# INTEGRATED AIR QUALITY MANAGEMENT

135 lecture hours – 45 credit hours

## CONTACT LECTURERS:

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## OBJECTIVES:

**Knowledge:** This course aims to equip students with scientific basis and engineering knowledge to understand the complexity of the air pollution problems, multiple effects of air pollution from local to global scales, and principal tools for integrated air quality management. The course has a specific focus to provide the solutions relevant for Asian regions to enhance students' understanding of the principal approaches to reduction of the emissions from key sources and improve air quality in the region.

**Skills:** The students on completion of this course would be able to:

- Design a framework of integrated air quality management using key technical and policy tools
- Calculate the emissions from major source categories and assess their relative contributions in a domain
- Analyze air quality monitoring data with QA/QC consideration
- Determine basic air pollution meteorology parameters and calculate ambient concentrations of air pollutants using Gaussian models
- Develop simple statistical models for ambient air quality prediction
- Operate HYSPLIT model to get trajectories of air masses

**Attitude:** After completing the course, the students are expected to be able to place air quality management in the overall context of the environmental quality management, climate change and sustainable development. The students will have a clear view on the needs for integrated approach and needs for deploying both traditional and advanced technological instruments for the effective air quality management. The students are expected to further develop their skills of management of big datasets resulting from monitoring, emission inventory and modeling results of air quality.

## CONTENT OF THE COURSE:

Chapter 1: **Air Pollution: Local, Regional and Global Issues (7 h)**

1. The Atmosphere and Air Environment
2. Development and Air Pollution
3. Basic Terminologies

4. Types of Air Pollutants: Particulate Matter, Gases, Primary and Secondary Air Pollutants
5. Sources of Air Pollutants: Man-made and Natural Sources
6. Expression of Air Quality: Measurement Units, Averaging Time, Air Quality Index (AQI)
7. Status and Issues of Air Pollution at Asian and Global Scale
8. Urban vs. Rural Air Pollution
9. *Exercises*
    - *Convert units of gaseous pollutants from mass/volume to volume/volume*
    - *Calculate AQI using US EPA and other AQI schemes*

Chapter 2: **Effects of Air Pollution (8 h)**

1. Health Effects of Air Pollution: General Effects, Effects of Specific Pollutants,
2. Health Effects of Ambient and Indoor Air Pollution
3. Effects on Local Environment
4. Effects on Ecosystems
5. Regional and Transboundary Effects: Acid Rain, Haze, Atmospheric Brown Cloud
6. Global Effects: Air Pollution and Climate, Ozone Layer Depletion
7. *Exercise: calculate the Global Warming Potential (GWP) of emissions on different time horizons*

Chapter 3: **Integrated Air Quality Management (8 h)**

1. Basic Concepts of Air Quality Management
2. Key Activities in Air Quality Management Program
3. Technical Tools for Air Quality Management
4. Economic Aspects of Air Quality Management
5. Integrated Approach to Source Emission Control: Control Techniques for Particulate Matter and Gases, Integrated Approach to Industrial and Vehicular Emissions Reduction
6. Clean Air Action Plans
7. Case Studies: Success and Failure in Air Quality Management
8. *Exercises: calculate final emissions from a stack of thermal power plant assuming applications of different control techniques*

Chapter 4: **Air Pollution Monitoring and Emission Inventory (9 h)**

1. Development in Air Pollution Monitoring Technologies
2. Design of Monitoring Program with QA/QC
3. Sampling and Analytical Techniques for Air Pollutants
4. Monitoring Methods for Ambient Air, Indoor Air and Emission Sources
5. Advanced Monitoring Techniques: Remote Sensing, Satellite, Wireless Sensor

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6. Emission Inventory: Calculation Methods and Data Requirement for Different Source Categories
7. Management of Monitoring and Emission Inventory Big Data (data validation using QA/QC, processing, storage, update, presentation, and publicizing)
8. *Exercises:*
   - *Analysis of diurnal variation patterns of key pollutants using time series monitoring data in relation to the emission sources and atmospheric processes*
   - *Download MODIS AOD and develop regression models between AOD and ground-based PM data with and without incorporation of meteorological variables*
   - *Calculation of emissions from traffic, residential cooking, and industrial sectors in a domain*

