acknowledgements

This document has been issued in January 2023. Preparation of this paper is coordinated by the Economic and Social Commission for Asia and the Pacific, through its Environment and Development Division, under the supervision of Sangmin Nam, Director, Environment and Development Division, Curt Garrigan, Chief, Environment and Development Policy Section and authorship by Matthew Perkins, Environmental Affairs Officer, and Carly L. Reddington.

This document also benefitted from contributions by Abigail Smith and Mervin Chin, whose inputs were integral to the production of this report. Financial support by the Republic of Korea is gratefully acknowledged.

For further information on this policy brief, please address your inquiries to:

Environment and Development Division United Nations Economic and Social Commission for Asia and the Pacific (ESCAP)

Email: ESCAP-EDD@un.org

Contents

Contents

Figure List

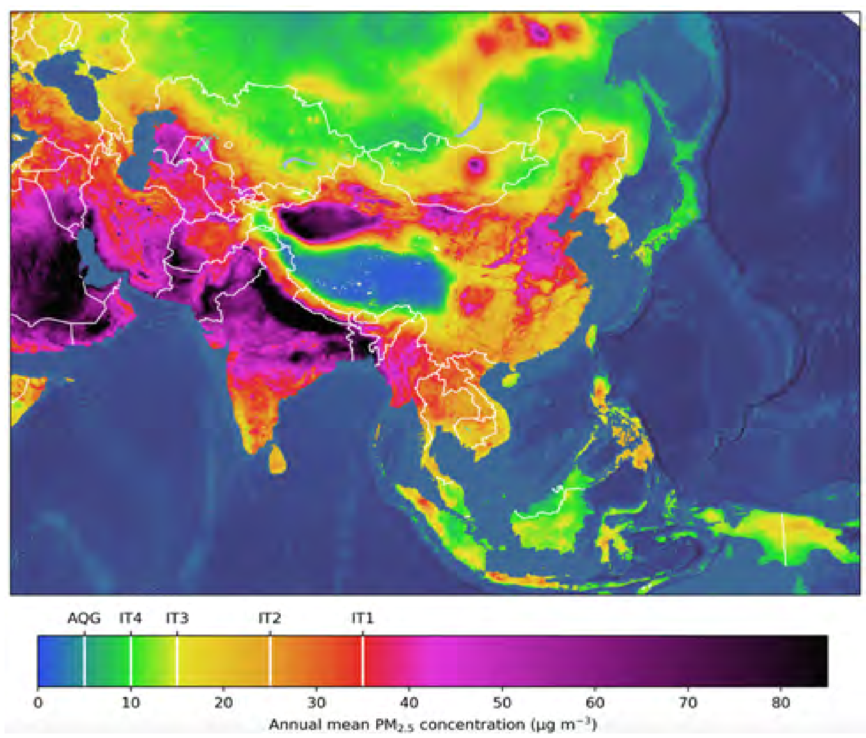
1. Introduction

Rapid population growth, industrialization, and urbanization combined with delayed enactment of environmental policies have led to serious air quality problems across Asia. In particular, the increase in fossil fuel consumption, as well as industrial production, vehicle use, and fertiliser application has driven an increase in air pollutant emissions over recent decades[202, 83], which has increased air pollution and deteriorated air quality. Megacities and urban regions in Asia frequently experience episodes of extremely poor air quality, particularly during stagnant weather conditions. During these air pollution episodes, high concentrations of outdoor or "ambient" fine particulate matter ($PM_{2.5}$; aerosol particles with aerodynamic diameter of 2.5 µm or less) concentrations are recorded with serious implications for human health.

At present, exposure to ambient $PM_{2.5}$ pollution is the largest environmental risk factor for disease and premature death in Asia. Long-term exposure to ambient $PM_{2.5}$ pollution was reported to be responsible for up to 3.6 million early deaths in Asia in 2019, which is around 80 deaths per 100,000 people. Exposure to indoor $PM_{2.5}$ pollution from combustion of solid fuels in the home is another important environmental health risk in Asia, being responsible for around 1.6 million early deaths in 2019[49]. In the future, population ageing is projected to increase the disease susceptibility to $PM_{2.5}$ pollution exposure in Asia [35, 37, 122].

In recent years, governments across Asia have begun to tackle these air quality problems by introducing various policies to reduce air pollutant emissions and concentrations. In some highly populated regions, emission control efforts have been demonstrated to have delivered substantial reductions in $PM_{2.5}$ concentrations, for example the Air Pollution Prevention and Control Action Plan of 2013-2017 in China[194, 190, 137].

Figure 1: Annual average surface $PM_{2.5}$ concentration over Asia 2021



Note: 1: Map of the annual average surface $PM_{2.5}$ concentration over Asia for the year 2021. The values of the World Health Organization (WHO) $PM_{2.5}$ Air Quality Guideline (AQG) of 5 µg m^{-3}, and Interim Targets (IT) of 10 µg m^{-3} (IT4), 15 µg m^{-3} (IT3), 25 µg m^{-3} (IT2), and 35 µg m^{-3} (IT1) (WHO, 2021a) are indicated on the colour bar. The figure was created using 0.01° × 0.01° resolution, hybrid $PM_{2.5}$ concentration data (including measurements and model data) from van Donkelaar et al. (2021) .

However, despite the introduction of some air pollution mitigation policies, ambient $PM_{2.5}$ pollution remains a problem, with measured annual mean concentrations well in excess of the World Health Organization (WHO) Air Quality Guideline concentration of 5 µg m^{-3} in many regions of Asia (Figure)1[139, 142, 90]. Furthermore, the overall ambient $PM_{2.5}$ exposure risk has been increasing, with increases mainly occurring in countries with a low to middle socioeconomic status e.g., countries in South Asia, Southeast Asia, and the Middle East[49].

There is a clear need for the introduction of increasingly stringent air pollution mitigation policies across Asia in the near term, in order to address the large and increasing health burden from air pollution. In addition, future reductions in the $PM_{2.5}$ - attributable disease burden will require strong improvements in air quality to offset the impacts from population ageing[34, 189]. These air quality improvements can be achieved by reducing air pollutant emissions either through the application of dedicated mitigation technologies or as a co-benefit of climate policy[37, 7]. It is essential that global organisations, national governments, and cross-regional partnerships promote regulatory change across Asia and overcome the frequent and numerous challenges to progress, particularly in countries of middle socioeconomic status with large and increasing ambient $PM_{2.5}$ pollution exposure[49].

2. A Regional Picture of Particulate Air Pollution in Asia

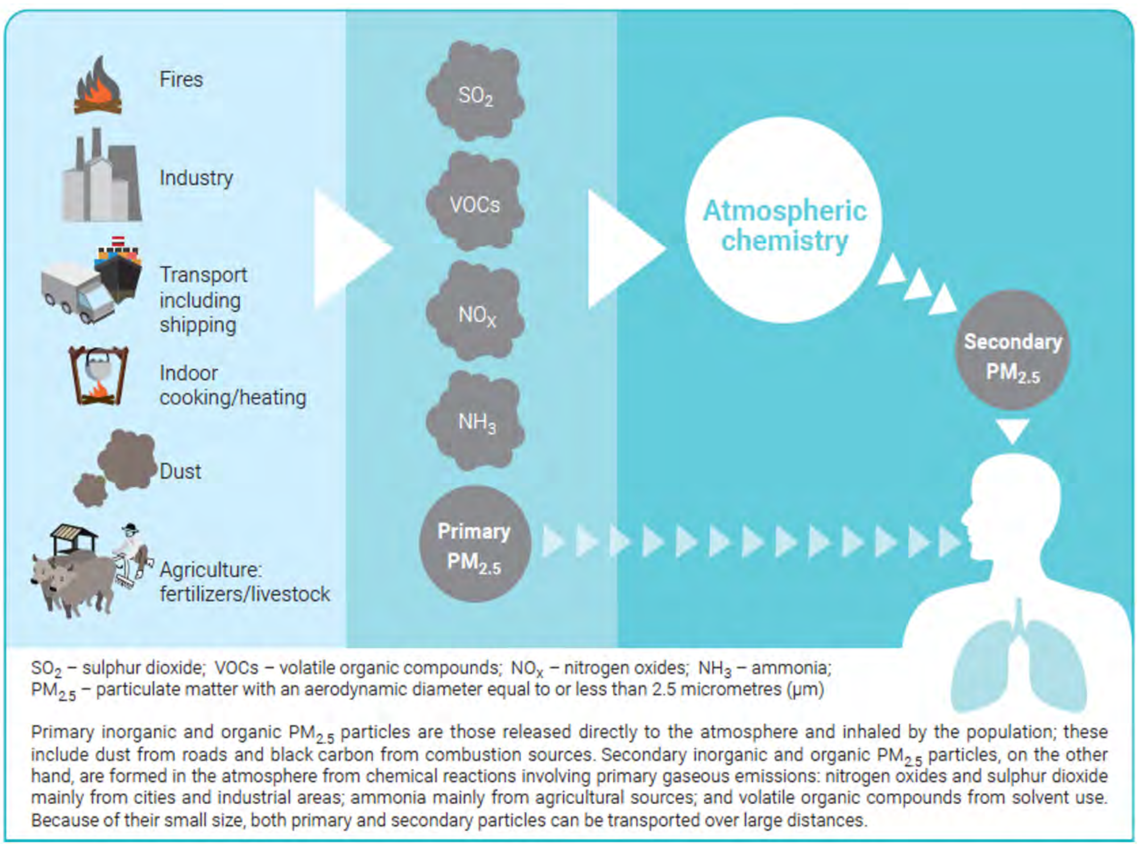
2.1 Ambient fine particulate matter ($PM_{2.5}$) pollution

This report will focus ambient particulate matter (PM), which is one of the most common air pollutants to be emitted from anthropogenic activities and poses the greatest health risk of all air pollutants currently measured. Atmospheric PM consists of a mixture of tiny solid particles and/or liquid droplets that are suspended in the air and are made up of a complex mix of natural and anthropogenic compounds. PM can either be emitted into the atmosphere directly as particulates from a range of sources ("primary PM") or formed in the atmosphere through chemical reactions of precursor gases ("secondary PM") (Figure 2).

Types of primary PM include fly ash, metals, salts, and carbonaceous particulates (including soot) from the combustion of fossil fuels and biomass, mineral dust or soil particles, sea salt, and biological particles like pollen and fungal spores. Secondary PM is formed from gases such as sulphur dioxide, nitrogen oxides, and volatile organic compounds (VOCs) from fuel combustion and industrial processes, and ammonia from agricultural activities. Biogenic VOCs, emitted in large quantities from vegetation, can also contribute to secondary PM formation.

Secondary PM is generally made up of mixtures of components, the most dominant of which are sulphate, nitrate, ammonium, and organic carbon. Atmospheric PM range in size from a few nanometres up to several microns in diameter, and depending on their size and chemical properties, can remain in the atmosphere from a few days to a few weeks.

Figure 2: Composition of $PM_{2.5}$ pollution, anthropogenic sources in Asia



Note: 2 Composition of $PM_{2.5}$ pollution and its key anthropogenic sources in Asia. Figure reproduced from UNEP (2018).

2.1.1 Health effects of $PM_{2.5}$ exposure

Fine PM (PM with a diameter of 2.5 microns or less), abbreviated to "$PM_{2.5}$", is particularly damaging to human health. Once $PM_{2.5}$ has been inhaled, its small size enables it to not only penetrate deep into the lungs, but also pass through the respiratory barrier and enter the bloodstream [46], thus affecting both the respiratory and cardiovascular systems.

Over the past few decades, evidence of the severity of the negative impacts of $PM_{2.5}$ exposure has mounted. Much of this evidence base is from long-term epidemiological studies conducted in Europe and North America, however, in recent years there has been a sharp increase in the evidence for air pollution related health outcomes in the Asian population[186]. Short-term exposure to $PM_{2.5}$ pollution (on the order of hours to days) can cause minor health effects, such as irritation of the eyes, nose, throat and/or lungs, and is also associated with exacerbating existing health issues such as asthma, and cardiovascular and respiratory diseases in Asian populations[75, 70, 78, 183, 22, 198, 149].

Long-term exposure to $PM_{2.5}$ (on the order of months to years) is associated with a range of negative health outcomes in Asian populations including cardiovascular diseases, respiratory diseases, birth defects, lung cancer, and subsequent premature mortality[156, 187, 185, 56, 94, 57, 24, 89, 76].

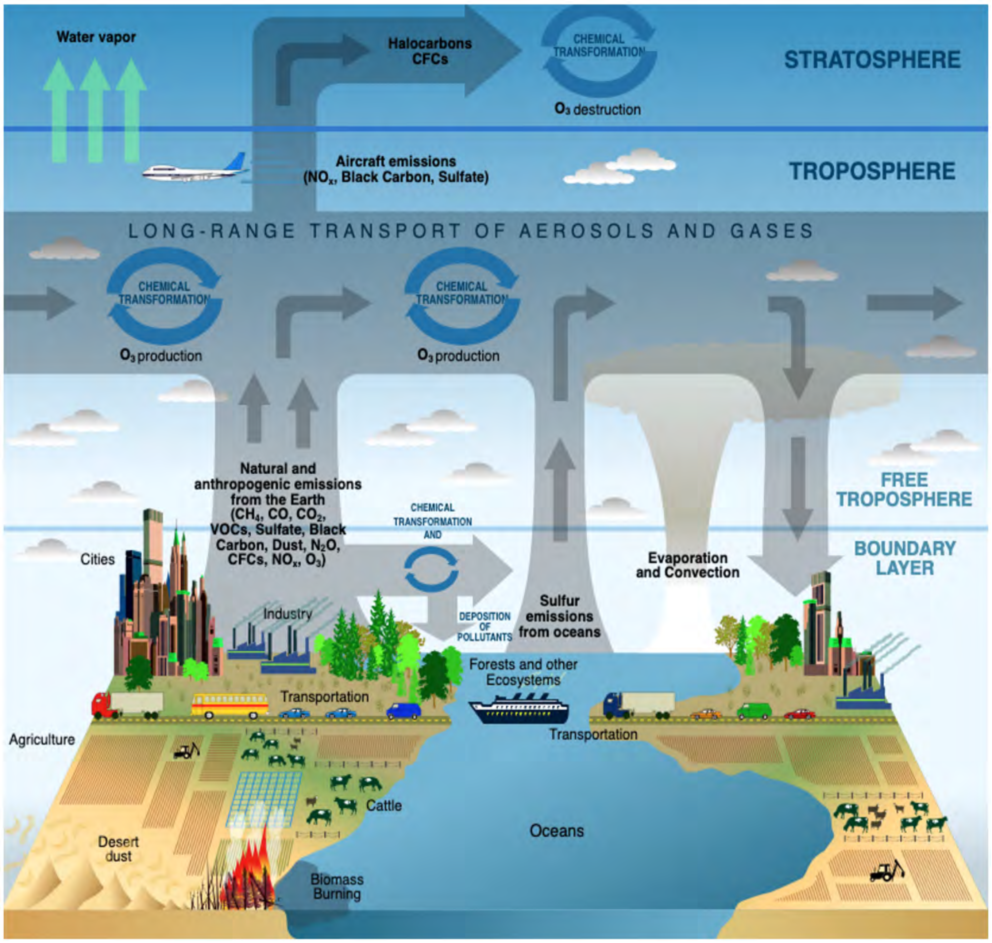
2.1.2 $PM_{2.5}$ concentrations in Asia

The population of Asia is exposed to some of the highest concentrations of $PM_{2.5}$ in the world (Figure 1). $PM_{2.5}$ exposure is particularly high in the South-East Asia WHO region, where measured $PM_{2.5}$ concentrations are above the global average in cities of all sizes[178]. In 2021, almost all of Asia's population (99.9 per cent) were exposed to levels of $PM_{2.5}$ pollution that are above the WHO Air Quality Guideline of 5 $\mu g\ m^{-3}$ [176], with over half the population exposed to levels above the WHO Interim Target 1 (35 $\mu g\ m^{-3}$) (using data from van Donkelaar et al. (2021)). Exposure to $PM_{2.5}$ concentrations that exceed the WHO guidelines can pose a significant risk to human health[176].

2.2 Physicochemical processing of $PM_{2.5}$ in the atmosphere

Poor air quality is mainly driven by strong emissions of air pollutants but can be exacerbated by unfavourable weather conditions[67]. The concentration of $PM_{2.5}$ in the atmosphere is determined by the emission flux in combination with atmospheric processes including dispersion, transport, loss and/or production via chemical reactions, and removal by precipitation and/or dry deposition (Figure 3). In urban areas, local temperature, winds, humidity, and precipitation can all have a strong influence on personal air pollution exposure, in addition to the location and strength of an emission source.

Figure 3: Long-range Transport of Aerosols and Gases



Note: 3 Schematic showing air pollutant emissions from various sources, and subsequent transport, chemical transformation, and loss processes in the atmosphere. Public domain image reproduced from https://commons.wikimedia.org/wiki/File:Atmosphere_composition_d

2.2.1 Local dispersion

Atmospheric stability dictates whether $PM_{2.5}$ pollution is well mixed through the troposphere or trapped closer to ground level. In the daytime, convection driven by solar heating causes the lower portion of the atmosphere to be unstable, mixing pollutants away from the surface (within the “boundary layer”; Figure 3). Under cloudy conditions or at night-time, radiative cooling of the surface leads to more stable conditions that trap air pollutants in a shallower mixed layer, under a temperature inversion. High concentrations of PM in the lower atmosphere can scatter and reflect incoming solar radiation, reducing heat flux into the boundary layer, which makes it more stable, and consequently can amplify pollutant build-up[103].

Within a city, the urbanisation-induced land use change can cause thermodynamic perturbations that facilitate the development of the boundary layer, increasing dispersion, however increased air pollutant emissions outweigh this affect[103]. The topography within and/or surrounding an urban region, also has a strong influence on air pollution dispersion[27]. Mountainous regions surrounding cities can cause surface winds coming from certain directions to be weaker (known as "terrain blocking"), reducing dispersion and causing accumulation of $PM_{2.5}$[18]. Shallow boundary layers, capped by strong temperature inversions and stagnant conditions are implicated in causing severe air pollution episodes, which are also amplified by terrains that limit dispersion, for example winter haze in eastern China[200, 55, 192].

2.2.2 Long-range transport & transboundary air pollution

Because $PM_{2.5}$ can remain in the atmosphere for days or weeks, it can be transported over large distances (Figure 3) and impact cities many hundreds of kilometres from its source. Certain weather conditions are associated with increasing long-range transport of $PM_{2.5}$ pollution across Asia. For example, the Northeast/ Winter Monsoon is often implicated in advecting heavier air pollution from northern regions of China to central and southern regions, where it can transport $PM_{2.5}$ over 2000 km in 2 days[121, 171].

Monsoon systems can also influence long-range transport of $PM_{2.5}$ pollution from open burning in Mainland Southeast Asia[8] and Equatorial Asia[124]. $PM_{2.5}$ pollution originating from fires in Southeast Asia, has been observed to have been transported to Southwest China[204], south-eastern Tibetan Plateau[131], Southern China, Taiwan, and Hong Kong[62]. $PM_{2.5}$ pollution from agricultural fires in India can also be transported over large distances to impact the air quality of neighbouring countries Bangladesh, Nepal, and Pakistan[84].

