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Air quality management status and needs of countries in South Asia and Southeast Asia

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ABSTRACT

Countries in South Asia and Southeast Asia are experiencing severe air pollution problems. Most countries lack technical capabilities and adequate air quality management (AQM) infrastructure. A capacity building workshop on AQM was organised from 19–23 September 2022 for countries in South Asia and Southeast Asia. A total of 17 countries (eight in South Asia and nine in Southeast Asia) participated in the workshop. Each country was invited to present on available AQM infrastructure, including challenges and needs. This article synthesises information on available AQM facilities, challenges and needs of the countries. The information reveals that, except for a few low-population countries and Thailand, most countries lack enough ambient air quality monitoring stations (AAQMS) based on the population-weighted criteria. It is also found that only a few countries have started compiling emissions inventories (EI) and performing air quality modelling, including air pollution impact assessments. It is noted that all countries have enacted air pollution mitigation regulations, including the development of clean policies and action plans. However, policies and action plans lack scientific evidence based on local data. The findings of this article, including challenges and gaps, provide immense opportunities for countries to invest in strengthening various components of AQM, including mobilising financial resources from international funding agencies.

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KEYWORDS

Air quality management, air quality monitoring, air pollution policies, population-weight criteria, capacity building

HIGHLIGHTS

- Most countries in South Asia and Southeast Asia lack adequate numbers of air quality monitoring stations.
- A few countries have started developing emissions inventories and air quality modelling.
- Countries face many challenges in AQM, including lacking technical capacities and financial resources.
- There are vast opportunities to invest in AQM, including mobilising financial resources from international agencies.

1. INTRODUCTION

With rapid urbanisation and industrialisation, countries of South Asia and Southeast Asia are experiencing severe air pollution problems. The air quality in these countries is deteriorating at an alarming rate due to increasing emissions of air pollutants from various sources, including industrial operations, construction, road traffic, residential cooking, open burning of agricultural residual and municipal waste, and other activities (Jabbar et al., 2022; Soejachmoen, 2019). In April 2022, the World Health Organization (WHO) published air quality data from 117 countries for 2020. The data revealed that almost 99% of the global population is respiring air that exceeds WHO air quality guideline values of 5 µg/m³ for $PM_{2.5}$ (particulate matter (PM) ≤ 2.5 µm), 15 µg/m³ for PM_{10} (PM ≤ 10 µm), and 10 µg/m³ for nitrogen dioxide (NO_2)) (WHO, 2021, 2022). As a result of exposure to a high level of air pollution, about nine million premature deaths were estimated yearly in 2019, mostly in developing countries, including Asian countries (Fuller et al., 2022). Many Asian cities are among the list of most polluted cities in the world. In fact, South Asia alone hosts nine most polluted cities out of 10 world's most polluted cities, with an ambient concentration of $PM_{2.5}$ exceeding WHO air quality guidelines of 5 µg/m³ (World Bank, 2022). Most countries in South Asia and Southeast Asia are lagging behind the timeframe for achieving the Sustainable Development Goals (SDGs) linked to improving air quality, including reducing the concentration levels of $PM_{2.5}$ to a level of 35 µg/m³, PM_{10} to a level of 70 µg/m³ and NO_2 to a level of 40 µg/m³ – an Interim Target (IT-1) set by WHO (HEI, 2020). The increasing air pollution is not only affecting human health and the environment but also causing a significant economic burden on the national health budget of countries and a significant loss in agricultural productivity (Pandey et al., 2021; Taghizadeh-Hesary & Taghizadeh-Hesary, 2020).

Air quality management (AQM) refers to all activities undertaken by regulatory authorities to avoid the harmful effects of air pollution on human health and the environment. Figure 1 shows the components of AQM, which include air quality monitoring, emission inventory development, air quality modelling, impact assessment, and mitigation policies and action plans. Air quality monitoring is done by establishing air quality monitoring stations in an area. The data is also used for legislation and compliance checks, impact assessments, developing air pollution control strategies and action plans, forecasting, and scientific research. At the same time, emission inventory development is a process of compiling emissions of air pollutants from var-

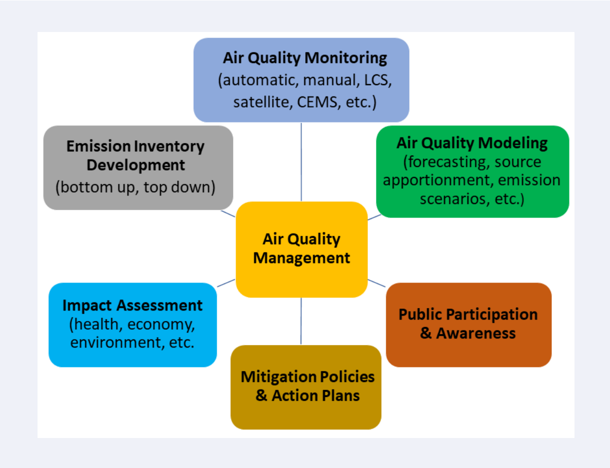

FIGURE 1. Components of air quality management.

ious emission sources. It is generally done through two approaches – bottom-up and top-down. The bottom-up approach is multiplying the activity data (amount of fuel consumption by source) with source-specific emission factors. The top-down approach derives emissions of air pollutants by inputting source characterisation and ambient air pollutant concentration into a suitable receptor model. Both approaches are necessary to validate emissions inventory data. Air quality modelling is a mathematical simulation of how air pollutants disperse and react in the atmosphere to affect ambient air quality. Air quality models are divided into three categories, namely, dispersion models (e.g., ADMS (Atmospheric Dispersion Modelling System), AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model), CALPUFF (California Puff Model), CMAO (Community Multiscale Air Quality Modeling System), etc.), photochemical models (e.g., CMAQ, CAMx (Comprehensive Air Quality Model with Extensions), REMSAD (Regional Modeling System for Aerosols and Deposition), UAM-V (Variable-Grid Urban Airshed Model), etc.), and receptor models (e.g., PMF (Positive Matrix Factorization), PCA (Principal Component Analysis), CMB (Chemical Mass Balance), MLR (Multiple Linear Regression)). Air quality models are used to estimate the concentration of air pollutants downwind from a source; photochemical models are used to simulate secondary pollutants (e.g., PM, ozone (O_3), etc.), whereas receptor models are used for identification and source apportionment of air pollutants. All three types of models are needed in AQM.

