Compendium of Technologies for Air Pollution Control

ESCAP

APCTT
Asian and Pacific Centre
for Transfer of Technology

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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.

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FOREWORD

It is a privilege to introduce this *Compendium on Technologies for Air Pollution Control*.

The Asian and Pacific Centre for Transfer of Technology (APCTT) of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), has long been dedicated to fostering innovation and technology cooperation and transfer across Asia Pacific. APCTT's mandate is to strengthen capabilities and facilitate development, adoption and diffusion of new and emerging in the region.

This document has been prepared under the project "Enhanced capabilities to adopt innovative technologies for city air pollution control in select countries of the Asia-Pacific" supported by the Korea ESCAP Cooperation Fund. The project objective was to strengthen policies and city level action plans to facilitate adoption of innovative technologies for controlling air pollution in Asia-Pacific. The project aimed to improve the availability of technical knowledge regarding innovative technologies, and good practices and enabling policies for air pollution control in three cities (Bangkok, Dhaka and Gurugram).

In our ongoing efforts to strengthen cooperation and transfer of technologies, this compendium takes a significant step forward. In recent years, technological interventions in air pollution control have gained considerable momentum. Therefore, there exists a pressing need for a consolidated resource that not only summarizes the currently available technologies but also critically evaluates their strengths and limitations. Importantly, this compendium is designed to provide a range of technology options for policymakers and urban city planners and provide knowledge and insights to make informed decisions.

This resource will undoubtedly contribute to the advancement of air pollution control efforts in the Asia Pacific region. We also hope it will be a working document and more technologies are added as they evolve. As we navigate the challenges posed by environmental degradation, we hope this compendium, along with other products and recommendations from the project, will guide us towards a cleaner and healthier future for all in Asia Pacific.

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Asian and Pacific Centre for Transfer of Technology
Economic and Social Commission for Asia and the Pacific

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This publication was prepared by Dr. Sagnik Dey from the Indian Institute of Technology Delhi under a consultancy assignment with ESCAP-APCTT. It benefited from comments and suggestions from Mr. Satyabrata Sahu and Mr Pankaj Kumar Shrivastav from the ESCAP-APCTT.

We gratefully acknowledge all of the above.

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LIST OF ABBREVIATIONS

ACI: Activated carbon injection

AOD: Aerosol optical depth

APC: Air pollution control

APCTT: Asian and Pacific Centre for Transfer of Technology

CEEW: Council on Energy, Environment, and Water

CPCB: Central Pollution Control Board

DALY: Disability-adjusted life year

DGCA: Directorate General of Civil Aviation

DPCC: Delhi Pollution Control Committee

DSI: Dry sorbent injection

ESP: Electrostatic precipitator

EV: Electric vehicle

FGD: Flue gas desulfurisation

GBD: Global Burden of Disease

GSC: Gravity settling chamber

IARI: Indian Agricultural Research Institute

ICAR: Indian Council of Agriculture Research

IoT: Internet of Things

LCA: Life cycle assessment

LMIC: Lower- and middle-income countries

LPG: Liquified petroleum gas

MSW: Municipal solid waste

NCAP: National Clean Air Program

NEERI: National Environmental Engineering Research Institute

NMVOC: non-methane volatile organic compounds

PM2.5: Fine particulate matter with aerodynamic diameter smaller than 2.5 µm

PM10: Particulate matter with aerodynamic diameter smaller than 10 µm

PMUY: Pradhan Mantri Ujjwala Yojana

PRB: Porous radiant burner

RCCI: Reactivity-controlled compression ignition

RCM: Reduced complexity model

RTO: Regenerative thermal oxidisers

SCR: Selective catalytic reduction

SCNR: Selective non-catalytic reduction

UAV: Unmanned aerial vehicle

UNIDO: United Nations Industrial Development Program

USAID: United States Agency for International Development

VOC: Volatile organic compounds

CHAPTER I: BACKGROUND AND RELEVANCE OF THE TECHNOLOGY COMPENDIUM

1.1 Air Pollution

Air pollution is a widespread environmental challenge with significant consequences for human health and the climate. Air pollutants include particulate matter and gaseous pollutants, either directly emitted from multiple sources (known as primary pollutants) or formed in the atmosphere by chemical reactions (known as secondary pollutants). Most common air pollutants in Asia-Pacific regions are particulate matter whose aerodynamic diameter is smaller than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$), SO_2, oxides of nitrogen, ozone, CO, Lead, and non-methane volatile organic compounds (NMVOCs).

South and Southeast Asian countries are one of the major air pollution hotspots where residential biomass combustion, vehicular emissions, fossil-fuel combustion in industrial, commercial, and energy sectors, open biomass burning, brick kilns, construction and road dust, and other disaggregated sectors are identified as the major emitting sectors.[1] Emissions of various pollutants are projected to increase manifold in the next few decades due to rising population and energy demand. In terms of $PM_{2.5}$ levels, South and East Asia and Sub-Saharan Africa pop out in global maps.[2,3] While recent efforts in East Asia have led to an improvement in air quality, opposite trends are observed in South Asia and Africa[4], where a majority of the world's most polluted cities lie.[5]

1.2 Health burden of air pollution in the Asia-Pacific region

Air pollution has been recognis ed as the leading environmental health risk globally.[6] The latest updates from the Global Burden of Disease (GBD) study[2] estimated that 6.7 million deaths globally were attributable to air pollution in 2019. The number has not changed much since 2015 because the gains in reducing the health burden of household air pollution due to the transition from solid fuel to clean fuel have been lost due to the rise in the burden of ambient air pollution. 90% of the deaths associated with air pollution were found to occur in lower and middle-income countries (LMICs).[3] For example, more than 2.5 million deaths and 85 million disability-adjusted life years (DALY) were attributed to air pollution in the South and Southeast Asian countries in 2019 (Table 1.1).

Table 1.1 Mortality and disability-adjusted life year estimates (along with 95% uncertainty intervals) are attributable to air pollution in South and Southeast Asian countries. Statistics are compiled from the Global Burden of Disease Study (2019).

Health Indicator	Region	Value	Lower Limit	Upper Limit
Mortality	South Asia	2,119,277	1,848,435	2,415,468
Mortality	Southeast Asia	501,271	410,034	592,076
DALY	South Asia	71,369,584	62,977,850	80,570,865
DALY	Southeast Asia	15,460,164	12,672,945	18,130,662

Numerous studies in the recent past have also established the linkage between air pollution and a wide range of health outcomes such as child mortality,[7,8] adverse birth outcomes,[9,10] acute respiratory infection,[11] child [12,13] and women anemia[14], child physical[15] and cognitive developmental failure[16,17], hypertension (Prabhakaran et al., 2020), diabetes-mellitus (Mandal et al., 2023), cancer and many more. The India Global Burden of Disease study systematically estimated the trends in mortality and morbidity burden attributable to ambient and household air pollution.[19,20]

Studies have shown that the rise in population and aging may partially compensate for the benefits of reducing air pollution exposure [1,21] Therefore, air pollution exposure needs to be reduced by a bigger margin for considerable health benefits. This requires effective planning for implementing mitigation measures under an air quality management plan.

1.3 Air quality management

Air quality management requires several steps. First and foremost, air quality at any location needs to be continuously monitored. The variability of air pollutants at any location is a result of variations in local emission source characteristics, regional transport (from upwind sources), and modulation of the background concentration by meteorology. To understand this variability, one needs to keep track of emissions of primary and secondary pollutants from various local and regional sources and the dispersion of pollutants in the atmosphere under heterogeneous meteorological conditions. Based on source-segregated information about relative contributions to air quality, clean air action plans are developed to reduce emissions and thereby improve air quality over time. The success or failure of implementing the clean air action plan can be judged by tracking air quality changes in the future.

Asia-Pacific countries made considerable progress since 2015 in their actions against air pollution, as captured by a recent UNEP survey. For example (Figure 1.1), all 41 countries have announced incentives for cleaner production in the industrial sector. 14 countries have set stricter vehicle emission standards, with another 20 countries are in the process of doing so. 37 countries have either implemented or are in the process of implementing policies banning waste burning.

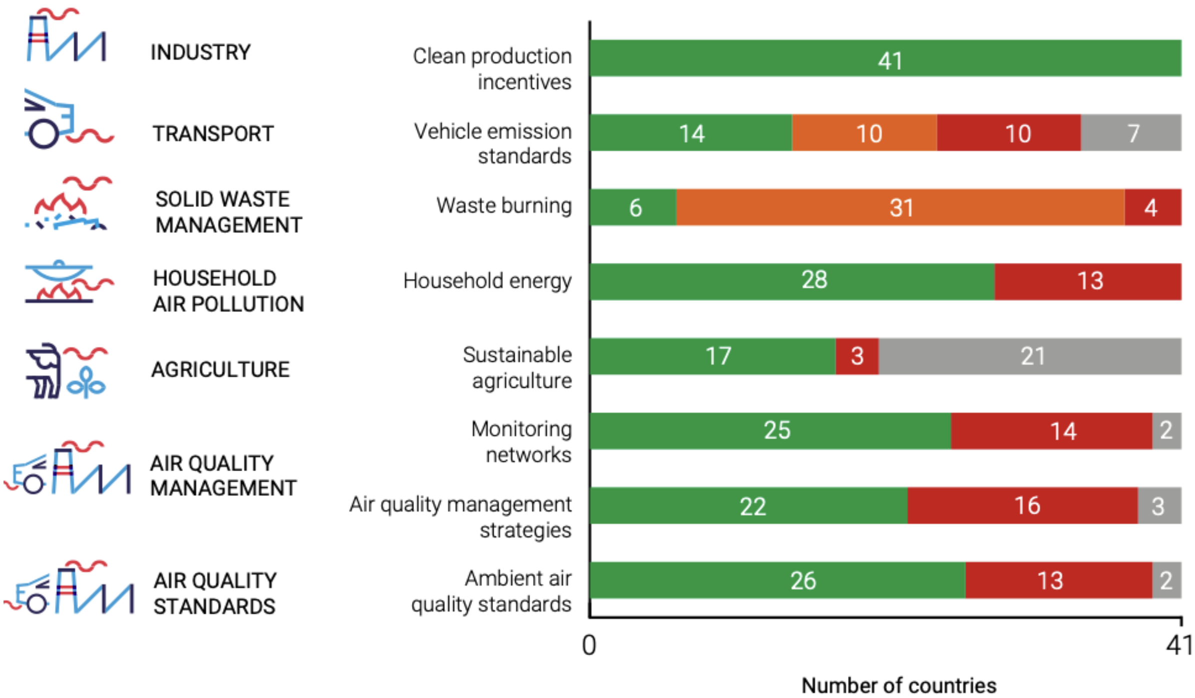


Figure 1.1 Progress of the Asia-Pacific countries towards sectoral actions for improving air quality. Source: UNEP survey (https://wedocs.unep.org/bitstream/handle/20.500.11822/36698/AAQAP_ES.pdf).

22 countries have formulated clean air action plans that include the expansion of ground monitoring networks, characteris ing emissions of gaseous and particulate pollutants from various sectors, and identifying sectoral contributions. 26 countries have set ambient air quality standards, while 13 countries are in the process of doing so. However, in resource-limited settings of developing countries, clean air action plans are facing implementation challenges due to a lack of adequate resources and technical expertise. [22,23] Moreover, the clean air action plans lack prioriti sation in terms of cost-effectiveness and feasibility.

Implementation of mitigation measures across the sectors with a timebound target is the most challenging part of the air quality management plan. Emission mitigations require interventions at policy and at the individual level, which in turn relies heavily on technological assistance for a wide range of activities. In most Asia-Pacific countries, a proper plan for sector-specific technology use is lacking.

1.4 Relevance of this technology compendium

The Asian and Pacific Centre for Transfer of Technology (APCTT) is a regional institution of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP). One of the key mandates of APCTT is to assist the ESCAP members and associate members in strengthening the environment for innovation and technology transfer in the member countries. The approach includes strengthening policies to facilitate the adoption of innovative technologies to mitigate air pollution in three South Asian cities – Dhaka in Bangladesh, Gurugram in India, and Bangkok in Thailand. This compendium is part of the continuous efforts of APCTT to aggressively promote technological interventions for accelerated progress towards clean air in Asia-Pacific cities. [24]

The first air pollution control technology compendium was compiled by UNIDO in 2007. [25] There have been several technological innovations after 2007, and the practices may have also changed. Moreover, the scope of technological interventions has expanded beyond just emission controls. Recently, a draft report on innovative technologies in air pollution control was published by APCTT [25], where the latest innovations were compiled. Since technological interventions have gained momentum in recent years, there is a clear need for a technology compendium that summaris es the currently available technology in one place and discusses its strengths and limitations given the existing case studies.

This compendium is an effort to address this gap. It compiles the available technologies relevant to various aspects of air quality management practices. The report provides policymakers and urban city planners with examples of the best cases around the world, so that they can implement these technologies to accelerate progress toward meeting clean air targets in their respective cities. The information provided in the report is taken from the open literature and is cited in the 'References.'

1.5 Structure of the Compendium Report

This technology compendium report is organised in the following way. This first chapter provides the background, motivation, and relevance of the report. The second chapter highlights the technology that is and can be (in the future) used in three key aspects of air quality management – monitoring, emission control, and removal. The third chapter discusses the potential opportunities for Asia-Pacific cities to utilis e the available technologies in air quality management, and the final chapter provides recommendations and ways forward.

CHAPTER II: TECHNOLOGY APPLICATIONS IN AIR QUALITY MANAGEMENT.

This chapter is organis ed into two sections. The first section focuses on the usage of technologies in air quality management in three broad categories: monitoring, emission controls, and removal. In each of the sub-categories, the existing cases are discussed including their strengths and limitations. The second section summaris es the best practices and potential uses of technologies in policy and behavioural interventions. The narrative focuses on transport, construction, waste management, brick kilns, industrial emissions, and other key emitting sectors that are identified in the existing source apportionment studies in Asia-Pacific countries. The technologies are presented sector-wise with a focus on country-specific implementation, potential applications, innovative quotient, efficiency, effectiveness, affordability, accessibility, strengths, and limitations.

2.1 Technology for air pollution monitoring

Accurate measurements of air pollutant concentrations are the foremost requirement in air quality management. In a regulatory framework, air pollution monitoring is managed by the pollution control boards of the respective countries. Over the years, the ground monitoring network has been expanded across the globe, but at varying pace depending on the availability of resources. A global analysis [26] revealed that only 24 out of 234 countries had more than three monitors per million population in 2016. Sixty percent of countries having 18% of the global population had no reference-grade monitors for $PM_{2.5}$. Most of the Asia-Pacific countries (Figure 2.1) have inadequate ground monitoring for managing air quality. This calls for the use of alternate technology as a complementary tool to the regulatory-grade monitors.

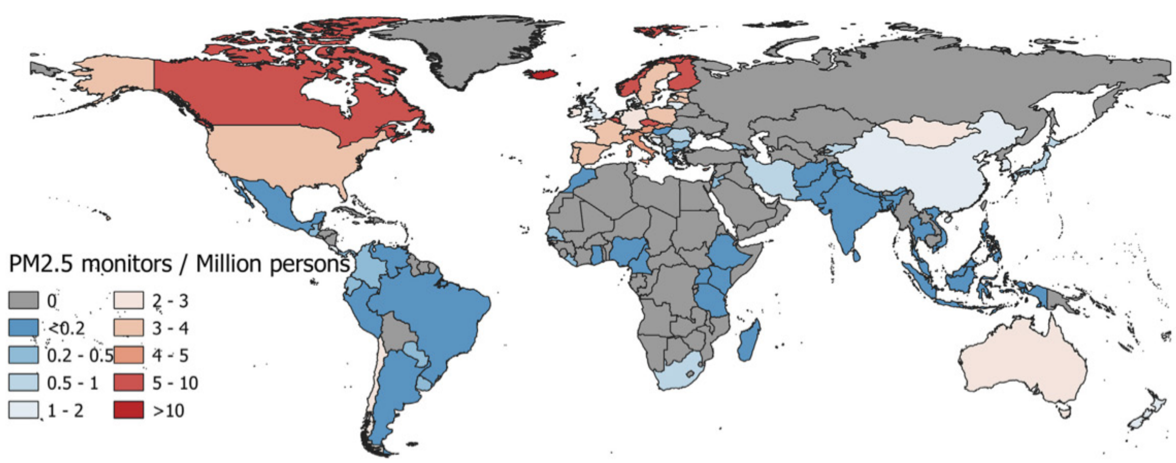


Figure 2.1 Distribution of $PM_{2.5}$ monitors per million population during 2010-2016. The figure is taken from Martin et al.[26]

2.1.1 Technology 1: Sensors and internet of things (IoT)

While the regulatory agencies in the Asia-Pacific countries are in the process of expanding the ground-monitoring network, sensor technology has emerged to provide useful information and complement ground monitoring in multiple ways. The biggest advantage of the sensor-based IoT technology is the affordable cost and high temporal frequency (seconds to minute) of data. Since the devices are portable, they are useful to monitor indoor air quality and personal exposure.

However, the sensor technology has several limitations and should not be used for regulatory purposes. The PM sensors work on the principle of laser scattering. Currently, there are four major categories of sensors that are used across the globe (Table 2.1). The biggest challenge is the durability and robustness of the sensors in different environmental conditions. The user should calibrate the sensors off- and on-field to derive meaningful results. This can be done by co- locating the sensor with reference-grade monitoring before the field deployment, preferably in the climate zone where it will be operated. [27,28] Devices that have two identical sensors are more useful in determining if one of the sensors starts drifting. For other devices with a single sensor, periodic co-locations will allow tracking of the biases in the data provided by the sensors. Gaseous sensors, on the other hand, have larger uncertainty and are more difficult to calibrate. [29] Finally, no uniform calibration algorithm can be set for the sensors; rather, the calibration should be done based on the local conditions.

Once the calibration and validation are maintained rigorously, the technology can provide multiple opportunities. Large deployment can enable hyperlocal monitoring at air pollution hotspots to identify local sources [30] across diverse micro-environments. These sensors can be used in mobile mode to track air pollution, which is most likely to be caused by traffic emissions, along major roads. [31] The data can be harnessed to segregate the regional background from the local sources. [32,33] These sensors, in tandem with statistical methods (such as positive matrix factoris ation and k-means clustering), have been utilis ed to identify pollution sources. [34]

Table 2.1 A comparative assessment of the available sensor characteristics.

	Plantower	Piera IPS3100	Sensirion SPS30	Alphasense OPC N3	Analyzer
Technology	Laser Scattering	Laser Scattering	Laser Scattering	Laser Scattering	Beta Mass Attenuation
Range	0-1000 µg/m³	0-6000 µg/m³	0-1000 µg/m³	0-2000 µg/m³	0-1000 µg/m³
Maintenance	High	Low (Auto Cleaning)	Low (Auto Cleaning)	Medium	Very High
Adoption	High	Low	Medium	Low	NA
AQ-SPEC Performance (PM2.5)	76-77%	69-90%	80-83%	52-67%	FEM
Lifetime	3 years	8 years	8 years	3 years	NA
Cost	X	2X	2X	4X	200X

2.1.2 Technology 2: Remote sensing

The advancement of remote sensing technology provides an opportunity to complement the inadequate ground monitoring in developing countries. Satellites do not directly measure levels of air pollutants at the surface; rather, they measure the outgoing radiation, and the retrieval algorithms derive column-integrated information. Primarily, remote sensing technology can be used to monitor surface $PM_{2.5}$ and PM_{10}, multiple gaseous pollutants, and detect open biomass burning. The satellite images can be processed to detect potential air pollution sources. The following sub-sections detail these applications with examples.

2.1.2.1 Monitoring $PM_{2.5}$

Over the years, the methodology has evolved to derive $PM_{2.5}$, the most important criteria pollutant, from the most common satellite product - columnar aerosol optical depth (AOD). Satellite-derived monthly $PM_{2.5}$ databases are available at an unprecedentedly high 1-km □ 1-km spatial scale for the entire globe (https://sites.wustl.edu/acag/datasets/surface-pm2-5/). For regional applications, satellite-derived $PM_{2.5}$ data are available on a daily scale. [35,36] The rising rate of $PM_{2.5}$ started slowing down [36,37] in many Asia-Pacific countries (Figure 2.2). Satellite-derived $PM_{2.5}$ data can be used for various air quality management applications. However, the data needs to be calibrated and validated against ground-based reference-grade monitoring for regional applications.