PM can also undergo inter-continental long-range transport, with $PM_{2.5}$ pollution produced in China impacting air quality in western Europe and the USA and vice versa[193].

2.2.3 Atmospheric removal

PM in the atmosphere is removed ultimately by either dry deposition or through precipitation (Figure 3). Dry deposition involves the transport of PM from the atmosphere onto surfaces in the absence of precipitation. The rate of dry deposition depends on the underlying surface type e.g., buildings, grass, cropland, forests, with generally enhanced dry deposition onto vegetation[46]. Precipitation is the main atmospheric removal process for $PM_{2.5}$ and can have a strong influence on $PM_{2.5}$ concentrations. For example, heavy rainfall during the Southwest/Summer Monsoon can substantially reduce $PM_{2.5}$ pollution over India and eastern China, resulting in $PM_{2.5}$ concentrations that are around 2 to 7 times lower than in wintertime[141, 191].

2.2.4 Climate change and air quality

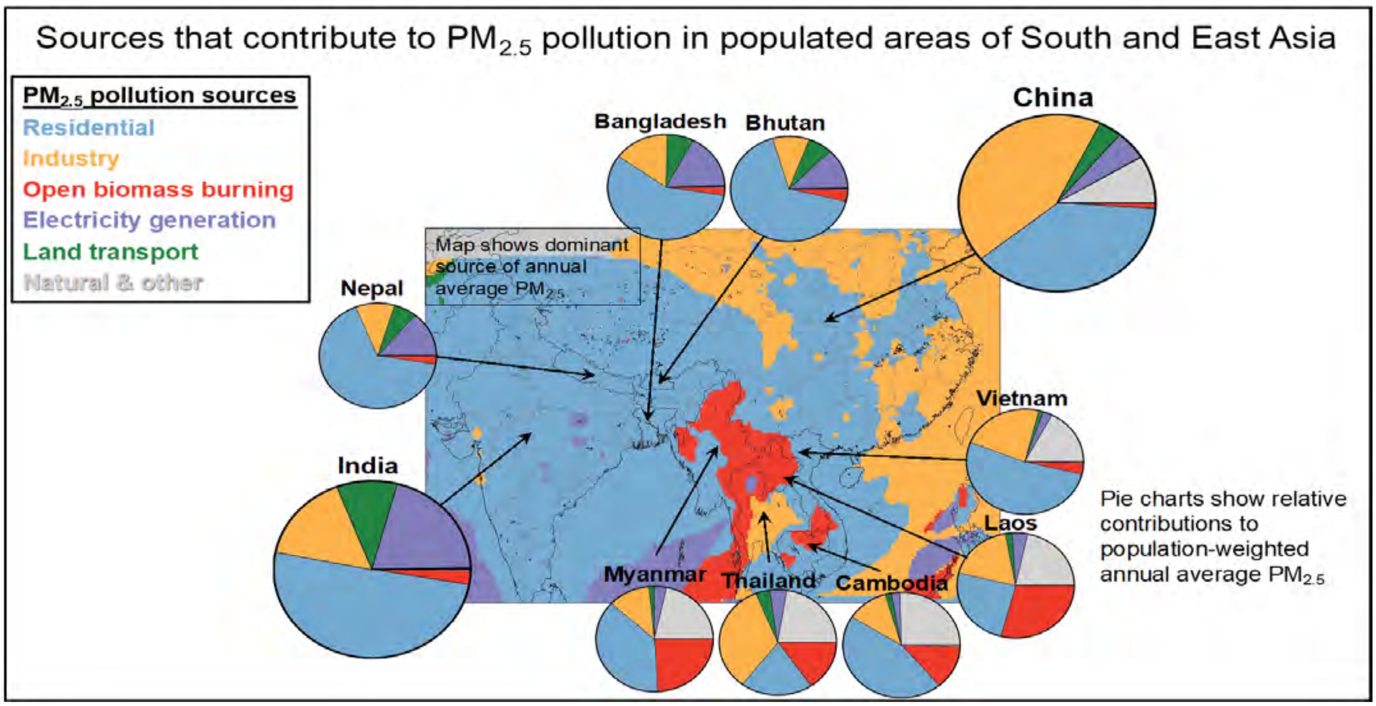
In terms of air quality management, it is important to consider that improvements in air quality through emission controls may be modulated by changes in weather conditions driven by climate change[67]. Future climate change may increase the frequency and duration of extreme weather conditions, including stagnation events and heat waves, which can exacerbate the exposure of urban populations to air pollution and increase air pollution mortality[61]. Furthermore, a warming climate, may influence natural source contributions to $PM_{2.5}$ pollution in Asia, potentially increasing emissions of mineral dust [117] and biogenic VOCs[95].

2.3 Key sources of $PM_{2.5}$ pollution

Understanding the dominant sources of air pollutants is critical to designing air pollution control strategies and interventions. The main sources of $PM_{2.5}$ pollution in Asia (Figure 2) typically include industrial processes, residential cooking and heating, transport, power generation, agricultural activities, forest and vegetation fires, construction, and natural sources. However, these sources and the degree to which they contribute to $PM_{2.5}$ pollution in cities can depend on the location, strength, and distribution of sources, the local meteorological conditions, the surrounding topography, and the season.

2.3.1 Regional overview of $PM_{2.5}$ sources

Figure 4: Sources that contribute to $PM_{2.5}$ pollution



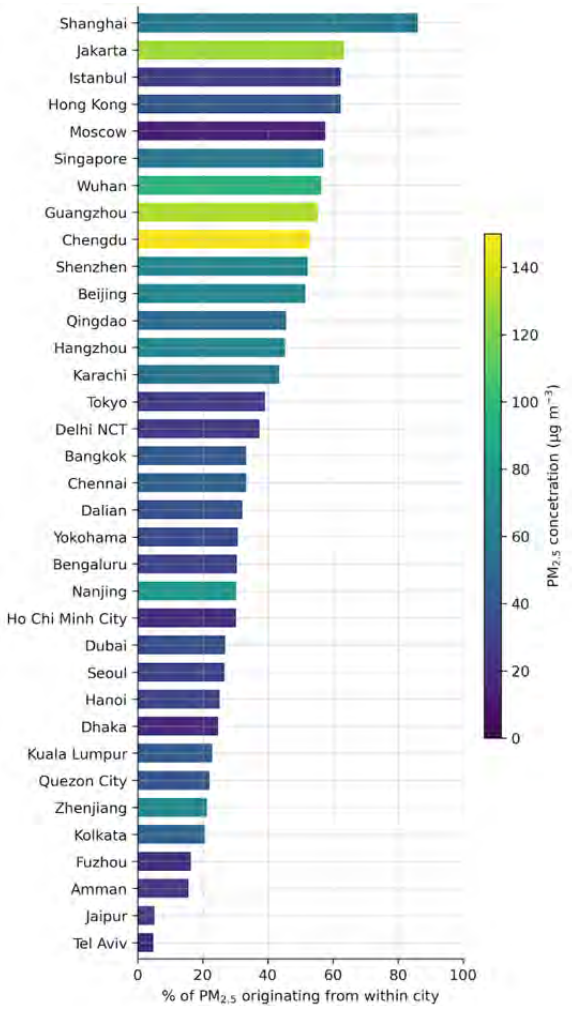
Note: 4 Relative contributions of different emission sectors to regional and national population-weighted annual average $PM_{2.5}$ concentrations in South and East Asia. The 'natural & other' category includes biogenic secondary PM, mineral dust, sea spray, and non-combustion agriculture. Figure was produced using data from Reddington et al. (2019).

In East Asia, the largest contributions to national population-weighted annual $PM_{2.5}$ concentrations are from the industrial and residential emission sectors (Figure 4). The next largest contributions are from natural sources (including mineral dust, sea spray, and biogenic secondary PM) and other anthropogenic sources such as non-combustion agricultural activities, power generation, and land transport. In South Asia, national population-weighted annual $PM_{2.5}$ is dominated by the contribution from the residential sector, with secondary contributions from power generation, industry, land transport, and open biomass burning[126, 35, 180]. Larger contributions of the power sector to $PM_{2.5}$ in South Asia compared to China are likely due to comparatively less regulation and implementation of end-of-pipe controls, along with lower energy efficiencies of power stations in India[170].

In Southeast Asia, the residential sector also dominates contributions to national population-weighted $PM_{2.5}$ in Myanmar, Viet Nam, and Cambodia (Figure 4). Industrial emissions contribute the largest fraction of national population-weighted $PM_{2.5}$ in Thailand, with relatively large contributions in Laos and Viet Nam. In Laos, the national population-weighted $PM_{2.5}$ is dominated by emissions from open biomass burning, which contribute substantially to $PM_{2.5}$ concentrations across Mainland Southeast Asia[127]. Open biomass-burning emissions are likely underestimated in South-east Asia[85, 125], and so they may make a larger contribution to $PM_{2.5}$ pollution than reported here.

2.3.2 Sources of within-city $PM_{2.5}$ pollution

Figure 5: Percentage of $PM_{2.5}$ from within city



Note: 5 Fractions of $PM_{2.5}$ originating from within city sources for 35 major cities in Asia. The colour scale represents population-weighted $PM_{2.5}$ concentrations. Figure was produced using atmospheric model data from Tessum et al. (2022) and is based on Figure 1 of the same article. Model $PM_{2.5}$ concentrations have not been corrected to measurements.

For city-level policies to improve air quality, it is important to know how much of the city's air pollution is generated within the city boundary compared to that transported in from surrounding areas[152]. For cities in Asia, the contribution of sources located within the city boundaries versus those located outside the city to $PM_{2.5}$ exposure varies substantially (Figure 5). For example, sources located within Shanghai are estimated to be responsible for most of its population's $PM_{2.5}$ exposure. While the opposite situation is estimated for Jaipur, with a large majority of its $PM_{2.5}$ coming from outside the city.

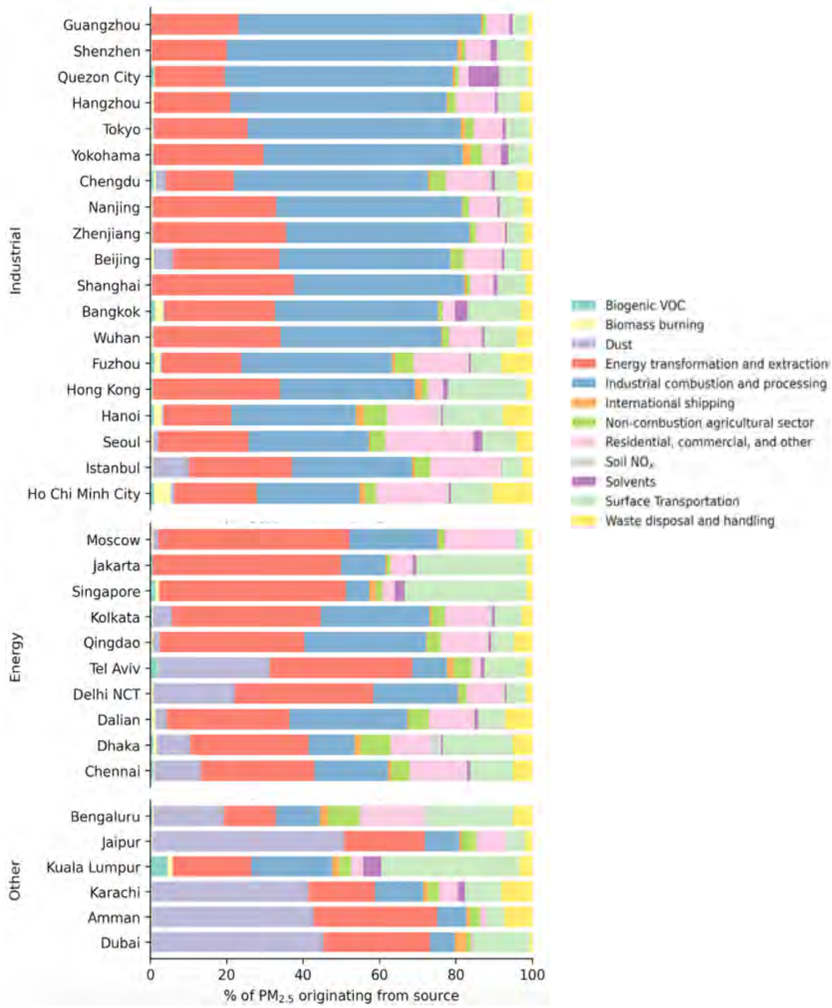
The greatest contributions to total $PM_{2.5}$ concentrations in the selected Asian cities in Figure 6, tend to be from industry, energy transformation and extraction, and residential and commercial activities[152]. Land transport is estimated to be the largest source of $PM_{2.5}$ concentration in only one city (Kuala Lumpur) but it makes important contributions to $PM_{2.5}$ in other cities such as Bengaluru, Singapore, Jakarta, and Hong Kong. The fractional contributions of the energy and transportation sectors to $PM_{2.5}$ concentrations within many Asian cities (Figure 6) are estimated to be larger than compared to the regional contribution estimates (Figure 4), this is likely due to the location of these sources within the boundaries of many Asian cities.

The industry, energy, residential, and transport sectors are the largest sources of $PM_{2.5}$ caused by within-city emissions[152]. The industry and energy sectors are also two of the largest sources of $PM_{2.5}$ caused by out-of-city emissions, with $PM_{2.5}$ pollution being transported from these sources into cities such as Nanjing, Chennai, Bangkok, Kuala Lumpur, and Seoul. The other out-of-city emission source responsible for large contributions to $PM_{2.5}$ in cities is dust, particularly for those cities located in the Middle East.

Open biomass burning, which includes agricultural residue burning and deforestation fires, is another important source of PM in Asia that is generally located outside city boundaries. Emissions from open biomass burning contribute to air pollutant concentrations in cities such as Bangkok[68] and Hanoi[86] shown in

Figure 6, but also in cities such as Chiang Mai[114, 155], Kunming[204], Nanjing[181], and other cities in China[25] and India[93]. Open biomass burning is known to cause serious regional air quality issues and public health impacts in India[84], Equatorial Asia[73], and Mainland Southeast Asia[127] particularly during the burning seasons.

Figure 6: Percentage of $PM_{2.5}$ by largest source, sector



Note: 6 Proportions of total $PM_{2.5}$ from 12 sources among 35 Asian cities, grouped by the largest sources: Industrial combustion and processing, Energy transformation and extraction, and Other sectors. Figure was produced using atmospheric model data from Tessum et al. (2022) and is based on Figure 2 of the same article.

Although there are many common sources of $PM_{2.5}$ concentrations across cities in Asia, there is strong variability in the sectors that contribute most (Figure 6). This means that when considering introduction of air quality mitigation measures at the city level, the city-specific sources and conditions should be considered prior to implementation[152].

2.4 Seasonal variability

The dominant sources and concentrations of $PM_{2.5}$ in urban regions can vary substantially by season. Many highly populated regions in Asia experience their greatest $PM_{2.5}$ concentrations during Northern Hemisphere wintertime. In areas of East and South Asia, regional population-weighted $PM_{2.5}$ concentrations in January are generally more than twice the concentrations in July [168].

Higher wintertime $PM_{2.5}$ concentrations in cities in East Asia are mainly due to the combination of increased fuel (particularly coal) consumption for heating[9] together with more stagnant meteorological conditions (i.e., weakened air pollution dispersion)[103, 98]. In South Asia, elevated wintertime $PM_{2.5}$ concentrations are caused by a combination of increased agricultural residue burning in northwest India[15, 69] and meteorological conditions, including reduced boundary layer height and increased relative humidity[106].

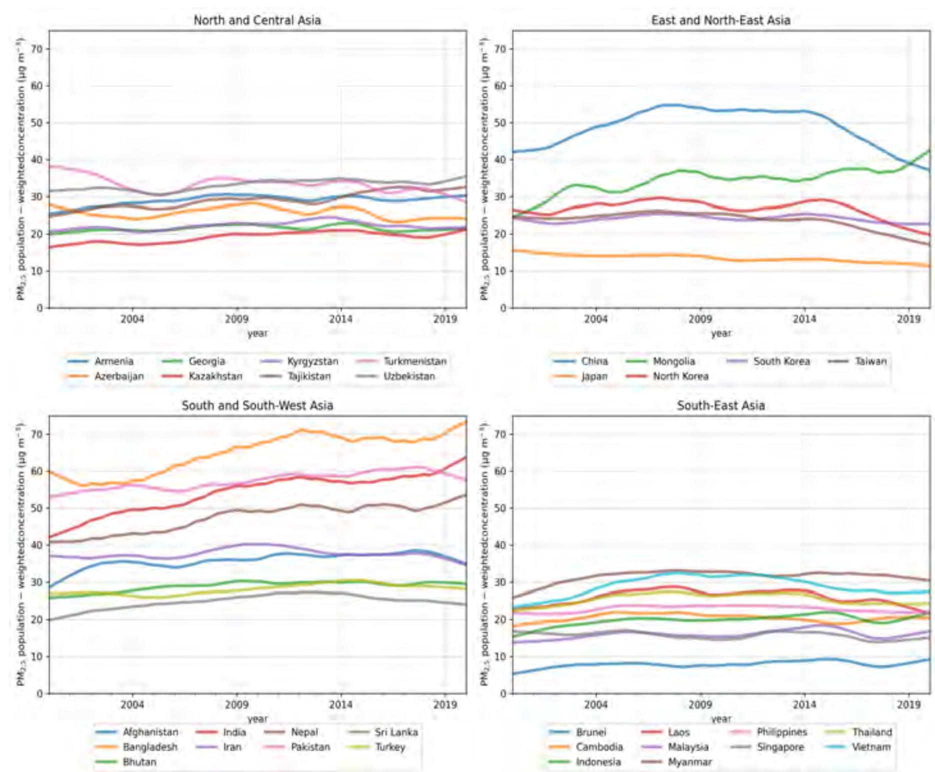
There is strong seasonal variability in open biomass burning emissions and their long-range transport, which peak at various times of year during spring to summer in different regions of Asia[145, 188, 25]. Peatland fires in Indonesia during June-October cause strong enhancements to $PM_{2.5}$ concentrations in cities across Equatorial Asia[124]. Deforestation and agricultural fires in Mainland Southeast Asia mainly occur during February-April coinciding with a widespread stable temperature inversion layer over much of the region[109] promoting high $PM_{2.5}$ concentrations. Increases in regional $PM_{2.5}$ concentrations in northern Asia occur during July-August due to wildfires[167, 168] which can be transported over large distances to impact Russian cities[43].

Sources of precursor gases that form secondary PM also display seasonal variability in Asia. For example, agricultural fertiliser application peaks in the summer in China, which induces seasonal variability in ammonia emissions[64]. Emissions of VOCs from vegetation also tend to peak in the summer, when temperatures are highest, enhancing biogenic secondary PM formation over India and China[20, 104]. Emissions of mineral dust from desert regions and its long-range transport influences the seasonal variability of $PM_{2.5}$ concentrations, particularly in the Middle East during July[5, 168].

2.5 Recent trends in ambient $PM_{2.5}$ pollution

Anthropogenic emissions of primary $PM_{2.5}$ and precursor gases have increased substantially across Asia over recent decades, although the magnitudes and rates of increases varied among different countries and regions. Early increases in emissions were largely driven by rapid urbanisation, industrialisation, and motorization [83] associated with huge population increases and economic growth. However, more recently some countries in Asia are beginning to or have succeeded in decoupling their air pollutant emissions from economic growth e.g., China, Indonesia, Pakistan, Sri Lanka, Thailand, and Viet Nam[159].