Air quality impact assessment is a technique to determine how much the existing concentrations of pollutants or potential emission sources affect the receptor sites. It is a part of environmental impact assessment (EIA) and can be used for strategic environmental planning. The selection of models and monitoring depends on the objective of the assessment. This involves several steps in the assessment process, such as source identification, prediction, evaluation of critical variables and potential changes in air quality. Whereas air pollution mitigation regulations, policies and action plans mainly aim to regulate the prevention, control and abatement of emissions of air pollutants from various sources. The regulations, policies and action plans vary depending on the target pollutant sources, cities and countries. Public participation involves the public in AQM activities and raising awareness about the harmful effects of air pollution.

Many countries in South Asia and Southeast Asia lack the technical capabilities to manage their air quality, including adequate infrastructure required for monitoring key air quality parameters, such as PM (PM_{10} and $PM_{2.5}$) and trace gases (carbon monoxide (CO), nitrogen oxides (NO_x), O_3, sulphur dioxide (SO_2), etc.). Most countries do not have air pollutant emission inventories, although few have compiled emission inventories for some point sources and cities. Countries lack the technical capabilities to use AQM tools for air pollution impact assessments and emissions scenario development. Most countries also lack effective air pollution mitigation policies and action plans supported by scientific evidence.

The capacity development programme aimed to enhance AQM capabilities in countries in South Asia and Southeast Asia in order to foster effective policy formulation and decision-making. The Asia-Pacific Network for Global Change Research (APN) provided financial support to organise two capacity building workshops on AQM in 2021 and 2022. The first five-day capacity building workshop was organised online from 13–17 September 2021, in which about

Country	Participants' Organisation	Website
Bangladesh	Ministry of Environment, Forest and Climate Change	http://www.moef.gov.bd/
Bhutan	National Environment Commission	http://www.nec.gov.bt/
Brunei	Department of Environment, Ministry of Development	http://www.env.gov.bn/
Cambodia	Ministry of Environment	https://www.moe.gov.kh/en
India	Ministry of Environment, Forest, and Climate Change	https://moef.gov.in/en/
Indonesia	Ministry of Environment and Forestry	https://www.menlhk.go.id/
Iran	Department of Environment	https://en.doe.ir/
Lao PDR	Ministry of Natural Resource and Environment	http://www.monre.gov.la/
Malaysia	Ministry of Environment and Water	https://www.doe.gov.my/en/utama-english/
Maldives	Ministry of Environment, Climate Change, and Technology	http://www.environment.gov.mv/v2/en/
Myanmar	Ministry of Transport and Communications	https://www.motc.gov.mm/
Nepal	Ministry of Forests and Environment	https://www.mofe.gov.np/
Pakistan	Ministry of Climate Change and Environmental Coordination	https://www.mocc.gov.pk/
Philippines	Environmental Management Bureau	https://emb.gov.ph/
Singapore	Ministry of Sustainability and the Environment	https://www.mse.gov.sg/
Sri Lanka	Ministry of Environment	http://www.env.gov.lk/web/index.php/en/
Thailand	Environmental Research and Training Center and Pollution Control Department	https://www.pcd.go.th/

TABLE 1. Country-wise participants' organisation.

200 participants from 29 countries participated. A detailed report on the workshop proceedings has been published on the APN website (Verma et al., 2022). The second five-day capacity-building workshop on AQM was organised from 19–23 September 2022 (onsite) for countries in South Asia and Southeast Asia. A detailed report on the workshop proceedings has been published on the APN website (Verma et al., 2023). The major objective of the workshops was to build the capacities of participating countries on AQM. The five-day workshops covered all aspects of AQM, including air quality monitoring, emissions inventory development, air quality modelling, air pollution impact assessment on health and the environment, and air pollution mitigation policies and action plans. AQM components are shown in Figure 1.

Participants from member countries of the ASEAN (Association of Southeast Asian Nations) Agreement on Transboundary Haze Pollution (ASEAN Haze Agreement) and the Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effects for South Asia (Malé Declaration) were invited to the workshop. A total of 17 countries' participants, including nine Southeast Asian (member countries of the ASEAN Haze Agreement: *Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, and Thailand*) and eight South Asian (member countries of the Malé Declaration: *Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, and Sri Lanka*) participated in the workshop. Participants were mainly government officials (policymakers, technical and scientific staff) working with the ministries of environment and pollution control agencies. Table 1 provides country-wise participants' organisations with their websites where readers may explore detailed country-specific information about the AQM status, such as air quality monitoring infrastructure, air quality modelling and impact assessment studies, rules and regulations, and policies and action plans. Furthermore, details of participants, including their name, designation, and affiliated organisation, are given in Annex 1 in the workshop report (Verma et al., 2023).

Although we did not have participants from Vietnam, we added AQM-related information from Vietnam in the article to provide complete coverage of Southeast Asia, collected through personal communication with the Northern Center of Environmental Monitoring (NCEM) and the Vietnam Environment Administration (VEA).

During the workshop, each participating country was invited to present the status of AQM in their country, including challenges and needs for effective air quality management. This article extracted information on the status of AQM in 17 countries of South Asia and Southeast Asia (plus Vietnam through desktop review and personal communication), including challenges and their needs for effective air quality management in their country. The information provided in this article will be useful to UN organisations, international organisations, and funding agencies in assisting the countries of South Asia and Southeast Asia in building their capacities on various components of AQM.

2. METHODOLOGY

During the workshop, each participating country was invited to make a presentation on the status of AQM in their country, including air quality monitoring facilities (monitoring stations: automatic, manual, low-cost sensors, infrastructure, country map with air quality monitoring stations, instruments, laboratories, manpower, etc.) and monitoring data; emission inventory developments (pollutants, sectors, data); studies on air quality modelling and impact assessments; air pollution mitigation plans, actions, and policies; success stories, lessons learned, and challenges; and any other information/data which countries would like to share during the workshop. From the countries' presentations, information about air quality monitoring facilities, emission inventory development, AQM and impact assessment studies, air pollution mitigation policies and action plans, challenges, and needs of the countries (required for effective management of air quality) were extracted and presented in this article.

3. RESULTS AND DISCUSSION – STATUS OF AQM

3.1. Ambient air quality monitoring stations

The objective of establishing ambient air quality monitoring stations (AAQMS) in an area is to measure concentrations of key air pollutants to define the air quality (good, moderate, unhealthy, very unhealthy, and hazardous) based on air quality index values derived from the monitoring data. There are several criteria suggested for establishing the number of AAQMS in an area, such as source attribution (industries, road traffic, power plants, etc.), location (urban, rural, remote), topography and meteorology, inhabitant populations, population density, target air pollutants, cost-effectiveness, and several other factors (Choudhary, Kaur, Saharan, & Kumar, 2022 and references therein). However, to get accurate information on population exposure to air pollution, population-weighted criteria are commonly recommended for establishing the number of AAQMS in an area. Table 2 provided recommendations on population-weighted criteria for establishing the number of AAQMS in an area (BIS, 2000).