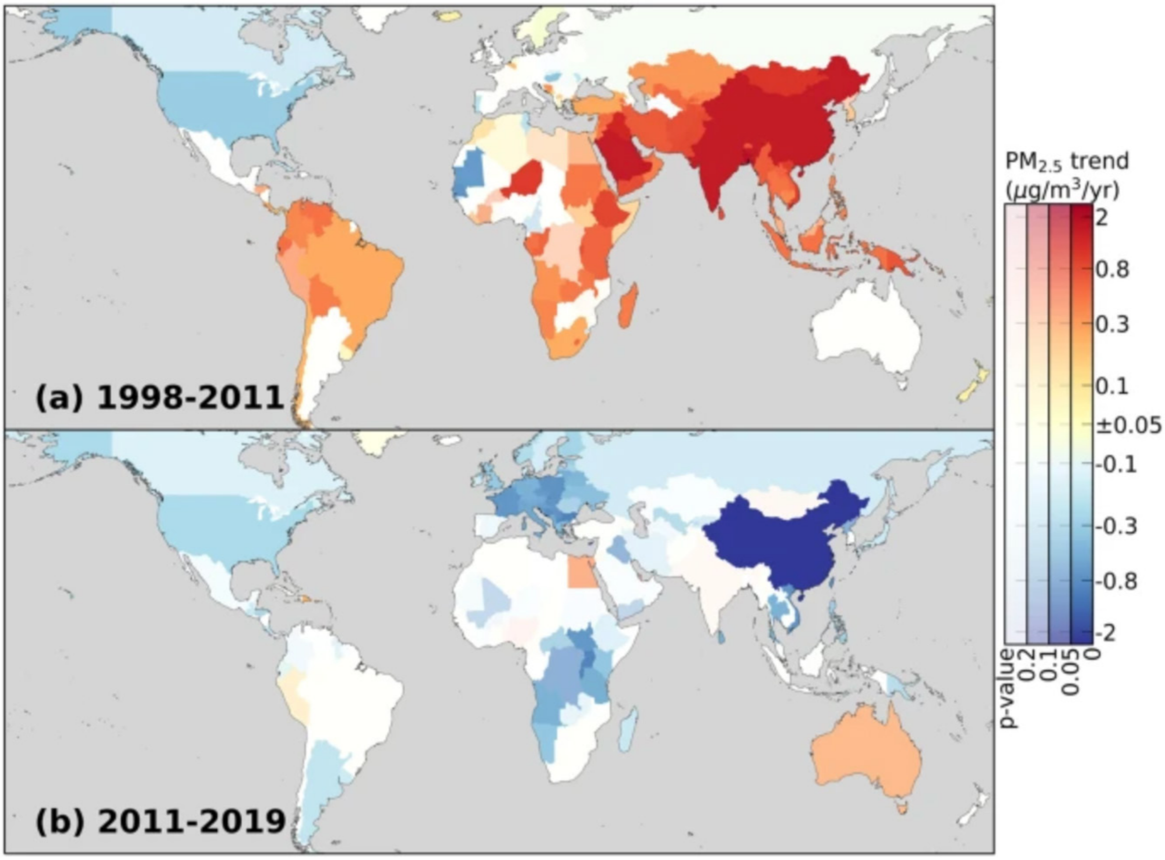


Figure 2.2 Annual trends in $PM_{2.5}$ derived from satellite data from 1998 to 2011 and 2011 to 2019. The figure is taken from Li et al. [37]

Tracking air quality at local and regional scale

Air quality in a city is not only affected by emissions from within the city but also by emissions transported by wind outside the city. Therefore, it is important to track quality inside the city boundary and outside within the local air shed. Ground monitoring by regulatory agencies is mostly limited to city boundaries, and therefore, satellite data can complement this for regional-scale information.

Demarcation of air sheds

In a recent report, Dey and Ganguly (2023)[38] demarcated regional air sheds in India along with city air sheds using satellite data. Similar analysis can be carried out for other Asia-Pacific countries with scarce ground data.

Identification of future sites for ground monitoring expansion

Satellite-$PM_{2.5}$ data also provides an opportunity to identify suitable sites for ground monitoring expansion. In a recent study, the rationale for the same was proposed for India, which can be adopted for other countries. [39]

Monitoring open biomass burning

Open biomass combustion is a major source of air pollution in South and Southeast Asia. Open fires from man-made or natural activities can be tracked by fire count and radiative power data provided by various satellites (e.g., https://firms.modaps.eosdis.nasa.gov/active_fire/).[40] Other than locating the open fires, high spatial resolution satellite data can be used for burnt area mapping. [41]

Locating small-scale point sources in satellite data

Satellite visible imageries at very high spatial resolution can be processed to detect locations of point sources such as brick kilns, rice mills, sugar mills, etc. These often flout regulatory emission norms. Tallying the marked locations in the satellite images with the approved list for environmental clearance from the government can identify the ones that are operated illegally.

2.1.2.2 Monitoring of gaseous pollutants

Besides $PM_{2.5}$, satellites also measure columnar concentrations of SO_2, NO_2, HCHO, NH_3, CO, O_3, and other trace gases. Similar to particulate pollution monitoring, algorithms are required to be developed to derive surface pollution levels from column-integrated information.

Currently, global NO_2 [43] and ozone [44] databases exist at a 1-km spatial scale for air quality applications. The methodology has been proposed to understand the potential sources for many other gaseous pollutants like HCHO.[45] Industrial and agricultural ammonia point sources were identified by Van Damme et al. [46] Using satellite data products, emissions of CO [47] and SO2 [48] were determined.

Beyond retrieving column-integrated concentrations, satellite data were used to infer emissions from point and area sources. Satellite data helped in understanding the reduction in global air pollution levels during the COVID-induced lockdown. [49] Emissions from coal-fed power plants can be tracked using satellite data. [50] For more details and a comprehensive review, one can follow Streets et al. [51] and Sun [52].

2.1.3 Technology 3: Unmanned Aerial Vehicles

Another technological innovation in recent times is the use of unmanned aerial vehicles (UAVs) in air quality monitoring and management. [53]

Managing drones requires specialised skills in hardware, software, and computing. Several commercial ventures that specialise in such technology have emerged in recent years in Asia-Pacific countries. However, the countries should have specific policy guidelines for such operations.

Recently, the Ministry of Civil Aviation, Government of India has announced new rules for UAV operations in India on 26th August 2021 and subsequently amended by the Drone Amendment Rules, 2022 to regulate UAV operations in India in partial suppression of the Unmanned Aircraft Systems Rules, 2021. The new rules are more liberal and cover a wide variety of activities.

- All drones must be registered with the Directorate General of Civil Aviation (DGCA)
- Operators must be over 18 years of age and registered with DGCA.
- Training certificates are not required for flying nano drones (weighing less than 250 g) and non-commercial micro-drones (weighing less than 2 kg).
- No permission is required to fly UAVs in the ‘green’ zones.

- Special permission is required to fly UAVs in 'yellow' zones of restricted airspace.
- 'Red' zones, which include military bases, nuclear plants, and other sensitive areas, are 'no-fly' zones.
- Nano- and micro-drones should be restricted up to 50 ft and within a speed limit of 25 m/s.

Many other Asian countries have also come up with country-specific guidelines for operating UAVs. The cities should consult the respective authorities before adopting this technology for air quality management practices.

UAVs or drones can be used in various ways. They can be equipped with high-resolution cameras, which can detect sources and gather photographic evidence of non-compliance. Air pollution sensors can be mounted on drones to capture air pollution levels at hotspots that are not easily accessible, like dumpsites. [54] Since drones can fly higher, sensors mounted on drones can provide information about the vertical extent of the pollution within the boundary layer. [55]

2.1.4 Technology 4: Chemical speciation for real-time source apportionment

Sources of air pollution in a city are traditionally derived by receptor modelling techniques applied to chemical speciation information derived by offline measurements. Such information forms the basis of the Clean Air Action Plan. However, offline measurements do not provide real-time information, and unless done repeatedly, the efficacy of sector-specific mitigation plans cannot be tested.

Recently, advancements in measurement technology and statistical techniques have allowed policymakers to derive source information in real-time and enabled them to make more informed decisions. [56] This requires simultaneous measurements of aerosol speciation, including water-soluble ions, metals, various carbonaceous particles, and trace gases. This is not possible with a single instrument; rather, a suite of very advanced instruments needs to be deployed, and the data needs to be analysed carefully.

Non-refractory sub-micron PM mass and the water-soluble ions can be derived in real-time by the instruments - ToF-AMS (time of flight aerosol mass spectrometer), ACSM (aerosol chemical speciation monitor), ToF-ACSM (time of flight aerosol chemical speciation monitor). Elements can be extracted in real-time by Xact 625i metal monitors. Water-soluble organic carbon can be derived online by AIM-IC (ambient ion monitor coupled-to-ion chromatography). Organic and elemental carbon can be measured by OC-EC analyser.

Conducting online aerosol speciation measurements allows real-time source apportionment of PM and specific pollutants like organics. [57] Receptor modelling techniques can be applied to continuous monitoring of particulate number size distribution using instruments like SMPS (scanning mobility particle sizer) and APS (aerosol particle sizer). Particle number size distribution-based source apportionment is robust and has been used across the globe. [58,59].

2.1.5 Technology 5: New generation reduced complexity models (RCMs)

Key considerations of air quality management are the cost-effectiveness of mitigations and scenario assessments. Chemical transport models can be used for assessing air quality changes in the future due to a certain intervention; however, such models are resource-intensive. New generation reduced complexity models (RCMs) have evolved in recent years to address this critical issue. These RCMs can provide information about air quality for a range of scenarios quickly and with minimal computing power. Fundamentally, these models first estimate the emission of a particular pollutant based on the activity data and then compute the concentration of the pollutant based on the transfer coefficients (that were originally derived from chemical transport model simulations). These models also provide information about the cost of controls for a wide range of interventions through optimis ing for a fixed clean air target.

RCMs that gained prominence in recent years are GAINS, [60,61] InMap, [62,] and BenMAP. [62,63] GAINS have been used for assessing air quality improvement due to local and regional scale interventions and have been used across the globe – India, [65] China, [66,67,] and Europe.[68] GAINS has the framework to be applied at a city scale and has been used for megacities Delhi [69,70] and Kolkata. [71] InMap and BanMap have been mostly used in the United States, but they have the potential for use in any country.

Several key learnings are important to note. First, the RCMs require robust activity data for a particular city or region as a first step. In Asia-Pacific countries, activity data for every potential air pollution source are not robust. Efforts should be made to compile activity data that is as robust as possible for improved emission estimates. Second, they rely on transfer coefficients derived from chemical transport models for computing the dispersion of air pollutants. Emission-concentration relationships derived over a particular region may not be representative of another region. Therefore, RCMs need to be tuned for regional applications. Third, emission factors also vary from region to region, and heterogeneity needs to be integrated into the RCMs. Fourth, the model-derived pollutant concentrations in the baseline case need to be evaluated before any subsequent applications. Finally, the models can be further improved with region-specific sources and control measures and their associated costs.

While these RCMs are very handy in scenario assessment, their current capability is mostly limited to a spatial scale of 10 km · 10 km and an annual temporal scale. In the future, these RCMs should be modified to derive information to understand the mitigation potential on a seasonal scale.

2.1.6 Comparative assessment of air quality monitoring and management technologies

Since many technologies emerged in recent times for a better understanding of the variability of local and regional sources and management of air quality, it is important to understand their strengths and weaknesses. The following Table 2.2 summaris es the comparative analysis of these technologies against traditional regulatory-grade stationary monitoring.

Table 2.2 A comparative assessment of the new generation technologies for air quality monitoring and management.

Technology	Strengths	Weaknesses
Sensor IoT	• Low cost • Portable • It can be used in mobile mode • Useful for hotspot management • Large-scale deployment can provide information on the spatial extent of interventions	• Needs frequent calibration – both on- and off-field • Durability is not uniform • Uncertainty is high • It cannot be used for regulatory purposes • Needs expertise in hardware, software, and data analytics
Satellite remote sensing	• Provides spatial coverage • Pollution can be tracked within airsheds • Emissions can be inferred in certain cases • Useful in identifying point sources	• Scale limitation • Missing data in case of cloud cover – needs additional analysis to fill data gaps • Algorithms need to be standardis ed before applications • Needs rigorous validation

Table 2.2 *(Continued)*

Technology	Strengths	Weaknesses
UAVs	• Useful in monitoring in inaccessible locations • Can provide real-time evidence of non-compliance	• Needs expertise in hardware, software, and data analytics • Needs to follow country guidelines • Restrictions in free operations
Online chemical speciation	• Useful for real-time source apportionment • Can be carried out in stationary and mobile mode	• Costly • Requires special training • Additional challenges in operating the instruments in continuous mode
RCMs	• Easy to compile and use by policymakers and regulators • Useful for multi-scenario assessments and future projections of air quality • Provides information about the cost-effectiveness of control measures • Provides information about health benefits for any inventions	• Accuracy depends on the robustness of input activity and other associated data • Requires regional standardisation • Scale (spatial and temporal) limitation

2.2 Emission Control Technologies

This section discusses the existing and new technologies that are either being used or are in the nascent stages of development for various emitting sectors.

2.2.1 Residential sector

Emissions from residential biomass and biofuel combustion continue to be a major contributor to ambient $PM_{2.5}$ in Asia Pacific countries. [56] Switching to clean fuel such as LPG is the best solution for curbing residential emissions. The Indian Government launched Pradhan Mantri Ujjwala Yojana (PMUY) to provide free LPG connections to rural households. However, the rising price of the LPG and operational constraints resulted in a delay in the full-scale transition (https://ccapc.org.in/policy-briefs/2019/8/6/ujjwala-2-from-access-to-sustained-usage) from solid fuel combustion. Several ideas were proposed to promote sustained LPG use (https://ccapc.org.in/policy-briefs/2019/ujjwala-enhancing-use-sustainably-prayas); however, implementation will take time. In the meantime, technological interventions can be adopted to reduce exposure and achieve health benefits.

2.2.2.1 Technology 1: Improved cookstoves

Over the years, several efforts were made to promote improved cookstove programs as the next best solution to curb solid fuel combustion for household activities. Improved cookstoves are designed to maximis e thermal and fuel efficiency and minimis e emissions. [68] One of the major barriers to promoting improved cookstoves is the lack of immediate acceptance by households in switching from century-old cooking practices. The following table is a comparative assessment of the common cookstoves that are used in different countries.

Table 2.3 Comparative assessment of various improved cookstoves used in different countries. The table was taken from Urmee and Gyamfi (2014).

ICS name	Type of fuel burn	Efficiency parameters	Material	Region	Comment	Reference
Envirofit International family of rocket stoves	Wood and derived wood fuel	80% emissions reduction, 60% fuel saving, 40% reduction in cooking time	Metal or metal with ceramic chamber	South America, Central America, Africa, and Asia	The cost without a chimney is ~US$30; the cost of a more advanced one is three times higher	Envirofit Winter 2013
Ugastoves	Wood and Charcoal	36% fuel saving; 58% for the rocket type	Metal with ceramic chamber	Uganda	Cost is US$5-11	Adkins et al.
Centrafricain improved stove	Wood	Reduce fuel by 25%	Metal with ceramic chamber	Chad and Cameroon	Cost US$11 to 16	Vitali`
BCSIR 1	Wood, cow dung cake, briquettes	50% reduction in fuel use	Ceramic with metal gates	Bangladesh	Cost US$2-4	USAID
Patsari wood-burning cookstove	Wood	Reduce emissions by 67%	Sand and mud with a small amount of cement and metal hotplate on top	Mexico	Cost ~US$130	Masera
BCSIR 2	Wood		Ceramic		Cost US$7	USAID
ONIL improved cookstove	Wood	99% reduction in CO emissions; 70% reduction in fuel use	Concrete with ceramic lining	Guatemala, Honduras, and Mexico	Cost US$87	Onil-International

Several major cookstove programs were initiated in Asian countries such as China, India, Nepal, Bangladesh, and Indonesia in the last several decades with mixed success (Figure 2.3). Efforts should continue with priority to provide access to alternate and cost-effective solutions to economically weak populations to move away from solid fuel to cleaner energy, as this is one of the most cost-effective mitigation pathways for the residential sector in South Asia. [59]

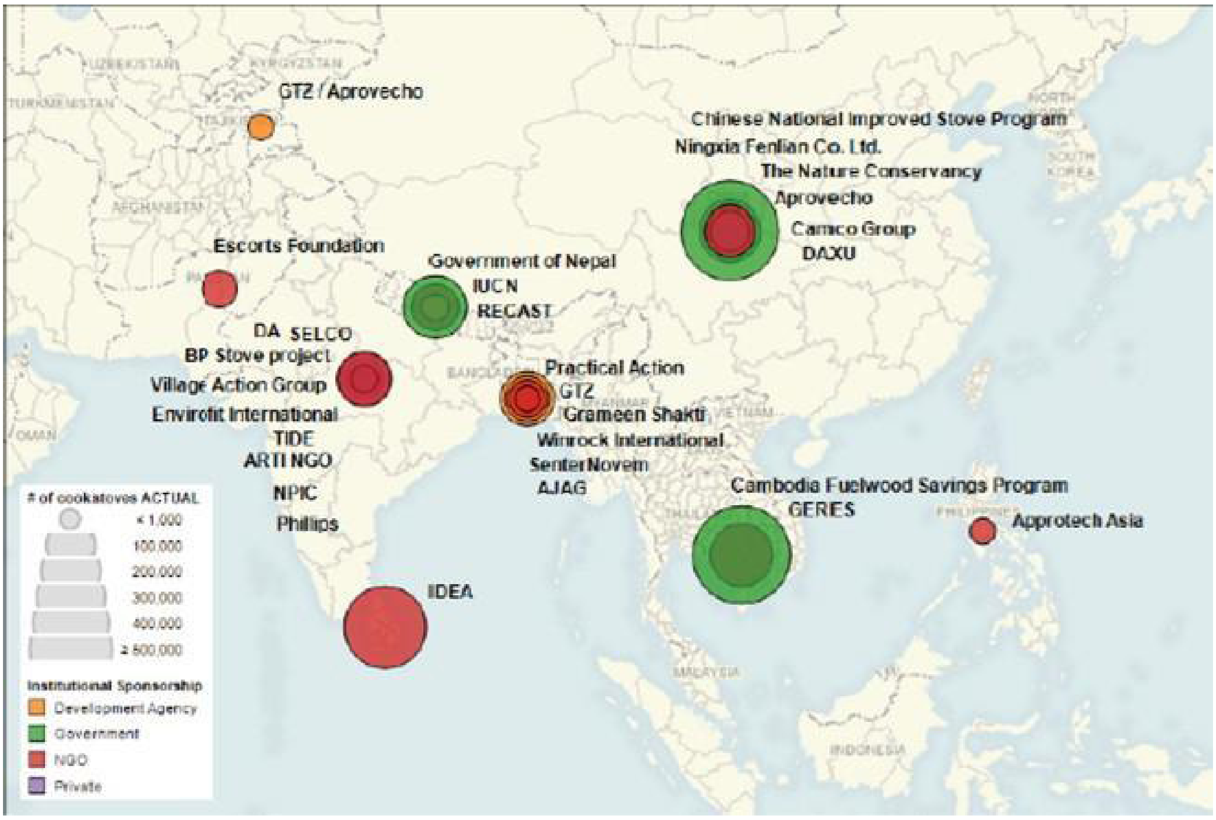


Figure 2.3 Asian cookstove programs in 2010. The figure is taken from Gifford (2010).[60]

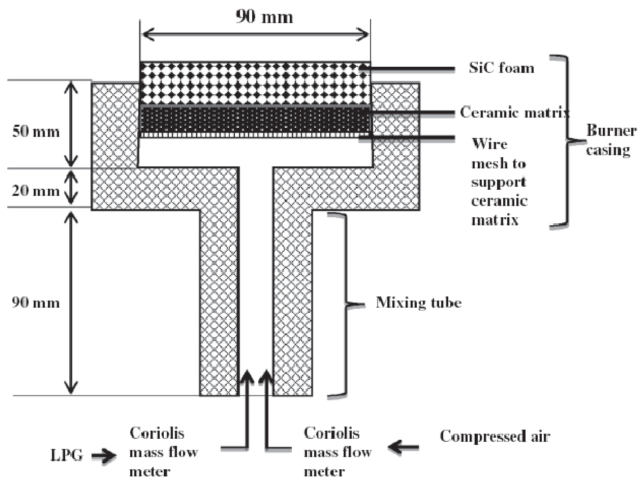
2.2.2.3 Technology 2: Fuel-efficient stoves to reduce LPG consumption

Since rising prices are one of the key deterrents to sustained LPG usage for residential activities in Asia-Pacific countries, reducing LPG consumption without hampering cooking practices can address the issue. There are two fuel-efficient stoves available in the market that can minimise LPG usage.

The first one is the Bharat Hi-Star Stove, invented by Bharat Petroleum Corporation Limited (https://www.bharatpetroleum.in/pdf/bpcl-launches-high-efficiency-lpg-stovejuly-4-2f1342.pdf). This stove, BIS 4246-certified, has a thermal efficiency of 74% against 68% efficiency in regular LPG stoves. The Agnisumukh Stove, IS 14612-certified, reduces LPG consumption by 70% (https://www.agnisumukh.com). The Agnisumukh Stove used the Porous Radiant Burner (PRB), which offers wider power modulation and flame stability range, lower emissions, and higher thermal efficiency than the conventional gas stoves.