Figure 7: National population-weighted $PM_{2.5}$ concentrations 2000-2020



Note: 7 National population-weighted $PM_{2.5}$ concentrations for Asian countries over the period of 2000 to 2020. Figures were produced using hybrid $PM_{2.5}$ concentration data (including measurements and model data) from van Donkelaar et al. (2021) and population data from the Gridded Population of the World project (GPW v4.11; CIESIN, 2016).

The most notable decreases in air pollutant emissions[202] and ambient $PM_{2.5}$ concentrations (Figure 7) have occurred in China during the last decade. Between 2015 and 2020, annual population-weighted $PM_{2.5}$ concentrations in China have decreased by around 30% [137, 133, 38].

These reductions in $PM_{2.5}$ concentrations have largely been attributed to decreasing anthropogenic emissions[201, 138, 41] due to emissions controls in the industrial sector and cleaner residential fuels[194]. Population-weighted annual $PM_{2.5}$ concentrations have also declined since 2015 in other parts of East Asia and in Southeast Asia, including in Taiwan, North Korea, Viet Nam, and Thailand.

In other countries in Asia, population-weighted annual $PM_{2.5}$ concentrations show either relatively small changes or steady increases over the past decade (Figure 7). Regional $PM_{2.5}$ concentrations in South Asia have remained persistently high, with population-weighted annual $PM_{2.5}$ concentrations in India, Nepal, and Bangladesh reaching their highest levels in 2020. These three countries, along with Pakistan and Mongolia, exceed the WHO Interim Target 1[176] for annual average $PM_{2.5}$ exposure (35 $\mu g\,m^{-3}$) in 2020.

In contrast, relatively low annual $PM_{2.5}$ exposures are measured in the high-income countries of Brunei, Singapore, and Japan; attaining the WHO Interim Targets 3 (10 $\mu g\,m^{-3}$) or 4 (15 $\mu g\,m^{-3}$) in 2020. Despite concentrated efforts to reduce $PM_{2.5}$ pollution across Asia, all national $PM_{2.5}$ concentrations in 2020 exceed the stringent WHO Air Quality Guideline of 5 $\mu g\,m^{-3}$.

3. Measuring Progress of Air Pollution Mitigation Policies

3. Measuring progress of air pollution mitigation policies

Monitoring air pollutant concentrations and how they change over time is an essential step in tackling particulate pollution in urban regions[158, 48] and demonstrating the success of emission control interventions. In addition, long-term measurements of ground-level air pollutant concentrations form the basis of epidemiologic research on public exposure to air pollutants and the associated health outcomes.

3.1 Ground based air pollution monitoring

Direct measurements of air pollutant properties using instruments that sample the air in their vicinity ("in-situ measurements") over a long time period are some of the most valuable for monitoring urban air pollution and associated health outcomes. Many countries in Asia have expanded their urban air pollution monitoring networks in recent years e.g., China, India, Malaysia, Viet Nam, Thailand, and South Korea, and now have comprehensive reference grade measurements of surface $PM_{2.5}$ concentrations with high spatial and temporal coverage. Making this data freely available to scientists, NGOs, and the general public is important to improve understanding of the sources and atmospheric processes that contribute most to urban air pollution and health impacts. Open access to measurement data across national borders can assist in tackling the problem of transboundary air pollution.

Figure 8: Ground-based $PM_{2.5}$ pollution monitoring stations in Asia

Note: 8: Map of ground-based $PM_{2.5}$ pollution monitoring stations in Asia with data available through OpenAQ. Red dots show locations of reference grade monitoring stations with PM2.5 concentration data available. Note that some stations may no longer be active.

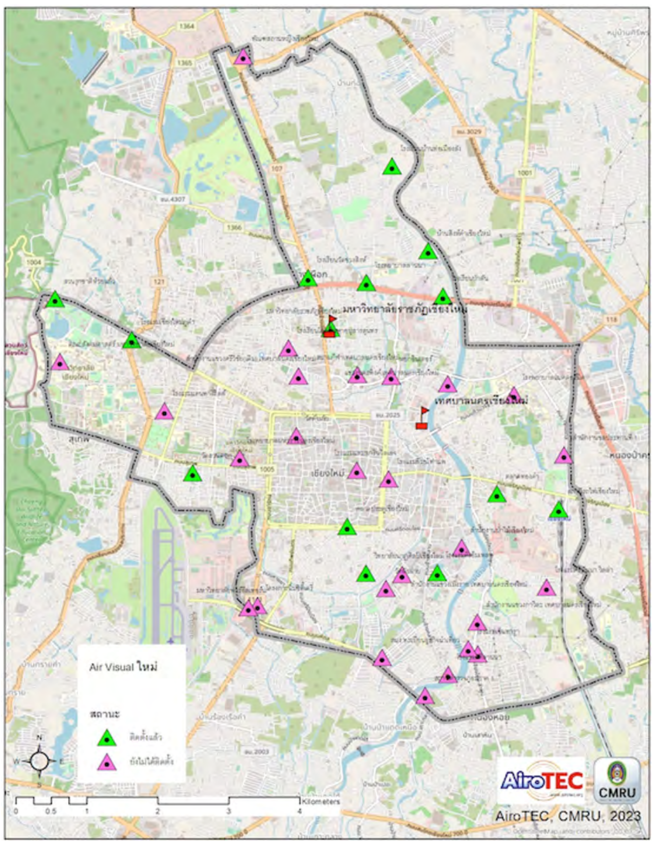
There are several organisations that are now synthesising air pollution measurement data and are making them freely available to the public via online platforms[162, 2, 178] . The organisation OpenAQ[112] collects, visualises, and disseminates air pollution measurement data from monitoring stations across the world. Measurement of air pollution has become increasingly widespread, and OpenAQ now have reference grade measurement data of $PM_{2.5}$ concentrations from over 130 countries, which includes 9,496 different locations (Figure 8), although many gaps remain over Southeast, West, and Central Asia.

3.2 Low-cost sensors

With recent rapid technological advances, a huge range of low-cost sensors are now widely available, providing measurements of a range of air pollutants, often in real time. These sensors are popular due to both their affordability and accessibility, and are particularly useful in cities with few or no existing reference grade measurements. The performance of low-cost PM sensors and the quality of the data they produce varies substantially[71], with the PM sensors subject to biases and calibration dependencies[51]. However, with careful sensor selection and deployment (following recommended practices in the literature[49], low-cost sensors can provide valuable data for long-term urban air quality monitoring[96].

An example of deploying low-cost sensors to increase the quality and quantity of existing air pollution monitoring data, is the Low-cost Air Quality Sensor Initiative[166] developed through partnerships between UN Economic and Social Commission for Asia and the Pacific (ESCAP) and Chiang Mai and Korat municipalities in Thailand. Through this initiative a total of 15 and 21 IQAir AirVisual Pro monitors have so far been installed in Chiang Mai (Figure 9) and Korat, respectively. As well as increasing measurement data coverage, this project will also make real-time air quality data accessible to the public.

Figure 9: Low-cost air quality sensors deployed in Chiang Mai



Note: 9 Map of low-cost air quality sensors deployed in Chiang Mai municipality, Thailand as part of the Low-cost Air Quality Sensor Initiative. Green triangles show the locations of IQAir AirVisual Pro monitors currently installed; purple triangles show planned installation locations.

Survey data from UNEP[159] suggests that increased access to low-cost sensors and the subsequent improved awareness of air pollution is playing a role in increasing public demand for enhanced global action on air quality. In partnership with IQAir, UNEP hosts the world's largest database of $PM_{2.5}$ measurements from a combination of low-cost sensors and reference grade monitoring stations[163]. A real-time interactive map tool provides estimates of global ambient $PM_{2.5}$ concentrations and age disaggregated $PM_{2.5}$ exposure in each country[66].

3.3 Remote sensing

Remote sensing of atmospheric PM relies on its ability to absorb and scatter light, which can be measured from the ground or space. The amount of sunlight blocked by particulates is known as the aerosol optical depth (AOD) and can be used to give an idea of ambient PM levels at the surface. There are several polar orbiting and geostationary satellites with instruments onboard capable of measuring AOD. The most widely used for air quality monitoring is the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Terra and Aqua satellites[135].

The advantage of satellite remote sensing for regional air quality monitoring is its high spatial and temporal coverage (e.g., Li et al., 2022b). However, there are large uncertainties associated with this type of data and retrievals of AOD can be limited or problematic in regions with high cloud cover or in coastal locations. Validation of satellite AOD retrievals with ground-based AOD measurements like those from the AErosol RObotic NETwork (AERONET) can improve the reliability of the data[6].

3.4 Computer modelling and machine learning

Computer models of the atmosphere are an attempt to mathematically represent the complex interactions of physical and chemical processes that air pollutant concentrations depend on. These models allow us to identify and examine the emission sources and the chemical and physical processes that control air pollution. The benefit of using atmospheric chemistry models is the ability to isolate emissions and/or processes, and to simulate air pollutant concentrations with high spatial and temporal coverage. The disadvantages of using these complex models include the high computational cost involved in performing simulations and the necessity to validate model predictions with measurements.

In cases where performing multiple, computationally expensive, atmospheric model simulations is implausible and/or required input data is unavailable, machine learning techniques can be employed instead[39, 65, 82]. Machine learning in air pollution research typically involves the development and use of algorithms that can predict response variables (e.g., $PM_{2.5}$ concentration) based on statistical associations with predictor variables (e.g., $PM_{2.5}$ measurements or complex model simulations), without explanatory knowledge.

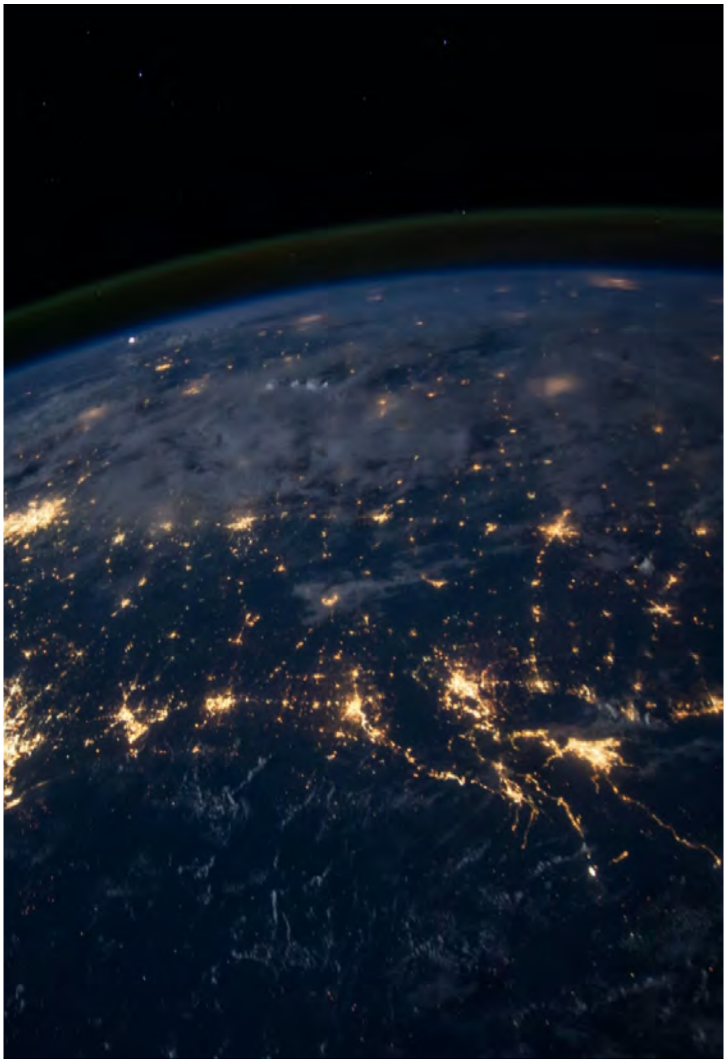
Machine learning approaches have the advantage of requiring fewer inputs than complex atmospheric models whilst being relatively quick and inexpensive to use. However, they have the disadvantage of being 'black boxes' that are difficult to interpret, so are less able to advance our understanding of the processes which cause atmospheric pollution.

Typically, they are not able to extrapolate beyond their training data to examine extreme or hypothetical scenarios. Recent advances are able to improve the 'explainability' of machine leaning algorithms, allowing insight into the role of specific predictor variables[99, 92].

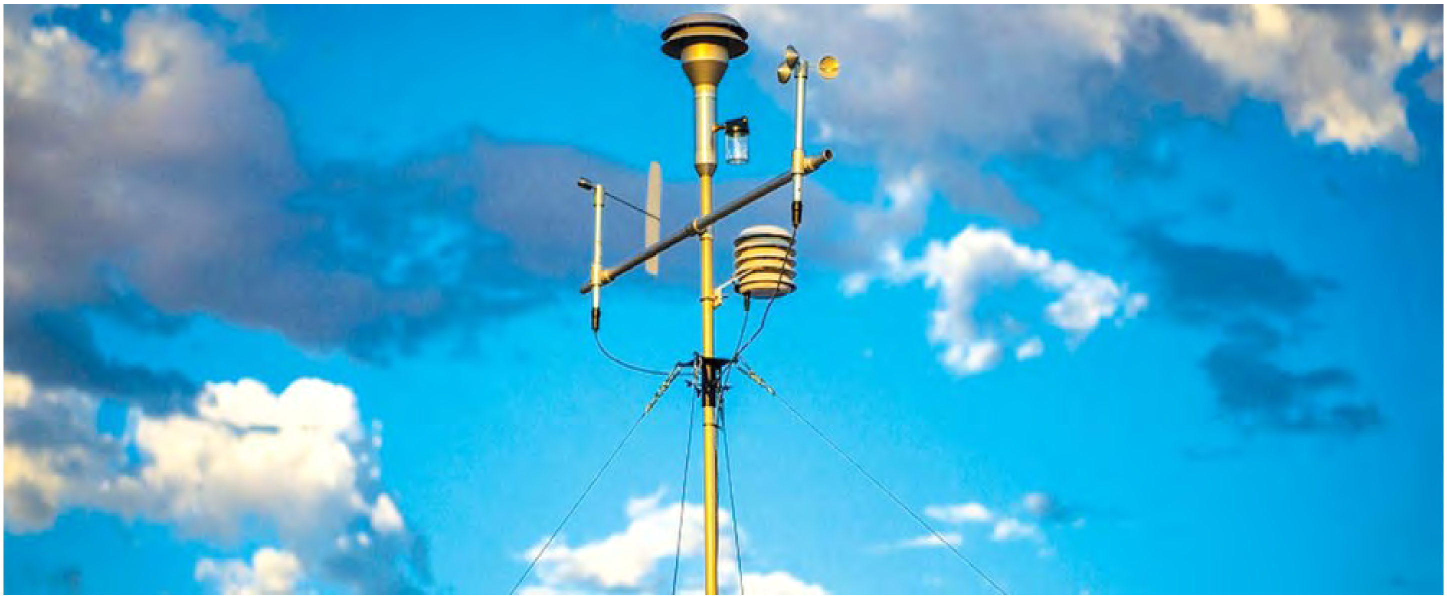
One example of machine learning is the use of emulators as computationally efficient proxies of a complex atmospheric model to quantify uncertainty in model predictions of particulate matter[87], to control for the effect of meteorology on air pollution[52], or to identify emission source contributions to changes in $PM_{2.5}$ concentration[37, 38, 39].

Another example is using machine learning algorithms to predict (forecast) air pollution levels given the meteorological conditions and pollutant concentrations on previous days[88].

Machine learning approaches are ideal for predicting air pollution levels due to their capacity to manage multiple variables and complex relationships between them.



3.5 Hybrid $PM_{2.5}$ data products



Validated AOD data products produced from satellite retrievals (Sect. 2.3) can be used to give an estimate surface $PM_{2.5}$ concentrations. There is an abundance of different methods to derive $PM_{2.5}$ concentrations from retrievals of AOD[59, 135]. A widely used method involves building statistical models to relate AOD, and other predictors such as land use data and meteorology, to ground-based measurements and model simulations of PM2.5 concentrations. The research paper from van Donkelaar et al. (2021)[168] apply a similar methodology to derive global monthly estimates of $PM_{2.5}$ concentrations for the period 1998–2019, which allows for the characterization of seasonal and episodic $PM_{2.5}$ exposure, as well as aid air-quality management. These hybrid datasets are generally better for regional-scale representation of $PM_{2.5}$ pollution.

However, where extensive ground-based $PM_{2.5}$ measurements exist along with the capacity run high-resolution air quality model simulations, hybrid data products can provide real-time, street-level $PM_{2.5}$ exposure distributions that are relevant for cities, for example the Personalised Real-Time Air Quality Informatics System for Exposure – Hong Kong[119, 23].

4. Examples of Previously Implemented Air Pollution Mitigation Policies

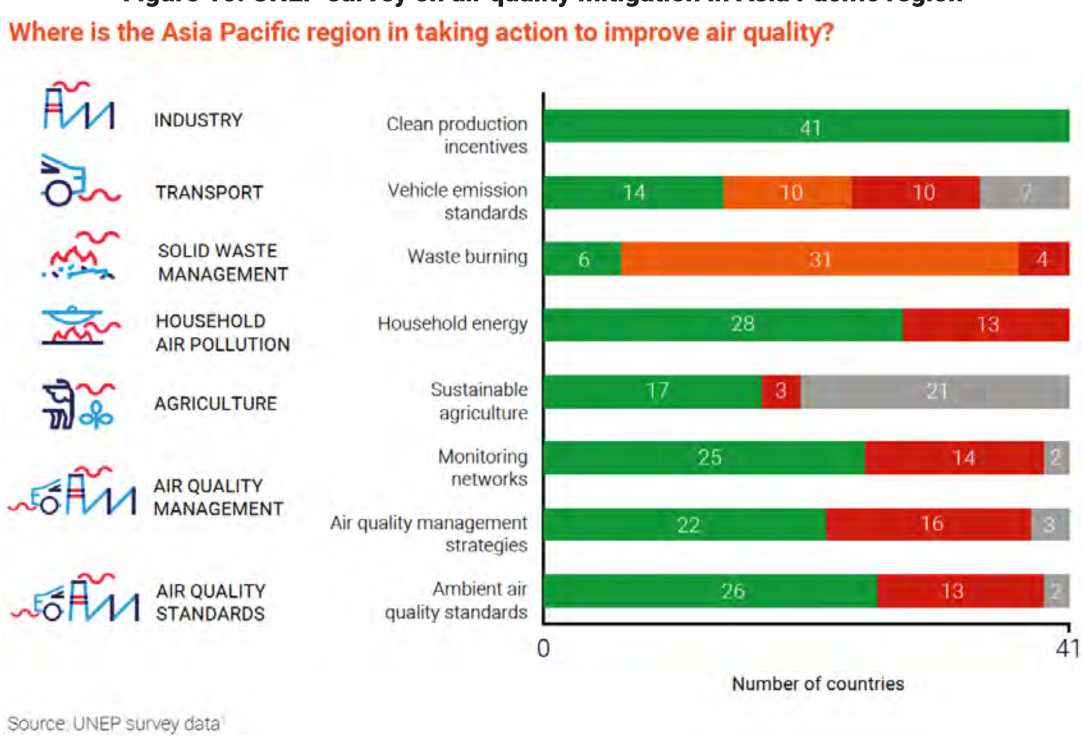
4. Examples of previously implemented air pollution mitigation policies

In recent years countries across Asia have successfully implemented a range of policies to mitigate and reduce $PM_{2.5}$ pollution from the key polluting sources. To address both country-wide and urban air pollution, central governments in several countries have introduced and adopted national air quality management programmes, such as the Draft Bangladesh Clean Air Act, India's National Clean Air Programme, Malaysia's Clean Air Action Plan, the National Electrical Vehicles Policy in Pakistan, and many others. The Chinese government have released a series of national policies over the last decade including the Air Pollution Prevention and Control Action Plan, the Three-Year Action Plan for Winning the Blue Sky Defence Battle, and more recently, the New Pollutant Control Action Plan.