Although, within the population-weighted criteria, there are some sub-criteria for establishing the number of AAQMS. However, in general, at least four monitors need to be installed per 100,000 to 1 million population to measure each air quality parameter: PM, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon monoxide (CO) (BIS, 2000; Steinar, Rob, & Helmis, 1999).

Countries in South Asia and Southeast Asia are operating or have installed a number of AAQMS for monitoring key air quality parameters, including PM (PM_{10}, $PM_{2.5}$), SO_2, NO_2, CO, Ozone (O_3), meteorology, and other parameters. While not all monitoring stations in the countries are equipped with monitors for all key air quality parameters, at least PM monitors are installed at the majority

Pollutant	Population of evaluation area	Minimum no. of AAQMS
SPM (or PM)	< 100,000	4
	100,000–1,000,000	4 + 0.6 per 100,000 population
	1,000,000–5,000,000	7.5 + 0.25 per 100,000 population
	> 5,000,000	12 + 0.16 per 100,000 population
SO_2	< 100,000	3
	100,000–1,000,000	2.5 + 0.5 per 100,000 population
	1,000,000–10,000,000	6 + 0.15 per 100,000 population
	> 10,000,000	20
NO_2	< 100,000	4
	100,000–1,000,000	4 + 0.6 per 100,000 population
	> 1,000,000	10
CO	< 100,000	1
	100,000–5,000,000	1 + 0.15 per 100,000 population
	> 1,000,000	6 + 0.05 per 100,000 population
Oxidants	- do -	- do -

TABLE 2. Recommended population-weighted criteria for establishing the number of AAQMS in an area (BIS, 2000).

of monitoring stations. In this section, air quality monitoring facilities, primarily the number of AAQMS operated or installed, are evaluated with population-weighted criteria. For simplicity, we used the criteria of four monitors for monitoring the key air quality parameters per million of population.

Table 3 and Figure 2 show an evaluation of the number of AAQMS operated or installed in countries in South Asia and Southeast Asia using the population-weighted criteria (number of AAQMS per million population).

As mentioned, countries need to operate at least four monitors for each key air quality parameter per million population to get better information on population exposure to air pollution. In South Asia, India is the largest country, with a population of over 1408 million (as of 2021). Considering its large population, India needs to operate 5,632 AAQMS nationwide. However, currently, India is operating 1,254 AAQMS in the country, and it needs 4,378 more AAQMS to fulfil the population-weighted criteria. Pakistan, with a population of over 231 million (as of 2021), operates only two air AAQMS in the country. However, at least 926 more AAQMS are needed to fulfil the population-weighted criteria. Similarly, Bangladesh, with a population of over 169 million (as of 2021), is operating 31 AAQMS in the country and needs at least 678 AAQMS to fulfil the criteria, and it needs to install 647 more AAQMS in the country. Iran, with a population of 88 million (as of 2021), is operating 200 AAQMS in its air quality monitoring network and needs at least 352 AAQMS to fulfil the population-weighted criteria and is required to install 152 more AAQMS. The population of Nepal is about 30 million (as of 2021), and as per the population-weighted criteria, it needs at least 120 AAQMS. Currently, Nepal is operating or has installed 27 AAQMS in the country, and it needs 93 more AAQMS in the country to fulfil the criteria. Sri Lanka, with a population of 22 million (as of 2021), operates only three AAQMS. However, it needs at least 88 AAQMS in the country to fulfil the criteria and is required to install 85 more AAQMS. Maldives and Bhutan are relatively smaller countries in South Asia, with a population of less than a million. Both countries have installed a sufficient number of AAQMS in the country to fulfil the population-weighted criteria for the number of AAQMS required.

In Southeast Asia, Indonesia is the largest country in terms of population, with 273.8 million (as of 2021). Indonesia is operating 56 AAQMS across the

Name of country	Population (in millions as of 2021)	Air quality monitoring stations				No. of AAQMS currently in operation or installed (f = b + c + d + e)	No. of AAQMS required as per population-weighted criteria (g = a × 4)	No. of AQMS required more (h = g – f)	CEMS
	(a)	Automatic[#] (b)	Manual[$] (c)	Mobile[€] (d)	LCS[£] (e)				
South Asia									
Bangladesh	169.4	31	NA	NA	NA	31	678	647	NA
Bhutan	0.777	2	1	NA	3	6	4	0	NA
India	1408	372	882	NA	NA	1254	5632	4378	Yes
Iran	87.92	200	NA	NA	NA	200	352	152	NA
Maldives	0.521	1	NA	NA	8	9	4	0	NA
Nepal	30.03	27	NA	NA	NA	27	120	93	NA
Pakistan	231.4	1	NA	1	NA	2	926	924	NA
Sri Lanka	22.16	2	1	NA	NA	3	88	85	NA
Southeast Asia									
Brunei Darussalam	0.45	7	NA	NA	NA	7	4	0	Yes
Cambodia	16.59	10	NA	1	53	64	66	2	NA
Indonesia	273.8	56	NA	NA	NA	56	1095	1039	Yes
Lao PDR	7.43	10	NA	1	NA	11	30	19	NA

Continued on next page

TABLE 3. Status of air quality monitoring in countries in South Asia and Southeast Asia, including the number of AAQMS currently in operation or installed, the number of AAQMS required to fulfil the population-weighted criteria, the number of AAQMS required more, and the continuous emission monitoring systems (CEMS) installed.

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TABLE 3. *Continued.*

Name of country	Population (in millions as of 2021)	Air quality monitoring stations				No. of AAQMS currently in operation or installed (f = b + c + d + e)	No. of AAQMS required as per population-weighted criteria (g = a × 4)	No. of AQMS required more (h = g – f)	CEMS
	(a)	Automatic# (b)	Manual$ (c)	Mobile€ (d)	LCS£ (e)				
Malaysia	33.57	68	14	3	NA	85	134	49	Yes
Myanmar	53.8	25	NA	NA	NA	25	215	190	NA
Philippines	113.9	54	55	NA	NA	109	456	347	Yes
Singapore	5.45	23	NA	NA	NA	23	22	0	Yes
Thailand	76.6	100	10	7	1680	1797	306	0	Yes
Vietnam*	98.5	104	NA	NA	150	254	394	140	Yes

NA – information not available.