A PRB has two zones for better flame stabilis ation: a preheating zone with low porosity and poor conductivity to avoid combustion and a combustion zone with highly radiating and conducting material. Preheating the air-fuel mixture with recycled exhaust gas heat is an effective method for the combustion of low-calorific fuels and fuel conservation (Palanisamy et al., 2023).

A domestic scale PRB burner with specifications of pressure regulator (1.2 bar) and burner size (80 nm) has been observed to have 71-73% thermal efficiency and also release less CO and NOx emissions (30-140 ppm; 0.2-3.5 ppm respectively). (https://www.iitg.ac.in/pmkumar/greencombustion.html)



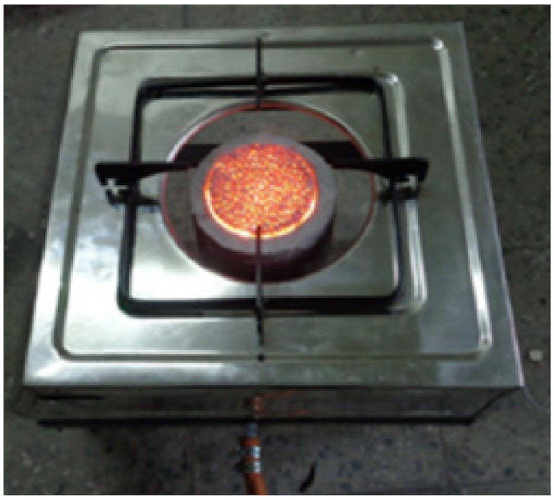


Figure 2.4: Porous Radiant Burner Stove

2.2.2.3 Technology 3: Clean cooking using electricity

Another alternative is the transition to clean cooking that uses electricity, which, in general, has higher fuel efficiency than LPG stoves. Currently, there are two types available for clean cooking – induction cooktops and electric cooktops. These options range in load between 700 watts to 2 kilowatts. The cooking technology, however, reflects a big difference between induction vs. electric cooking. An induction cooktop offers a 40% faster temperature response than electric cooking and, hence, is more energy efficient.

Induction cooking

The electricity flows through a coil to generate a magnetic field under the ceramic surface for induction cooking. Currents are induced in the induction-compatible pans, and heat is generated instantly. The induction cooktops can detect when the cookware is removed, and it stops generating heat. Thus, the cooking appliances for induction cooking are safer for children. However, the major limitation of induction cooking is that only vessels made of ferrous materials are compatible.

Electric cooking

Electric cooktops, on the other hand, offer centralis ed heat. They have an electrical current that flows through a metal coil underneath the glass or ceramic surface. The coil becomes heated and starts glowing due to electrical resistance. It then transfers heat through the glass using infrared energy. The burner holding the cookware gets hot, and the food is cooked by the transfer of heat between the cooktop and the vessel.

The following table summarises the strengths and weaknesses of these two types of cooking.

Cooking type	Strengths	Weaknesses
Induction Cooktop	• No residual heat and lower energy costs • Cooler kitchen area • Cooktops remain cool to the touch after cooking • Easier to clean • Faster cooking times	• More expensive • Only induction-compatible cookware can be used • The magnetic field can interfere with other appliances

Cooking type	Strengths	Weaknesses
Electric Cooktop	• Easier to install and use • Some residual heat can be used to keep food warm for a long time • Heat can be controlled to minimis e usage	• Residual heat can be a hazard, particularly to the children • Takes longer cooking time • Coils may provide uneven distribution of heat

Solar cookers are gaining popularity for large-scale community cooking. Several models are available commercially, where solar power is harnessed to generate heat. These cookers are more environment-friendly as they use renewable energy rather than electricity.

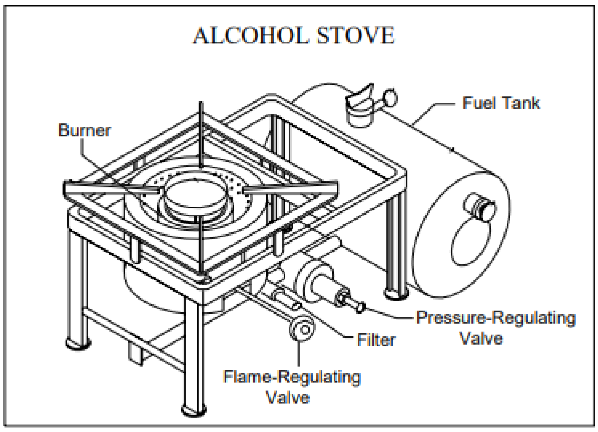
Despite its benefits, the adoption of electrical cooking is poor. In a recent policy brief, Pal argued what it takes to make the transition in India. [61] A recent India Residential Energy Survey 2020 reveals that only around 5% of Indian homes use electric cooking devices, and in rural areas, the number is even lower (2.5%). A CEEW report highlights the preparedness of Indian homes for electric cooking (https://www.ceew.in/publications/are-indian-homes-ready-for-electric-cooking-transition). The key findings of this report are as follows:

- Electric cooking is mostly concentrated among wealthy households in India.
- Mostly, rice is cooked using electric rice cookers.
- Only 50% of the electric cooking households use it on a daily basis.
- With the price rise of the LPG, electric cooking is increasingly becoming cost-effective, but the upfront expenditure remains a major challenge.

2.2.2.4 Technology 4: Alcohol gas stoves

The global production of alcohol is on the rise, sparking efforts since the mid-2000s to commercialis e cookstoves fuelled by alcohol. Ethiopia pioneered the use of ethanol and methanol for cooking through the Project Gaia initiative. The stoves used in this project were canister-based Origo stoves, operated by methanol or ethanol, produced by a Swedish company. These stoves come equipped with a 1.2 L canister and weigh approximately 1.8 kg. One canister refill can power this cookstove for approximately 6–8 hours.

The Nimbkar Agricultural Research Institute (NARI) developed an ethanol-pressuris ed cook stove that operates on a 50% ethanol-water mixture. This stove yields outputs comparable to traditional LPG and kerosene stoves while offering straightforward flame regulation.



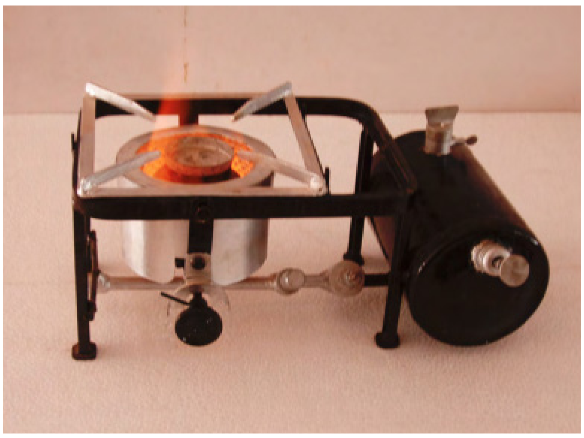


Figure 2.5: Alcohol Stoves developed by NARI.

2.2.2 *Diesel generator sets*

In South and Southeast Asian countries, power cuts are quite common, particularly in summer, due to the gap between electricity generation and consumption. This prompts widespread use of diesel generator (DG) sets in residential and commercial places and in medical facilities. DG sets are one of the key sources of emitting particulate and gaseous pollutants.

2.2.2.1 Technology 1: Retrofit emission control device Chakr Shield 2.0

Chakr Shield 2.0 is a control measure developed by the Chakr Foundation that uses retrofit technology to reduce the particulate emissions by 80% emitted by DG sets. This technology can be very helpful in reducing the particulate matter without causing any damage to the DG set itself. The working principle of the retrofit technology is provided in Figure 2.6 . Its filtration unit consists of mainly two parts: The oxidation stage and the passive regenerative trap. The oxidative stage reduces the particulate emission by 20%, which further enters the second part, i.e., the regenerative particulate trap. The remaining 60% of PM is cleaned in the second unit.

The technology, suitable for retrofit in DG sets ranging from 15 KVA to 2000 KVA, has a life span of 12 years. Currently, the technology received approval for retrofit emission control devices from the Central Pollution Control Board, India, for the range 250-550 KVA.

Working principle-Chakr shield 2.0

The exhaust from the DG set enters the filtration i.e., Dual Oxidation Flow Filter. There are two stages of filtration in the system.

1. Oxidation Stage
2. Regenerative Stage

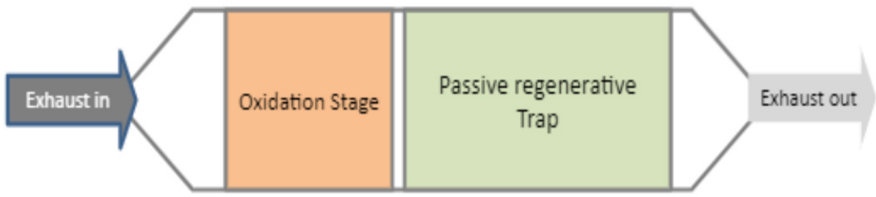


Figure 2.6 Chakr-shield - working principle of retrofit technology applied to a DG set (Source: chakr. in).

2.2.2.2 Technology 2: Retrofit emission control systems

Two types of retrofit emission control systems are available for DG sets. A diesel particulate filter can be installed to capture and filter out 90% of the diesel combustion-generated PM from the exhaust. Diesel oxidation catalyst can be used to filter out gaseous pollutants like CO hydrocarbons. These devices are available for DG sets of capacity ranging between 125 KVA to 2000 KVA.

2.2.3 *Transport sector*

Broadly, controlling emissions from the transport sector includes two types of approaches. The first one is innovation in the automobile industry towards zero emission, including alternate fuels. The second type of intervention involves retrofit technology use. Several exhaust after-treatment technologies exist that can reduce emissions from engines. These can be categoris ed as catalytic converters, trap adsorbers, and filters. [62]

The catalytic converter is a device that uses a catalyst to activate oxidation and/or reduction reactions to transform harmful air pollutants (e.g., CO, HCs, NOx) into harmless compounds. Traps and adsorbers are used to control emissions when engine operating conditions are not suitable for catalytic converters. They store the pollutant for a short period and release it for catalytic reactions when the conditions become suitable. Filters are used in petrol and diesel engines to reduce particulate matter emissions.

2.2.3.1 Technologies for spark-ignition engines

Three-way catalyst

This has been the main emission control technology for petrol vehicles for the last 40 years. The components, such as catalytic coating, substrate, and mounting material, have evolved over time to achieve better performance. The technology operates in a closed-loop system where an oxygen sensor regulates the air-to-fuel ratio, oxidis es Hydrocarbons (HC) and CO to water and $CO_{2,}$ and reduces NOx to nitrogen.

Gasoline particulate filter

This technology comprises a honeycomb filter structure made from synthetic ceramic material and is used to filter particulate matter emissions from petrol vehicle exhaust (AECC, 2017). They use three trapping mechanisms to capture particles: interception, impaction, and diffusion.

The trapping mechanism employed depends on the size of the particle. Diffusion is used to trap smaller particles, while interception and impaction are used to trap larger particles. Therefore, the initial filtration efficiency of a new GPF can vary for different particle sizes. While smaller and larger particles are effectively trapped, particles around 200 nm in diameter may have a lower filtration efficiency.

Activated carbon canister

This device consists of a plastic case containing activated carbon that adsorbs the petrol vapor as it is emitted from the fuel tank during heating or refuelling. The adsorbed fuel vapor is then released into the engine, regenerating the canister when the vehicle is moving. This adsorption-desorption cycle continues for the vehicle lifecycle (EEA, 2016).

2.2.3.2 Technologies for Compression Ignition Engines

Exhaust gas recirculation (EGR)

This technology re-circulates a portion of engine exhaust back into the engine to cool and reduce peak combustion temperature and pressure. This inhibits NO_x formation.

Most modern EGR systems use an electronic EGR valve to regulate the recirculation of exhaust gas. When the engine is idling, the EGR valve is closed, and there is no EGR flow into the manifold. As the engine warms up, the EGR valve begins to open gradually. When the engine is under load, and the combustion temperature rises, the valve opens further, allowing exhaust gases to leak back into the intake manifold. This process has a cooling effect, which can lower the combustion temperature and reduce the formation of NOx (He et al., 2017).

Diesel oxidation catalyst

This technology converts CO and HC to CO2 and water, similar to the three-way catalyst, but has little effect on NO_x. It oxidis es some HCs that are adsorbed onto the carbon particles and decreases the mass of diesel particulate emissions (https://www.attacproject.eu/).

Selective catalytic reduction (SCR)

This technology is an advanced emission control technology that reduces NO_x by injecting a liquid-reducing agent into the exhaust steam of a diesel engine through a special catalyst. The design of SCR technology is such that it permits nitrogen oxide (NOx) reduction reactions to take place in an oxidis ing atmosphere.

It reduces levels of NOx using ammonia as a reductant within a catalyst system. A typical diesel vehicle consumes approximately 2.5 – 3 liters of reducing agent for every 100 liters of diesel to meet the Euro 6 (equivalent to Bharat Stage 6) standard. SCR can reduce NO_x emissions by 95%. The SCR exhibits promising performance with a warmed-up engine; however, during cold start, NOx emissions exceed EURO 6 regulations. (Praveena and Martin, 2018; Mera et al., 2021).

Lean NOx trap (LNT)

This technology is a simpler solution than selective catalytic reduction and is used to capture NO_x emissions from diesel engines. LNT catalysts are typically composed of at least one precious metal component and one alkali or alkaline-earth component, which are supported on a high surface area of refractory oxide. These catalysts operate in a cyclic manner, whereby the catalyst stores or traps NO_x as nitrate species during a lean period of operation (when excess oxygen in the exhaust hinders the chemical reduction of NO_x). Periodically, a short, rich pulse is introduced so that the trapped NOx is released and reduced to N_2, thereby regenerating the trapping capacity of the catalyst (Vrabie et al., 2016). This can be used in combination with a selective catalytic reduction for more efficient NO_x emission control.

ACCT

ACCT is a technique that reduces NOx emissions during cold starts. The system consists of an AdBlue tank, pump, reactor, fluid tank, and injector. AdBlue is hydrolyzed into CO2, gaseous water, and gaseous ammonia with exhaust energy. The hydrolyzed products are cooled and converted into ACCT fluid, which drops NOx emissions more effectively at low exhaust temperature conditions such as urban driving or stop-and-go scenarios. However, its high price limits its use (Gao et al., 2021).

HC absorbers

A disclosed system for purifying automobile exhaust gases involves an arrangement where an HC absorber catalyst for absorbing HC and a NOx absorber catalyst for absorbing NOx is positioned before an exhaust gas purifying catalyst. In the traditional setup, the exhaust gas is initially absorbed by the HC and NOx absorber catalysts before the exhaust gas purifying catalyst is activated. Subsequently, following the activation of the exhaust gas purifying catalyst, the exhaust gas passes through the HC absorber catalyst or similar components. This process enables the separation of HC and NOx previously absorbed by the HC absorber catalyst or similar components, which are then purified by the exhaust gas purifying catalyst (Shinoya Hirota & Toshiaki Tanaka,1998).

HC adsorbers are used to reduce HC emissions during cold starts until the catalyst warms up and can be effectively used to control HC emissions.

Diesel particulate filter

This technology is most commonly used to reduce particulate emissions from diesel vehicles. In wall-flow filters, PM is removed from the exhaust by physical filtration using a honeycomb structure similar to the catalyst but with channels blocked at alternate ends. Due to this, the exhaust gas flows through the walls, and PM gets deposited. Currently, diesel particulate filters can work with more than 90% efficiency. However, they must be cleaned periodically to maintain the efficiency (Lazar et al., 2011).

Ammonia slip catalyst

The substrate used is a ceramic monolith made of cordierite, which is a combination of several inorganic oxides with high thermal and mechanical resistance. This ensures that even significant changes in temperature or mechanical stresses cannot damage the catalyst. The honeycomb shape, with its very fine squared channels, provides a large surface area due to the structure of pores. The lower layer consists of a base metal oxide wash coat that contains the platinum active species. This is where the high-rate NH_3-oxidation reactions take place, in addition to the NO oxidation to NO_2.

The SCR coating corresponds with the top layer where ammonia is stored to reduce the NOX produced in the oxidation reactions of the previous layer, as well as the non-reduced NO_X coming in the flow from the SCR catalyst. In this way, a portion of the NH_3 is oxidis ed, and another portion is stored (Gil et al., 2013).

This technology improves the performance of the selective catalytic reduction system. This converts almost all of the NH_3 to nitrogen rather than in NO_x and also converts HC and CO to CO_2.

RCCI (Reactivity Controlled Compression Ignition)

A dual-fuel engine is a diesel engine that can run on both gaseous and liquid fuels. When running in gas mode, the engine works according to the Otto process, where the lean air-fuel mixture is fed to cylinders during the suction stroke. Emissions change in dual-fuel combustion. Natural gas-diesel dual-fuel engines have shown reductions of up to 60% in NO_x and PM emissions. However, these emission levels rely on both the types and quantities of fuels utilis ed (Kassa et al.,2019).

A more advanced technology called Reactivity Controlled Compression Ignition (RCCI) has been discovered. RCCI is a process that optimis es combustion by blending at least two fuels of different reactivity and using multiple injections. Low-reactivity fuel is mixed with air and exhaust gases, and high-reactivity fuel is injected directly into the combustion chamber. Examples of fuel pairings for RCCI include gasoline and diesel mixtures, ethanol and diesel, and gasoline with a cetane-number booster (https://www.w-erc.com/services/rcci/).

Kumar et al. 2019 have demonstrated that RCCI and oxygen enrichment can simultaneously reduce particulate matter (PM) and NOx emissions while improving performance.

2.2.3.3 Technologies for Transition to Electric Vehicles

2.2.3.3.1 Technology 1: Retrofit emission control technologies

The vehicles that are manufactured in more recent years are equipped with these technologies to meet the strict emission standards set by many countries. For older cars that do not conform to stricter standards, some of these technologies can be used in 'retrofit' mode (where it is technically feasible), but the cost may be disproportionately higher than the valuation of the vehicle.

2.2.3.3.2 Technology 2: Conversion to EVs

The other option for the older vehicles is to convert them to electric vehicles. Several prominent automobile companies offer such services. [64] Countries are coming up with policies to promote such conversion for greater environmental benefits. For example, in Delhi (https://ev.delhi.gov.in/retro-fitment), conversion for 10+ years old diesel vehicles and 15+ years old petrol vehicles is allowed with prior approval.

2.2.3.4 Advanced charging technologies for promoting EV adoption

One of the key aspects of the slow adoption of EVs is the lack of adequate charging infrastructure in the cities. A charger for an EV can range from a simple household plug to a high-powered supply. The Society of Automotive Engineers (SAE) has developed specific guidelines regarding EVs (Ahmed et al., 2018, Smart Sci, 36-53). A detailed classification of EV charging technologies (Fig 2.7) is provided in Khalid et al., 2022, J. Energy Storage).

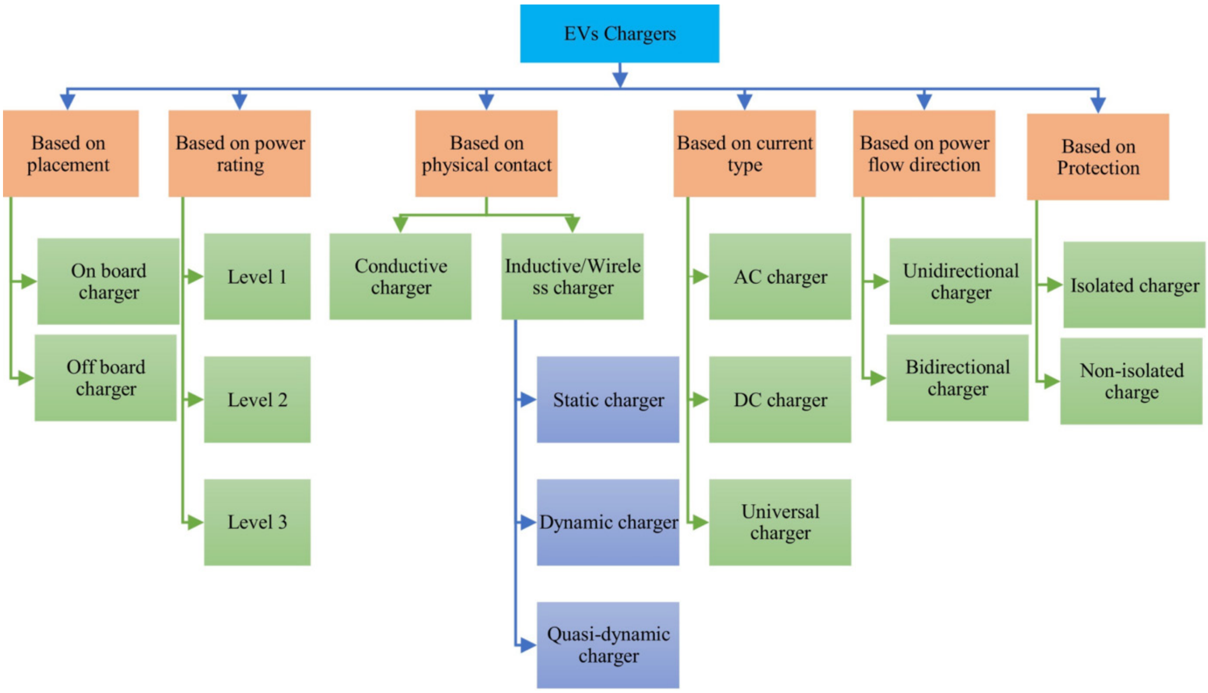


Figure 2.7 Detailed classification of EV charging technologies. Source: Khalid et al. (2022).