Chapter 5: **Meteorology and Air Quality Modeling (9 h)**

1. Meteorology: Atmospheric Processes Affecting Pollutant Dispersion and Removal
2. Types of Air Pollution Models: Dispersion, Receptor and Statistical Models
3. Application of Dispersion Modeling for Air Quality Management
4. Gaussian Models and Applications
5. Chemical Transport Models and Applications
6. Largrangian Trajectory Models
7. Statistical Models and Applications
8. Management of Big Dataset of Air Pollution Modeling Results: Evaluation, Processing, Presentation and publicizing
9. *Exercises:*
   - *Calculate ambient concentrations from a stack emission*
   - *Apply HYSPLIT to get backward and forward trajectories of air masses for a location*
   - *Develop regression models to predict pollutant concentrations using time series analysis of selected pollutants, meteorology, and source parameters*
   - *Evaluate model performance using scatter plots and model performance statistics*

Chapter 6: **Special Topics of Air Environment Management (4 h)**

1. Noise Pollution and Management
2. Odor Pollution and Management
3. Photochemical Smog and Surface Ozone Pollution

## ACADEMIC MATERIALS

**Textbook:**

1. Wark, K., Warner, C. F. & Davis, T.W. (2003). *Air Pollution: Its Origin and Control.* New York: Harper & Row Publishers.

**Reference books:**

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1. Seinfeld, J. H. & Pandis, S. N. (2006). Atmospheric Chemistry and Physics: from air pollution to climate change. New York: Wiley Interscience.

2. Godish. T. (1994). Indoor Air Pollution Control. Boca Raton, Florida: Lewis Publishers.

3. Noll, K. E. (1999). Fundamentals of Air Quality Systems - Design of Air Pollution Control Devices. U.S.A.: American Academy of Environmental Engineers.

4. Kim Oanh, N. T. (Ed.) (2012). Integrated air quality management: Asian case studies. New York: CRC press, Taylor & Francis.

5. Wight, G. D. (1994). Fundamentals of Air Sampling. Boca Raton, Florida: Lewis Publishers

**Journals/ Magazines/ Websites:**

1. Air and Waste Management Association, *Air & Waste Management Association*
2. Atmospheric Environment, *Elsevier*
3. Aerosol and Air Quality Research, *Taiwan Association for Aerosol Research*
4. Atmospheric Pollution Research, *Elsevier*
5. Environmental Science and Technology, *America Chemical Society Publications*
6. http://www.unep.org/tools/default.asp?ct=air
7. http://www.who.int/topics/air_pollution/en/
8. http://www.epa.gov/airquality/
9. http://ec.europa.eu/environment/air/quality/
10. http://cleanairinitiative.org/portal/index.php
11. Video clips (online materials, WBI for AQM practices, etc.)

# INTEGRATED AIR QUALITY MANAGEMENT

## 1. Introduction

Economic growth with industrialization, urbanization and motorization, and consequent changes in land use/cover bring in a better life to people around the world but also puts a huge pressure on the environment. The management capacity for the environment, in general, and air quality, in particular, has not been developed at the same pace especially in developing countries. Dirty fuels are still widely used in low efficient combustion devices which are not equipped with adequate control technologies hence releasing large quantities of atmospheric emissions. As the results, high pollution levels are observed in the ambient air. Of the most concern from the health effect point of view is the fine particulate matter, $PM_{2.5}$ (particles with size below 2.5 µm) which has been reported at episodic levels in many places in developing countries. Surface ozone ($O_3$, a secondary pollutant, is of concern due to its toxic and phytotoxic effects as well as the climate warming effect.

Air pollution presents a significant threat to human health and the environment globally. This in turn affects the economy through the increased mortality, morbidity, damage to crops and properties, and loss of tourism. According to Health Effects Institute (HEI, 2020), air pollution was the 4$^{th}$ leading risk factor for early death worldwide that caused about 6.67 mil. deaths, sharing 12% of the global total mortality from all causes. Specifically, long-term exposure to ambient $PM_{2.5}$, $O_3$, and household air pollution cause 4.14 mil., 365,000, and 2.31 mil. death worldwide in 2019, respectively (HEI, 2020).