The clean air action plans introduced in China have been particularly successful in delivering substantial reductions in urban $PM_{2.5}$ pollution in recent years[201, 41, 138]. Thus, demonstrating the potential effectiveness of national policies for improving city-level air quality. The action plans have included a wealth of stringent emissions control measures, targeting individual sectors and sources[194, 33]. The combination of effective air pollution monitoring across urban regions in China (alongside increased availability of the data in recent years) with a strong interest from the scientific community, has enabled a thorough analysis and attribution of the impact of these measures on air pollutant concentrations.

The measures that were reported to have driven the strongest reductions in $PM_{2.5}$ concentrations between 2013-2017 were the strengthening of emission standards in the industrial and power generation sectors, upgrades on industrial boilers whilst phasing out inefficient industrial capacities, and the promotion of clean fuels in the residential sector[194].

Figure 10: UNEP survey on air quality mitigation in Asia Pacific region



Note: 10 Progress towards adoption of key actions that can significantly improve air quality. Results are from the UNEP (2021) survey on 41 countries in Asia. Figure was taken from UNEP (2021).

More broadly across Asia, air quality management programmes and complimentary policies have meant that since 2015 there has been widespread implementation of stronger emission controls for the industrial sector, with substantial progress in energy efficiency and renewable energy policies (Figure 10)[159]. Promising progress has also been made in the transport, residential, and agricultural sectors (Figure 10), with the survey on 41 countries in Asia revealing that by 2020:

- 56 per cent of countries had established vehicle emission standards
- 34 per cent of countries had light-duty vehicle emission standards at Euro 4 level or equivalent.
- 31 per cent of countries were using diesel with a maximum sulphur content of 50 ppm or less.
- 68 per cent of countries had adopted clean residential cooking and heating programmes, benefitting 500 million people.
- 90 per cent of countries had introduced some form of regulations to prohibit open burning of household waste.
- 41 per cent of countries had implemented programmes to promote sustainable agricultural practices including improved management of agricultural residues and livestock manure.

Despite the implementation and demonstrated success of clean air policies in some regions, $PM_{2.5}$ exposure remains high across most Asian countries and the attainment of national and WHO air quality targets in populated regions is limited. The introduction of air pollution measures and interventions, and subsequent progress towards clean air, is uneven across Asia, with low- and middle-income countries experiencing the greatest $PM_{2.5}$ exposures.

Furthermore, in some regions where $PM_{2.5}$ concentrations have decreased, concentrations of another air pollutant (ground-level ozone) have increased over a similar time frame[137, 139]. Therefore, it is clear that more progress needs to be made in order to reduce air pollution to within healthy limits across much of Asia.

5. Recommendations for $PM_{2.5}$ Pollution Mitigation

5. Recommendations for $PM_{2.5}$ pollution mitigation

This section will draw on results relevant for $PM_{2.5}$ pollution from[157, 158], which identifies the most effective 25 measures to reduce air pollution in Asia, providing cost-effective options specifically suited to Asian countries (see Table 1, 2, 3). Implementing these measures could help 1 billion people breathe cleaner air by 2030 and reduce global warming by a third of a degree Celsius by 2050[158]. We also include state-of-the-art recommendations for reducing $PM_{2.5}$ pollution from recent scientific literature relevant for cities in Asia. We note that because of uneven progress in air pollution mitigation across Asia, selected Asian countries and/or cities will have already adopted some of the effective measures to control $PM_{2.5}$ pollution listed below. Prioritisation and implementation of the recommended measures must consider country- and city-specific aspects, such as the key air pollution sources, local geography, and existing socioeconomic conditions[158].

Table 1: Next-stage air quality measures

Next-Stage Air Quality Measures	
Agricultural crop residues	Manage agricultural residues, including strict enforcement of bans on open burning
Residential waste burning	Strictly enforce bans on open burning of household waste (and encourage centralized waste collection
Prevention of forest and peatland fires	Prevent forest and peatland fires through improved forest, land and water management and fire prevention strategies
Livestock manure management	Introduce covered storage and efficient application of manures
Nitrogen fertilizer application	Establish efficient applicationincrease green areas
Brick kilns	Improve efficiency and introduce emissions standards
International shipping	Require low-sulphur fuels and control of particulate emissions
Solvent use and refineries	Introduce low-solvent paints; leak detection; incineration and recovery

Note: 11 Clean air measures recommended by UNEP (2019) that are relevant for reducing $PM_{2.5}$ pollution in Asia. Table is adapted from Table A: "The Top 25 Clean Air Measures" UNEP (2019).

Table 2: Regional Application of Conventional Measures

Regional Application of Conventional Measures	
Post-combustion controls	Introduce state-of-the-art end-of-pipe measures to reduce air pollutant emissions at power stations and in large-scale industry
Industrial process emissions standards	Introduce advanced emissions standards in industries
Emissions standards for road vehicles	Strengthen all emissions standards; special focus on regulation of light- and heavy-duty diesel vehicles
Vehicle inspection and maintenance	Enforce mandatory checks and repairs for vehicles
Dust control	Suppress construction and road dust; increase green areas

Note: 12 Clean air measures recommended by UNEP (2019) that are relevant for reducing $PM_{2.5}$ pollution in Asia. Table is adapted from Table A: "The Top 25 Clean Air Measures" UNEP (2019).

Table 3: Regional Application of Conventional Measures

Measures Contributing to Development Priority Goals with Benefits for Air Quality	
Clean cooking and heating	Use clean fuels; substitution of coal by briquettes
Renewables for power generation	Use incentives to foster extended use of wind, solar and hydro power for electricity generation and phase out the least efficient plants
Energy efficiency standards for industry	Introduce ambitious energy efficiency standards for industry
Electric vehicles	Promote the use of electric vehicles
Improved public transport	Encourage a shift from private passenger vehicles to public transport

Note: 13 Clean air measures recommended by UNEP (2019) that are relevant for reducing $PM_{2.5}$ pollution in Asia. Table is adapted from Table A: "The Top 25 Clean Air Measures" UNEP (2019).

5.1 Industrial sector (including the power sector)

The industrial and power generation sectors are two of the largest contributing emission sources to $PM_{2.5}$ in Asia[158].

5.1.1 Large stationary combustion sources

Recommendations for reducing $PM_{2.5}$ associated with this source focus on strengthening industrial emission standards in all industries (e.g., in power plants, iron and steel plants, cement factories, glass production, chemical industry, etc.)[157,193]. Technological improvements including state-of-the-art end-of-pipe controls should be implemented in power stations and large-scale industry to reduce emissions of PM and precursor gases (sulphur dioxide and nitrogen oxides (NOx)) through, e.g., flue gas desulfurization, de-NOx catalysts, and electrostatic precipitators [7, 157].

To compliment application of stronger emissions standards, mandatory enhanced energy efficiency standards should be introduced for industry[157, 159], accompanied by phasing out of outdated industrial capacity and inefficient fossil fuel power plants [193]. For electricity generation, extended use of wind, solar and hydro power should be fostered through incentives and adoption of renewable energy policies, alongside a reduction in investment in fossil fuels[157].

5.1.2 Industrial volatile organic compounds

Industrial VOCs are an important source of secondary $PM_{2.5}$ in Asia[107]. VOCs are used/produced and emitted from a range of different industries, including petrochemical, pharmaceutical, chemical pesticide production, paint production, furniture manufacturing, packaging and printing, dyeing, wood processing etc.[58, 140]. Recommendations to reduce sources of solvent-derived VOCs include the use of low-solvent paint for industrial and domestic applications; replacing with water-based paints, inks, and coatings where possible [157, 3]. Implementation of leak detection and repair standards should be required to reduce VOC sources in chemical and petrochemical industries [173].

Recommendations to reduce the emissions of VOCs involve the use of covers, gas-collecting methods, seals, and vapour recovery during the manufacturing process and application of VOC-containing paints, coatings, and other substances [3, 173]. End-of-pipe treatments of waste VOC-containing gases should be introduced, with methods including adsorption, absorption, filtration, or incineration [3, 173].

5.1.3 Brick kilns

Brick production is often a relatively small, informal industry that can strongly contribute to local $PM_{2.5}$ concentrations in and around urban regions in Asia[129, 146, 180]. Recommendations to reduce emissions from brick manufacturing involves the shift to modern brick kiln technologies e.g., Hybrid Hoffmann kilns, Zig-zag kilns, and Vertical Shaft Brick kilns, that are more efficient and less polluting [1,44].

To compliment application of cleaner technologies, emissions standards should be introduced with enforced upgrades or closures required for facilities failing to comply[158, 173]. To improve uptake of clean technologies in brick manufacturing, governments, policy makers and other relevant stakeholders should offer financial assistance e.g., loans to covert high retrofit costs, alongside provision of awareness campaigns for kiln owners on the associated benefits, and training programmes for kiln labour[1].

5.2 Residential sector

5.2.1 Residential cooking and heating

The burning of solid fuels like coal, wood and animal dung, for cooking and heating is a substantial source of ambient $PM_{2.5}$ pollution (Sect. 3.3)[158], but also contributes significantly to household air pollution. Recommendations for reducing $PM_{2.5}$ emissions from the residential sector focus on using cleaner fuels such as electricity, natural gas, or liquefied petroleum gas (LPG) in cities and LPG and advanced biomass cooking/heating stoves in rural areas[158].

Where coal is widely used, focus should be on reducing the ash and sulphur content of the coal[28] or substitution of coal by briquettes. Factors that will enable success in reducing residential sector contributions to $PM_{2.5}$ pollution are increasing policy-maker and public awareness of the impacts of solid-fuel combustion on health, whilst utilising lessons learned from the design of previous clean cooking and heating programmes introduced in China and India[158].

5.2.2 Residential waste burning

For many households in lower-income regions of Asia, open burning of residential waste is a relatively easy and low-cost method of disposal.

To eradicate this source of $PM_{2.5}$ pollution, bans on open burning of residential waste should be strictly enforced, for example by imposing fines or penalties, and awareness of legal prohibitions should be promoted[158].

Residential waste burning should be replaced with centralized waste collection and disposal or incineration[158]. Where waste incineration is employed, it is critical to implement combustion technologies with strict emissions controls[40, 179].

Enabling factors include implementing regulation on engineered landfills and incineration and/or collaboration with informal sector for recycling to reduce the amount of waste generated[158].

5.3 Land transport sector

Recommendations for reducing air pollutant emissions from land transport involve strengthening all emissions standards with special focus on regulation of light- and heavy-duty diesel vehicles[158] . More specifically, the goal should be for the on-road transport sector to move towards effective introduction of, and compliance with, Euro-6 (VI) or China 6a/6b (VIA/VIB) equivalent emission standards for all new vehicles and machinery, with a phase-out of old vehicles[48, 7, 28].

The adoption of improved emissions standards should be complemented by a maximum permitted sulphur content of 10 ppm in diesel and gasoline[158]. The factor that will enable these emissions standards transitions is collaboration between environmental agencies, transport agencies, oil companies, and vehicle manufacturers[158]. Success of emissions standards in terms of improving air quality will rely on compliance[48]. Thus, enforced vehicle inspection and maintenance e.g., at the roadside or in public testing stations, should be implemented to ensure standards are being met[158, 48].

Alongside improvements in emissions standards, policies should also be introduced to promote and support the use of electric vehicles, with an aim for 50 per cent of the car fleet to be electric by 2030-2040[158, 7]. There should also be a strong action to encourage a shift from private passenger vehicle ownership to active and/or public transport usage[158]. To promote this shift, public transport systems should be enhanced (e.g., introduction of Rapid Mass Transit systems, cleaner buses etc.)[48], complemented by bike sharing systems[158] and improved provision of safe and accessible cycling environments[17, 165].

In cities with large areas of unpaved roads, focus should be on reducing re-suspended road dust through sealing of road surfaces and applying other measures, including sprinkling of water or chemical agents[54, 158].

5.4 Agricultural sector (non-combustion activities)

The approach to reduce $PM_{2.5}$ pollution from agricultural activities is through the reduction of emissions of ammonia which contributes to secondary formation of PM in the atmosphere. The two key measures to reduce agricultural ammonia emissions are to improve livestock manure management and to improve the efficiency of fertilizer application[158].

Improved manure management practices involve covered storage of manures and enclosed systems for manure treatment including anaerobic digestion, with efficient incorporation of its residual products into soils as organic amendments[158, 7]. For non-industrial or small farms without appropriate facilities, manure could be delivered to central processing facilities, or the outdoor grazing of animals be extended[7]. Reducing protein-rich feeding in livestock farming is a further, relatively low-abatement cost, option for reducing ammonia emissions from manure, but levels must be assessed to avoid undermining animal productivity and welfare[196].

Recommendations for improved synthetic fertilizer use include optimized and efficient application of urea and/or use of urease inhibitors, with a switch to ammonium nitrate, controlled/slow-release fertilizers where applicable[158, 154]. Further recommendations are to promote the use of organic fertilizers with efficient application and incorporation deep into the soil[154], improving the coupling between cropland and livestock production systems to increase recycling of manure[195, 196].

To promote the adoption of sustainable farming practices, financial incentives for farmers (e.g., through direct economic benefits and/or increased productivity) are a key factor, along with benefits to the farm itself and/or environment[116]. Abatement costs of reducing ammonia emissions from agriculture are likely to be far outweighed by the overall societal benefits[196].

5.5 Open biomass burning

5.5.1 Agricultural residue/waste burning

Open burning of agricultural waste or residues in the field remains a widespread practice in many countries in Asia, despite laws in most of these countries prohibiting it[14, 123, 203]. To improve the effectiveness of open burning bans, strict enforcement should be combined with working alongside farmers to provide viable no-burn alternatives for crop residues[158].

Viable alternatives include conversion of residues to biomass pellets or biogas for bioenergy purposes or mechanised collection of residues into bales for on- or off-site use, both of which have the potential for generating additional incomes for the farmers[158]. Non-bioenergy uses for baled crop residues include growing mushrooms, brick production, livestock feed (depending on the crop), and animal bedding[158].

Important sustainable agricultural practices involve retention of crop residues after harvesting, either planting seeds directly through stubble (low- or no-till conservation agriculture) or incorporating residues into the soil as mulch. These practices can have multiple co-benefits including improved soil health and a decreased need for fertilizers (thus reducing ammonia emissions; Sect. 6.4)[158, 123].

Overall, the implementation of sustainable agricultural mechanisation e.g., Happy Seeder systems, will be vital to assist farmers (particularly smallholders) in effectively managing agricultural residues and generating additional profits [136]. The provision of financial support to smallholder farms, through incentives, loans, and other financial schemes from governments and/or private investment, can reduce financial barriers associated with upfront machinery costs and will facilitate the adoption of sustainable agricultural mechanisation[136].

Active engagement with stakeholders on agricultural emission controls and sustainable agricultural practices, including training on modern mechanization and techniques, and empowerment of farmers, will aid success in reducing burning[14].

5.5.2 Deforestation & peatland fires

The use of slash and burn practices for land clearance for agricultural purposes is widespread in many countries in Asia, particularly Mainland Southeast Asia[16, 115] and Equatorial Asia[4]. Furthermore, extensive deforestation and drainage of Indonesian peatlands have made these regions increasingly vulnerable and susceptible to repeated burning[81].

Strict enforcement of regulations prohibiting the use of fire to prepare lands for plantation agriculture will mitigate fire-derived $PM_{2.5}$ pollution in some regions but not all. For example, a moratorium on primary forest and peatland conversion in Indonesia has been ineffective in reducing deforestation or fires in many areas[148, 53] due to multiple challenges[60]. Policies that combine a forest/peatland moratorium with incentives and livelihood support for farmers (e.g., by creating a market for forest and agroforestry products) and/or increased community forest and fire management are likely to be more successful[148, 158, 132, 111].

Improved management of forest/peatlands and plantations, with engagement between central and local governments, will be crucial for reducing future deforestation and associated fires[110, 111]. A further step that should be taken to reduce peatland fires is peatland restoration (including both re-wetting and revegetation), with co-benefits associated with biodiversity conservation, climate mitigation, and sustainable livelihoods[10]. Community involvement and participation in peatland restoration, along with ongoing engagement with farmers, landowners, and the local community is essential for success of restoration initiatives[174, 10, 175, 151].

The economic benefits of effective peatland restoration (from reductions in costs connected to land-use damage and health impacts from fire-derived $PM_{2.5}$ exposure) could outweigh the cost of restoration, providing evidence to support ongoing peatland restoration efforts[74].

Overall, it is crucial to prevent future forest and peatland fires through a combination of improved forest, land, and water management and fire prevention strategies [158]

5.6 Shipping sector

Air pollutant emissions from domestic and international shipping and the management of these sectors are important for improving air quality in coastal and inland river cities in Asia, particularly those with major ports and/or high levels of marine traffic[118, 100, 26].

Recommendations for reducing $PM_{2.5}$ pollution from shipping involve the requirement of low-sulphur fuels and control of PM emissions for all maritime vessels[158]. Shipping emissions controls across coastal regions of Asia should match or improve on those currently implemented in the Domestic Emission Control Area (ECA) established in China[105].

Plans for near-term future emission controls should follow those set by the International Maritime Organization for other ECAs (mandate sulphur cap at 0.1 per cent and Tier III NOx standard for new ships) for maximum $PM_{2.5}$ - related health benefits[197]. Reciprocal regulatory agreements with neighbouring cities regarding shipping emissions should be implemented to reduce transboundary air pollution issues[79].