2.2.3.4.1 Charging based on physical contact

Technology 1: Conductive charging

The power transfer mode is through direct contact with the vehicles, and hence, it is more efficient. Based on the position of chargers, conductive charging is divided into onboard and off-board charging.

In onboard charging, the charger is placed inside the vehicle, while in off-board charging, the charger is placed outside the vehicle. Onboard chargers are mostly considered slow chargers, whereas off-board chargers can be fast chargers.

Technology 2: Inductive charging

The power is transferred by utilis ing an electromagnetic field without establishing any physical contact with the vehicle. This is also known as wireless charging and can be used to automate the charging of EVs. It eliminates the shock rises owing to the wires, but the limitation is low efficiency due to high power loss.

Inductive charging is categoris ed into three types. Static charging has the benefit of appropriate charging locations such as home garages, parking lots, etc.; however, they cannot solve the issue of driving on highways. Quasi-dynamic charging is used on shortstops during driving. In dynamic wireless charging, vehicles are charged continuously while driving through a specially designed charging road.

2.2.3.4.2 Charging based on power rating

EV charges are given power ratings by SAE as Level 1, Level 2, and Level 3. AC Level 1 charging is done at the customer's location, and the battery is charged during the night using an existing single-phased electrical circuit at residential units of 2-3 kW. AC level 2 charging is done at public places such as shopping malls, markets, offices, etc. These chargers deliver 6-7 kW power to stationary vehicles. Level 3 DC chargers are ultra-fast chargers that can transfer DC power at 50 to 350 kW rates. More details are available in Khalid et al.

2.2.3.4.3 Charging based on power flow direction

Technology 1: Unidirectional charger

For unidirectional chargers, power can only flow from the grid to the vehicle. It restricts power injection into the grid. The typical circuit of the unidirectional charger contains an electromagnetic inference filter with a bridge rectifier and then an added PFC circuit. The desired isolation transformer can be cascaded considering cost, size, and efficiency factors. The heavy load on the grid by multiple EV charging demands the simple and easy operation of chargers provided by the unidirectional charger.

Chargers with the active front part can control the phase angle of current even with unidirectional current (power) flow, which can be utilis ed to control the local reactive power of the grid. Increasing heavy penetration of EVs and unidirectional chargers with active current control can help the grid meet most utility objectives; however, it avoids bidirectional chargers' performance and economic efficiency

Technology 2: Bidirectional charger

For bidirectional chargers, power flow enables various demand-side management planning vehicle-to-grid and grid-to-vehicle applications (Habib, S. et al. (2018), Int. J. Energy Res. They are made up of two parts: an AC-DC bidirectional converter to manage the grid-power factor and a DC-DC bidirectional converter to control output parameters such as voltage and current regulation of the battery.

Bidirectional charging infrastructure is suited only to level-2 charging due to its cost-utility and primary purpose. Level-1 lags in terms of cost-effectiveness, while fast charging conflicts with basic aspirations. The demerits of bidirectional chargers reflect on the battery due to the frequent charging-discharging cycle. Smart metering in the advanced distribution system is a must for successfully implementing such technology with essential safety factors.

2.2.4 Industry and Power Sector

2.2.4.1 Technology 1: Electrostatic Precipitators

Electrostatic precipitators (ESPs) are the most widely used devices capable of effectively controlling particle emissions from steel plants, power plants, and other process industries like cement. [65] ESPs are essential tools in the process of cleaning up flue gases. They are highly effective at reducing particle pollution, including those particles whose sizes are approximately 1 micron (0.00004 inch) in diameter, and some precipitators can remove particles of 0.01 micron in diameter. In addition, they can handle large volumes of gas at various temperatures and flow rates, removing either solid particles or liquid droplets. [66]

The ESP uses electrical forces to move the particles out of the flowing gas stream and onto collector plates. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the centre of the flow lane. Figure 2.8 shows electrostatic precipitator components.

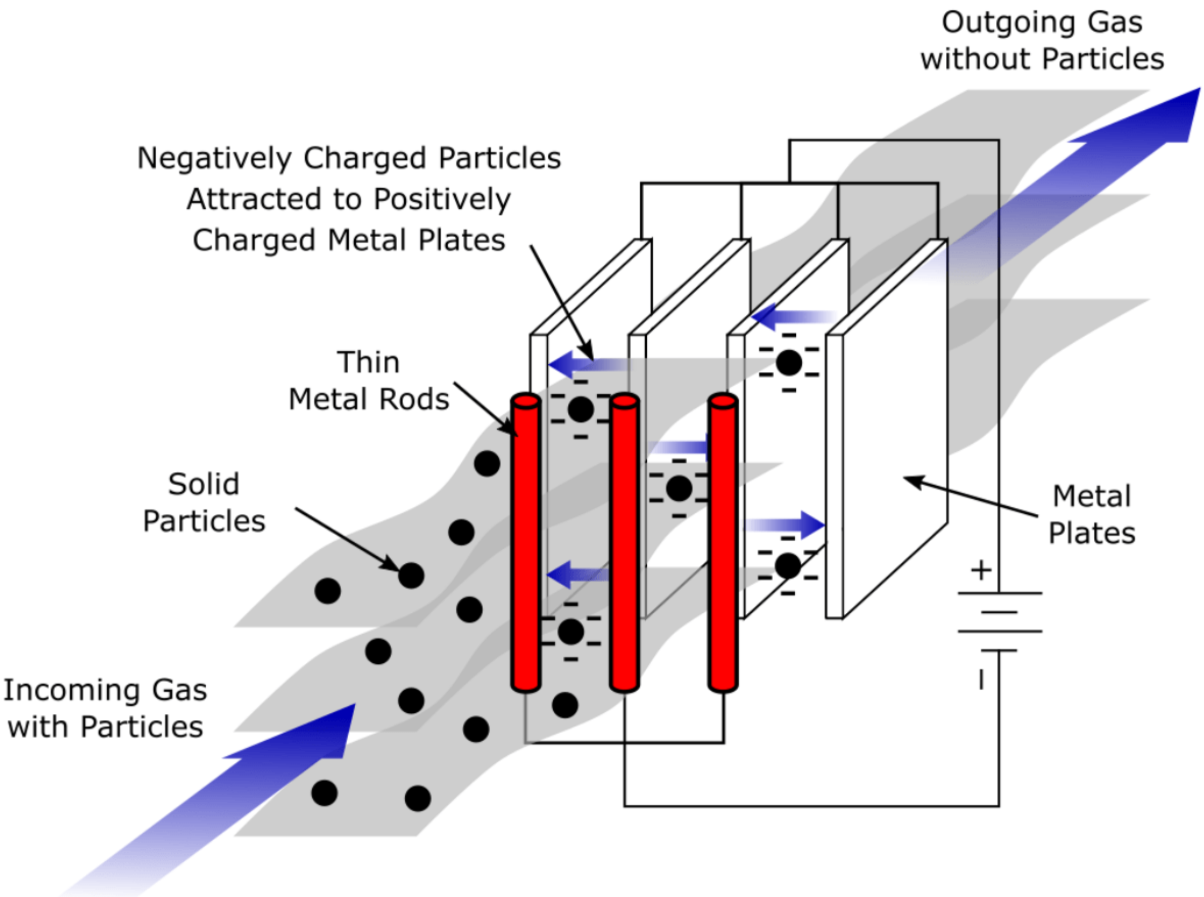


Figure 2.8 Schematic diagram of electrostatic precipitator (source: https://savree.com/en/encyclopedia/electrostatic-precipitator-esp).

ESPs are configured in several ways. Some of these configurations have been developed for special control action, and others have evolved for economic reasons. The types are (1) the plate-wire precipitator, the most common variety; (2) the flat plate precipitator; (3) the tubular precipitator; (4) the wet precipitator, which may have any of the previous mechanical configurations; and (5) the two-stage precipitator.

2.2.4.2 Technology 2: Baghouse (fabric filtration)

A baghouse is an air pollution control device that removes particulates and gas released from commercial processes in the air. Power plants, steel mills, pharmaceutical producers, food manufacturers, chemical producers, and other industrial companies often use baghouses to control the emission of air pollutants. Dust-bearing gases are passed through fabric filter bags, which are suspended upside down in a large chamber called a baghouse. A baghouse may contain thousands of bags, which are often distributed among several compartments. This allows individual compartments to be cleaned while others remain in operation. [67]

Baghouses are classified by the cleaning method used. The three most common types of baghouses are mechanical shakers, reverse gas, and pulse jet.

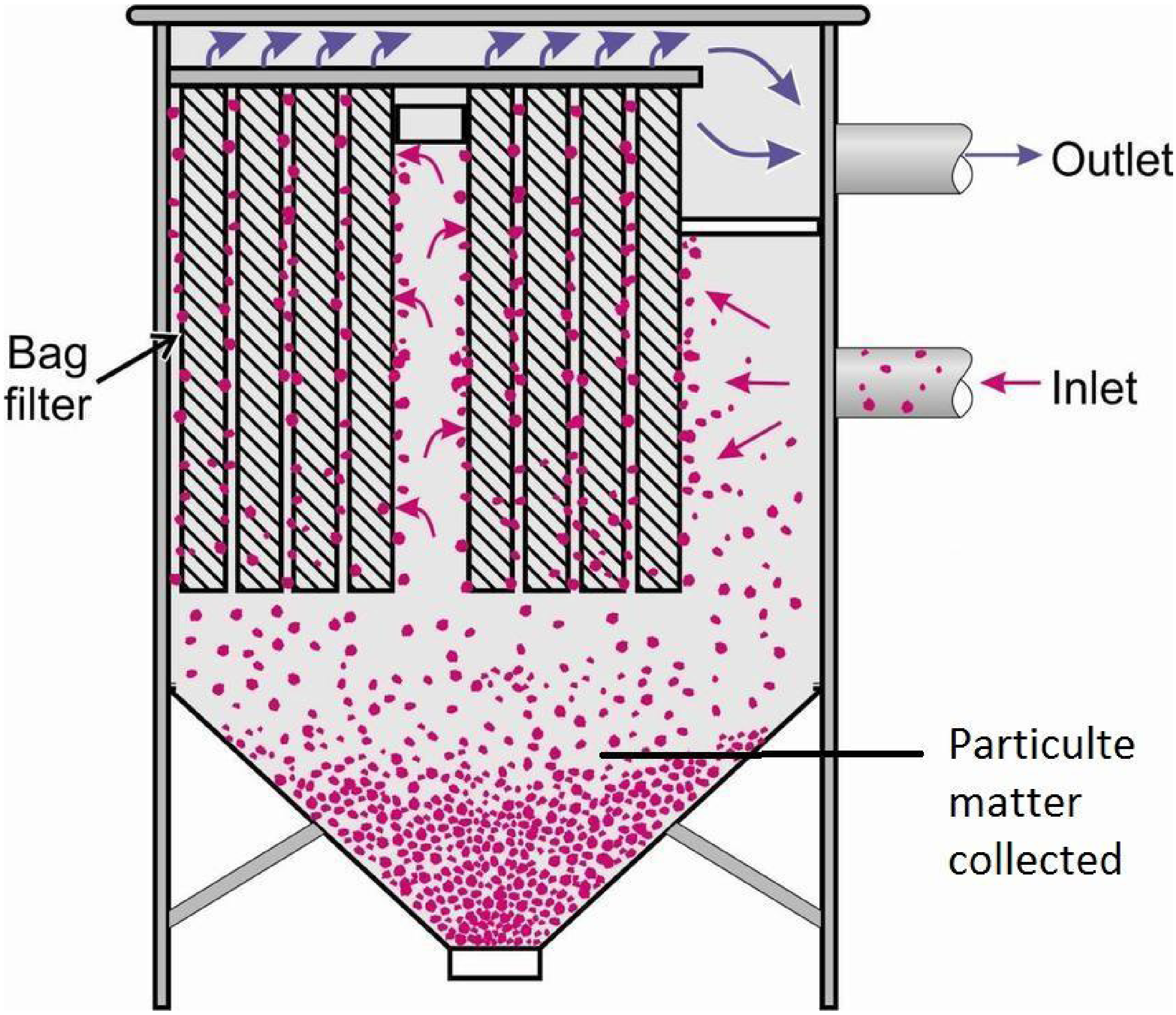


Figure 2.9 Schematic of baghouse (fabric filter). The figure is taken from Reed et al. (2012). [68]

2.2.4.3 Technology 3: Cyclone

Cyclones are designed for many applications. Cyclones themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose as pre-cleaners for more expensive final control devices such as fabric filters or ESPs.

Cyclones use inertia to remove particles from the gas stream. The cyclone imparts a centrifugal force on the gas stream, usually within a conical-shaped chamber. Cyclones operate by creating a double vortex inside the cyclone's body. The incoming gas is forced into a circular motion down the cyclone near the inner surface of the cyclone tube. At the bottom of the cyclone, the gas turns and spirals up through the centre of the tube and out of the top of the cyclone. [69]

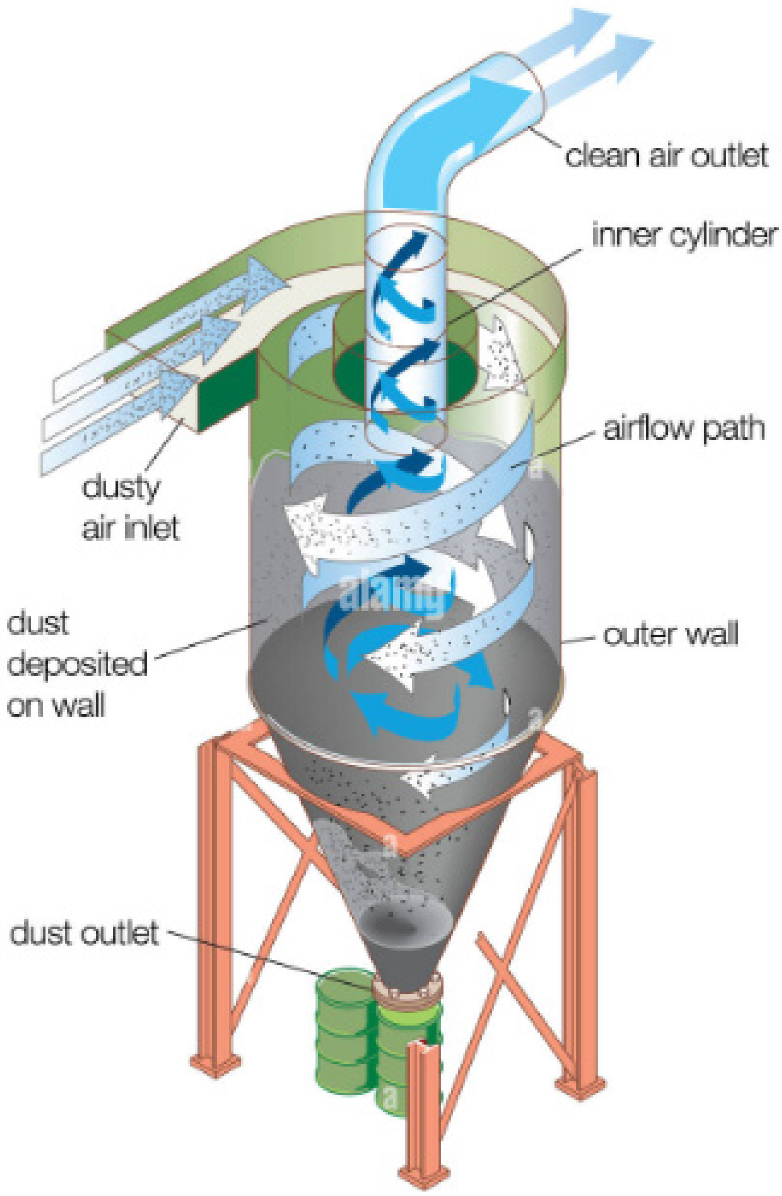


Figure 2.10 Cyclone (source:https://www.britannica.com/technology/cyclone-technology).

2.2.4.4 Technology 4: Selective catalytic reduction

Selective catalyst reduction (SCR) is arguably the most widely used technique for NOx reduction. SCR of NOx is classified as an after-treatment solution for emission control and is commonly used in combustion turbines, natural gas engines, and diesel engines, which generate pollutants like NOx and carbon particulates post-combustion.

In SCR, a reagent (usually 19% or 29% aqueous ammonia, anhydrous ammonia, or urea) is injected into the exhaust stream of the combustion machine (turbine or engine), which is maintained at a specific temperature depending on the catalyst used. The heat vaporis es the ammonia.

Nitrogen gas and NOx present in the flue gas stream react with vaporis ed ammonia in the presence of a catalyst (which speeds up the reaction) to yield diatomic nitrogen (N_2), water, and trace amounts of CO_2 – harmless products that are expelled from the exhaust pipe. The reagent is optimized by maintaining a near-equal ratio with the NOx to be removed from the flue gas stream (Li et al., 2018).

2.2.4.5 Technology 5: Selective Non-Catalytic Reduction (SNCR)

SNCR is an alternative method for NOx reduction commonly employed in power plants that burn coal, oil, waste, and biomass. The SNCR technique involves injecting a reagent into the combustion gases at a high temperature without the aid of a catalyst.

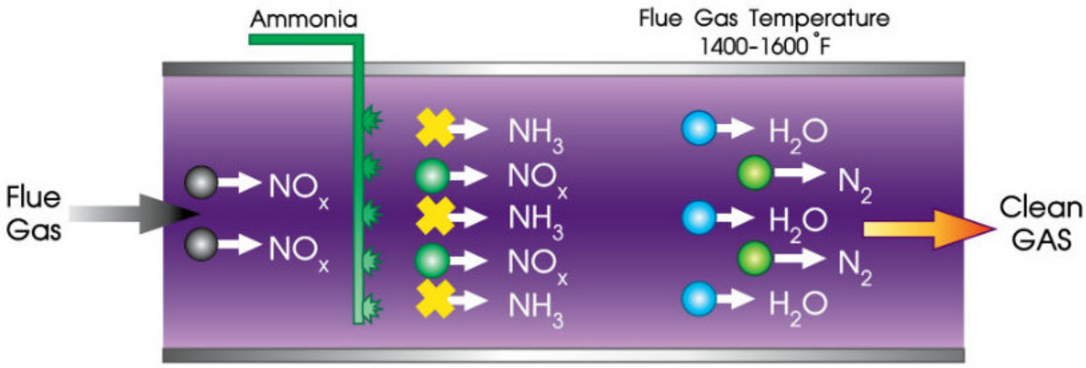


Figure 2.11 Schematic diagram shows SNCR working principle (Source: https://ifsolutions.com/power-plant-nox-reduction-scr-vs-sncr/).

In SNCR, aqueous ammonia or urea is injected into the flue gases from the combustion process at temperatures between 1600°F and 2100°F (870°C to 1150°C) to reduce NOx to nitrogen gas (N_2), $CO_{2,}$ and water (H_2O). The basic chemical principle is that at a high temperature, ammonia or urea reacts with NOx from the combustion gases to yield nitrogen gas (N_2) and water vapor (H_2O). SNCR can be used to reduce NOx by about 30 – 70 % (von der Heide 2011).

2.2.4.6 Technology 6: Flue Gas Desulfurisation (FGD)

This technology is used to reduce sulphur dioxide emitted from power plants run on fossil fuels. While there are various methods to achieve FGD, the most popular techniques use a two-stage process of fly ash removal and SO_2 removal. In addition to sulphur elimination, nitrogen oxides, and particulate impurities can also be eliminated during FGD.

The most economical means of removing SO_2 from a flue gas stream is via a chemical reaction with a reagent. Suitable reagents should render SO_2 harmless to the environment whilst also producing a by-product that does not damage the environment. The most common reagents used in FGD systems are lime (calcium oxide) and limestone ($CaCO_3$). Other reagent alternatives exist, e.g., ammonia, but limestone is the most widely adopted. The main reason for limestones' widespread adoption is that they are plentiful, cheap, and easy to access; all these factors depend, however, upon geographical location. By-products of the flue gas desulphuris ation process are usually calcium sulphite ($CaSO_3$) and/or calcium sulphate ($CaSO_4$). The by-product produced depends upon which reagent and which FGD system design is used. Irrespective of the reagent and design, the by-product is usually calcium-based.