Developing Asia has the highest recorded levels of air pollution and associated number of mortality (HEI, 2020) which are the consequence of the large emissions from both domestic and transboundary sources. The prevalent monsoons in Asia enhance the long-range transboundary transport of pollutants. The most notable examples of the air pollution long-range transport in Asia include the Southeast Asian haze, acid rain, dust storm and Atmospheric Brown Clouds (ABC). These transboundary phenomena may cause multiple effects on regional air temperature, precipitation, agriculture, air quality, and human health, and currently attract increasing attention from research community, public and policy makers.

This chapter highlights the principles of integrated air quality management (AQM) with a focus on Asia. The content also reflects the new development of monitoring and modeling technologies, the use of Internet of Thing (IoT) and citizen-based science for timely dissemination of the air quality data so that immediate and appropriate actions can be taken to reduce the levels and exposure to air pollution in a specific domain.

## 2. Fundamentals of Air Quality Management

### 2.1 Common air pollutants and effects

Ambient air quality is a dynamic and complex environmental phenomenon which exhibits large temporal and spatial variations reflecting changes in source emission, meteorological and topographical conditions. The air quality is normally expressed using the concentrations of individual pollutants (ppm, µg/m$^3$) or using the Air Quality Index (AQI), an aggregate measure of color scales, to facilitate the public information. Air pollution is commonly defined as the presence in the outdoor and indoor air of substances, in concentration and duration, that are sufficient to produce measurable adverse effects on human beings, animals, vegetation or materials. These substances are the air

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pollutants which are generally classified into particulate matter (PM) and gaseous pollutants. Examples of the gaseous pollutants with their general classifications are shown in Table 1. PM is generally classified based on the size range, e.g., fine, and coarse particles, or by chemical and physical properties such as black carbon (BC), organic carbon (OC), sulphate or nitrate particles. The pollutants are also commonly classified based on their emissions and formation processes into the primary and secondary air pollutants. The primary pollutants are those directly emitted from the sources, e.g., soil dust, BC particles, flyash particles, carbon monoxide (CO), etc. while the secondary pollutants are formed in atmosphere from the precursors, e.g., secondary particles (sulfates and nitrates) and $O_3$.

**Table 1. Types of gaseous air pollutants**

| Class | Primary | Secondary |
|---|---|---|
| S-containing | $SO_2$, $H_2S$ | $SO_3$, $H_2SO_4$, $MSO_4$ |
| Organic | HC compounds | Ketones, aldehydes, acids, organic aerosols |
| N-containing | NO, $NH_3$ | $NO_2$, $MNO_3$ |
| Oxides of carbon | CO, $CO_2$ | None |
| Halogen compounds | HCl, HF | None |
| Photochemical oxidants | VOC, $NO_x$, etc. | $NO_2$, $O_3$, $H_2O_2$, PAN |

Note: $MSO_4$ , $MNO_3$ are sulfate and nitrate salts (e.g. ammonium); PAN: peroxyacetyl nitrate, a photochemical oxidant

In large cities of Asian developing countries, ambient air quality has worsened and approached dangerous levels. Available measurements data show high levels of $PM_{2.5}$ and $PM_{10}$ (particles with the aerodynamic size less than 10 µm) in developing Asia which are of the most health concern. Levels of other commonly measured pollutants including $O_3$, CO, sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$ = NO + $NO_2$) and lead (Pb) vary significantly among cities. Other air toxics such as volatile organic compounds (VOC), e.g., benzene, semi-VOC, e.g., polycyclic aromatic hydrocarbons (PAHs), pesticides, heavy metals (e.g., mercury Hg) have not yet adequately characterized and reported. Indoor air pollution is also serious due to the use of dirty fuel in low-efficient cookstoves.