* Personal communication with the Northern Center of Environmental Monitoring (NCEM), Vietnam Environment Administration (VEA), Vietnam.

Continuous ambient air quality monitoring stations (CAAMS) – data acquired automatically to the data centre.

$ Monitoring station operated manually, such as changing PM filter paper and analysis of samples manually in the laboratory.

€ A vehicle with installed necessary monitoring instruments and equipment which can be taken to the desired location for air quality monitoring.

£ Low-cost sensors (LCS) are portable air quality monitoring sensors that can be installed and operated at desired locations with minimum operating cost. LCS sends data to the server through the wireless network. LCS used a light scattering technique for determining the concentration of particles (e.g., PM) and non-dispersive infrared radiation absorption (NDIR) for gaseous pollutants. Common techniques used in the LCS are summarised by Bucek, Maršolek, and Bılek (2021).

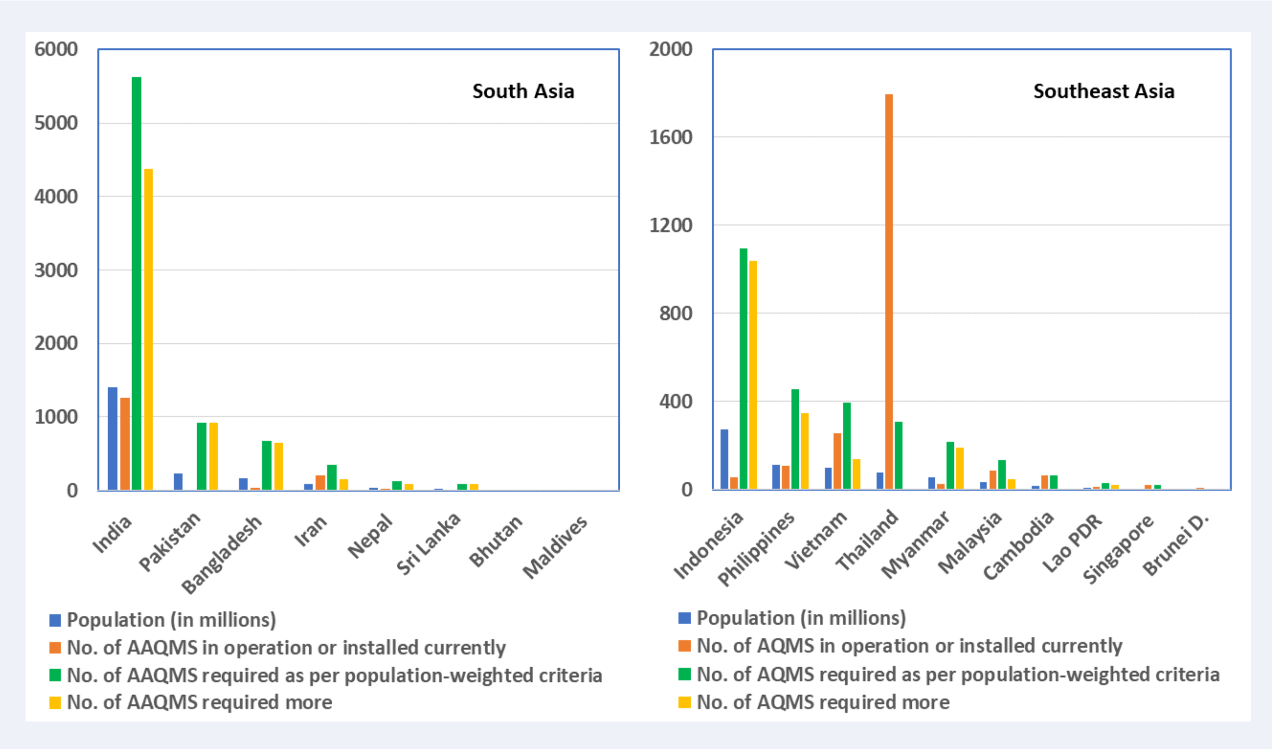

FIGURE 2. Number of AAQMS in countries in South Asia and Southeast Asia, including the number of AAQMS in operation or installed currently (including LCS), the number of AAQMS required as per population-weighted criteria, and the number of AAQMS required more.

country. However, considering its large population size, it needs to operate at least 1,095 AAQMS to fulfil the population-weighted criteria and is required to install 1,039 more AAQMS to fulfil the criteria. Similarly, the Philippines, with pollution of 114 million (as of 2021), is operating or has installed 109 AAQMS in the country. Considering its population size, the Philippines needs to operate 456 AAQMS in the country to fulfil the population-weighted criteria and is required to install 347 more AAQMS. With more than 98.5 million of the population (as of 2021), Vietnam is operating 254 AAQMS and requires 394 AAQMS to fulfil the criteria and needs 140 AAQMS more. Thailand, with a population of 77 million (as of 2021), is operating 1,797 AAQMS in the country, including 100 automatic, ten manual, seven mobile, and 1680 LCS, which are more than enough AAQMS required to fulfil the population-weighted criteria for the number of AAQMS in the country. Malaysia, with a population size of 33.6 million (as of 2021), is operating 85 AAQMS across the country; however, it needs 134 AAQMS to fulfil the criteria and required 49 more AAQMS in the country. Myanmar, with a population of 54 million (as of 2021), is operating 25 AAQMS in the country; it needs 215 AAQMS to fulfil the population-weighted criteria and needs 190 AAQMS more. Cambodia, with a population of 16.59 million, is operating 64 AAQMS across the country, and it needs 66 AAQMS to fulfil the population-weighted criteria and needs just two more AAQMS for that. Lao PDR, with a population of 7.43 million (as of 2021), is operating 11 AAQMS in the country. Considering population size, Lao PDR needs 30 AAQMS to fulfil the criteria and 19 more AAQMS. In the case of Singapore and Brunei Darussalam, both countries are operating enough numbers of AAQMS in the country and fulfil the population-weighted criteria for the number of AAQMS.

It could be noted that the population-weighted criteria for establishing the number of AAQMS have some limitations. The criteria are mostly applicable in the urban region where a considerable size of the population lives. In island countries, such as Indonesia, the Philippines, and the Maldives, where the population is scattered and live on many islands, these countries may choose to establish the number of AAQMS based on the population size living on a specific island rather than based on the whole country's population.