The wet throwaway FGD design is the most common FGD design employed by fossil-fired power stations today. Pulveris ed limestone is mixed with water to form an alkaline-based slurry. An alkaline slurry is any slurry with a pH exceeding 7.0, but for operational purposes, the pH desired for the slurry is usually 8.0 (system design dependent).

Flue gas is discharged from the power station water tube boiler, passes through a baghouse or ESP, and is then passed to the desulphuriser. The flue gas temperature is approximately 150 ºC (300 ºF) or more when it enters the flue gas desulphuriser. Sulphur dioxide gas is entrained within the flue gas and is separated via wet scrubbing (Cordoba et al., 2015).

2.2.4.7 Technology 7: ACI (Activated Carbon Injection)

The use of ACI is arguably the most efficient and cost-effective way to minimis e mercury, dioxins, and furans emissions from power generation stations. Activated carbon, in its powdered form, provides a large surface area that permits increased pollutant absorption with a subsequent reduction in emissions of up to 90% (Ma et al., 2021).

ACI attached to the fabric filter permits further purification of emitted gases as it eliminates particulate matter from discharged air. This technology involves the use of filters within a baghouse to collect particles generated within the power station. [70]

2.2.4.8 Technology 8: DSI (Dry Sorbent Injection)

The injection of a dry alkaline gas into a stream of flue gas is a cheap but effective method of eliminating acid gases. The most used sorbent gases are sodium bicarbonate, hydrated lime, and trona (sodium sesquicarbonate).

DSI systems remove hydrogen chloride (HCl) and other acid gases through two basic steps.

- First, a powdered sorbent is injected into the flue gas, where it reacts with the HCl. The sorbents most commonly associated with DSI are sodium sesquicarbonate, sodium bicarbonate, and hydrated lime.
- Next, the compound is removed by a downstream particulate matter control device such as an ESP or a fabric filter, also referred to as a baghouse. Fabric filters are generally more effective (when combined with DSI) than ESPs with respect to overall HCl reduction. A DSI system with a fabric filter is expected to achieve 90% removal of HCl, while an ESP only achieves 60% removal.

2.2.4.9 Technology 9: Gravity settling chamber

A gravity settling chamber (GSC) is used to control PM emissions. The polluted gas is passed through the long chamber, allowing particles (mostly large with a diameter greater than 75 µm) to settle down by gravity. The linear gas velocity inside the chamber is lower than that of the duct as the cross-section area of the duct is much smaller than that of the chamber (WH), which results in the gravitational settling of large particles.

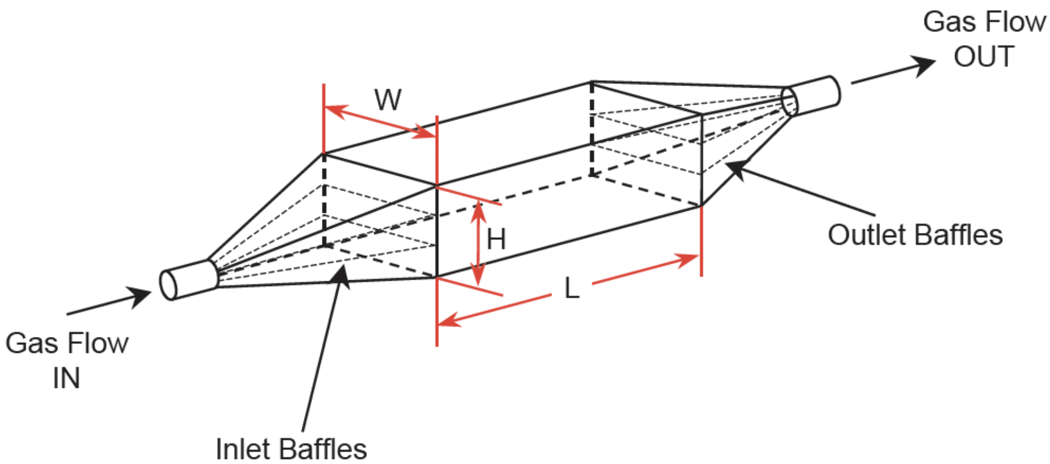


Figure 2.12 Gravity settling chamber.

GSCs need to be periodically cleaned. Since this only addresses large particles, its use in commercial industries has declined over the years because of the more stringent emission norms. Today, GSCs can be used in metallurgical industries, emitting highly polluted gas.

2.2.4.10 Technology 10: Centrifugal separators

Centrifugal separators use centrifugal force to drive particles to the collection surface. When the gas stream is forced to spin within the large-diameter cyclones (Figure), the mass of the particles causes them to move closer to the cyclone wall and settle into the hopper of the cyclone. The clean gas is then released.

For particles greater than 20 µm in diameter, large cyclones with 30-180 cm diameter are used. These can be operated at low cost and at relatively high temperatures. Small cyclones with diameters 8-30 cm allow faster spinning of the gas stream. Each tube has limited gas handling capacity, so a large number of tubes are mounted in a parallel setting. For particles smaller than 5 µm in diameter, the separation efficiency sharply decreases. These also are not very useful for large (30-50 µm) particles because these particles may plug the spinner vanes in the multicyclone tubes.

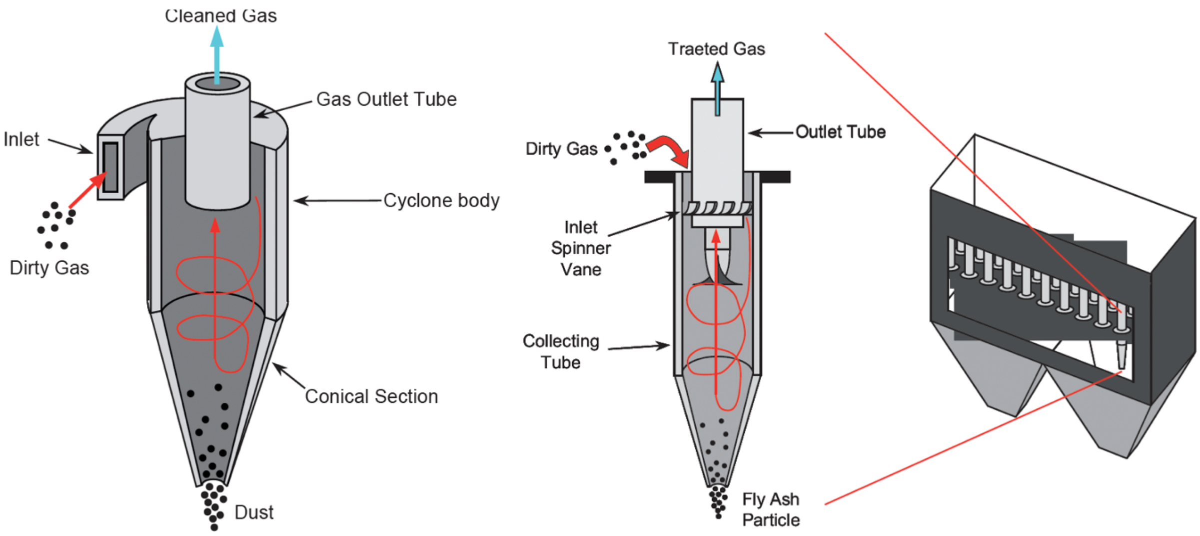


Figure 2.13 (Left) Large-diameter cyclone and (Right) small-diameter multicyclone. (Source: Air pollution control engineering, N. de Nevers).

2.2.4.11 Technology 11: Particulate wet scrubbers

The scrubber works on the principle of particles coming in contact with liquid drops and getting adhered to the drops. Therefore, it is important to introduce a large number of drops properly into the gas stream. Particles are separated from the gas and liquid drop mixture using a cyclone. The liquid is then separated from the solid and recycled.

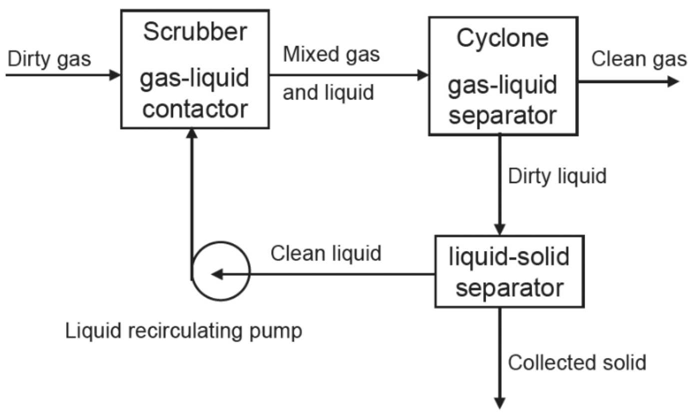


Figure 2.14 Particulate scrubbers.

The contact of the gas that needs to be cleaned with liquid drops can be achieved in three different ways.

Counter-flow scrubbers: The spray nozzles are on the roof of the scrubbers. The liquid falls by gravity, while the gas stream enters from the bottom of the scrubber and flows upwards.

Cross-flow scrubbers: Multiple spray nozzles are located on the roof of the scrubber and dispense the liquid uniformly over the incoming gas coming horizontally. The liquid is collected at the bottom of the device. Its efficiency improves with decreasing liquid drop size and increasing the height of the scrubber. However, if the drop size is too small, vertical velocity will be too low.

Co-flow scrubbers: Both the gas and the liquid water enter at the left and exit at the right, while the liquid enters at a right angle to the gas glow.

2.2.4.12 Thermal processes

The thermal processes are based on the separation principle and use combustion to remove pollutants from air exhaust (https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/oxi-x-thermal-processes).

Technology 1: Regenerative thermal oxidis ers (RTO)

RTOs are used to purify exhaust air with solvents and odours. The exhaust air contaminated with air pollutants is fed through a regenerative heat exchanger, which warms up the exhaust close to the reaction temperature. All the pollutants are converted into harmless substances when exposed to high temperatures in the combustion chamber. The purified gas is then fed back through the heat exchanger when it cools, completing the regenerative circuit. The purified gas is then released into the air. The technology has excellent thermal efficiency and low maintenance and operating expenditure.

There are a few variants available in the market.

Variant	Technical application
Oxi.X RTO	The combustion energy pre-heats the exhaust air and allows the system to operate in auto-thermal mode with no external energy required.
Oxi.X TR	Recuperative thermal systems are suitable for removing high levels of organic pollutants in the exhaust air. Its disadvantage is the high energy consumption, particularly when air volume flow is low.
Oxi.X DF	The direct-fired thermal oxidis er is a special variant that is suitable for the combustion of critical substances, including explosives, toxic, and carcinogens.

Figure 2.15 (Top) Regenerative thermal oxidation, (Middle) Recuperative thermal oxidiser, (Bottom) Thermal incinerator. Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/oxi-x-thermal-processes.

Technology 2: High-efficient burner systems

For the thermal process-based control systems, the design and operation of the burner is important. These burners can be used for different systems depending on the need. For example, the Oxi.X burner uses hollow cylinder flame technology to produce cleaner gas at a lower combustion chamber temperature than most conventional burners. The nozzle is specifically designed for use in Oxi.X TR systems. It allows significant energy savings and a reduction in the combustion chamber temperature up to 40°C lower than conventional burners.

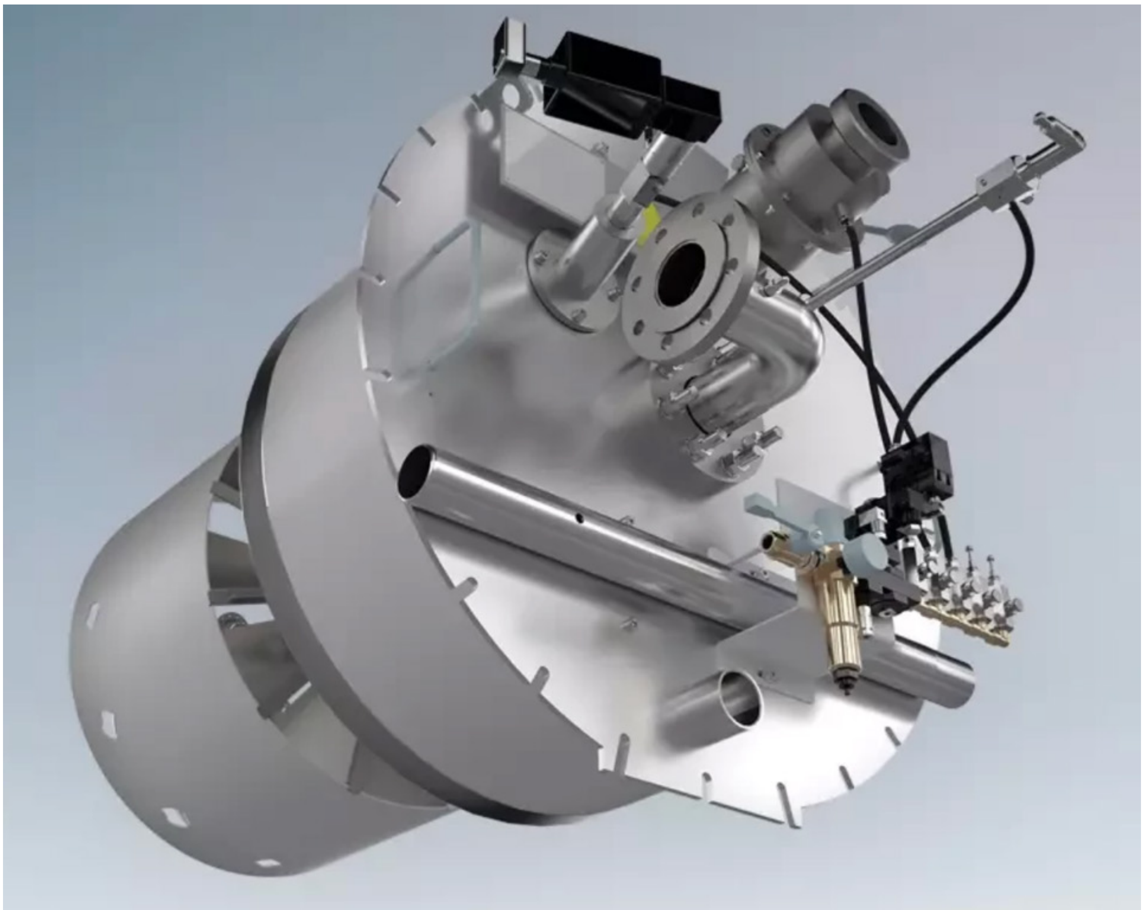


Figure 2.16 High efficient burner technology (Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/thermal-processes/oxi-x-burner-technology).

2.2.4.13 Sorptive processes

Sorptive processes include adsorption and absorption. The purpose of the adsorption process is to concentrate the pollutants. It is required when the exhaust air contains pollutants that form a physical bond with the adsorbent. As a result, they are removed from the air and concentrated in the adsorbent. Absorption removes pollutants from the exhaust air. It is usually used for cleaning flue gases.

Technology 1: Evaporative gas cooling and conditioning

This technology enhances air pollution control performance, protects downstream equipment, reduces gas volumes, and increases production capacity. Incinerators, kilns, and furnace exhaust gases are cooled prior to baghouse filtration, which reduces the volume of exhaust gas to be filtered and hence protects the baghouse fabric filter.

Figure 2.17 Evaporative gas cooling and conditioning (Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorpt-x-ac).

Technology 2: Wet scrubbers

This technology is used to remove acid gas by exposing it to an alkaline agent. This leads to the formation of a stable salt by chemical reaction, which subsequently is removed with the liquid in a spray chamber. The most common reagents used are NaOH, Na,$_2$CO$_{3,}$ and $Mg(OH)_2$. For gas streams with acid gases and particulates, the scrubber controls the contaminants on one system with minimal pressure drop, low water usage, and low maintenance.

Figure 2.18 Wet scrubbers (Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorpt-x-sw)

Technology 3: Biogas purification

This technology is designed to capture more than 98.5% of methane and remove H_2S, CO_2, and siloxanes from the digester gas produced at agricultural and manure facilities, wastewater treatment plants, and landfill sites. There are two different technologies – water scrubbing and membrane separation.

The water scrubbing system uses waste absorption technology to process biogas from the anaerobic digester and purify it to pipeline quality natural gas. Membrane separation technology operates on the gas permeation principle, and its design allows for fast start-up and minimal attention and maintenance requirements.

Technology 4: Cross-flow packed bed filters

This system is based on the sorptive process and is suitable for purifying hot exhaust gas flows. The benefits are a long life span, low-pressure loss, and maintenance. The adsorbent used is mostly limestone, and it can be easily disposed of.

Figure 2.19 Cross-flow packet bed filters. Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorpt-x-sq.

Technology 5: VOC concentration

The Sorpt.X CD/CC system is based on a sorptive process and is commonly used for continuously purifying large exhaust air volume flows containing low levels of VOCs. It can be used for continuous desorption and treatment of pollutants without pressure fluctuations, can be used without additional fuel, and can be combined with a variety of oxidation technologies. It has multiple benefits, such as low CO_2 emissions, low operating expenditure, long life span, and little maintenance.

Figure 2.20 VOC concentration. Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorpt-x-cd-cc.

Technology 6: Carbon adsorption

In a regenerative carbon adsorption system, the solvents are adsorbed on activated carbon. When the carbon gets saturated, it is regenerated with steam, making it condensed, which allows the solvents to be removed easily.

The technology can recover up to 99% of solvents for reuse, remove VOCs and hazardous air pollutants, increase profitability by reducing solvent expenses, and be applied to a wide range of solvents.

Figure 2.21 Carbon adsorption. Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorpt-x-ca.

Technology 7: Liquid distillation

This system is suitable for treating the effluent from a regenerable carbon adsorption solvent recovery system. It separates solvent mixtures into individual solvents in chemical, pharmaceutical, and other industries and makes them suitable for recycling and reuse. It also removes solvent contaminants from wastewater.

Figure 2.2.1 Liquid distillation. Source: https://www.durr.com/en/products/environmental-technology/exhaust-gas-and-air-pollution-control/sorpt-x-sorptive-processes/sorptx-ld-liquid-distillation.

2.2.5 Brick Kilns

Brick kilns cater to the rural employment of millions of people in South Asia, but they are one of the major polluters. Most of the brick kilns in this part of the world are fixed chimney kilns (FCK), which are not energy efficient. The major problems in the conventional FCKs are illustrated in Figure 2.22.

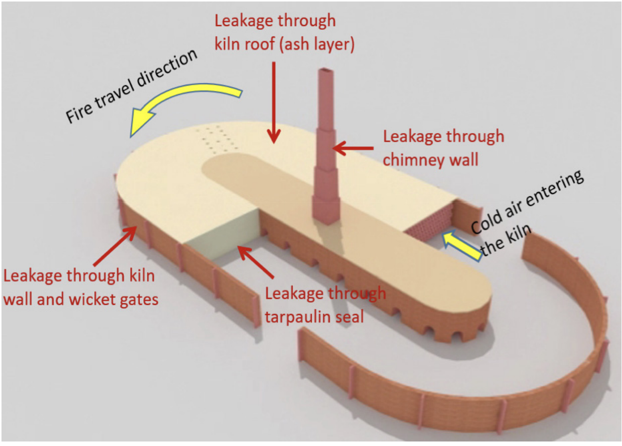


Figure 2.22 Problems in the conventional fixed chimney brick kilns. Source: cseindia.org.

There are three options for clean brick production technologies.

2.2.5.1 Technology 1: Improved zig-zag kilns (IZK)

The IZK technology stacks the bricks in a zig-zag pattern instead of a straight line, which alters the way coal is loaded and redirects the airflow. This reduces fuel consumption by 19-40% relative to FCK, [72-74], increases burning efficiency, and reduces emissions of pollutants. The FCK kilns can be converted to improved zig-zag kilns at the same site without any impact on brick quality and within half a year.

In India, the MoEFCC has mandated a minimum height of ~90 ft for the IZKs. The dug wall (Figure 2.23) is generally 10-11 ft. The length of the chamber varies between 6-9 ft. Better zigzagging of the airflow can be achieved by decreasing the length of the chamber. Therefore, for natural draft zig-zag kilns, six feet long chambers are recommended.

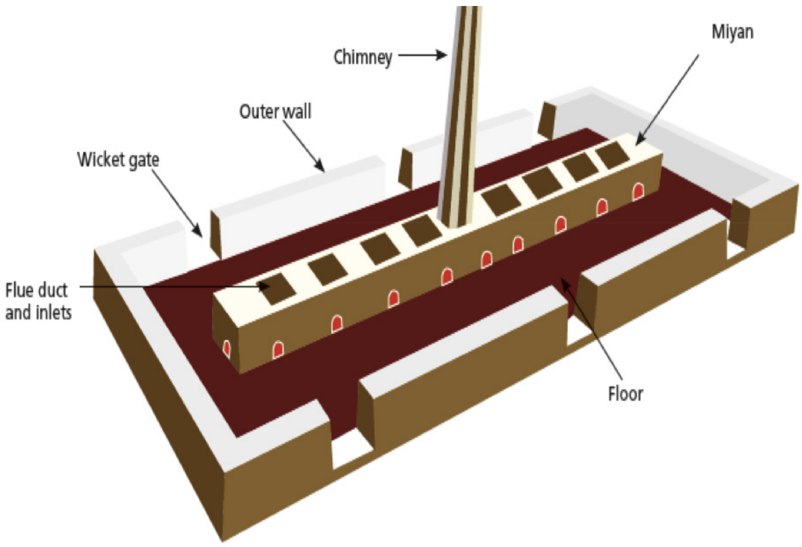


Figure 2.23 Main components of a zig-zag kiln. Source: cseindia.org.