5.7 Cross-sector air pollution mitigation

5.7.1 Decarbonisation and climate mitigation

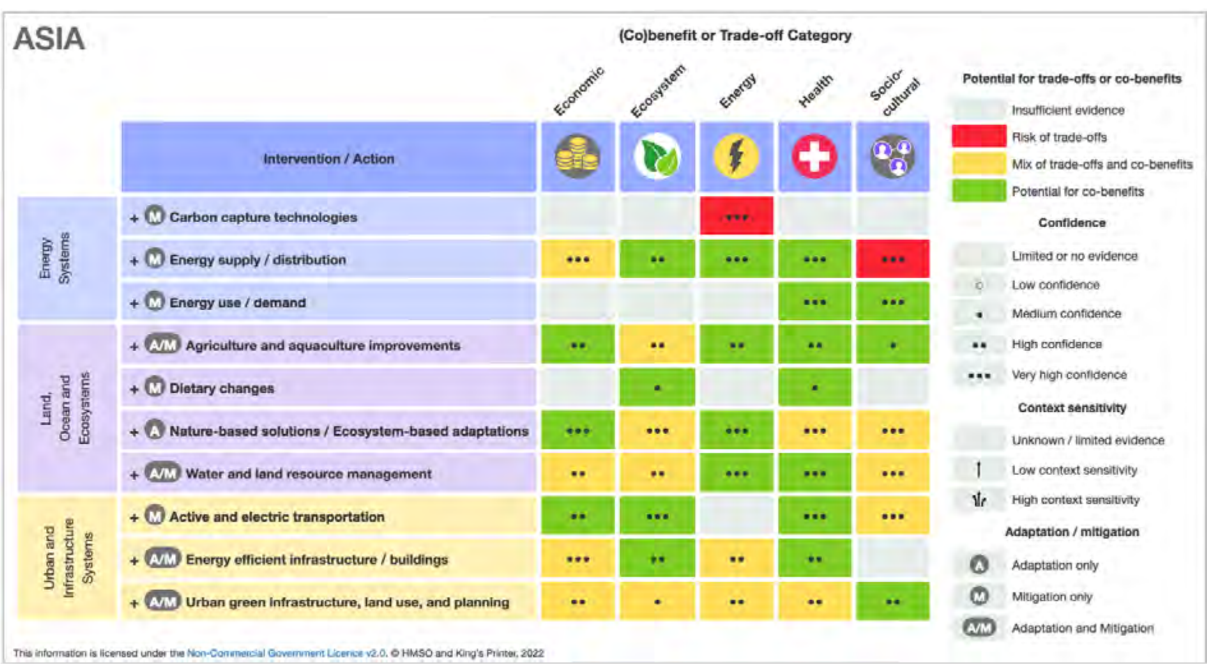
Efforts to reduce greenhouse gas emissions to mitigate future climate change can also lead to reductions in co-emitted air pollutants, resulting in improved air quality in Asia countries[182, 31, 47, 77, 150]. The economic savings due to air quality and health co-benefits of climate change mitigation policies could offset the implementation costs of greenhouse gas emissions reductions[101, 169, 130, 128]. There are many different intervention options available across all sectors discussed above that could drive simultaneous reductions in greenhouse gas and air pollutant emissions[158, 7, 18, 184].

Many of these options have already been presented in previous sections e.g., promoting renewable energy (Sect. 6.1.1), transitions to clean residential energy (Sect 6.2), and reductions in emissions from the transport and agricultural sectors (Sects. 6.3, 6.4, and 6.6) and open burning (Sect. 6.5)[158].

More substantial reductions in PM2.5 pollution can be delivered through implementation of climate change mitigation policies in combination with stringent air pollution control measures[122, 134, 37]. Policies that combine climate mitigation with multi-sectoral air quality management and sustainable development measures will be more successful in reducing the public health burden of air pollution, whilst helping to achieve multiple UN Sustainable Development Goals (SDGs)[158, 7].

The Climate Co-benefit Portal[120] can aide in identifying specific climate mitigation measures that lead to co-benefits (including improved air quality and other factors) across different regions and contexts (Figure 11). For example, transitioning to active and electric transportation for climate mitigation purposes has strong potential for public health and ecosystem co-benefits through reductions in air pollution and improved air quality (see Figure 11) [120].

Figure 11: (Co)benefit or Trade-off Category for Asia



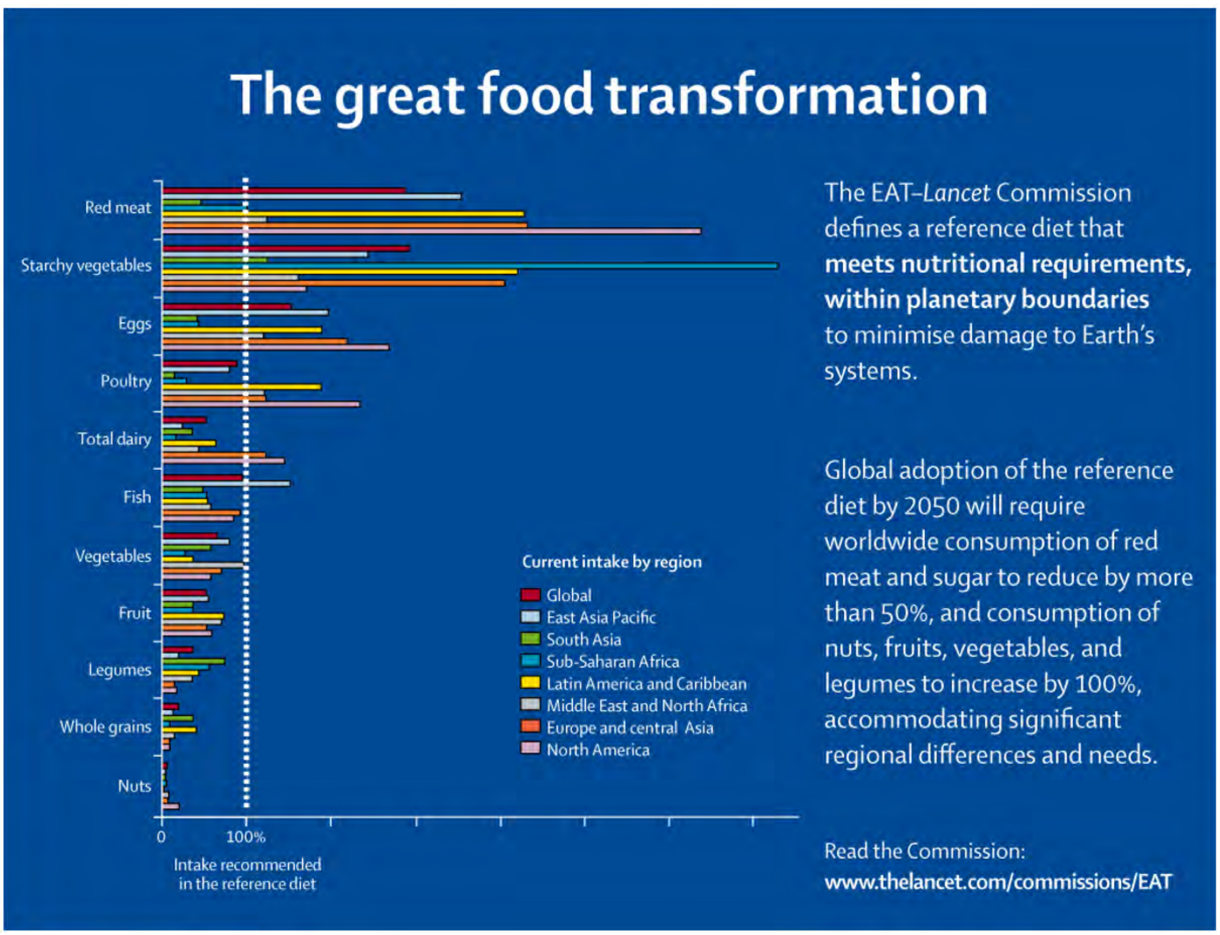
Note: 14 Potential co-benefits and trade-offs of implementing different climate interventions/actions across Asia. Figure is reproduced from the University of Leeds Climate (Co)benefits Portal, which uses a systematic literature review approach to bring together available scientific evidence on the co-benefits of climate adaptation and mitigation options.

5.7.2 Alternative diets and food waste reduction

The agricultural sector is a large emitter of air pollutants and greenhouse gases. Urban populations in Asia can complement emission control strategies in this sector (Sect. 6.4) by reducing demand through reduced food waste and/or altering food consumption patterns[7, 196, 97]. Transitioning toward more plant-based, less meat-intensive diets (following recommendations from the Chinese Nutrition Society [30] or the EAT-Lancet Commission[153] (Figure 12) would reduce both livestock production and crop production for livestock feed, reducing associated ammonia emissions and secondary $PM_{2.5}$ [7, 196, 97].

Transitioning toward more plant-based diets is also associated with nutritional health benefits[143]. Dietary change is mostly driven by personal choice and is therefore a low- or no-cost option for air pollution mitigation. However, to change consumers' preferences on a city or country scale, governments and local authorities can play an important role in promoting healthy, less meat-intensive diets along with implementing healthy public food procurement and service policies[196, 177, 13].

Figure 12: (Co)benefit or Trade-off Category for Asia



Note: 14 Potential co-benefits and trade-offs of implementing different climate interventions/actions across Asia. Figure is reproduced from the University of Leeds Climate (Co)benefits Portal, which uses a systematic literature review approach to bring together available scientific evidence on the co-benefits of climate adaptation and mitigation options.

5.7.3 Personal strategies to reduce $PM_{2.5}$ exposure

Reducing the sources and emissions of $PM_{2.5}$ and other air pollutants through public policies and control measures is imperative for reducing the $PM_{2.5}$ - related public health burden in cities. However, exposure to urban $PM_{2.5}$ pollution can be limited in certain situations on a personal level by modifying behaviour. Avoidance of high $PM_{2.5}$ concentrations can be particularly important for people whose age and/or existing health conditions increase their vulnerability to $PM_{2.5}$ exposure.

The key measures that can be implemented to minimise or reduce personal exposure to ambient $PM_{2.5}$pollution include limiting physical exercise outdoors during highly polluted days or near air pollution sources, avoiding major roads or other pollution sources when commuting, and/or wearing an N95 or similar grade facemask during severe air pollution events[21, 80].

Provision of air quality alert or early warning systems can also be highly effective and can empower urban populations make informed decisions when planning journey routes, modes of transport, and/or outdoor activities[72, 21]. Cleaner route planning features can already be accessed through mobile applications for some cities to aide individual travel and activity decisions[23] (Sect. 4.5).

Certain strategies can also be implemented to minimise personal exposure to $PM_{2.5}$ pollution in indoor environments, for example effective ventilating of cooking areas and using portable indoor air cleaners fitted with high-efficiency PM filters[21].

The latter type of intervention is being tested by the Chiang Mai municipality, in partnership with the UN ESCAP, through the Air Filter Initiative for Maternal Health[166].

This initiative involves implementing high quality air filters in the homes of selected pregnant women, with the aim of avoiding negative maternal and prenatal health outcomes related to indoor $PM_{2.5}$ exposure.

5.8 Regional cooperation on air pollution mitigation

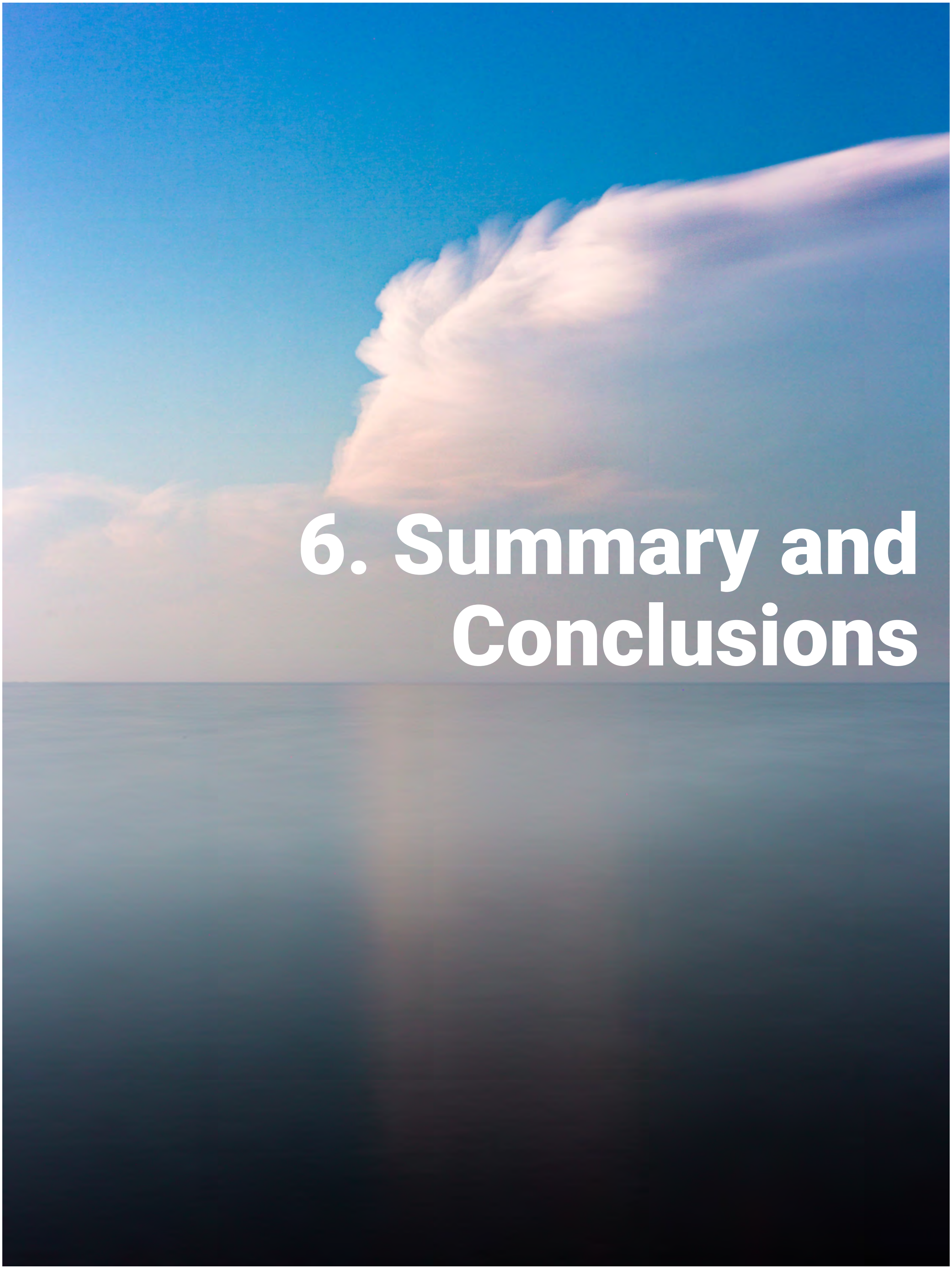
The physical and chemical properties of atmospheric particulates (Sect. 3.1) mean that $PM_{2.5}$ pollution can remain in the atmosphere on the order of days to weeks, enabling it to be transported over huge distances (Sect. 3.2.2), across cities, state boundaries, and national borders[42, 36, 108]. There are many cities in Asia where a large portion of the within-city $PM_{2.5}$ pollution is imported from sources located outside the city limits (Sect. 3.3)[151, 179]. The transboundary nature of ambient $PM_{2.5}$ pollution means that regional cooperation and coordination can be crucial for strengthening international, national, and city-level air pollution management frameworks[158, 180].

Many successful regional partnership initiatives have been established in Asia to tackle transboundary air pollution issues. One example is the Association of Southeast Asian Nations[12]. Agreement on Transboundary Haze Pollution (AATHP), which involves a commitment from 10 Member States to coordinate efforts to monitor and tackle haze pollution arising from peatland and forest fires[11].

The associated Roadmap on ASEAN Cooperation towards Transboundary Haze Pollution Control with Means of Implementation was adopted in 2016, serving as a strategic framework for the implementation of the AATHP and other collaborative actions to control transboundary haze pollution[11]. The Roadmap includes key strategies for reducing air pollutant emissions from the agricultural sector (Sect. 6.4) and open burning (Sect. 6.5) such as sustainable management of peatlands[10, 160], agricultural land, and forests[11].

A second example is the Asia Pacific Clean Air Partnership (APCAP)[161], which was established to serve as platform to improve coordination of clean air programs in the region, generate and disseminate knowledge on air pollution mitigation measures and policies, provide technical assistance on air quality management, and support assessments to identify clean air solutions.

The UNEP (2019) report[158], which provides actionable, science-based, clean air solutions for countries in Asia Pacific, was a product of close collaboration with the APCAP and the Climate and Clean Air Coalition (CCAC).



6. Summary and Conclusions

Effective development and implementation of policies and strategies to reduce urban air pollution will depend on many factors that will be specific to each city. These factors including the dominant source contributions to ambient $PM_{2.5}$ pollution, the physical urban characteristics, and the local weather conditions, alongside the city's capacity to implement measures and its resource availability[158]. In other words, there is no single policy or combination of measures that will effectively reduce air pollution in every city, as the local context will need to be considered in each case. However, there are several measures and considerations, summarised below, that are relevant for combatting $PM_{2.5}$ pollution throughout Asia.

Figure 13: Measures and Considerations

Continuing Priority Measures:

- Providing access to clean household energy for cooking and heating.
- Implementation of stringent emission controls in the industrial and transport sectors.

Emerging Priority Measures:

- Promoting sustainable agricultural practices (including improved fertilizer application and manure management, prevention of residue burning, and reduced land clearance of forests and peatlands).
- Improved energy efficiency across sectors and promotion of renewable energy sources.

Additional Policy Considerations

- Coordinate efforts to simultaneously reduce $PM_{2.5}$ pollution and mitigate climate change in co-benefit orientated energy-climate policies.
- Include effective management of other air pollutants, such as ground level ozone, alongside PM2.5 to achieve maximum public health benefits [164, 33]
- Foster collaboration between national governments, local authorities, businesses, and civil society for coordinated action on $PM_{2.5}$ pollution, including key stakeholder engagement and integration in decision making [157]
- Establish effective regional cooperation (or utilise existing regional partnerships) to jointly address transboundary air pollution issues
- Enhance long-term air pollution monitoring and identification of key polluting sources, alongside improved data sharing of historical and real-time measurements.

Further priorities for air quality management can be broken down regionally. In East Asia, the implementation of conventional $PM_{2.5}$ pollution controls on the industrial, transport, and residential sectors are well underway. Despite these measures, the industrial and residential sectors are projected to remain large contributors to $PM_{2.5}$ pollution in the near-term future[37], with the implementation and associated air quality benefits of end-of-pipe controls largely exhausted by 2030[28].

Future attainment of the WHO Interim Targets 3 and 4 for $PM_{2.5}$ will require continued application of increasingly stringent end-of-pipe controls, implementation of enhanced energy-efficient technologies and renewable energy policies, and strong reductions in PM2.5 precursor gas (ammonia and VOCs) emissions[158, 33, 28, 29]. Furthermore, strategies for tackling residential emissions could be expanded from a predominant focus on households in northern China[102] to areas of southern China[36].

In South Asia, the priorities for effective air quality management include enhanced application of conventional emission controls in the industrial and transport sectors and accelerated transition to clean fuel technologies for cooking[158, 180]. Increased attention should also be given to reducing $PM_{2.5}$ pollution from other sources, including brick kilns (through increased adoption of less polluting, modern technologies), household waste and agricultural residue burning (through prevention and provision of viable alternatives), and agricultural practices (through improved fertilizer application and manure management)[158, 180].

In Southeast Asia, the main priority areas are consistent with those for South Asia, with additional emphases on prevention of land clearance/deforestation fires and sustainable peatland management[158, 11]. For high-income countries in Asia (Brunei Darussalam, Japan, Republic of Korea, and Singapore), where conventional emission controls have been widely implemented, priority areas include reducing emissions from the agricultural and shipping sectors and coordinated climate and air pollution mitigation[158]. Regional cooperation with other surrounding countries will also be key in helping to reduce imported, transboundary $PM_{2.5}$ pollution.