Continuous Emission Monitoring System (CEMS) is a real-time point source emission monitoring of air pollutants (e.g., PM, CO, carbon dioxide (CO_2), SO_2, NO_x, hydrochloric acid (HCl), ammonia (NH_3), volatile organic compounds (VOC_s), mercury (Hg), etc.) from large industries, such as refineries, cement plants, power plants, chemical industries and other manufacturing industries in which smoke is emitted from the stacks. CEMS provides a real-time concentration of air pollutants which could be used for regulatory purposes, including compliance checks. In South Asia, only India has started operating and installing the CEMS in several industries. At the same time, no information is available about the installations of CEMS in the industries of the rest of the South Asian countries, namely Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka, and Maldives. In Southeast Asia, Brunei Darussalam, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam have installed or started installing the CEMS in their heavy industries and power plants. At the same time, no information is available about the installation of CEMS in Cambodia, Lao PDR and Myanmar.

The information given in Table 3 and Figure 2 on the numbers of AAQMS operated or installed in the countries of South Asia and Southeast Asia revealed that, except Bhutan, Maldives, Brunei Darussalam, Singapore, and Thailand, most countries are not operating or have installed enough numbers of AAQMS in the countries which could fulfil the population-weighted criteria for the adequate numbers of AAQMS. This implies that population exposure to air pollution information, which uses for air pollution health impact assessment, is unreliable in South Asia and Southeast Asia. On the other hand, the information in Table 3 provides immense opportunities for countries to invest more in strengthening their air monitoring network, including the mobilisation of financial resources from international funding agencies to countries for establishing more air quality monitoring stations.

It could also be noted that, except for Thailand, most countries in South Asia and Southeast Asia are operating traditional instruments for air quality monitoring, which requires significant financial resources to operate the AAQMS. This provides an opportunity to explore the use of LCS for air quality monitoring since operating the LCS requires comparatively lesser financial resources. Also, only 8 out of 18 countries have installed or are in the process of installing the CEMS in their heavy industries. This provides significant business opportunities to invest financial resources to install the CEMS in the industries of these countries.

3.2. Emissions inventory development

Emissions inventory (EI) data (in addition to air quality monitoring data) is a primary requirement for formulating effective air pollution mitigation policies and action plans. Figure 3 provides qualitative information on the status of emissions inventory development in countries in South Asia and Southeast Asia, while detailed information is given in Table 4. In South Asia, only three out of eight countries (Iran, the Maldives and Nepal) have developed or started developing their EI. For example, Iran has developed EI for CO, nitrogen oxides (NO_x), sulphur oxides (SO_X), VOC and PM from various sources in ten major cities; Maldives has developed EI of organic carbon (OC), black carbon (BC), PM, NH_3, SO_2, NO_x, VOCs, methane (CH_4), CO and CO_2 including future emissions scenarios. Nepal has started developing EI from the brick and cement industries. No information is available on the status of EI development in the remaining South Asia countries in (India, Bangladesh, Pakistan, Bhutan and Sri Lanka).

In Southeast Asia, six out of ten countries (Cambodia, Indonesia, Malaysia, Myanmar, the Philippines and Thailand) have developed or started developing EI. For example, Cambodia has developed EI for OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources; Indonesia completed the

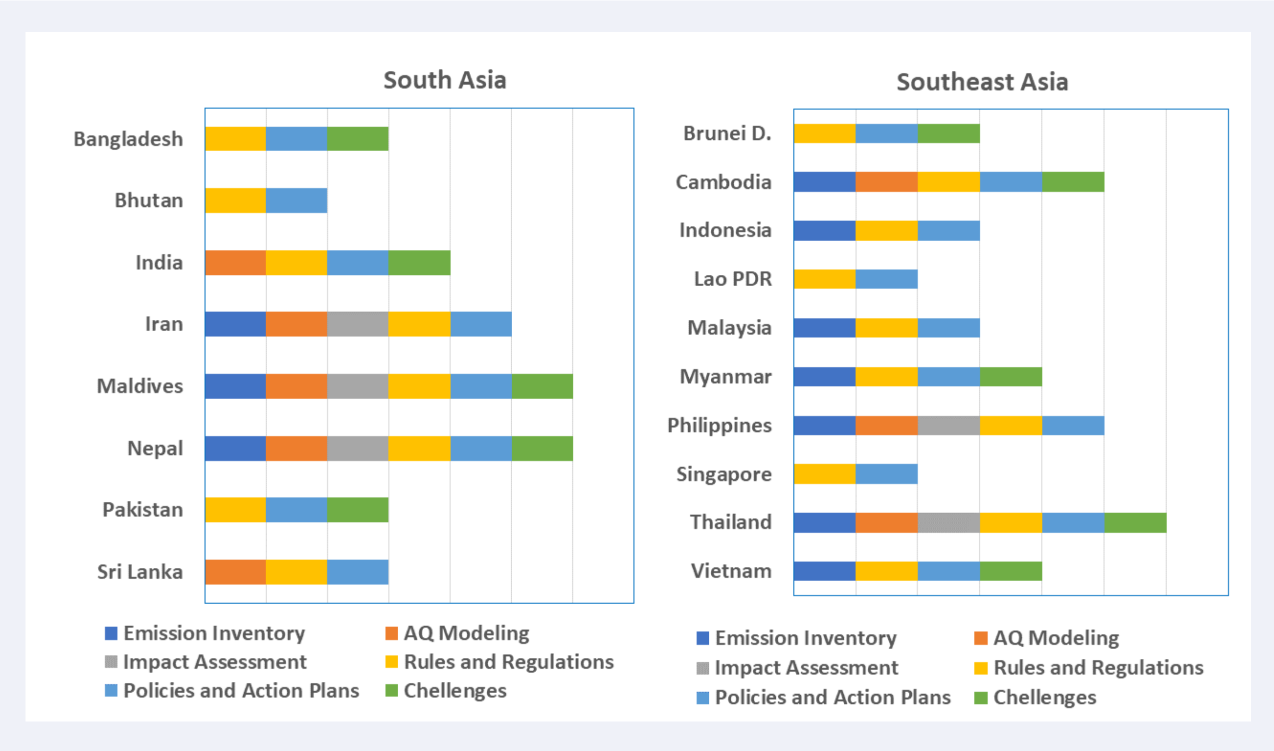

FIGURE 3. Qualitative information on the status of emission inventory development, air quality modelling, impact assessment, rules and regulations, policies and action plans, and challenges of countries in South Asia and Southeast Asia in AQM. Detailed information is given in Table 4.