2.2.5.2 Technology 2: Vertical shaft brick kiln (VSBK)

The VSBK technology uses hot exhaust gases for the gradual heating of the unfired bricks in a continuous process. It is more suitable for small-scale manufacturers and needs less land than FCK. This technology reduces fuel consumption by 48-60% relative to FCK. [72-74] While traditional FCKs can operate 5-6 months per year, VSBKs can operate year-round. [75] However, the typical production capacity of VSBKs is low, bricks are not as red as FCK and hybrid Hoffman kilns, and they need to be located on highlands. This enhances the cost and is a major reason for low acceptance from the builders.

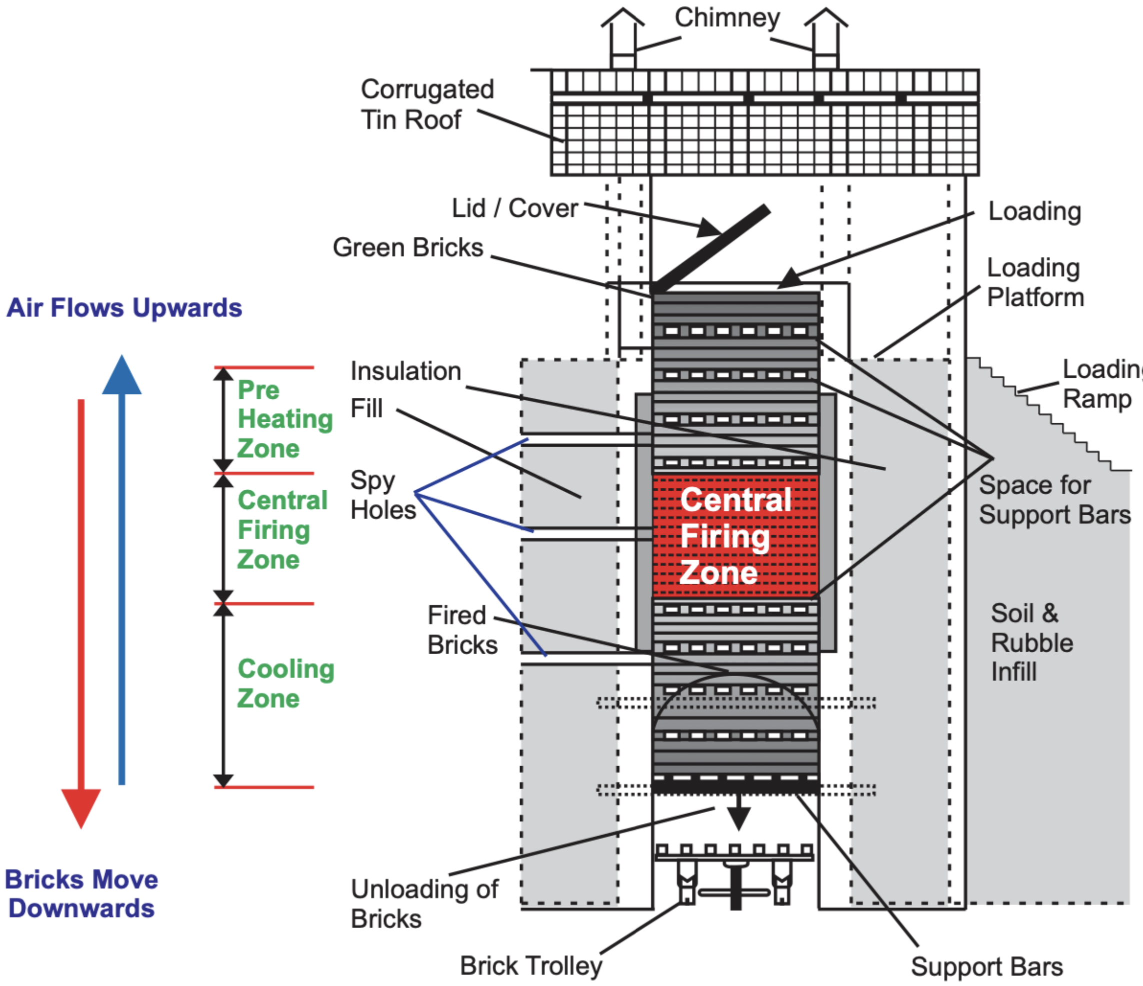


Figure 2.24 Schematic diagram of a vertical shaft brick kiln. Source: https://www.devalt.org/.

2.2.5.3 Technology 3: Hybrid Hoffman kilns (HHK)

HHKs have a rectangular-shaped annular circuit with an arched roof. The structure is usually covered with shades. The fire moves through the bricks stacked in the annual space. They do not have tall chimneys; rather, hot flue gases are diverted to the drying tunnels through the duct and then released in the air through a rectangular opening.

They are more capital-intensive and require high land. This technology reduces fuel consumption by 38-60% relative to FCK. [72-74] Despite all these benefits, the adoption rate for this technology is slow. [76]

Figure 2.24 Hybrid Hoffman kilns. Source: https://www.shareweb.ch

2.2.6 Waste management

2.2.6.1 Municipal solid waste

Municipal solid waste (MSW) remains a major problem in modern societies, even though the significant efforts to prevent, reduce, reuse, and recycle. At present, municipal solid waste incineration (MSWI) in waste-to-energy plants is one of the main management options in most developed countries. The technology for recovering energy from MSW has evolved over the years, and now sophisticated air pollution control (APC) equipment ensures that emissions comply with the stringent limits established in developed countries. The role of incineration in waste-to-energy processes in the ambit of MSW management, giving an overview of the MSWI technologies and APC devices used for cleaning the gaseous emissions.

Nowadays, modern systems embrace different methodologies, in general, aiming as much as possible to achieve sustainable global solutions. Life Cycle Assessment (LCA) tools have been used to assess the potential environmental burdens of different waste management strategies from environmental, energetic, and economic points of view. These calculations have shown that landfilling, even if gas is recovered and leachate is collected and treated, should be avoided due to the fact that waste resources are inefficiently utilis ed.[77] Alternatives include incineration, material recycling, anaerobic digestion, or composting. [78]

2.2.6.1.1 Technology 1: Incineration and pollution control technology

Incineration is a combustion process at high temperatures that allows complete oxidation of solid wastes, liquids, or gases. The main problems associated with these processes are probably the large volume of gaseous emissions, which may pose environmental health risks, and hazardous solid wastes that remain after incineration as fly ash or air pollution control (APC) residues.[79]

The huge amount of gases produced during combustion contains air pollutants harmful to the environment that must comply with stringent regulatory limits. Thus, depending on the desired cleaning degree, different air pollution control (APC) systems may be used.

Gas composition dictates the respective control mechanisms in incinerators. The gas mixture leaving the incineration furnace has three main types of components that have to be removed to the possible extent before the exit at the stack:

- Fly ash, which is composed of particles pneumatically transported by the gaseous flow;
- Acids and acids precursors, such as sulphur dioxide, nitrogen oxides, and hydrochloric acid;
- Dioxins and analogs that are compounds formed by radical recombination with structures such as polychlorodibenzodioxins and the respective furan analogues.

The hot gas mixture, leaving the furnace, exchanges heat at the surface of the heat exchanger vertical tubes, inside which the high or medium pressure steam is generated and before entering the cleaning systems, part of this gas is diverted through a booster to be injected in the cameras below the moving grate of the furnace. This gas recycling is essential in terms of overall energy recovery and also very important to promote easier control of the stoichiometric excess of oxygen in the furnace. The remaining effluent gas mixture has to be cleaned by several unit operations in the gas cleaning systems.

A large number of unit operations based on primary separation processes can be used for the gas cleaning of the flue gas generated in waste incineration systems. In the table below, for each type of flue gas pollutant, a combination of unit operations is indicated with the respective typical range of reduction.

Pollutant	Pollution control technology used	Reduction (%)
Sox	Wet scrubber and dry multi-cyclone	50-90
Hcl	Wet scrubber or semi-dry	75-95
NOx	Selective catalytic reduction	10-60
Heavy metal	Dry scrubber + ESP	70-95
Fly ash	ESP+ Fabric hose filter	95-99.9
Dioxins and furans	Activated Carbon+ Fabric hose filter	50-99.9

Fly ash generated at waste incinerators is usually contaminated with heavy metals and other dangerous substances and has to be treated as a hazardous residue, requiring inertis ation before the disposal is controlled landfill. The activated carbon, in powder form, is very often used to adsorb organic pollutants such as dioxins and furans. The main types of equipment used for the removal of solid particles of fly ash and activated carbon are cyclones, electrostatic precipitators, and fabric hose filters.

Cyclones are rather efficient for the removal of solid particles with an average diameter of over 100 µm from gaseous flows. Since steel or stainless steel can be used for the construction of cyclones, the range of permissible operating temperatures is rather wide. In gas cleaning of flue gas from incinerators, cyclones are very often used as primary separators, followed by other separating units designed for the retention of particles of smaller size present in the fly ash.

The acids present in the flue gas, such as HCl and HF and the precursor of acid SO_2, can be separated by different processes: dry process (with the use of a solid adsorbent), semi-dry (with the use of a spray absorber), wet process (with aqueous solutions). Nitrogen oxides content in flue gas are usually reduced by two reactive processes: SNCR (selective non-catalytic reduction) and SCR (selective catalytic reduction).

The increase of CO and/or volatile organic compounds (VOCs) content in the flue gas is a strong indication of inappropriate burning conditions in the furnace. Several adjustments by the control systems can be adopted, but the more common are:

i. Increase of raw air inlet to the furnace;

ii. Reduction of flue gas recycling to the furnace;

iii. Slight increase of pressure below the grid.

Although very efficient for over 99% of the particles, the electrostatic precipitators, and the fabric hose filters are not effective for nanoparticles or for the smaller sub-micron particles. Flue gas exhaust at the stack, although very clean, has a small content of nanoparticles. Recent concerns on the physiological effect of respirable nanoparticles induced research on their study and on methods of avoiding their presence in the exhaust flue gas. Improving particle aggregation and deducting seems to be the more promising alternative and intense research is being conducted in that direction. So far, it has proved that very fine dust and nanoparticles can be effectively aggregated by water-dispersible polymers with controlled water compatibility.

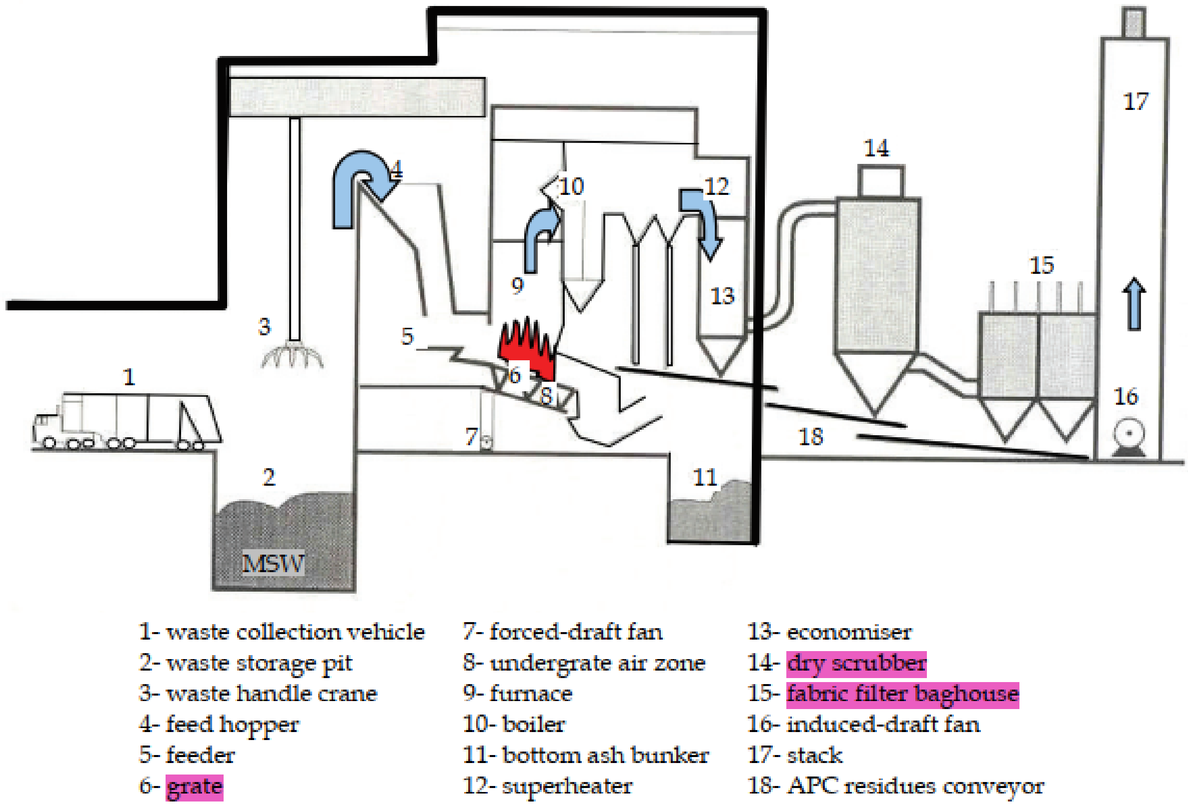


Figure 2.25 Simplified scheme of an MSW incinerator (Source: Quina et al., 2011)[79]

2.2.6.2 Agricultural crop waste burning

One of the key seasonal sources of air pollution in South Asian countries is agricultural crop waste burning, which is more common in the Kharif season than in the Rabi season. The reduced gap between the two seasons in order to manage water consumption judiciously created a situation where the farmers needed to get rid of the stubble in a few days to prepare the field for winter crops. [80,81] Due to the lack of infrastructure and knowledge about its potential negative impact on the environment, farmers find it easy to burn the stubble and clear the field.

Kaur et al.[82] have provided a comprehensive summary of the various options for managing paddy stubble and subsequent wheat cultivation (Figure 2.9). The stubble can be managed in-situ or ex-situ. The following diagram provides various options available for both practices and also the plantation techniques for the succeeding wheat crop.

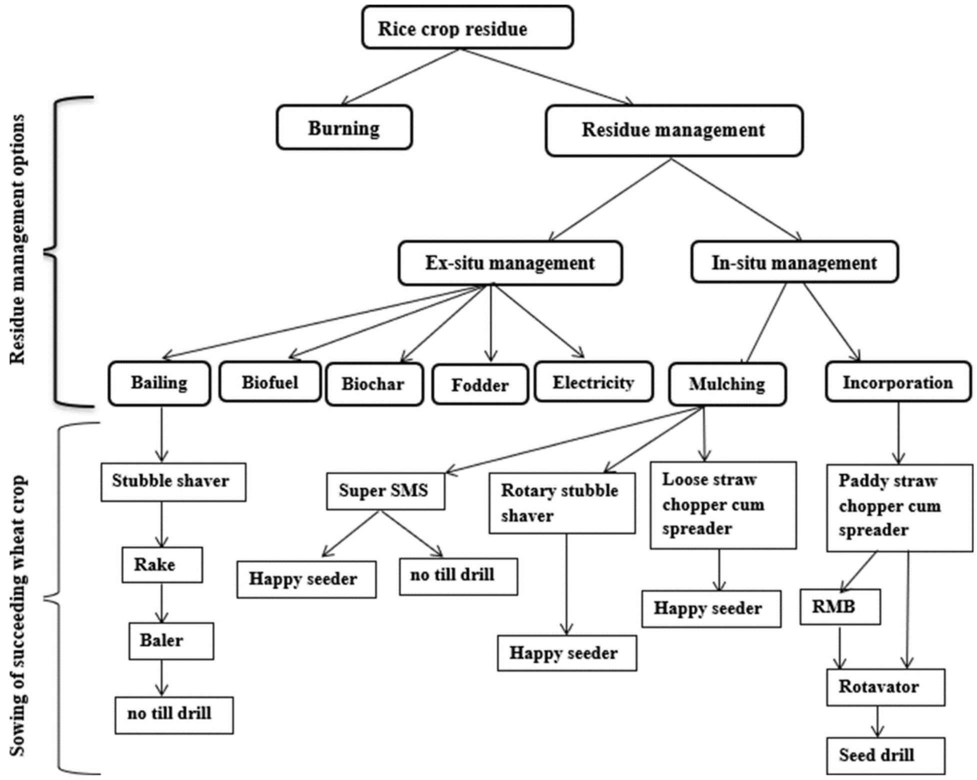


Figure 2.26 Various in-situ and ex-situ rice residue management options and techniques for the succeeding wheat crop. The figure is taken from Kaur et al.

2.2.6.2.1 In-situ management

Technology 1: Happy Seeder

The Happy Seeder is a tractor-mounted implement that combines a zero-tilling seeder with a straw management unit. The latter comprises serrated rotating flails attached to a roller that shreds and cleans the residues in front of the Tyne openers and then deposits the residue around the seeded row as mulch. This is done in one simple operation of direct drilling in the presence of standing as well as loose surface residues. The residue left on the surface as mulch helps reduce evaporation losses, suppresses weed growth, buffers soil moisture and temperature, and facilitates a more efficient uptake of water and nutrients by plant roots [Keil et al. 2021].

Figure 2.27 Happy seeder.

Technology 2: Super SMS for combined harvester

The 'Super Straw Management System' (Super SMS) can be attached to the combine harvester, which enables uniform spreading of residue across the harvesting width [Keil et al. 2021].

It is an additional piece of equipment attached to the combine harvester, so it cuts standing stubble into small pieces and spreads on the soil surface. In this method of crop harvesting and straw management, both are done in a single operation through modified combine harvesters. [Source: Internet]

Figure 2.28 Super SMS.

Technology 3: Hydraulic RMB Plow

The Hydraulic Reversible Moldboard (RMB) Plow is a type of plow used in agriculture. It's designed to be mounted on tractors and is used for primary tillage to turn over soil, bury crop residue, and prepare the ground for planting.

The RMB Plow helps mitigate this issue by offering an effective alternative to the traditional method of stubble burning.

1. **Incorporation of crop residue**: The plow can efficiently bury crop residue or stubble deep into the soil during primary tillage. This burial of crop residue prevents it from being exposed on the surface, where it can be easily burned. When buried, the stubble decomposes gradually, enriching the soil and reducing the need for burning.
2. **Enhanced decomposition**: By breaking down the stubble and mixing it into the soil, the Plow aids in accelerating the decomposition process. This natural decomposition contributes to soil health by increasing organic matter content and nutrient availability.

Figure 2.29 Hydraulic reversible mouldboard plow.

Technology 4: Chopper cum loader for paddy straw

Flail-type chopper cum loader for paddy straw cuts straw from the bottom collects straw, and loads it into the trailer. The width of the machine is 1.5m, and the power requirement is 35 hp. Field capacity of flail type chopper cum loader varied from 0.25 to 0.35 ha/h.

Figure 2.27 Chopper-cum-loader

A trail-type machine developed by the Punjab Agricultural University, Ludhiana Centre, was modified in different phases to convert into a mounted-type machine. The first prototype of the machine had two separate units, i.e., cutting and chopping units. It consisted of a rotary shaft mounted with flails to harvest the straw and a chopping unit fitted with knives. [Source: ICAR Report]

Figure 2.30 Chopper-cum-spreader

Technology 5: Agricultural machines

Apart from this, farmers can manage crop residues effectively by employing agricultural machines like the Rotavator, which is used for land preparation and incorporating crop stubble in the soil; Hay Baler used to compress a cut crop so that it is easy to handle and store; and the Reaper Binder, used for harvesting paddy stubble and making it into bundles, and zero till seed drill, used for land preparations to directly sow seeds in a crop stubble (Pandey et al.2020). These bundles are then transported for ex-situ utilis ation in a range of activities (see next sub-section).

Figure 2.31 Agricultural machines (rotavator, hay baler, and reaper binder) used in ex-situ stubble management.

2.2.6.2.2 Ex-situ management

Utilisation as livestock fodder

Rice straw has been a prudent feed supply, particularly in the lean period when the green fodder supply is limited. The major drawback of residue utilis ation as fodder is poor nutrient content with remarkably high tissue silicon content, which creates a physical barrier hampering the microbial degradation process. Technological improvements, especially pre-treatment, help farmers with the sustainable utilis ation of straw as fodder.