Across all countries in Asia, adoption of effective clean air measures could substantially reduce the health burden due ambient $PM_{2.5}$ pollution exposure, whilst helping to achieve multiple UN SDGs. Implementing stringent air pollution mitigation policies, alongside ambitious climate action, will be crucial to avoid an increasing $PM_{2.5}$ - attributable health burden in the near-term future[34, 37, 189, 122].

References

1. Abbas, A., Sajid, M. B., Iftikhar, M. A., et al. (2021). Assessment of long-term energy and environmental impacts of the cleaner technologies for brick production. Energy Rep., 7, pp. 7157-7169, 10.1016/j.egyr.2021.10.072.
2. AQCIN. (2023). Beijing Air Pollution: Real-time Air Quality Index (AQI). Retrieved February 27, 2023, from https://aqicn.org/city/beijing/
3. ADB (2022). Asian Development Bank (ADB). Air Quality in Asia: Why Is It Important, and What Can We Do? https://www.adb.org/publications/air-quality-asia.
4. Adrianto, H. A., Spracklen, D. V. & Arnold, S. R. (2019). Relationship between fire and forest cover loss in Riau Province, Indonesia between 2001 and 2012. Forests, 10, 1–17. https://doi.org/10.3390/f10100889.
5. Al-Taani, A. A.; Nazzal, Y.; Howari, F. M.; Yousef, A. (2019). Long-term trends in ambient fine particulate matter from 1980 to 2016 in United Arab Emirates. Environ. Monit. Assess., 191, 143, DOI: 10.1007/s10661-019-7259-9.
6. Alvarado, M. J., McVey, A. E., Hegarty, J. D., Cross, E. S., Hasenkopf, C. A., Lynch, R., Kennelly, E. J., Onasch, T. B., Awe, Y., Sanchez-Triana, E., & Kleiman, G. (2019). Evaluating the use of satellite observations to supplement ground-level air quality data in selected cities in low- and middle-income countries. Atmospheric Environment, 218, 117016. https://doi.org/10.1016/J.ATMOSENV.2019.117016.
7. Amann, M. et al. (2020). Reducing global air pollution: the scope for further policy interventions Phil. Trans. R. Soc. A., 378, 20190331. https://doi.org/10.1098/rsta.2019.0331.
8. Amnuaylojaroen, T., Inkom, J., Janta, R., & Surapipith, V. (2020). Long Range Transport of Southeast Asian PM2.5 Pollution to Northern Thailand during High Biomass Burning Episodes. Sustainability, Vol. 12, Page 10049, 12(23), 10049. https://doi.org/10.3390/SU122310049.
9. Archer-Nicholls, S., Carter, E., Kumar, R., Xiao, Q., Frostad, J., Forouzanfar, M. H., Cohen, A., Brauer, M., Baumgartner, J., & Wiedinmyer, C. (2016). The regional impact of cooking and heating emissions on air quality and disease burden in China. Environmental Science & Technology, 50(17), 9416–9423. https://doi.org/10.1021/acs.est.6b02533.
10. ASEAN (2021a). Association of Southeast Asian Nations. Report of the final review of the ASEAN peatland management strategy (APMS) 2006–2020. ASEAN Secretariat, Jakarta. https://asean.org/book/report-of-the-final-review-of-the-asean-peatland-management-strategy-apms-2006-2020/.
11. ASEAN (2021b). Association of Southeast Asian Nations. Roadmap on ASEAN Cooperation towards Transboundary Haze Pollution Control with Means of Implementation. Jakarta: ASEAN Secretariat, February 2021. https://asean.org/wp-content/uploads/2021/08/Roadmap-on-ASEAN-Cooperation-towards-Transboundary-Haze-17-Feb-21.pdf
12. ASEAN. (2023, February 27). ASEAN. Retrieved from ASEAN: https://asean.org/
13. Barbour, L., Lindberg, R., Woods, J., Charlton, K., & Brimblecombe, J. (2022). Local urban government policies to facilitate healthy and environmentally sustainable diet-related practices: a scoping review. Public Health Nutrition, 25(2), 471. https://doi.org/10.1017/S1368980021004432.
14. Bhuvaneshwari, S.; Hettiarachchi, H.; Meegoda, J.N. Crop Residue Burning in India: Policy Challenges and Potential Solutions. (2019). Int. J. Environ. Res. Public Health, 16, 832. https://doi.org/10.3390/ijerph16050832.
15. Bikkina, S., Andersson, A., Kirillova, E.N. et al. (2019). Air quality in megacity Delhi affected by countryside biomass burning. Nat. Sustain., 2, 200–205. https://doi.org/10.1038/s41893-019-0219-0.
16. Biswas, S., Vadrevu, K. P., Lwin, Z. M., Lasko, K., & Justice, C. O. (2015). Factors controlling vegetation fires in protected and non-protected areas of Myanmar. PLoS One, 10, e0124346. https://doi.org/10.1371/journal.pone.0124346.
17. C40 Cities Climate Leadership Group (2023). How to grow cycling by improving equity and accessibility. Implementation Guides. C40 Cities Climate Leadership Group, C40 Knowledge Hub. https://www.c40knowledgehub.org/s/article/How-to-grow-cycling-by-improving-equity-and-accessibility
18. Cai, W., Xu, X., Cheng, X., Wei, F., Qiu, X., & Zhu, W. (2020). Impact of "blocking" structure in the troposphere on the wintertime persistent heavy air pollution in northern China. Science of The Total Environment, 741, 140325. https://doi.org/10.1016/J.SCITOTENV.2020.140325.
19. Cai, W. et al. (2021). The 2020 China report of the Lancet Countdown on health and climate change. Lancet Public Health 6 e64–81. https://doi.org/10.1016/S2468-2667(20)30256-5.
20. Cao, J., Situ, S., Hao, Y., Xie, S., and Li, L. (2022). Enhanced summertime ozone and SOA from biogenic volatile organic compound (BVOC) emissions due to vegetation biomass variability during 1981–2018 in China, Atmos. Chem. Phys., 22, 2351–2364, https://doi.org/10.5194/acp-22-2351-2022.

21. Carlsten, C., Salvi, S., Wong, G.W.K., Chung K. F. (2020). Personal strategies to minimise effects of air pollution on respiratory health: advice for providers, patients and the public. European Respiratory Journal. 55 (6) 1902056; https://doi.org/10.1183/13993003.02056-2019.

22. Chankaew, K., Sinitkul, R., Manuyakorn, W., Roekworachai, K. and Kamalaporn, H. (2022). Spatial Estimation of PM2.5 Exposure and its Association with Asthma Exacerbation: A Prospective Study in Thai Children. Annals of Global Health, 88(1), p.15. DOI: http://doi.org/10.5334/aogh.3513.

23. Che, W., H.C. Frey, J.C.H. Fung, Z. Ning, H. Qu, H.K. Lo, L. Chen, T.-W. Wong, et al. (2020). PRAISE-HK: a personalized real-time air quality informatics system for citizen participation in exposure and health risk management, Sustain. Cities Soc., 54, Article 101986, 10.1016/j.scs.2019.101986.

24. Chen, J., & Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. Environment International, 143. https://doi.org/10.1016/J.ENVINT.2020.105974.

25. Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M. S., et al. (2017). A review of biomass burning: Emissions and impacts on air quality, health and climate in China. Science of the Total Environment, 579, 1000– 1034. https://doi.org/10.1016/j.scitotenv.2016.11.025.

26. Chen, C., Saikawa, E., Comer, B., Mao, X., & Rutherford, D. (2019). Ship emission impacts on air quality and human health in the Pearl River Delta (PRD) region, China, in 2015, with projections to 2030. GeoHealth, 3, 284– 306. https://doi.org/10.1029/2019GH000183.

27. Chen, Z.Y., Chen, D.L., Zhao, C.F., Kwan, M.-P., et al. (2020). Influence of meteorological conditions on PM2. 5 concentrations across China: a review of methodology and mechanism, Environ. Int., 139, 105558. https://doi.org/10.1016/j.envint.2020.105558.

28. Cheng, J., Tong, D., Zhang, Q., Liu, Y., Lei, Y., Yan, G., Yan, L., Yu, S., Cui, R. Y., Clarke, L., Geng, G., Zheng, B., Zhang, X., Davis, S. J., & He, K. (2021a). Pathways of China's PM2.5 air quality 2015–2060 in the context of carbon neutrality. National Science Review, 8(12). https://doi.org/10.1093/NSR/NWAB078.

29. Cheng, J., Tong, D., Liu, Y., Bo, Y., Zheng, B., Geng, G., He, K., & Zhang, Q. (2021b). Air quality and health benefits of China's current and upcoming clean air policies. Faraday Discussions, 226(0), 584–606. https://doi.org/10.1039/D0FD00090F.

30. Chinese Nutrition Society. (2016). Dietary guidelines for Chinese residents. People's Medical Publishing House, Beijing, 2016.

31. Chowdhury, S., Dey, S. & Smith, K.R. (2018). Ambient PM2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. Nat. Commun., 9, 318. https://doi.org/10.1038/s41467-017-02755-y.

32. CIESIN (2016). Center for International Earth Science Information Network - CIESIN - Columbia University. Gridded population of the world, version 4 (GPWv4): population count. Palisades, NY: NASA socioeconomic data and applications center (SEDAC). https://sedac.ciesin.columbia.edu/data/collection/gpw-v4.

33. Clean Air Asia (2020). China Air 2020—air pollution prevention and control progress in Chinese cities. Clean Air Asia, Beijing 2020. https://cleanairasia.org/sites/default/files/2021-05/-%201.1%20China%20Air%202020%20-%20Air%20Pollution%20Prevention%20and%20Control%20Progress%20in%20Chinese%20Cities.pdf.

34. Conibear, L., Butt, E. W., Knote, C., Arnold, S. R., and Spracklen, D. V. (2018a). Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India, Nat. Commun., 9, 617, https://doi.org/10.1038/s41467-018-02986-7.

35. Conibear, L., Butt, E. W., Knote, C., Arnold, S. R., and Spracklen, D. V. (2018b). Stringent emission control policies can provide large improvements in air quality and public health in India, GeoHealth, 2, 196–211, https://doi.org/10.1029/2018GH000139.

36. Conibear, L., Reddington, C. L., Silver, B. J., Knote, C., Arnold, S. R., & Spracklen, D. V. (2021). Regional Policies Targeting Residential Solid Fuel and Agricultural Emissions Can Improve Air Quality and Public Health in the Greater Bay Area and Across China. GeoHealth, 5(4), e2020GH000341. https://doi.org/10.1029/2020GH000341.

37. Conibear, L., Reddington, C. L., Silver, B. J., Arnold, S. R., Turnock, S. T., Klimont, Z., & Spracklen, D. V. (2022a). The contribution of emission sources to the future air pollution disease burden in China. Environmental Research Letters, 17(6). https://doi.org/10.1088/1748-9326/AC6F6F.

38. Conibear, L., Reddington, C. L., Silver, B. J., Chen, Y., Arnold, S. R., & Spracklen, D. v. (2022b). Emission Sector Impacts on Air Quality and Public Health in China From 2010 to 2020. GeoHealth, 6(6), e2021GH000567. https://doi.org/10.1029/2021GH000567.

39. Conibear, L., Reddington, C. L., Silver, B. J., Chen, Y., Knote, C., Arnold, S. R., & Spracklen, D. v. (2022c). Sensitivity of Air Pollution Exposure and Disease Burden to Emission Changes in China Using Machine Learning Emulation. GeoHealth, 6(6), e2021GH000570. https://doi.org/10.1029/2021GH000570.

40. de Titto E. and Savino A. (2019). Environmental and health risks related to waste incineration. Waste Management & Research., 37(10):976-986. doi:10.1177/0734242X19859700.

41. Ding D, Xing J, Wang S, Liu K and Hao J (2019). Estimated contributions of emissions controls, meteorological factors, population growth, and changes in baseline mortality to reductions in ambient PM2.5 and PM2.5 -related mortality in China, 2013–2017. Environ. Health Perspect., 127 EHP4157. https://doi.org/10.1289/EHP4157.

42. Du, X.; Guo, H.; Zhang, H.; Peng, W.; Urpelainen, J. Cross-state air pollution transport calls for more centralization in India's environmental federalism. Atmos. Pollut. Res. 2020, 11, 1797–1804. http://doi.org/10.1016/j.apr.2020.07.012.
43. Efimova, N. V., and Rukavishnikov, V. S. (2021). "Assessment of Smoke Pollution Caused by Wildfires in the Baikal Region (Russia)" Atmosphere, 12: 1542. https://doi.org/10.3390/atmos12121542.
44. Eil, A., Li, J., Baral, P., Saikawa, E. (2020). Dirty Stacks, High Stakes : An Overview of Brick Sector in South Asia. World Bank, Washington, DC. © World Bank. License: CC BY 3.0 IGO. https://openknowledge.worldbank.org/handle/10986/33727.
45. Feng, S., Gao, D., Liao, F., Zhou, F., Wang, X. (2016). The health effects of ambient PM2.5 and potential mechanisms. Ecotoxicol Environ Saf,;128:67-74. doi:10.1016/j.ecoenv.2016.01.030 pmid:26896893.
46. Feng, H., Ding, Y., Zou, B. et al. (2022). Vegetation-related dry deposition of global PM2.5 from satellite observations. J. Geogr. Sci., 32, 589–604. https://doi.org/10.1007/s11442-022-1962-0.
47. Fujimori S, Hasegawa T, Takahashi K, Dai H, Liu J-Y,Ohashi H, Xie Y, Zhang Y, Matsui T and Hijioka Y. (2020). Measuring the sustainable development implications of climate change mitigation Environ. Res. Lett. 15 085004, https://doi.org/10.1088/1748-9326/ab9966.
48. GAHP (2020). Air Pollution Interventions: Seeking The Intersection Between Climate & Health. Global Alliance on Health and Pollution (GAHP), AirQualityAsia, and The Schiller Institute for Integrated Science and Society at Boston College. https://gahp.net/wp-content/uploads/2020/06/AirPollutionReport_6_22_Final.pdf.
49. GBD (2020). GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet, 396, 1135–59. https://doi.org/10.1016/S0140-6736(20)30752-2.
50. Geng, G., Zheng, Y., Zhang, Q. et al. (2021). Drivers of PM2.5 air pollution deaths in China 2002–2017. Nat. Geosci. 14, 645–650. https://doi.org/10.1038/s41561-021-00792-3.
51. Giordano, M. R., Malings, C., Pandis, S. N., Presto, A. A., McNeill, V. F., Westervelt, D. M., Beekmann, M., & Subramanian, R. (2021). From low-cost sensors to high-quality data: A summary of challenges and best practices for effectively calibrating low-cost particulate matter mass sensors. Journal of Aerosol Science, 158, 105833. https://doi.org/10.1016/J.JAEROSCI.2021.105833.
52. Grange, S. K., Carslaw, D. C., Lewis, A. C., Boleti, E., and Hueglin, C. (2018). Random forest meteorological normalisation models for Swiss PM10 trend analysis, Atmos. Chem. Phys., 18, 6223–6239, https://doi.org/10.5194/acp-18-6223-2018.
53. Groom, B., Palmer, C., & Sileci, L. (2022). Carbon emissions reductions from Indonesia's moratorium on forest concessions are cost-effective yet contribute little to Paris pledges. P. Natl. Acad. Sci. USA, 119(5), e2102613119. https://doi.org/10.1073/pnas.2102613119.
54. Gulia, S., Goyal, P., Goyal, S.K. et al. Re-suspension of road dust: contribution, assessment and control through dust suppressants - a review. Int. J. Environ. Sci. Technol. 16, 1717–1728 (2019). https://doi.org/10.1007/s13762-018-2001-7.
55. Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., Du, Z.,Wu, Z., et al. (2014). Elucidating severe urban haze formation in China. P. Natl. Acad. Sci. USA. 111. 49, pp. 17373–17378. https://doi.org/10.1073/pnas.1419604111.
56. Guo, C., Zhang, Z., Lau, A.K.H., Lin, C.Q., Chuang, Y.C. et al. (2018). Effect of long-term exposure to fine particulate matter on lung function decline and risk of chronic obstructive pulmonary disease in Taiwan: a longitudinal, cohort study. The Lancet Planetary Health, 2, pp. e114-e125. https://doi.org/10.1016/s2542-5196(18)30028-7.
57. Guo C., Chan T.C., Teng Y.C., et al. (2020). Long-term exposure to ambient fine particles and gastrointestinal cancer mortality in Taiwan: a cohort study. Environ. Int.; 138: 105640. https://doi.org/10.1016/j.envint.2020.105640.
58. Guo X, Shen Y, Liu W, Chen D, Liu J. Estimation and Prediction of Industrial VOC Emissions in Hebei Province, China. Atmosphere. 2021; 12(5):530. https://doi.org/10.3390/atmos12050530
59. Handschuh, J., Erbertseder, T., Schaap, M., Baier F. (2022).Estimating PM2.5 surface concentrations from AOD: a combination of SLSTR and MODIS, Remote Sens. Appl.: Soc. Environ., 26, Article 100716, 10.1016/j.rsase.2022.100716.
60. Harrison, ME, Ottay, JB, D'Arcy, LJ, et al. (2020). Tropical forest and peatland conservation in Indonesia: Challenges and directions. People Nat., 2: 4– 28. https://doi.org/10.1002/pan3.10060.
61. Hong, C., Zhang, Q., Zhang, Y., Davis, S.J., Tong, D., et al. (2019). Impacts of climate change on future air quality and human health in China, Proc. Natl. Acad. Sci. U. S. A, 116 (35), pp. 17193-17200, 10.1073/pnas.1812881116.
62. Huang, K., Fu, J. S., Hsu, N. C., Gao, Y., Dong, X., Tsay, S.-C., & Lam, Y. F. (2013). Impact assessment of biomass burning on air quality in Southeast and East Asia during BASE-ASIA. Atmospheric Environment, 78, 291–302. https://doi.org/10.1016/j.atmosenv.2012.03.048.
63. Huang, W.-R., Wang, S. -H., Yen, M.-C., Lin, N. -H., & Promchote, P. (2016). Interannual variation of springtime biomass burning in Indochina: Regional differences, associated atmospheric dynamical changes, and downwind impacts. Journal of Geophysical Research: Atmospheres, 121, 10016–10028. https://doi.org/10.1002/2016JD025286.
64. Huang, X., Song, Y., Li, M., Li, J., Huo, Q., Cai, X., Zhu, T., Hu, M., and Zhang, H. (2012). A high-resolution ammonia emission inventory in China, Global Biogeochem. Cy., 26, GB1030, https://doi.org/10.1029/2011GB004161.

65. Iskandaryan D, Ramos F, Trilles S. (2020). Air Quality Prediction in Smart Cities Using Machine Learning Technologies Based on Sensor Data: A Review. Applied Sciences. 10(7):2401. https://doi.org/10.3390/app10072401.

66. IQAir. (2023, February 27). IQAir/UNEP. Retrieved from IQAir : https://www.iqair.com/unep

67. Jacob, D. J. and Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43.1, pp. 51–63. https://doi.org/10.1016/j.atmosenv.2008.09.051.

68. Janjai, S., Suntaropas, S., & Nunez, M. (2009). Investigation of aerosol optical properties in Bangkok and suburbs. Theoretical and Applied Climatology, 96, 221–233. https://doi.org/10.1007/s00704-008-0026-4.