EI in 30 cities; Malaysia has developed the EI of SO_2, NO, PM, and CO from industrial sources; Myanmar has developed EI for PM, NO_x, CO, CO_2, CH_4, and VOCs from road transport and agriculture sector; the Philippines has developed EI from stationary and mobile sources and developed an online EI databank; and Thailand has developed the EI of $PM_{2.5}$, NO_x, non-methane volatile organic compounds ($NMVOC_s$), SO_2 for the Bangkok Metropolitan Region (BMR) and 77 provinces. Vietnam has started to develop a guideline for EI development for the country. No information is available on the status of EI development in the rest of the countries of Southeast Asia (Brunei Darussalam, Lao PDR, and Singapore).

3.3. Air quality modelling

Air quality modelling is a crucial aspect of AQM. It involves estimating the concentration of air pollutants downwind from sources like industry and road transportation. These models also simulate secondary pollutants like PM and O_3, aid in identifying and apportioning pollution sources, provide air pollution forecasts, understand weather patterns and transport mechanisms through meteorological data input, conduct impact assessments, and support regulatory decision-making.

The status of air quality modelling in countries in South Asia and Southeast Asia is given in Figure 3 and Table 4. In South Asia, India has started air quality forecasting using the WRF-Chem and SILAM in Delhi and National Capital Region (NCR) and other major cities in India. Iran has conducted point source modelling (e.g., power plants) and air quality forecasting in Tehran. The Maldives has developed emissions scenarios for air pollutants, while some researchers have undertaken dispersion modelling in Nepal. Sri Lanka has recently acquired the AERMOD model. No information is available about the status of air quality modelling in Bangladesh, Bhutan and Pakistan.

In Southeast Asia, Cambodia has developed emission scenarios for air pollutants. The Philippines is conducting dispersion and source apportionment modelling, while Thailand is conduct-

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Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
South Asia						
Bangladesh	NA	NA	NA	- Environment Conservation Act 1995 - Environment Conservation Rule 1997 - Air Pollution Guideline 2021 - Air Pollution Control Rules 2022 - Gazette Notification for Construction dust management	- National Environment Policy 2018 - Phasing out leaded fuels - Ban on two-stroke vehicles - Promoting CNG vehicles - Banning old vehicles - Implement vehicle emissions standards - Policies on emission reduction from Brick Kilns - Ban on high sulphur-containing coal	- Euro 4 vehicles - Transboundary air pollution - Modern technology for Industrial pollution - Brickfield management - Open Burning - Coverage of open space area - Online monitoring system - Capacity building - Lack of funds and research
Bhutan	NA	NA	NA	- Environmental Assessment Act 2000 - National Environment Protection Act 2007 - Euro VI Emission standards	- Electric vehicle initiative - Sustainable Low-Emission Urban Transport System - Guidelines on Industries	NA

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TABLE 4. Status of development of emission inventory, air quality modelling, impact assessment, air pollution mitigation policies and action plans, and challenges.

TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
India	NA	Air quality forecasting using WRF-Chem and SILAM in Delhi-NCR and major Indian cities	NA	- Air Prevention and Control of Pollution Act 1981 - Environment Protection Act 1986 - National Ambient Air Quality Standards 2009	- National Ambient Air Monitoring Programme - National Clean Air Programme - Fuels of BS VI standards - Phasing out old - EV Policy launched - Intelligent Traffic Management System - Cleaner fuels (CNG, CBG, and ethanol blending) - Stringent norms for power plants and industries - Real-time tracking of industrial emissions - Ujjawala scheme for cleaner cooking fuel - Waste management – Swatch Bharat, EPR	- Many non-attainment cities - Dust contributing to PM_{10} & $PM_{2.5}$ in most urban areas - Lack of scientific evidence for policies - Complexity in developing action plans - Implementation of actions plans and target setting - Lack of stakeholders participation - Limited public involvement - Lack of coordination among relevant agencies - Limited monitoring and evaluation of the implementation of action plans - Financial constraints

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Iran	Developed emission inventories for CO, NO_x, SO_X, VOC & PM from various sources in 10 major cities	Conducted air quality modelling from point source emissions (e.g., power plants) and forecasting of air quality in Tehran	Conducted air pollution health impact assessment in Tehran	- Environmental Protection Act 1974 - National Clean Air Regulations 1975 - Clean Air Law 2017	- Review of air pollutant permissible limits for industries. - Development of air pollution reduction action plans for 18 cities - Clean Air Law implementation review - Development of air pollution emission inventories for cities. - Upgrading fuel standard and vehicle emission standards	NA
Maldives	Developed emission inventories of OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources	Developed air pollution emission scenarios	NA	Policy framework and planning to guide the overall development direction of the Maldives from 2019-2023	- Revision of vehicle and vessel emission standards and - Development of fuel quality standards - Development of emission inventories - Implementation of Integrated Transport Master Plan - Expansion of Air Quality Monitoring network.	- Lack of financial resources - Lack of technical capacity and human resources - Lack of public interest - Limited air quality data, including emission sources. - Lack of technology
Nepal	Developed emission inventories from the brick and cement industry	Conducted some dispersion modelling by researchers	Study on air pollution health impacts conducted in Kathmandu Valley in 2021	- Environmental Protection Act 2019 - Environment Protection Regulation 2020 - National Environment Policy 2021	- Kathmandu Valley Air Quality Management Action Plan 2019 - Various standards: NAAQS 2012, Vehicular Emission Standard, Incinerators, Brick Industry, and Cement	- Continuous operation of AQMS - Shifting from EURO III to EURO IV - Continuous industrial monitoring - Emission inventory and air quality modelling - Open burning and forest fires

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Pakistan	NA	NA	NA	- Pakistan Environmental Protection Act 1997 - NEQS for Industries 2000 - NEQS for vehicles 2009 - NAAQS 2010	- Installation of pollution control technologies in steel industries - Smog action plan implementation - Implementation of EV Policy and EURO-V Standard Fuel	- Vehicular emission and crop burning - Inconsistent in data collection - 18th Constitutional Amendment - Lack of capacity
Sri Lanka	NA	Started air quality modelling using the AEROMOD software	NA	- National Environmental Act - Management environment policies - Air quality management unit - National air quality management policy	- Permissible Ambient Air Quality Standards 2008 - Stationary Source Emission Control 2019 - Vehicle Emission Testing Programme 2013 - Introduced low sulphur diesel 2014 - Banded burning of plastic in 2017 - Introduced EURO4 standard in 2018	NA
Southeast Asia						
Brunei Darussalam	NA	NA	NA	- Environmental Protection and Management 2016 for air pollution control and opening burning - A comprehensive review of air quality preventive and mitigation measures	- Target is set to achieve 100% good days in a year of PM10 less than 50 μg/m^3 by 2035 - Enforcement of continuous environmental monitoring systems in industries	- Unregulated open burning activities. - The lack of participation of public and industries stakeholders in complying to air guidelines - Unprecedented weather changes (e.g., prolonged dry conditions)