Pre-treatment can be defined as physical, chemical, and biological processes for improving the palatability of livestock feed. Physical pre-treatments encompass grinding, soaking in water, steam pressure, pelleting, and gamma irradiation, with soaking being the most commonly practiced. [Dutta et al. 2022]

Technology 1: Paper production

Rice straw is a sustainable and eco-friendly option for the paper and pulp industry. In addition to wheat straw, paddy straw can be used for paper production. Well-established chemical methods are used to extract the cellulose and phenolic compounds from the straw and utilis e them for paper production. Reports said that in Punjab, nearly 50% of the paper industry uses straw, thereby reducing burning and environmental degradation. The sludge generated from the paper industry can be used for energy generation through the bio-methanation process. [Dutta et al. 2022]

Technology 2: Compost preparation

At the Indian Agricultural Research Institute, New Delhi, Pusa decomposer, a consortium of seven fungi, has been developed on the basis of their lingo cellulolytic enzyme production potential. Since composting technology has been recognis ed as the most suitable means to convert agro-waste into a nutrient-enriched product that conditions soil and nourishes plants, this technology has great significance in the present scenario. The methodology is also tested at a large scale at IARI farm for bioconversion of farm agro-wastes. Currently, Pusa decomposer is being provided in the form of capsules and liquid formulation and can decompose the agri-residue in situ within 25 days.

Technology 3: Biogas preparation

Rice straw can be used for the production of biofuel through anaerobic digestion. Biogas is a mixture of different component gases like methane (CH4), CO2, hydrogen sulphide (H2S), oxygen, nitrogen, and other trace gases, but high CH4 content is always desirable due to its high energy density. There are four important steps of anaerobic digestion, namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. [Dutta et al. 2022].

A biogas plant combined with commercial farms and processing units was set up in Fazilka, Punjab, as a novel initiative towards green energy. This plant generates biogas using rice straw through bio-methanation technology [Bhubaneshwari et al.2019]

Technology 4: Power Generation

The use of surplus rice straw as a sole input or in combination with coal in the power plant is considered to be a viable tool for generating power. Burning in the boiler or gasifier under zero or low oxygen environment with high temperature converts the residues into producer gas (calorific value: 1000–1200 Kcal/Nm3 and constitutes of CO, H, and N), which has lower calorific value compared to liquefied petroleum gas with zero environmental. On average, a gasifier with a capacity of 1 Kilowatt-electric (kWe) requires almost 8 tonnes of paddy straw. [Dutta et al. 2022]

Technology 5: Production of bio-oils

Bio-oil is a high-density liquid that comes from organic wastes like bagasse, wheat residue, and rice hull through pyrolysis (>500°C). Bio-oils have multipurpose uses, such as in boilers, heat generation, operating gas turbines, and transportation. The heating value of bio-oils is around 55% of diesel and much more eco-friendly as it is devoid of SO2 and contains very little NO2. [Dutta et al. 2022]

Foreign organis ations (Dynamotive Energy Systems situated in British Colombia, Canada) patented bio-oil production technology (www.dynamotive.com: accessed on 03.12.2020). In India, public institutes like the Punjab State Council of Science and Technology (PSCST) and the Punjab Energy Development Agency (PEDA), through collaborative technology, are trying to come out with innovative technology for the production of bio-oils from rice straws [Dutta et al. 2022]

2.2.7 Dust control

There are two broad categories of technologies to control dust emissions from road, construction, and mining operations.

2.2.7.1 Technology 1: Dust suppressants

Dust suppressant mixed with water, when sprayed over a construction site or a site where soil dust is emitted at a high rate, suppresses the dust by enhancing the settlement process (https://globalroadtechnology.com/dust-control-methods/).

Moisture on the surface can cause particles to stick together longer and reduce dust emissions. Water spraying using sprinklers mounted on a slow-moving vehicle is the most common practice. However, the effectiveness of this and the longevity of the effect depends on local conditions.

Technology 2: Chemical agents

Several chemical agents can be used to suppress dust. Salts and brines are very common as they can absorb moisture from air and increase the surface tension of water film between particles, but they are corrosive. Bitumen emulsions are another possibility, but there is a chance of release of PAHs. Liquid polymers and synthetic fluids are used to bind and coat surfaces to control road dust emissions. Lignosulfonate has good water solubility and can be used, but leaching may happen during rainfall.

Global road technology (https://globalroadtechnology.com/dust-control-methods/) has several specific technologies broadly under the above two categories available for commercial use.

Haul-loc: Ultra concentrate uses liquid crystal polymer technology to improve the efficiency and effectiveness of water cart operations by up to 500%. It saves water, eliminates dust, and improves the safety of the roads.

Activate: It is a cutting-edge dust control technology that makes water work harder, better, and more efficiently. It is injected through existing dust spray systems or trucks. It is useful for stone and quarry crushers and conveyors used for road construction.

Activate UG: It is a super-activated dust control technology for underground mining. This is injected into water supply lines and sprayed through existing systems for the longwall, miners, and conveyors, and it is mostly effective for airborne coal and silica dust.

Wet-loc: it is a non-drying and non-setting synthetic fluid designed to adsorb into soil particles and prevent them from being airborne. It is a waterless application and is ideal for underground mining roads, areas with heavy traffic, and speedways.

Drill and blast applications: It helps to super-activate the water used in drilling and blasting. The chemical interaction binds the surface of fine-cutting piles and prevents them from being airborne.

Soil loc: It is a cost-effective wind-erosion technology that is designed to protect croplands. It is designed to be applied for the rural sector, and equipment such as sprayers can be used. It allows irrigation and rainfall to penetrate through its crust at a controlled rate but restricts both wind and rill erosion of soil.

Ore loc: It is a liquid polymer that locks fine particles together, encapsulating and demobilis ing fugitive dust. It is designed for the resource sector and can be directly applied to raw materials using existing or specially designed spray-bar systems. It does not affect the burning properties of coal or the material.

Rubble loc: It is a cost-effective dust and wind erosion control technology designed for use on demolition sites, material stockpiles, and natural disaster settings. It can be applied through standard water trucks, hydro-mulchers, or irrigation systems. It is simple to use and stops hazardous substances such as silica, asbestos, or heavy metals from being airborne.

2.3 Technologies for removing air pollutants from the air

There are multiple types of air purification technologies.

2.3.1 Technology 1: Mechanical filtration

High-efficiency particulate air (HEPA) filtration is a type of mechanical filtration that removes particulates from the air by more than 99.97%. HEPA filters must be tested and certified for commercial use. Mechanical filters – both HEPA and non-HEPA are made of fabrics and operate by simply collecting particles in the fibres. The air molecules are allowed through the filters, but the particles get trapped.

Mechanical filters can remove particles such as pollen, dust, mold spores, asbestos, smoke, dust mite allergens, bacteria, and viruses based on their efficiency ratings.

Figure 2.32 HEPA filters. Source: elemntalairsystems.com

Advantage: It eliminates the smallest particles very efficiently.

Limitation: It may restrict airflow.

2.3.2 Technology 2: Activated carbon

Activated carbon is carbon that has been processed to give it a large surface area of microscopic pores, which can adsorb pollutants. They have been used to purify air and water for decades. The activated carbons capture small particles in the tiny pores that are too small to be captured by mechanical filters. They are quite efficient in removing VOCs and odours. Some mechanical filters have additional dusting of activated carbons to enhance their efficiency in removing particles.

Figure 2.33 Activated carbons. Source: elementalairsystems.com

Advantage: It removes extremely small particles, chemicals like VOCs, and odours.

Limitation: It may restrict airflow.

2.3.3 Technology 3: Ionisation technique

The device releases negative ions in the air, and it causes the particles to stick to each other, making them heavier and settling down. If they are operated in a closed environment, charged particles usually get deposited on the walls and furniture. When the charge neutralis es, the particles can be released back into the air, making it less effective.

While ionis ers can reduce particulate matter concentration, they can increase another pollutant – ozone. Therefore, this technology should be tested thoroughly before its use. Most residential ionis ers are not powerful enough to cause substantial improvement in air quality.

Figure 2.34 Ionisers. Source: elementalairsystems.com

Advantage: It takes particles out of the air and deposits them on the walls or furniture.

Limitation: The particles that get deposited are released back into the air when the charge neutralis es.

2.3.4 Technology 4: UV light

Ultraviolet (UV) light is a high-energy form of electromagnetic radiation and is not visible to the naked eye. Not all UV lights can harm bacteria and viruses. Only the highest energy wavelength (100-280 nm, known as UV-C) can damage bacteria and viruses, and that is true if they are exposed to UV light for a long period. This poses a challenge as UV-C is extremely harmful to human beings.

Advantage: It can damage bacteria and viruses when exposed to the UV for a long time.

Limitation: It can produce harmful ozone and can burn skin and eyes if exposed to humans for a long time.

2.3.5 Technology 5: Ozone generators

Ozone can neutralis e some chemicals given a long period of time (often months). In the market, several ozone generators are available, but prolonged exposure to ozone can cause several health problems, including respiratory and lung problems and lung tissue damage. Due to this, health professionals suggest not to use this technology for air purification.

Advantage: It can neutralis e some chemicals given sufficient time.

Limitation: It is bad for human health, causing a range of health outcomes.

Out of these five types of technology, ozone generators, UV light, and ionis ers are not that common. The ozone generators and UV light technology have considerable risks, while the ozone-producing potential for ionis ing technology needs to be tested. Therefore, most commercially available purifiers use mechanical filtration and activated carbon technology.

2.3.6 Technology 6: Pulsed-radio wave-based purification

A sixth pulsed-radio wave-based purification technology emerged recently (devic-earth.com). Pulsed radio waves are periodic bursts of radio waves or radio frequency energy. Earlier, this technology was used in wastewater treatment. Pulsed radio waves create a weak electric field that affects very small particulate matter and results in the formation of temporary dipoles. This accelerates particle agglomeration, which in turn makes particles heavy, and the particles get deposited by gravitational settling.

Advantage: It is effective for PM2.5 and PM10

Limitation: The technology does not work for gaseous pollutants and particles larger than 20 µm and the peer review of this technology is ongoing.

2.4 Biofiltration techniques

This is an alternate technique that can be used to eliminate air pollutants from organic-product-based industries, and it requires low maintenance costs. Biofilters comprise at least one bed of biologically active material. The polluted gas is vented from the source through the filter. Aerobic degradation will happen in the biofilm if microbes that may use them are available. (Sheoran, K. et .(2022), ACS Engineering)

Other common techniques, such as adsorption technique, thermal oxidation technique, and catalytic oxidation techniques have certain limitations, particularly for dilute industrial VOC emissions. For example, VOCs may accumulate on activated carbon and thus form a new waste that needs to be removed. Self-incarceration of VOC is difficult in thermal oxidation techniques due to the external fuel being supplied with increased heat for degradation, thereby elevating the cost of the operation. Catalytic oxidation can be clogged due to catalytic poisoning in the presence of chlorinated organic and sulphides. This technique has the potential to be the alternative for such cases.

2.5 Compilation of pollutant-wise available technologies

In this section, the available technologies are grouped according to the pollutant they can be used to remove.

Pollutant	Applications	Technology
PM	Industrial processes and Power plants	Gravity settling chamber
		Centrifugal separator
		Particulate wet scrubbers
		Electrostatic precipitator
		Filters
NO_x	Gas turbines	Reduction peak temperature: 70-85% efficiency
		Reduction residence time at peak temperature: 70-80% efficiency
		Chemical reduction: 70-90% efficiency
		Oxidation of NO_x with subsequent absorption: efficiency data not available
		Removal of nitrogen: efficiency data not available
		Use of sorbent: 60-90% efficiency
	Internal combustion engines	Reduction peak temperature: 20-97%% efficiency
		Reduction residence time at peak temperature: efficiency data not available
		Chemical reduction: 80-90% efficiency
		Oxidation of NO_x with subsequent absorption: 80-95% efficiency
		Removal of nitrogen: efficiency data not available
		Use of sorbent: 60-90% efficiency
VOCs	Industries	Thermal oxidation
		Catalytic oxidation
		Adsorption
		Condensation, Refrigeration and Cryogenics
		Biological oxidation
Persistent and Chlorinated Organic Pollutants	Municipal solid waste management	Incineration
		Chemical destruction
		End-of-pipe practices
Hydrocarbon and CO	Gas turbines	Catalytic combustion
		Catalytic control
		After treatment, catalyst deactivation
Ozone	Ambient air	Controlling NO_x and VOC emissions from power plants, transport, and industrial sources
	Aircrafts	Adsorption, thermal, and catalytic decomposition
SO_x and H_2SO_4	Industry and power plants	Absorption techniques
		Adsorption techniques
		Alternate fuels

CHAPTER III: OPPORTUNITIES FOR ASIA-PACIFIC CITIES

This chapter builds upon the previous section, where the opportunities in technological interventions are identified and compiled. The chapter showcases selective case studies and discusses the opportunities for Asia-Pacific countries to implement technological solutions in combating air pollution.

3.1 IoT-based hyperlocal monitoring and local source characteris ation.

One of the major difficulties in air quality management in LMICs is the lack of periodic updates on the sector-specific emissions of various pollutants. This hinders assessing the efficacy of the local interventions and understanding whether the contribution of local sources in a city has reduced over time or not. Very limited ground monitoring further adds to the problem as the spatial heterogeneity at a finer scale (influenced by local source distributions) cannot be determined.

IoT-based monitoring of air quality at a hyperlocal scale can provide a solution to this issue. Technological advancement of IoT-based sensors (both in terms of hardware and software) and their low cost allowed for large-scale deployment in cities. Sensors are calibrated before deployment to ensure data robustness. Recent studies showed that robust calibration performance can be achieved by ensuring data quality (e.g., Campmier et al., 2023; Sahu et al., 2021; Sreekanth et al., 2022; deSouza et al., 2022). These sensors can also be used on mobile platforms to identify point or area sources (Apte et al., 2017).

Recent deployments of IoT-based sensors across the LMICs and developed countries have generated the following learnings.

- IoT sensors should be followed up continuously to check performance degradation in contrasting environments (deSouza et al., 2023) to maintain the rigor of the data (Giordano et al., 2021).
- Methodologies have evolved to identify the variation in the background level and isolate the local signal. (Apte et al.)
- The high-resolution data can be used to identify the local sources (Wang et al., 2023) and manage pollution hotspots.

Opportunities for Asia-Pacific cities

Most Asia-Pacific cities have no or very limited ground monitoring. These cities can adopt IoT sensors to understand the pollution heterogeneity in the hotspots, expand public awareness and influence behavioural change, examine the impacts on marginalis ed populations and links to health surveillance data, and assess intervention efficacy.

3.2 Satellite applications in air quality management at airshed levels for Asia-Pacific countries

Since air quality in any city is affected by regional transport of pollution from upwind sources, tracking regional air quality beyond the city boundaries is critical.

Opportunities for Asia-Pacific cities

Asia-Pacific countries with poor ground networks can use satellite data as a complementary tool for the following applications.

- The changes in regional pollution levels given the changing meteorology and interventions can be tracked continuously.
- The availability of a satellite-derived database for $PM_{2.5}$, ozone, and NO2 at a 1-km spatial scale allows for the identification of the local hotspots.

- The potential sites for the expansion of the ground network can be determined based on the regional heterogeneity of air pollution levels.
- Satellite-derived products can further be downscaled to map air quality at municipal ward levels by integrating with IoT-based sensors and other predictor variables (Tiwari et al., 2023).

3.3 Real-time source apportionment in cities

Megacity Delhi has always been in the news for air pollution. Two major steps towards air pollution mitigation in Delhi were taken to facilitate policy decisions parallelly – the first one is setting up a supersite for real-time source apportionment under the state regulatory agency Delhi Pollution Control Committee (DPCC) and the second is establishing a decision support system under the central government Ministry of Earth Sciences (MoES).

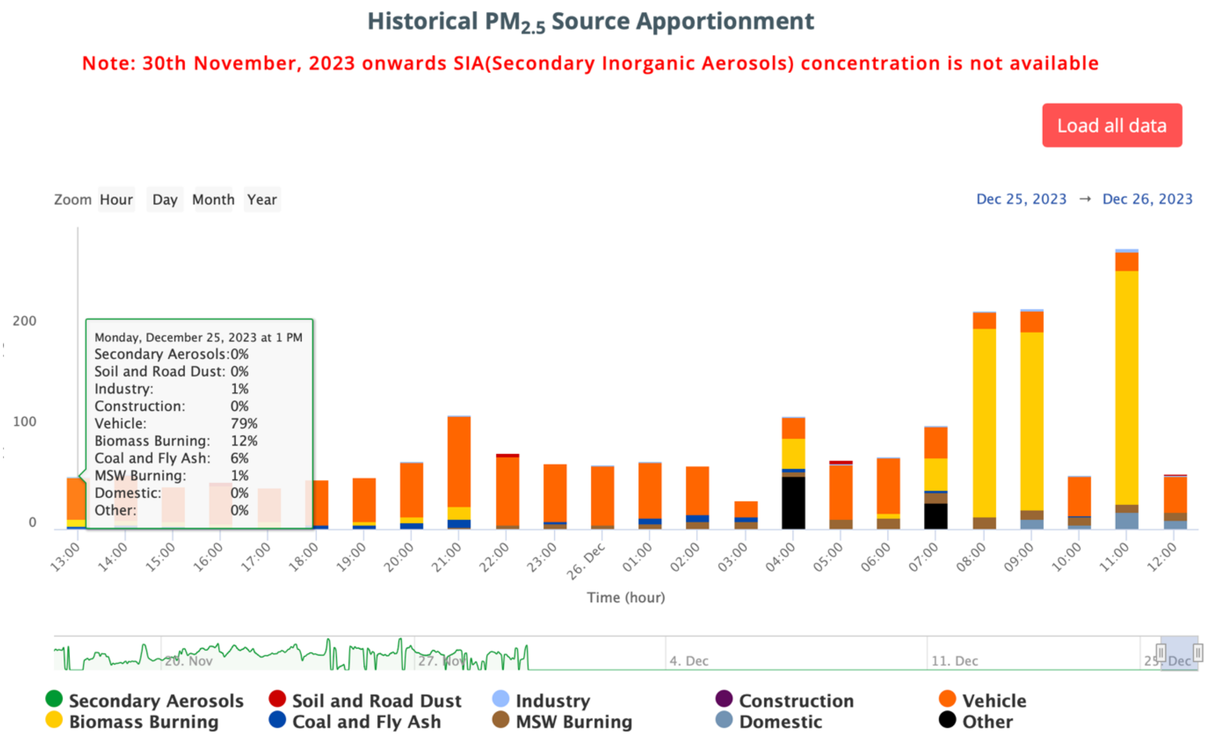


Figure 3.1 Source characterisation for Delhi on a real-time basis at an hourly scale based on Delhi supersite. Source: raasman.com.

The DPCC establishment provides real-time information about source contributions at an hourly scale based on online sampling of aerosol speciation. Figure 3.1 shows the data for 25th to 26th Dec 2023, where a large contribution of transport emissions in the late evening and early morning hours is visible. On the morning of 26th Dec, the data picks up the signature of open burning. The data is disseminated to the public in real-time (http://raasman.com/dashboard/realtime_source).

The MoES effort also provides real-time information on source characteristics for the entire city based on chemical transport modelling (Jena et al., 2021). Since emission inventory is not available in recent years at the desired spatial and temporal scale, satellite data are assimilated on a daily basis, and it was found that such assimilation improved the model performance (Govardhan et al.). The modelling setup also allows scenario analysis, where the policymakers can test potential reduction in ambient $PM_{2.5}$ in Delhi if emissions are reduced from a particular sector within Delhi and/or from neighbouring districts. Figure 3.2 demonstrates two such scenarios, where policymakers can test air quality improvements for 20% and 40% reductions in emissions. The decision support system also forecasts air quality for the next 48 hours.