69. Jethva, H., Torres, O., Field, R.D. et al. (2019). Connecting Crop Productivity, Residue Fires, and Air Quality over Northern India. Sci. Rep., 9, 16594. https://doi.org/10.1038/s41598-019-52799-x.

70. Kaihara, T., Yoneyama, K., Nakai, M. et al. (2021). Association of PM2.5 exposure with hospitalization for cardiovascular disease in elderly individuals in Japan. Sci. Rep., 11, 9897. https://doi.org/10.1038/s41598-021-89290-5.

71. Kang, Y., Aye, L., Ngo, T. D., & Zhou, J. (2022). Performance evaluation of low-cost air quality sensors: A review. Science of The Total Environment, 818, 151769. https://doi.org/10.1016/J.SCITOTENV.2021.151769.

72. Kelly, F.J., Fuller, G.W., Walton, H.A. and Fussell, J.C. (2012), Monitoring air pollution: Use of early warning systems for public health. Respirology, 17: 7-19. https://doi.org/10.1111/j.1440-1843.2011.02065.x.

73. Kiely, L., Spracklen, D. V., Wiedinmyer, C., Conibear, L., Reddington, C. L., Arnold, S. R., et al. (2020). Air quality and health impacts of vegetation and peatfires in Equatorial Asia during 2004-2015. Environment Research Letters, 15, 094054. https://doi.org/10.1088/1748-9326/ab9a6c.

74. Kiely, L., Spracklen, D.V., Arnold, S.R. et al. (2021). Assessing costs of Indonesian fires and the benefits of restoring peatland. Nat. Commun., 12, 7044. https://doi.org/10.1038/s41467-021-27353-x.

75. Kim, T.Y., Kim, H., Yi, S.M., Cheong, J.P. and Heo, J. (2018). Short-term Effects of Ambient PM2.5 and PM2.5-10 on Mortality in Major Cities of Korea. Aerosol Air Qual. Res., 18: 1853-1862. https://doi.org/10.4209/aaqr.2017.11.0490.

76. Kim, I. S., Yang, P.S., Lee, J., Yu, H.T. et al. (2020a). Long-term fine particulate matter exposure and cardiovascular mortality in the general population: a nationwide cohort study. J. Cardiol., 75, pp. 549-558. https://doi.org/10.1016/j.jjcc.2019.11.004.

77. Kim, S. E., Xie, Y., Dai, H., Fujimori, S. et al. (2020b). Air quality co-benefits from climate mitigation for human health in South Korea. Environ. Int., 136, p. 105507, 10.1016/j.envint.2020.105507.

78. Kim, Y., Park, E.H., Ng, C.F.S. et al. (2021). Respiratory function declines in children with asthma associated with chemical species of fine particulate matter (PM2.5) in Nagasaki, Japan. Environ Health, 20, 110. https://doi.org/10.1186/s12940-021-00796-x.

79. Kim, S.K., van Gevelt, T., Joosse, P., Bennett, M.M. (2022). Transboundary air pollution and cross-border cooperation: insights from marine vessel emissions regulations in Hong Kong and Shenzhen. Sustain. Cities Soc., 80, Article 103774. https://doi.org/10.1016/j.scs.2022.103774.

80. Kodros, J. K., O'Dell, K., Samet, J. M., L'Orange, C., Pierce, J. R., & Volckens, J. (2021). Quantifying the health benefits of face masks and respirators to mitigate exposure to severe air pollution. GeoHealth, 5, e2021GH000482. https://doi.org/10.1029/2021GH000482.

81. Konecny, K., Ballhorn, U., Navratil, P., Jubanski, J., Page, S. E., Tansey, K., Hooijer, A., Vernimmen, R., and Siegert, F. (2016). Variable carbon losses from recurrent fires in drained tropical peatlands, Glob. Change Biol., 22, 1469–1480, https://doi.org/10.1111/gcb.13186.

82. Kumar, K.,and Pande, B.P. (2022). Air pollution prediction with machine learning: a case study of Indian cities. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-022-04241-5

83. Kurokawa, J. and Ohara, T. (2020). Long-term historical trends in air pollutant emissions in Asia: Regional Emission inventory in ASia (REAS) version 3, Atmos. Chem. Phys., 20, 12761–12793, https://doi.org/10.5194/acp-20-12761-2020.

84. Lan, R., Eastham, S.D., Liu, T. et al. (2022). Air quality impacts of crop residue burning in India and mitigation alternatives. Nat. Commun. 13, 6537. https://doi.org/10.1038/s41467-022-34093-z.

85. Lasko, K., Vadrevu, K. P., Tran, V. T., Ellicott, E., Nguyen, T. T. N., Bui, H. Q., & Justice, C. (2017). Satellites may underestimate rice residue and associated burning emissions in Vietnam. Environment Research Letters, 12, 085006. https://doi.org/10.1088/1748-9326/aa751d

86. Lasko, K., Vadrevu, K. P., & Nguyen, T. T. N. (2018). Analysis of air pollution over Hanoi, Vietnam using multi-satellite and MERRA reanalysis datasets. PLoS One, 13(5), e0196629. https://doi.org/10.1371/journal.pone.0196629.

87. Lee, L. A., Reddington, C. L., and Carslaw, K. S. (2016). On the relationship between aerosol model uncertainty and radiative forcing uncertainty, P. Natl. Acad. Sci. USA, 113, 5820–5827, https://doi.org/10.1073/pnas.1507050113.

89. Li, J., Liu, F., Liang, F. et al. (2020). Long-term effects of high exposure to ambient fine particulate matter on coronary heart disease incidence: a population-based Chinese cohort study. Environ. Sci. Technol., 54, pp. 6812-6821. https://doi.org/10.1021/acs.est.9b06663.

90. Li, S., Sedra, S., Zou, B., Liu, J., Xiong, Y., & Muhammad, B. (2022a). PM2.5 Concentration Exposure over the Belt and Road Region from 2000 to 2020. International Journal of Environmental Research and Public Health, 19(5).

91. Li, D.; Xue, Y.; Qin, K.; Wang, H.; Kang, H.; Wang, L. (2022b). Investigating the Long-Term Variation Trends of Absorbing Aerosols over Asia by Using Multiple Satellites. Remote Sens., 14, 5832. https://doi.org/10.3390/rs14225832.

92. Linardatos, P., Papastefanopoulos, V., & Kotsiantis, S. (2020). Explainable AI: A Review of Machine Learning Interpretability Methods. Entropy 2021, Vol. 23, 18, 23(1), 18. https://doi.org/10.3390/E23010018.

93. Liu, T. et al. (2018). Seasonal impact of regional outdoor biomass burning on air pollution in three Indian cities: Delhi, Bengaluru, and Pune. Atmos. Environ., 172, 83–92. https://doi.org/10.1016/j.atmosenv.2017.10.024.

94. Liu, C., Li, Q., Yan, L., Wang, H., Yu, J. et al. (2019a). The association between maternal exposure to ambient particulate matter of 2.5 um or less during pregnancy and fetal congenital anomalies in Yinchuan, China: a population-based cohort study, Environ. Int., 122, pp. 316-321, 10.1016/j.envint.2018.11.030.

95. Liu, S., Xing, J., Zhang, H., Ding, D., Zhang, F., Zhao, B., Sahu, S. K., & Wang, S. (2019b). Climate-driven trends of biogenic volatile organic compound emissions and their impacts on summertime ozone and secondary organic aerosol in China in the 2050s. Atmospheric Environment, 218, 117020. https://doi.org/10.1016/J.ATMOSENV.2019.117020.

96. Liu, X., Jayaratne, R., Thai, P., et al. (2020). Low-cost sensors as an alternative for long-term air quality monitoring, Environ. Res., 185, Article 109438, 10.1016/j.envres.2020.109438.

97. Liu, X., Tai, A. P. K., Chen, Y., Zhang, L., Shaddick, G., Yan, X., & Lam, H. M. (2021). Dietary shifts can reduce premature deaths related to particulate matter pollution in China. Nature Food, 2:12, 2(12), 997–1004. https://doi.org/10.1038/s43016-021-00430-6.

98. Lou, S., Yang, Y., Wang, H., Smith, S. J., Qian, Y., & Rasch, P. J. (2019). Black carbon amplifies haze over the North China Plain by weakening the East Asian winter monsoon. Geophysical Research Letters, 46, 452– 460. https://doi.org/10.1029/2018GL080941.

99. Lundberg, S.M., Erion, G., Chen, H. et al. (2020). From local explanations to global understanding with explainable AI for trees. Nat. Mach. Intell., 2, 56–67. https://doi.org/10.1038/s42256-019-0138-9.

100. Lv, Z., Liu, H., Ying, Q., Fu, M., Meng, Z., Wang, Y., Wei, W., Gong, H., and He, K. (2018). Impacts of shipping emissions on PM2.5 pollution in China, Atmos. Chem. Phys., 18, 15811–15824, https://doi.org/10.5194/acp-18-15811-2018.

101. Markandya A, Sampedro J, Smith S J, Van D R, Pizarro-irizar C, Arto I and González-eguino M (2018). Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study, Lancet Planet. Health, 2, e126–33, https://doi.org/10.1016/S2542-5196(18)30029-9.

102. Meng, W., Shen, H., Yun, X., Chen, Y., Zhong, Q., Zhang, W., Yu, X., Xu, H., Ren, Y., Shen, G., Ma, J., Liu, J., Cheng, H., Wang, X., Zhu, D., & Tao, S. (2020). Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China. Environmental Science and Technology, 54(21), 13458–13466. https://doi.org/10.1021/acs.est.0c04019.

103. Miao, Y.; Li, J.; Miao, S.; Che, H.; Wang, Y.; Zhang, X.; Zhu, R.; Liu, S. (2019). Interaction Between Planetary Boundary Layer and PM2.5 Pollution in Megacities in China: a Review. Curr. Pollut. Rep., 5, 261– 271, https://doi.org/10.1007/s40726-019-00124-5.

104. Mogno, C., Palmer, P. I., Knote, C., Yao, F., and Wallington, T. J. (2021). Seasonal distribution and drivers of surface fine particulate matter and organic aerosol over the Indo-Gangetic Plain, Atmos. Chem. Phys., 21, 10881–10909, https://doi.org/10.5194/acp-21-10881-2021.

105. MOT (2018). Ministry of Transport of the People's Republic of China 2018 Implementation scheme of the domestic emission control areas for atmospheric pollution from vessels available at: https://www.msa.gov.cn/public/documents/document/mtex/mzm1/~edisp/20181219111335546.pdf

106. Murari, V.; Kumar, M.; Mhawish, A.; Barman, S. C.; Banerjee, T. (2017). Airborne particulate in Varanasi over middle Indo-Gangetic Plain: variation in particulate types and meteorological influences. Environ. Monit. Assess., 189, 157, DOI: 10.1007/s10661-017-5859-9 .

107. Nault, B. A., Jo, D. S., McDonald, B. C., Campuzano-Jost, P., Day, D. A., Hu, W., Schroder, J. C., Allan, J., Blake, D. R., Canagaratna, M. R., Coe, H., Coggon, M. M., DeCarlo, P. F., et al. (2021). Secondary organic aerosols from anthropogenic volatile organic compounds contribute substantially to air pollution mortality, Atmos. Chem. Phys., 21, 11201–11224, https://doi.org/10.5194/acp-21-11201-2021.

108. Nguyen, L. S. P., Hian-Wui Chang, J., Griffith, S. M., Hien, T. T., Soon-Kai Kong, S., Le, H. N., Huang, H. Y., Sheu, G. R., & Lin, N. H. (2022). Trans-boundary air pollution in a Southeast Asian megacity: Case studies of the synoptic meteorological mechanisms and impacts on air quality. Atmospheric Pollution Research, 13(4), 101366. https://doi.org/10.1016/J.APR.2022.101366.

109. Nodzu, M. I., Ogino, S., Tachibana, Y., & Yamanaka, M. D. (2006). Climatological description of seasonal variations in lower tropospheric temperature inversions layers over the Indochina Peninsula. Journal of Climate, 19, 3307–3319. https://doi.org/10.1175/JCLI3792.1.

110. Nurrochmat, D.R., Boer, R., Ardiansyah, M., Immanuel, G., Purwawangsa, H. (2020). Policy forum: reconciling palm oil targets and reduced deforestation: landswap and agrarian reform in Indonesia, Forest Policy Econ., 119, Article 102291, 10.1016/j.forpol.2020.102291.

111. Nurrochmat, D. R., Suryanto, Nurrochmat, N. A., Tarigan, S., Siregar, I. Z., Rizki, D. L. Y., Radjawali, I., & Sulistio, H. (2023). Indonesia's options in becoming a high-income country: Accelerating the turning point in deforestation? Forest Policy and Economics, 148, 102905. https://doi.org/10.1016/J.FORPOL.2022.102905.

112. OpenAQ. (2023, February 27). OpenAQ. Retrieved from OpenAQ: https://explore.openaq.org/

113. Peng, J., Hu, M., Shang, D., Wu, Z., Du, Z., Tan, T., Wang, Y., Zhang, F., and Zhang, R. (2021). Explosive secondary aerosol formation during severe haze in the North China Plain. Environmental Science and Technology, 55.4, pp. 2189–2207. https://doi.org/10.1021/acs.est.0c07204.

114. Pengchai, P., Chantara, S., Sopajaree, K., Wangkarn, S., Tencharoenkul, U., & Rayanakorn, M. (2009). Seasonal variation, risk assessment and source estimation of PM10 and PM10-bound PAHs in the ambient air of Chiang Mai and Lamphun, Thailand. Environmental Monitoring and Assessment, 154, 197–218. https://doi.org/10.1007/s10661-008-0389-0.

115. Phairuang, W., Hata, M., & Furuuchi, M. (2017). Influence of agricultural activities, forest fires and agro-industries on air quality in Thailand. Journal of Environmental Sciences, 52, 85–97. https://doi.org/10.1016/j.jes.2016.02.007.

116. Piñeiro, V., Arias, J., Dürr, J. et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nat. Sustain. 3, 809–820. https://doi.org/10.1038/s41893-020-00617-y.

117. Pommier, M., Fagerli, H., Gauss, M., Simpson, D., Sharma, S., Sinha, V., Ghude, S. D., Landgren, O., Nyiri, A., and Wind, P. (2018). Impact of regional climate change and future emission scenarios on surface O3 and PM2.5 over India, Atmos. Chem. Phys., 18, 103–127, https://doi.org/10.5194/acp-18-103-2018.

118. Pongpiachan, S., Hattayanone, M., Choochuay, C., Mekmok, R., Wuttijak, N., Ketratanakul, A. (2015). Enhanced PM10 bounded PAHs from shipping emissions, Atmos. Environ., 108, pp. 13-19. https://doi.org/10.1016/j.atmosenv.2015.02.072.

119. PRAISE. (2023, February 27). PRAISE. Retrieved from The Hong Kong University of Science and Technology: https://praise.hkust.edu.hk/

120. Priestley International Centre for Climate. (2023, February 27). Climate (Co)benefits Portal. Retrieved from Priestley International Centre for Climate: https://priestleycentre.shinyapps.io/climatecobenefitsportal/

121. Qin, K., Wu, L., Wong, M. S., Letu, H., Hu, M., Lang, H., Sheng, S., Teng, J., et al. (2016). Trans-boundary aerosol transport during a winter haze episode in China revealed by ground-based Lidar and CALIPSO satellite. Atmospheric Environment 141, pp. 20–29. https://doi.org/10.1016/j.atmosenv.2016.06.042.

122. Rafaj, P. et al. (2021). Air quality and health implications of 1.5C–2C climate pathways under considerations of ageing population: a multi-model scenario analysis Environ. Res. Lett. 16 045005. https://doi.org/10.1088/1748-9326/abdf0b.

123. Raza, M.H.; Abid, M.; Faisal, M.; Yan, T.; Akhtar, S.; Adnan, K.M.M. (2022). Environmental and Health Impacts of Crop Residue Burning: Scope of Sustainable Crop Residue Management Practices. Int. J. Environ. Res. Public Health,19, 4753. https://doi.org/10.3390/ijerph19084753.

124. Reddington, C. L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y. Y., Arnold, S. R., & Spracklen, D. V. (2014). Contribution of vegetation and peat fires to particulate air pollution in South-east Asia. Environment Research Letters, 9, 094006. https://doi.org/10.1088/1748-9326/9/9/094006.

125. Reddington, C. L., Spracklen, D. V., Artaxo, P., Ridley, D. A., Rizzo, L. V., & Arana, A. (2016). Analysis of particulate emissions from tropical biomass burning using a global aerosol model and long-term surface observations. Atmospheric Chemistry and Physics, 16, 11083–11106. https://doi.org/10.5194/acp-16-11083-2016

126. Reddington, C. L., Conibear, L., Knote, C., Silver, B. J., Li, Y. J., Chan, C. K., Arnold, S. R., and Spracklen, D. V. (2019). Exploring the impacts of anthropogenic emission sectors on PM2.5 and human health in South and East Asia. Atmos. Chem. Phys., 19, 11887–11910, https://doi.org/10.5194/acp-19-11887-2019.

127. Reddington, C. L., Conibear, L., Robinson, S., Knote, C., Arnold, S. R., & Spracklen, D. V. (2021). Air pollution from forest and vegetation fires in Southeast Asia disproportionately impacts the poor. GeoHealth, 5, e2021GH000418. https://doi.org/10.1029/2021GH000418.

128. Reis, L. A., Drouet, L., & Tavoni, M. (2022). Internalising health-economic impacts of air pollution into climate policy: a global modelling study. The Lancet Planetary Health, 6(1), e40–e48. https://doi.org/10.1016/S2542-5196(21)00259-X.

129. Saha, C. K. & Hosain, J. (2016) Impact of brick kilning industry in peri-urban Bangladesh, International Journal of Environmental Studies, 73:4, 491-501, DOI: 10.1080/00207233.2016.1179014.

130. Sampedro, J., Smith, S. J., Arto, I., González-Eguino, M., Markandya, A., Mulvaney, K. M., Pizarro-Irizar, C., & van Dingenen, R. (2020). Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways for energy supply. Environment International, 136, 105513. https://doi.org/10.1016/j.envint.2020.105513.

131. Sang, X. F., Zhang, Z. S., Chan, C. Y., & Engling, G. (2013). Source categories and contribution of biomass smoke to organic aerosol over the southeastern Tibetan Plateau. Atmospheric Environment, 78, 113–123. https://doi.org/10.1016/j.atmosenv.2012.12.012.

132. Santika, T, Wilson, KA, Budiharta, S, et al. (2019). Heterogeneous impacts of community forestry on forest conservation and poverty alleviation: Evidence from Indonesia. People Nat., 1: 204– 219. https://doi.org/10.1002/pan3.25.

133. Shi, W., Bi, J., Liu, R., Liu, M., & Ma, Z. (2021). Decrease in the chronic health effects from PM2.5 during the 13th Five-Year Plan in China: Impacts of air pollution control policies. Journal of Cleaner Production, 317, 128433. https://doi.org/10.1016/J.JCLEPRO.2021.128433.