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Cambodia	Developed emission inventories of OC, BC, PM, NH_3, SO_2, NO_x, VOCs, CH_4, CO, and CO_2 from various sources	Developed air pollution emission scenarios	NA	- Environmental Protection and Natural Resource Management Law 1996 - Air Pollution Control and Noise Disturbance sub decree 1999 - Circular on Measures to Prevent and Reduce Ambient Air Pollution 2020	- Ambient Air Quality Standard - Emission Standard for Mobile Sources - Emission Standard for Stationary Sources - Technical Guideline to Control Air Pollution from Industries	- Limited resources and equipment for air pollution control, monitoring, and inspection - Limited technical expertise in air quality management - Limited source analysers and modern technologies - Limited cooperation in information and data sharing by industries - Lack of technical and financial support
Indonesia	Emission inventory in 30 cities has been completed.	NA	NA	- Decree on Air Pollutant Standard 2020 - Regulation on Implementation, Protection and Management of Environment 2021 - Decree on Environmental Quality Index 2021 - Decree on Continuous Industrial Monitoring Information System 2021	- Law enforcement for the prevention of forest fires - Encouraging public participation in air pollution control activities - Enforcement of fuel standards - Strengthening of air quality standard - Installation of emission control systems in industries - Development of emission inventories	NA

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Lao PDR	NA	NA	NA	- Environmental Protection Law 2013 - Decree on National Environmental Standard 2017 - Decision of Pollution Control 2021	- Upgrading existing AQM stations by installing additional instruments. - Expanding the AQM network nationwide by installing new AQM stations - Improving air quality data management and information system	NA
Malaysia	Developed emission inventories of SO_2, NO, PM, and CO from various sources	NA	NA	- Control of emission from diesel engines regulations 2000 - Control of petrol and diesel properties regulations 2007 - Clean air regulations 2014	- Every premise shall install an air pollution control system - Technical guideline on performance evaluation of air pollution control system - Industries are encouraged to implement seven environment mainstreaming tools - Implementation of Euro 5 fuel quality	NA
Myanmar	Developed emission inventory of PM, NO_x, CO, CO_2, CH_4, and VOCs from road transport and agriculture sector	NA	NA	- National environment policy 2019 - Environment Conservation Law 2012 and Rule 2014	National environmental quality guidelines 2015	- Insufficient monitoring stations - Lack of resources, technologies, awareness, and cooperation

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Philippines	Developed emission inventories from stationary and mobile sources and developed online emission inventory databank	Conducted dispersion and source apportionment modelling	NA	- Clean air act 1999 - Implementing Rules and Regulation 2000 - National ambient air quality guideline values for criteria pollutants 2000 - National emission standards for source-specific air pollutants 2000	- Guidelines for designation of attainment and non-attainment areas 2005 - Emission charge system - Emission averaging of existing sources - Updating of Best Available Control Technologies - Airshed management - Online emissions inventory system	NA
Singapore	NA	NA	NA	- Environmental Protection and Management Act - Air impurities regulations - Off-road diesel engine emissions regulations - Prohibition on the use of open fires - Vehicular emissions regulations - Transboundary haze pollution act	- Comprehensive policies for air pollution control from stationary sources - Development control and environmental assessments - Licensing and pollution control - Encourage the adoption of vehicles with low emissions - Periodic inspection of vehicles	NA

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TABLE 4. *Continued.*

Name of country	Emission inventory	Air quality modelling	Impact assessment	Air pollution control and abatement regulations	Air pollution mitigation policies and action plans	Challenges
Thailand	Conducted emission inventories of $PM_{2.5}$, NO_X, $NMVOC_S$, SO_2 in BMR region and 77 Provinces	Conducted air quality modelling using the models (WRF-Chem, Chemax, GAINS, CALINE4, AERMOD, CMB, and PMF)	Evaluated health impacts and social impacts using the models (BenMAP Abacas, LEAP-IBC)	- Automotive emission standards for new and in-used motor vehicle 1994 - Environment Act 2004 - Energy Conservation Promotion Act 2009 - Volatile Organic Compounds in Ambient Air 2007 - National ambient air quality standards 2022	- Development of vehicle pollution control strategy - PM2.5 National Action Plan Agenda and Plan 2020 - Periodic inspection licensing of vehicles for pollution control - Develop NDC to manage air pollution and Climate Change with a target of carbon neutrality in 2050 and zero emission in 2065	- PM and O_3 still exceed the standards. - Increasing number of vehicles - Extreme traffic congestion - Low dispersion of pollutants - Lack of technical and financial support - Lack of scientific evidence for policies - Complexity in developing action plans, implementation and target setting
Vietnam	Guideline for EI development for the country is under preparation.	NA	NA	- Law on environmental protection - National technical regulation on ambient air quality - Circular on technical procedures for air emissions monitoring - Decree on environmental protection planning, strategic environmental assessment, environmental impact assessment and environmental protection plans	- Directive on increasing control of air pollution - Circular on environmental protection in industrial clusters, business zones, services centres, and craft villages - National action plan on air quality management by 2020, vision to 2025 - Implementation of solutions to control crop residue open burning in some provinces - Lower sulphur diesel - National technical regulation on controlling emissions from heavy industries	- Limited resources (technical, human resources, financial support) and infrastructure for air quality management - Limited cooperation in data and information compilation and data sharing by industries and organisations - Lack of coordination among relevant agencies - Limited public involvement - Limited scientific evidence at local levels

NA – information not available.

ing air quality modelling using the WRF-Chem (Weather Research and Forecasting Model coupled with Chemistry), GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies), CALINE (California Line Source), AERMOD, CMB, and PMF (Figure 3 and Table 4). No information is available about the status of air quality modelling in Brunei Darussalam, Indonesia, Lao PDR, Malaysia, Myanmar and Singapore. Some studies on the application of air quality modelling have been conducted by various individual research groups/organisations in the region, but the national governments were not part of those studies.