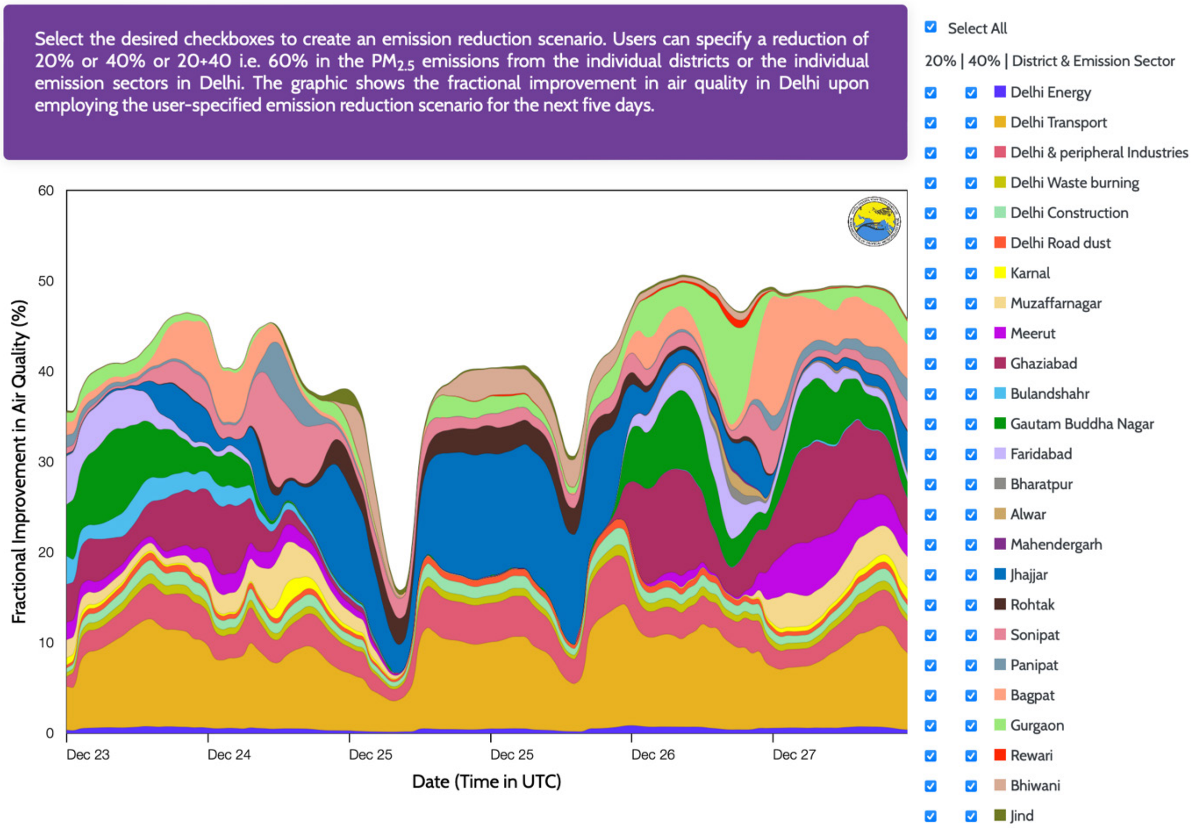


Figure 3.2 Hourly $PM_{2.5}$ and expected reduction due to a 20% and 40% decline in emissions from various sectors and from neighbouring and local regions. Source: https://ews.tropmet.res.in/dss/scenario.php.

Though their objectives are the same, the methodology of the DPCC and MoES efforts are different and complementary. While the DPCC supersite setup uses online monitoring of aerosol chemical speciation, the MoES effort uses a chemical modelling setup to derive source characteristics. Each method has its own uncertainty, but both provide valuable insights into the source signature on a real-time basis so that informed decisions can be taken.

Opportunities for Asia-Pacific cities

Other Asia-Pacific cities can replicate the Delhi effort and set up such a system for better air quality management. Key considerations are as follows:

- The cities should have a robust emission inventory covering neighbouring regions for baseline analysis.
- The cities should establish a supersite at a representative location of the cities for full chemical speciation monitoring.
- A second supersite in an upwind location (depending on the financial resource) within the city airshed would allow a comparative assessment of source characteristics within the city and outside the city. Such comparison would provide real-time information about the efficacy of city-scale interventions.
- The same modelling setup will also be useful for cost-effectiveness analysis using RCMs.
- The sectoral mitigation plans can be linked to the decision support system-based information for more effective management.

3.4 Intervention studies

3.4.1 Effectiveness of Applying Dust Suppressant in Delhi

The effectiveness of the dust suppressant was evaluated in three locations of Delhi – Sarai Kale Khan (road construction site), Narela (building construction site), and Dilshad Garden flyover (road construction site). PM_1, $PM_{2.5,}$ and PM_{10} were monitored before and after the applications at different time intervals, and based on the results, NEERI concluded that a 50-60% initial reduction can be achieved after 10 mins. PM levels remained lower by 30% up to 6 hours after the application. The following table summaris es the result (Source: https://cpcb.nic.in/air/Advisory2_27.09.2019.pdf).

Table 3.1 Percentage reductions in PM_{10}, $PM_{2.5,}$ and PM_1 after the application of dust suppressant in Delhi. The table is taken from the CPCB report.

Session	Time Lag (after application)	PM_{10} (% reduction)	$PM_{2.5}$ (% reduction)	PM_1 (% reduction)	Overall efficiency (% reduction)
Morning	10 min	59.01	62.37	62.03	61.13
	1 hour	56.11	53.60	54.20	54.64
	2 hour	50.38	48.95	48.51	49.28
	3 hour	43.84	42.42	42.63	42.96
	6 hour	40.52	36.79	36.32	37.88
Evening	10 min	59.60	59.01	59.56	59.39
	1 hour	55.82	51.09	52.31	53.07
	2 hour	48.52	43.16	44.21	45.30
	3 hour	42.39	39.03	38.56	39.59
	6 hour	39.26	33.48	31.69	34.81

Opportunities for Asia-Pacific cities

This case study demonstrated that the technology can be adopted by other cities to reduce PM loading at a shorter time scale, particularly at major construction and other hotspots. However, cities should continue with sustainable solutions to mitigate emissions.

3.4.2 Effectiveness of smog tower in Delhi

A smog tower was installed at Baba Kharag Singh Marg, Connaught Place, New Delhi. The tower, made of a combination of RCC and steel structure, has a height of 24.2 m above ground level, and it can filter 1000 m^3 of air per second. The installation has 40 fans that can operate at a speed of 960 RPM and an airflow rate of 25 m^3 per second.

Studies revealed that the smog tower reduces air pollution levels by 17% in a 100 m radius with an operational cost of INR 15 lakh per month. The action taken report placed before the green tribunal (https://greentribunal.gov.in/sites/default/files/news_updates/REPORT%20BY%20DPCC%20IN%20OA%20NO.663%20of%202023%20In%20re%20News%20item%20published%20in%20Indian%20Express%20dated%2007.10.2023%20titled%20GRAP%20Stage%201%20kicks%20in%20as%20air%20quality%20dips%20to%20poor,%20condition%20likely%20....pdf) also says that there is no improvement in ambient air quality in terms of particulate matter after the installation of smog tower at other locations. To make a significant impact, more than 450,000 such towers are required for a city like Delhi. This led to the overall conclusion that the smog tower was not a cost-effective solution to reduce ambient pollution levels in a city like Delhi.

Opportunities for Asia-Pacific cities

The case study suggests that such an outdoor filtration system has a very limited impact, mostly within proximity. Unless such towers are deployed in large numbers, it will not be effective. An estimate by Guttikunda and Jawahar (2020) suggests that Delhi needs at least 5 million smog towers in winter, with each one of capacity to clean 25000 m^3 volume of air per hour (that has been recently installed) for 500 billion USD. Clearly, this is not a cost-effective solution. Cities should not blindly use such technologies to mitigate air pollution; rather, they focus more on sustainable solutions. However, such technologies can be used in places where the footfall is very high, and there is potential to reduce exposure substantially, particularly for vulnerable populations (e.g., schools, hospitals, etc.). It is also advised that such technology uses solar power and not the traditional power generated from coal-fed plants. Otherwise, the net consequence will be higher emissions from power plants elsewhere.

3.4.3 Urban greening

Urban greening has been proposed as a natural solution for environmental problems faced by the cities. The connection between urban greening and air pollution levels is contradictory (see Figure 3.3) in the literature (Kumar et al., Env Int, 2019). There are studies demonstrating that vegetation leaves can remove particulate matter by dry deposition (e.g., McDonald et al., 2007) and adsorb gaseous pollutants through their stomata (e.g., Yin et al., 2011). Increased green cover can reduce temperature and, in turn, reduce energy demand in a city, thereby indirectly contributing to less fossil-fuel combustion and improving air quality (Akbari et al., 1997). However, the effect could be reversed in winter when this can enhance fossil fuel and biomass combustion (Simpson and McPherson, 1998). Some trees emit hydrocarbons. A recent modelling study (Yu et al., EST, 2022, 56) found that urban greening can reduce near-surface temperature, improving thermal comfort, but biogenic volatile organic compound emissions may enhance surface ozone under certain conditions, and it has the potential to alter $PM_{2.5}$ concentration via radiative feedback.

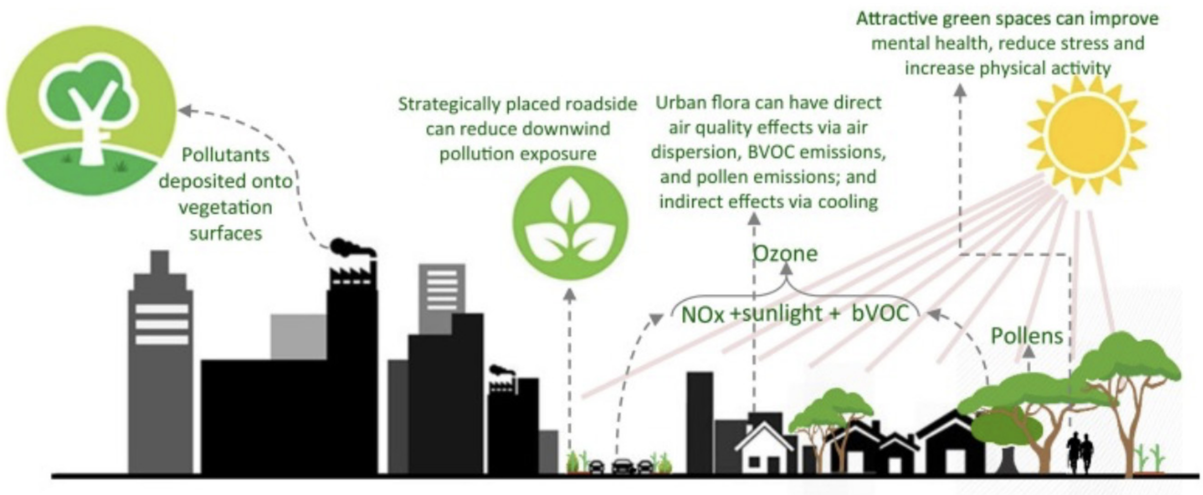


Figure 3.3 Schematic diagram showing air quality benefits and degradation pathways due to green infrastructure in an urban environment. Source: Kumar et al. (2019).

Due to such contradictory evidence on the nexus between urban greening and air quality, cities should not blindly engage in plantation drives and randomly plant tree saplings. For example, green infrastructure between sources (e.g., traffic) and receptors (e.g., commuters) was found to act as a natural barrier. In open-road conditions, a continuous line of thick vegetation barrier was found to reduce downwind pollutant concentrations by up to 60% (Abhijith et al., 2017). The effectiveness of such barriers depends on the porosity, height, and width of the barrier and, most importantly, on the vegetation species (Baldauf, 2017).

Cities are continuously evolving, and urban greening needs to be an integral part of urban planning. However, this should be done through consultation with experts and based on scientific studies to maximis e the benefits.

CHAPTER IV: RECOMMENDATIONS AND WAY FORWARD

The technology compendium summaris es the available technologies that can be utilis ed in air pollution monitoring, controlling emissions from the various sectors, and removing air pollutants. It also compiles the existing case studies from Asia-Pacific countries and discusses the outcomes given their merits and limitations. This chapter provides recommendations on effective ways to implement technological interventions in the Asia-Pacific cities.

4.1 Systematis e a hybrid monitoring and data analytics framework within the city airshed

One fundamental limitation for the Asia-Pacific countries in the battle against air pollution is the lack of an adequate regulatory-grade monitoring network. The high initial and maintenance costs of regulatory-grade monitors result in a slow network expansion in most countries. India has launched the National Clean Air Program, yet it lags way behind its own target, followed by the Central Pollution Control Board's thumb rule (Guttikunda et al., Atm Env, 2023). In many other South Asian countries, ground monitoring is even scarcer.

The existing network is not suitable for assessing the efficacy of any technological interventions at a local scale in any Asia-Pacific cities unless the intervention is implemented within proximity of the monitor. With multiple sources and other factors influencing local air quality, it is difficult to tease out the signal of a single or a group of interventions using data from one monitor. Therefore, the cities should build up a hybrid monitoring system focusing on the air shed.

At the hotspots, a dense network of IoT-based sensors (duly calibrated against the nearest regulatory-grade monitor) can provide better insights into the local factors. Satellite-derived information can help track the regional air quality, and a comparative analysis of air quality changes within and outside the cities can provide evidence of regional vs local influences. Monitoring (online or offline) of particulate composition and gaseous pollutants can provide insights into the changing nature of the source profiles.

The most important aspect is linking these data to the interventions. There is no uniform way to design the sensor network; rather, it should cater to the requirements. For example, if the air quality benefit of the conversion of the brick kilns to the improved zig-zag technology needs to be assessed, IoT sensors can be deployed (if no regulatory-grade monitors exist) both in upwind and downwind directions of the brick kilns or a cluster of kilns. Reduced emissions due to the conversion of brick kilns to cleaner technology should benefit air quality more downwind than upwind (if other factors remain unchanged). This should be reflected in the analysis of the sensor data (after removing the effect of meteorology in the pre- and post-intervention period). Analysis of satellite data (e.g., Shaw et al., 2020) can provide supporting evidence of reduced emissions, if any, due to the interventions. The same framework can be applied to power plants or other industries.

However, such a system does not exist in the Asia-Pacific cities, and it requires not just the technology but also a data analytical system to support its operation. A detailed approach towards this direction has been provided recently by Gani et al. (2022). The key aspects of such a system are (a) the instrumentation set up in a complementary and integrative manner, (b) measurement system design based on the application, (c) data architecture, and (d) data integration into a 'decision support system' and analysis for air quality management.

4.2 Engage with academia and corporate partners

The administration in Asia-Pacific cities often lacks the required technical expertise to implement technological interventions and data analysis to support the air quality management plan. Therefore, they must foster partnerships with academia for technical inputs and relevant industry partners to accelerate and scale up technological interventions.

The NCAP of India has created a framework for engaging with academia through the creation of a national knowledge network where each non-attainment city is paired with an institute of repute (IoR) https://pib.gov.in/PressReleasePage.aspx?PRID=1882836. The IoRs are contacted by the city officials for technical expertise in a range of activities such as emission inventory development, source apportionment, and carrying capacity studies, as well as providing scientific inputs in various action plans, data analysis, and technology testing. Two types of funding mechanisms were made available for such engagements. First, dedicated funding was earmarked for each IoR against each task they were assigned by the city for technical expertise. Secondly, each non-attainment city was also allotted funds for improving air quality and meeting the NCAP target. The cities were given a free hand to utilis e the fund as per the requirement, and some of this fund is being utilis ed by the cities to engage with the IoRs. This engagement can be replicated by the city administration of other Asia-Pacific countries with their own Institutions.

Industry engagement in the field of air quality management is still in the nascent stage in Asia-Pacific countries. Most LMICs lack the financial resources required for a comprehensive air quality management plan. Therefore, they can leverage the corporates to expand the monitoring network and scale up technological interventions.

4.3 Consult with relevant stakeholders and establish administrative coordination

Adoption of new technologies requires adequate planning in terms of financial resources and logistics. The cities should consult with all relevant stakeholders to understand the pros and cons and the implications before full-scale adoption of any new technology. The process may differ for different technology.

The application of advanced technologies for air quality monitoring requires specialis ed training. City administration can either engage with experts or develop the capacity of their own officials. However, emission controls through technology adoption are a gradual process and require investment, the magnitude of which depends on the scale of interventions. For example, old power plants need massive infrastructural changes to implement FGD, and the cost, according to a C-STEP report, could be INR 3.91-3.96 lakh crore by 2030. Therefore, consultation with the power sector is important to work out the implementation plan and a layout for financial burden sharing to minimis e the negative impact of power tariffs.

For the agricultural waste sector, consultation with farmers is important to decide on the best in-situ and ex-situ management practices based on crop variety, local factors, and logistics support. Technological interventions in the transport sector require support from the automobile industry. Public outreach programs with effective communication will promote behavioural changes for faster and smoother adoption of new technology at an individual level. The cultural aspects posing barriers to the complete transition to clean cooking in households can be addressed through public awareness.

While certain sectors are directly under the jurisdiction of the city administration, many important sectors are managed by state and central administrations in Asia-Pacific countries. Therefore, in a federal system, strong city-state- centre coordination is of utmost importance in enabling successful technology adoption across the sectors. A city airshed may cut across state boundaries, and hence, interstate coordination needs to be established. Unless technology is adopted and implemented across all key emitting sectors, the impact on city air quality may not be visible.

4.4 Conduct pilots for efficacy checks of new technologies

Currently, no uniform policy exists for technology start-ups across the board. There is a lack of clarity on the requirement of certification for a technology to be adopted. This has caused a dilemma and delay in adopting certain technologies wholeheartedly. For example, the CPCB has put on hold the open dissemination of air pollution data from IoT sensors unless a certification system is in place. The National Physical Laboratory was given the mandate to set up the certification system for all sorts of air pollution measurements. While the effort is commendable and a welcome step, it is not clear whether the core sensor, the data quality, or both need to be certified. This is particularly important as studies have shown that the IoT sensors can provide reliable data after rigorous calibration, and the sensors need frequent checks to maintain data quality. Therefore, even if the sensor is certified before or after calibration, its performance may vary depending on local conditions. Moreover, the data accuracy requirement also depends on the application. As a result, the adoption of this technology gets delayed and is mostly restricted to academia. Similarly, many innovations in the field of air filtration have emerged in recent times, and these technologies require thorough evaluation under contrasting environments as their performance may vary with local conditions.

A policy framework needs to be evolved to test new technologies in the pilot before their full-scale adoption. The policy should then enable smooth pilot-to-field deployment of the technologies following norms that can be fixed for the type of application.

4.5 Set sector-specific interim targets with timelines

Most Asia-Pacific cities are racing against time to clean their air. Since 2015, the countries made a lot of progress, but the progress needs to be accelerated. Many Asia-Pacific countries have air quality management plans with clean air targets. However, it is not possible to check progress and do course corrections, if any are required, without any interim targets. Moreover, there is no accountability for any sector without any sector-specific target.

Specific interim targets should be set by every emitting sector to enable tracking progress. For example, a specific timeline can be set for converting all brick kilns to cleaner technology with clear annual targets. Set annual increments of EV charging stations could be an interim target for the transport sector. The number of machines for in-situ stubble management and the number of plants that can use pellets made up of stubble (promoting ex-situ practices) could be interim targets. Each city should set these targets for all key sectors in coordination with the state and central administration.

4.6 Prepare a technology adoption strategy

This compendium has provided multiple technology options for the city to adopt for air pollution mitigation. Technology requirements may vary across the cities depending on the sectoral contributions, geographic location, and the clean air implementation plan. Therefore, the cities should prepare a technology adoption plan with clear policy guidelines for each sector.

The plan should outline how the cities should assess and evaluate the technologies based on their own requirements and prioritis e their applications. Some key features and metrics could be feasibility, accessibility, effectiveness, potential to scale up, implementation cost, and acceptability. Cities should also be involved in scenario analysis using RCMs to assess the cost-effectiveness of various technologies to help them make an informed decision. The sectors that co-emit greenhouse gases can be given priority. Such a strategy should be reviewed periodically.

4.7 Make technological interventions inclusive of the decision support system

The cities should develop a decision support system and link mitigation plans based on technological interventions accordingly. Delhi's decision support system can serve as a good example, but it also has the potential to improve. For example, the early warning system currently indicates the sectoral and regional contributions to Delhi's air quality, but it does not prioritis e any mitigation controls. Such a decision support system should establish baselines to assess the potential impacts of technology adoption in a particular sector to enable the policymakers to compare against actual data. If road dust contribution is projected to increase in the next few days, the decision support system should provide estimates for potential reduction in PM2.5 due to the use of dust suppressant. The cities should then prioritis e dust control technologies in the hotspots and check their efficacy against the baseline calculations. A similar strategy should be taken across the sectors, with the technological adoption strategy being an inclusive component of the decision support system.

4.8 Accelerate progress toward carbon neutrality

China's CO_2 emissions decreased by 48.4% between 2005 and 2020 (Liu et al., Nature Rev Earth & Environ, 2021). This was achieved by first setting sub-national and sectoral targets as part of their five-year plans. Once the targets are achieved by driving towards reducing the share of conventional fossil-fuel energy, the plans are updated subsequently. Such aggressive measures not only enabled China to meet the objectives outlined in the Nationally Appropriate Mitigation Actions and Nationally Determined Contributions but also helped cities like Beijing reduce air pollution levels drastically. Technological intervention in a strategic manner has been touted as a major factor in China's remarkable progress toward cleaner air (Lewis, 2023).

China has demonstrated that it is possible to bend down the pollution curve in a few years. Every city should be encouraged, and plan based on its own capacity and resources to accelerate its progress toward carbon neutrality for sustainable growth. Scientific evidence should support policy decisions, and the policy framework should be flexible enough to accommodate changes based on the evidence.

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