134. Shim, S.; Sung, H.; Kwon, S.; Kim, J.; Lee, J.; Sun, M.; Song, J.; Ha, J.; Byun, Y.; Kim, Y.; et al. (2021). Regional Features of Long-Term Exposure to PM2.5 Air Quality over Asia under SSP Scenarios Based on CMIP6 Models. Int. J. Environ. Res. Public Health, 18, 6817. https://doi.org/10.3390/ijerph18136817.

135. Shin, M., Yoojin Kang, Seohui Park, Jungho Im, Cheolhee Yoo & Lindi J. Quackenbush (2020). Estimating ground-level particulate matter concentrations using satellite-based data: a review, GIScience & Remote Sensing, 57:2, 174-189, DOI: 10.1080/15481603.2019.1703288.

136. Shyamsundar, P. et al. (2019). Fields on fire: alternatives to crop residue burning in India. Science, 365, 536–538. https://doi.org/10.1126/science.aaw4085.

137. Silver, B., Reddington, C. L., Arnold, S. R., and Spracklen, D. V. (2018). Substantial changes in air pollution across China during 2015–2017. Environ. Res. Lett. 13, 114012. https://iopscience.iop.org/article/10.1088/1748-9326/aae718.

138. Silver, B., Conibear, L., Reddington, C. L., Knote, C., Arnold, S. R., and Spracklen D. V. (2020a). Pollutant emission reductions deliver decreased PM2.5 -caused mortality across China during 2015–2017. Atmos. Chem. Phys., 20 11683–95. https://doi.org/10.5194/acp-20-11683-2020.

139. Silver, B., He, X., Arnold, S. R., and Spracklen, D. V. (2020b). The impact of COVID-19 control measures on air quality in China. Environ. Res. Lett., 15, 084021. https://iopscience.iop.org/article/10.1088/1748-9326/aba3a2.

140. Simayi, M., Shi, Y., Xi, Z., Ren, J., Hini, G., & Xie, S. (2022). Emission trends of industrial VOCs in China since the clean air action and future reduction perspectives. Science of The Total Environment, 826, 153994. https://doi.org/10.1016/J.SCITOTENV.2022.153994.

141. Singh, V., Singh, S., & Biswal, A. (2021). Exceedances and trends of particulate matter (PM2.5) in five Indian megacities. Science of The Total Environment, 750, 141461. https://doi.org/10.1016/J.SCITOTENV.2020.141461.

142. Southerland, V. A., Brauer, M., Mohegh, A., Hammer, M. S., van Donkelaar, A., Martin, R. v., Apte, J. S., & Anenberg, S. C. (2022). Global urban temporal trends in fine particulate matter (PM2·5) and attributable health burdens: estimates from global datasets. The Lancet Planetary Health, 6(2), e139–e146. https://doi.org/10.1016/S2542-5196(21)00350-8.

143. Springmann, M., Godfray, H. C., Rayner, M. & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. Proc. Natl Acad. Sci. USA, 113, 4146–4151. https://doi.org/10.1073/pnas.1523119113.

144. Stolzenburg, D., Fischer, L., Vogel, A. L., Heinritzi, M., Schervish, M., Simon, M.,Wagner, A. C., Dada, L., et al. (2018). Rapid growth of organic aerosol nanoparticles over a wide tropospheric temperature range. P. Natl. Acad. Sci., USA. 115.37, pp. 9122–9127. https://doi.org/10.1073/pnas.1807604115.

145. Streets, D. G., Yarber, K. F., Woo, J.-H., and Carmichael, G. R. (2003), Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions, Global Biogeochem. Cycles, 17, 1099, doi:10.1029/2003GB002040, 4.

146. Subhanullah, M.; Ullah, S.; Javed, M.F.; Ullah, R.; Akbar, T.A.; Ullah, W.; Baig, S.A.; Aziz, M.; Mohamed, A.; Sajjad, R.U. (2022). Assessment and Impacts of Air Pollution from Brick Kilns on Public Health in Northern Pakistan. Atmosphere, 13, 1231. https://doi.org/10.3390/atmos13081231

147. Sun, W., Wang, D., Yao, L., Fu, H., Fu, Q., Wang, H., Li, Q., Wang, L., et al. (2019). Chemistry triggered events of PM2.5 explosive growth during late autumn and winter in Shanghai, China. Environmental Pollution, 254, p. 112864. https://doi.org/10.1016/j.envpol.2019.07.032.

148. Suwarno, A., van Noordwijk, M., Weikard, H. P. & Suyamto, D. (2018). Indonesia's forest conversion moratorium assessed with an agent-based model of Land-Use Change and Ecosystem Services (LUCES). Mitig. Adapt. Strateg. Glob. Chang., 23, 211–229. https://doi.org/10.1007/s11027-016-9721-0.

149. Tabaei, S., Hadei, M., Pasalari, N. et al. (2023). Association between short-term exposure to PM and cardiovascular mortality in Iran: a systematic review and meta-analysis. Air Qual Atmos Health. https://doi.org/10.1007/s11869-023-01307-2.

150. Tang, R., Zhao, J., Liu, Y. et al. (2022). Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. Nat. Commun., 13, 1008. https://doi.org/10.1038/s41467-022-28672-3.

151. Terzano, D., Attorre, F., Parish, F., Moss, P., Bresciani, F., Cooke, R. and Dargusch, P. (2022). Community-led peatland restoration in Southeast Asia: 5Rs approach. Restor. Ecol., 30: e13642. https://doi.org/10.1111/rec.13642.

152. Tessum, M. W., Anenberg, S. C., Chafe, Z. A., Henze, D. K., Kleiman, G., Kheirbek, I., et al. (2022). Sources of ambient PM2.5 exposure in 96 global cities. Atmosph. Environ., 286:119234, doi: 10.1016/j.atmosenv.2022.119234 .

153. The EAT-Lancet Commission (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet Commissions, 393(10170), 447-492. doi:https://doi.org/10.1016/S0140-6736(18)31788-4

154. Ti, C., Xia, L., Chang, S. X. & Yan, X. (2019). Potential for mitigating global agricultural ammonia emission: a meta-analysis. Environ. Pollut., 245, 141–148.

155. Tsai, Y. I., Soparajee, K., Chotruksa, A., Wu, H. C., & Kuo, S. C. (2013). Source indicators of biomass burning associated with inorganic salts and carboxylates in dry season ambient aerosol in Chiang Mai basin, Thailand. Atmospheric Environment, 78, 93–104. https://doi.org/10.1016/j.atmosenv.2012.09.040.

156. Tseng, E., Ho, W.C., Lin, M.H. et al. (2015). Chronic exposure to particulate matter and risk of cardiovascular mortality: Cohort study from Taiwan. BMC Public Health, 15, p. 936. https://doi.org/10.1186%2Fs12889-015-2272-6.

157. UNEP (2018). Air Pollution in Asia and the Pacific: Science-based Solutions – Executive Summary. Climate and Clean Air Coalition (CCAC), United Nations Environment Programme (UNEP), and Asia Pacific Clean Air Partnership. https://wedocs.unep.org/20.500.11822/26861.

158. UNEP (2019). Air Pollution in Asia and the Pacific: Science-based Solutions. Climate and Clean Air Coalition (CCAC), United Nations Environment Programme (UNEP), and Asia Pacific Clean Air Partnership. https://www.ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions-summary-full-report.

159. UNEP (2021). United Nations Environment Programme. Actions on Air Quality in Asia and the Pacific – Executive Summary. https://wedocs.unep.org/20.500.11822/36698

160. UNEP (2022). United Nations Environment Programme. Global Peatlands Assessment: The State of the World's Peatlands - Evidence for Action toward the Conservation, Restoration, and Sustainable Management of Peatlands - Summary for Policy Makers. https://wedocs.unep.org/20.500.11822/41236.

161. UNEP. (2023, February 27). Why Asia Pacific Clean Air Partnership matters. Retrieved from UNEP: https://www.unep.org/asia-and-pacific/asia-pacific-clean-air-partnership/why-asia-pacific-clean-air-partnership-matters

162. UNEP. (2023a). World Environment Situation Room. Retrieved February 27, 2023, from https://data.unep.org/article/pollution-and-waste

163. UNEP. (2023b, February 27). Monitoring air quality. Retrieved from UNEP: https://www.unep.org/explore-topics/air/what-we-do/monitoring-air-quality?_ga=2.208289554.1615840343.1674142449-110719830.1671478208

164. UNEP & APCAP (2019). United Nations Environment Programme & Asia Pacific Clean Air Partnership (APCAP). PM2.5 and Ozone Co-Control - Clean Air Policy Brief 2019. https://wedocs.unep.org/20.500.11822/28847.

165. UNESCAP. (2019, October 14). The Future of Asian and Pacific Cities. Retrieved from ESCAP/Knowledge Products: https://www.unescap.org/publications/future-asian-and-pacific-cities-2019-transformative-pathways-towards-sustainable-urban#

166. UNESCAP. (2023, February 27). ESCAP/Projects. Retrieved from Urban Air Pollution: https://www.unescap.org/projects/urban-air-pollution/interventions

167. van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, https://doi.org/10.5194/acp-10-11707-2010, 2010.

168. van Donkelaar, A., Hammer, M. S., Bindle, L., Brauer, M. et al. (2021). Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty, Environmental Science & Technology, 55 (22), 15287-15300. https://doi.org/10.1021/acs.est.1c05309.

169. Vandyck T, Keramidas K, Kitous A, Spadaro J V, van Dingenen R, Holland M and Saveyn B (2018). Air quality co-benefits for human health and agriculture counterbalance costs to meet
Paris Agreement pledges, Nat. Commun., 9, 4939, https://doi.org/10.1038/s41467-018-06885-9.

170. Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., Chaliyakunnel, S., Frostad, J., Klimont, Z., Martin, R. V., Millet, D. B., Philip, S., Walker, K., and Wang, S. (2018). Source influence on emission pathways and ambient PM2.5 pollution over India (2015–2050), Atmos. Chem. Phys., 18, 8017–8039, https://doi.org/10.5194/acp-18-8017-2018.

171. Wang, J., Zhang, M., Bai, X., Tan, H., Li, S., Liu, J., Zhang, R.,Wolters, M. A., et al. (2017). Large-scale transport of PM2.5 in the lower troposphere during winter cold surges in China. Scientific Reports, 7, 13238. https://doi.org/10.1038/s41598-017-13217-2.

172. Wang, Y., Chen, J., Wang, Q., Qin, Q., Ye, J., Han, Y., Li, L., Zhen, W., et al. (2019). Increased secondary aerosol contribution and possible processing on polluted winter days in China. Environment International, 127, pp. 78–84. https://doi.org/10.1016/j.envint.2019.03.021.

173. Wang, H.L., Sun, S.M., Nie, L., Zhang, Z.S., Li, W.P., Hao, Z.P. (2023). A review of whole-process control of industrial volatile organic compounds in China, J. Environ. Sci. https://doi.org/10.1016/j.jes.2022.02.037.

174. Ward C, Stringer LC, Warren-Thomas E, Agis F, Hamer K, Pettorelli N, et al. (2020). Wading through the swamp: what does tropical peatland restoration mean to national-level stakeholders in Indonesia? Restoration Ecology 28:817–827. https://doi.org/10.1111/rec.13133.

175. Ward, C. et al. (2021). Smallholder perceptions of land restoration activities: rewetting tropical peatland oil palm areas in Sumatra, Indonesia. Reg. Environ. Chang., 21, 1–17. https://doi.org/10.1007/s10113-020-01737-z.

176. WHO (2021a). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. License: CC BY-NC-SA 3.0 IGO. https://apps.who.int/iris/handle/10665/345329.

177. WHO (2021b). Action framework for developing and implementing public food procurement and service policies for a healthy diet. Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO. https://www.who.int/publications/i/item/9789240018341.

178. WHO (2022). WHO Ambient Air Quality Database: 2022 Update. Status report. World Health Organization. Available online: https://www.who.int/publications/m/item/who-air-quality-database-2022.

179. WHO. (2023, February 27). Environment, Climate Change and Health. Retrieved from WHO: https://www.who.int/teams/environment-climate-change-and-health/healthy-urban-environments/other-sectors

180. World Bank (2022). Striving for Clean Air: Air Pollution and Public Health in South Asia. World Bank, Washington, DC. License: Creative Commons Attribution CC BY 3.0 IGO. https://www.worldbank.org/en/region/sar/publication/striving-for-clean-air

181. Wu, Y., Han, Y., Voulgarakis, A., Wang, T., Li, M., Wang, Y., Xie, M., Zhuang, B., & Li, S. (2017). An agricultural biomass burning episode in eastern China: Transport, optical properties, and impacts on regional air quality. Journal of Geophysical Research: Atmospheres, 122(4), 2304–2324. https://doi.org/10.1002/2016JD025319.

182. Xie, Y., Dai, H., Xu, X., Fujimori, S., Hasegawa, T., Yi, K., Masui, T., and Kurata, G. (2018). Co-benefits of climate mitigation on air quality and human health in Asian countries. Environ. Int. 119 309–18. https://doi.org/10.1016/j.envint.2018.07.008.

183. Xie, Y., Li, Z., Zhong, H., Feng, X. L., Lu, P., Xu, Z., Guo, T., Si, Y., Wang, J., Chen, L., Wei, C., Deng, F., Baccarelli, A. A., Zheng, Z., Guo, X., & Wu, S. (2021). Short-Term Ambient Particulate Air Pollution and Hospitalization Expenditures of Cause-Specific Cardiorespiratory Diseases in China: A Multicity Analysis. The Lancet Regional Health - Western Pacific, 15, 100232. https://doi.org/10.1016/j.lanwpc.2021.100232.

184. Xing, J. et al. (2020). The quest for improved air quality may push China to continue its CO2 reduction beyond the Paris Commitment. Proc. Natl Acad. Sci., 117, 29535–42. https://doi.org/10.1073/pnas.2013297117.

185. Yang, Y., Tang, R., Qiu, H. et al. (2018). Long term exposure to air pollution and mortality in an elderly cohort in Hong Kong, Environ. Int., 117, pp. 99-106. https://doi.org/10.1016/j.envint.2018.04.034.

186. Yang, Z., Mahendran, R., Yu, P., Xu, R., Yu, W., Godellawattage, S., Li, S., Guo, Y. (2022). Health Effects of Long-Term Exposure to Ambient PM2.5 in Asia-Pacific: a Systematic Review of Cohort Studies. Curr. Environ. Health. Rep., 9(2):130-151. https://doi.org/10.1007/s40572-022-00344-w.

187. Yin, P., Brauer, M., Cohen, A., Burnett, R. T., Liu, J., Liu, Y., Liang, R., Wang, W., Qi, J., Wang, L., & Zhou, M. (2017). Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men. Environmental Health Perspectives, 125(11), 117002-1-117002–117011. https://doi.org/10.1289/EHP1673.

188. Yin, S. (2020). Biomass burning spatiotemporal variations over South and Southeast Asia. Environ. Int., 145, 1–12. https://doi.org/10.1016/j.envint.2020.106153.

189. Yue, H., He, C., Huang, Q., Yin, D., and Bryan, B. A. (2020). Stronger policy required to substantially reduce deaths from PM2.5 pollution in China. Nat. Commun., 11, 1462. https://doi.org/10.1038/s41467-020-15319-4.

190. Zhai, S., Jacob, D. J., Wang, X., Shen, L., Li, K., Zhang, Y., Gui, K., Zhao, T., and Liao, H. (2019). Fine particulate matter (PM2.5) trends in China, 2013–2018: separating contributions from anthropogenic emissions and meteorology". Atmospheric Chemistry and Physics. https://doi.org/10.5194/acp-19-11031-2019.

191. Zhang, L., Liao, H., & Li, J. (2010). Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. Journal of Geophysical Research: Atmospheres, 115(D7), 0–05. https://doi.org/10.1029/2009JD012299.

192. Zhang, Q., Quan, J., Tie, X., Li, X., Liu, Q., Gao, Y., and Zhao, D. (2015). Effects of meteorology and secondary particle formation on visibility during heavy haze events in Beijing, China. Science of the Total Environment, 502, pp. 578–584. https://doi.org/10.1016/j.scitotenv.2014.09.079.

193. Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., Feng, T., Zheng, B., Lu, Z., et al. (2017). Transboundary health impacts of transported global air pollution and international trade. Nature 2017 543:7647, 543(7647), 705–709. https://doi.org/10.1038/nature21712.

194. Zhang, Q., Zheng, Y. X., Tong, D., Shao, M., Wang, S. X., Zhang, Y. H., et al. (2019a). Drivers of improved PM2.5 air quality in China from 2013 to 2017, P. Natl. Acad. Sci. USA, 49, 24463–24469, https://doi.org/10.1073/pnas.1907956116.

195. Zhang, C. et al. (2019b). Rebuilding the linkage between livestock and cropland to mitigate agricultural pollution in China. Resour. Conserv. Recycl. 144, 65–73.

196. Zhang, X., Gu, B., van Grinsven, H. et al. (2020). Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. Nat. Commun., 11, 4357. https://doi.org/10.1038/s41467-020-18196-z.

197. Zhang, Y., Eastham, S. D., Lau, A. K. H., Fung, J. C. H., & Selin, N. E. (2021). Global air quality and health impacts of domestic and international shipping. Environmental Research Letters, 16(8), 084055. https://doi.org/10.1088/1748-9326/AC146B.

198. Zhang, Y., Yin, Z., Zhou, P., Zhang, L., Zhao, Z., Norbäck, D. et al. (2022). Early-life exposure to PM2.5 constituents and childhood asthma and wheezing: findings from China, Children, Homes, Health study. Environ. Int, 165, 107297, 10.1016/j.envint.2022.107297.

199. Zhao, D., Xin, J., Gong, C., Quan, J., Liu, G., Zhao, W. et al. (2019). The formation mechanism of air pollution episodes in Beijing city: insights into the measured feedback between aerosol radiative forcing and the atmospheric boundary layer stability, Sci. Total Environ., 692, pp. 371-381. https://doi.org/10.1016/j.scitotenv.2019.07.255.

200. Zhao, X. J., Zhao, P. S., Xu, J., Meng,, W., Pu, W. W., Dong, F., He, D., and Shi, Q. F. (2013). Analysis of a winter regional haze event and its formation mechanism in the North China Plain, Atmos. Chem. Phys., 13, 5685–5696, https://doi.org/10.5194/acp-13-5685-2013.

201. Zheng Y, Xue T, Zhang Q, Geng G, Tong D, Li X and He K (2017). Air quality improvements and health benefits from China's clean air action since 2013. Environ. Res. Lett., 12, 114020. https://iopscience.iop.org/article/10.1088/1748-9326/aa8a32.

202. Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., Peng, L., Qi, J., Yan, L., Zhang, Y., Zhao, H., Zheng, Y., He, K., and Zhang, Q. (2018). Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys., 18, 14095–14111, https://doi.org/10.5194/acp-18-14095-2018.

203. Zheng, W. and Luo, B. (2022). Understanding pollution behavior among farmers: exploring the influence of social networks and political identity on reducing straw burning in China. Energy Res. Social Sci., 90, Article 102553, 10.1016/j.erss.2022.102553.

204. Zhu, J., Xia, X., Che, H., Wang, J., Zhang, J., & Duan, Y. (2016). Study of aerosol optical properties at Kunming in southwest China and long-range transport of biomass burning aerosols from North Burma. Atmospheric Research, 169, 237–247. https://doi.org/10.1016/j.atmosres.2015.10.012.