3.4. Impact assessment

Air quality impact assessment is an important part of EIA and is used for strategic environmental planning. In South Asia, Iran in Tehran, and Nepal in Kathmandu (through a research organisation) conducted air pollution impacts on health. (Figure 3 and Table 4). No information on air pollution impact assessment on health and the environment in Bangladesh, Bhutan, India, Maldives, Pakistan, and Sri Lanka is available. In Southeast Asia, Thailand is assessing the health and social impacts of air pollution by using impact assessment models, including BenMAP (Environmental Benefits Mapping and Analysis Programme), ABaCAS (Air Benefit and Cost and Attainment Assessment System), and LEAP-IBC (Low Emissions Analysis Platform – Integrated Benefits Calculator). Whereas no information is available about air pollution impact assessment in the rest of the Southeast Asian countries.

3.5. Mitigation policies and action plans

Air pollution mitigation regulations, policies, and action plans mainly aim to prevent, control, and abate emissions of air pollutants from various sources to avoid adverse impacts on health and the environment. The regulations, policies, and action plans are varied with target pollutants sources, cities, and countries. It is noted that all countries of South Asia and Southeast Asia have formulated air pollution mitigation regulations, policies, and action plans depending on their needs and resources. Countries-wise air pollution mitigation regulations, policies, and action plans are briefly summarised in Table 4 and presented in Figure 3. The majority of air pollution control and abatement regulations include the Environment Conservations Act, Environment Assessment Rule, Air Pollution Control and Prevention Act, Environment Protection Act, Environmental Protection Law, National Clean Air Regulations, Clean Air Law, Air Pollution Guideline, National Ambient Air Quality Standards, stationary and mobile source-specific emission standards, and other related rules and regulations.

Whereas in the case of air pollution mitigation policies and action plans, countries of South Asia and Southeast Asia, depend on their needs and resources, have established National Environment Policy, National Air Monitoring Programme, National Clean Air Programme, implementation of clean fuel standards (e.g., low sulphur), setting up clean air targets, phasing out old vehicles and leaded fuels, introducing electric vehicles, improvement in traffic management, introduction of clean fuels (e.g., compressed natural gas (CNG), compressed bio gas (CBG) and ethanol blending), development and enforcement of emission standards for stationary and mobile sources, development of emission inventories for various emission sources, installation of emission control technologies in industries and power plants, development and enforcement of emission reduction action plans in cities, enforcement of stringent emission standards for industries and power plants, real-time monitoring of industrial emissions, introduction of clean cooking fuel (e.g., liquefied petroleum gas (LPG)), banning on open burning of municipal waste and agriculture residues, prevention and control of forest fires, setting up and management of airsheds, and several other relevant policies and action plans.

3.6. Challenges

Challenges in AQM are obstacles in the progress of achieving clean air goals. Table 4 summarises common challenges faced by the countries of South Asia and Southeast Asia. It revealed that South Asia and Southeast countries are facing enormous challenges in effectively managing air quality in their countries. One of the major challenges is the lack of scientific evidence at the local level to formulate effective air pollution mitigation policies and action plans and set up clean air targets. Regulations and policies are generally formulated referring to the UN guidelines and widespread local perceptions rather than authentic scientific evidence. In most countries in South Asia and Southeast Asia, local or regional level meteorology (e.g., prevailing stagnant weather conditions) play a crucial role in building up episodic higher pollution levels.

Countries in South Asia and Southeast Asia face common challenges, such as high pollution levels in major cities (e.g., India, Indonesia and the Philippines), the need for continuous air quality monitoring networks, emissions inventories, and air quality modelling. They also struggle with addressing dust contributions to PM levels in urban areas, creating effective action plans, implementing actions, setting targets, and adopting improved emissions standards (e.g., Euro 4, 5, 6). Other challenges include handling open waste burning, lacking modern emission reduction technologies for mobile and stationary sources, limited stakeholder participation, coordination issues among agencies, insufficient monitoring data and policy evaluation, transboundary impacts, and limitations in technical and financial resources.

3.7. Opportunities

Challenges always come with solutions and offer abundant opportunities for exploration. Countries in South Asia and Southeast Asia are currently grappling with various challenges in AQM and the pursuit of clean air goals (refer to Section 3.6). Despite these challenges, there are numerous avenues for exploration and utilisation.

For instance, Table 3 reveals that many countries in these regions do not operate enough AAQMS to meet population-weight criteria for obtaining reliable data on air pollution exposure. Traditional air quality monitoring instruments are predominantly used, demanding substantial financial resources for operation. This situation prompts an opportunity to consider LCS for air quality monitoring, which require comparatively fewer financial resources. Additionally, several countries have begun installing or are in the process of setting up CEMS, creating substantial business prospects for investments in these countries.

Furthermore, only a few countries have started developing EIs and establishing facilities for air quality modelling. Health impact assessments due to air pollution remain rare, and many countries lack scientifically-backed air pollution regulations and policies. These challenges underscore significant opportunities for governments to enhance air quality monitoring networks, establish emission inventories, assess impacts on health, ecosystems, economies, and the environment, and support the formulation of evidence-based air pollution policies and action plans.

International funding agencies have a role to play in leveraging technical and financial resources to help countries expand their air quality monitoring networks, introduce CEMS, establish EI development facilities, and foster science-driven policies. These initiatives collectively contribute to the effective management of air quality.

4. CONCLUSION

This article compiles data from 17 South Asian (Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, Sri Lanka) and Southeast Asian (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand) countries, gathered during an AQM workshop in September 2022, and supplemented by personal communication for Vietnam. Assessing against population-weighted criteria (four monitors per million people), it is evident that, barring Thailand and lower-population nations, both South Asian and Southeast Asian countries lack sufficient AAQMS, compromising reliable air pollution exposure data. Only eight of 18 nations are implementing or planning to implement CEMS. South Asia sees three out of eight countries (Iran, Maldives, Nepal) developing EI, and Southeast Asia has six out of ten countries (Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Thailand) doing the same. Air quality modelling is undertaken by a few (India, Iran, the Philippines and Thailand), and impact assessment studies are rare except for Iran, Nepal and Thailand. While all countries have air pollution regulations and action plans, scientific evidence to support them is lacking. The article underscores substantial opportunities for countries to enhance air quality monitoring, install CEMS, consider LCS, establish EI development facilities, and undertake air quality modelling and impact assessments. This presents an ideal moment for the UN, international organisations, and funding agencies to financially and technically assist countries in bolstering AQM components, achieving clean air targets, and enhancing air quality.

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