**Particulate matter (PM)**

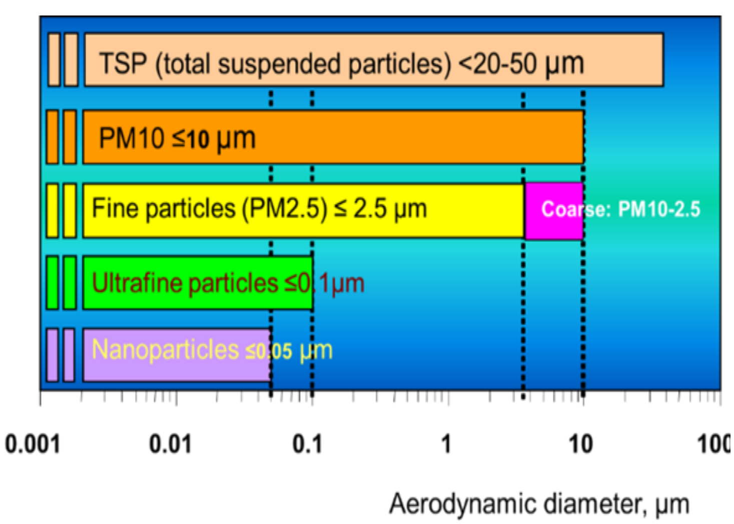


**Fig. 1. Particulate matter size ranges and terminologies**

The atmospheric particles involve solid and liquid matters suspended in the air, ranging from the size above the largest gas molecules to about 20-50 µm (Fig. 1). Exposure to PM may cause serious health effects, including inflammation of respiratory tract, exacerbation of existing airway disease, impairment of pulmonary defense mechanisms, alteration in airway reactivity to antigens, etc. Atmospheric particles may contain toxic components, such as BC, OC, sulfates, nitrates, heavy metals, among others. The toxic materials such as carcinogenic compounds of PAHs, dioxins and pesticides are adsorbed/absorbed on the particle surface, especially on the fine particles. Smaller particles ($PM_{2.5}$) are more harmful because they can penetrate deeply into lungs. Atmospheric particles also interact directly and/or indirectly with the Earth's radiation energy balance and can subsequently affect the global climate (IPCC, 2007).

In several Asian countries, $PM_{2.5}$ episodes are often reported during the dry seasons, due to the stagnant atmosphere coupled with the increased emissions from biomass open burning and enhanced long-range transport.

**Surface ozone ($O_3$)**

$O_3$ in the atmosphere exists in two layers. The stratospheric $O_3$, with the $O_3$ layer heart at around 25 km, absorbs the harmful ultraviolet solar radiation and protects life on the Earth hence is called the 'good ozone'. Oppositely, the "bad ozone" that exists near the Earth surface or the tropospheric/surface/ground-level $O_3$ which is a harmful air pollutant formed in the air from precursors of VOC and $NO_x$ (see section 6.3 for details). Surface $O_3$ causes toxic effects to human health (e.g., inflammation of respiratory tract, cough, sore throat, breathing difficulty, etc.), materials, and environment. $O_3$ caused 365,000 deaths worldwide in 2019 (HEI, 2020) and millions of tonnes of crop yield losses annually (UNEP, 2018). It is a well-known phyto-toxicant that adversely affects vegetation hence can reduce the growth and yield of agricultural crops and forests (Danh et al., 2016). The tropospheric $O_3$ is also a strong greenhouse gas (GHG) with a strong positive radiative forcing (IPCC, 2007). In the boundary layer of the atmosphere (generally below 2 km) the residence time of $O_3$ is about a day. In the upper part of the troposphere the residence time of ozone may reach a few weeks which enables the long-range transport.

It is reported that the background levels of $O_3$ in the northern hemisphere increased more than 2 times as compared to the pre-industrial period and now reaches levels of 35-40 ppb. The peak $O_3$ levels are now observed above the WHO guideline (100 ppb, 8h) in many places in the world (WHO, 2021). The booming of cities in Asia creates mixed land-use patterns with cities surrounded by agricultural fields. This leads to high risks of $O_3$ exposure for crops in downwind areas of city centers where $O_3$ is potentially high.

**Carbon monoxide (CO)**

CO is a product of incomplete combustion which is released in large quantities from vehicle engines, low-efficient cookstoves and open burning of solid waste and crop residue, and accidental fires. In urban areas, CO is normally high at the busy roadside. CO has a high affinity to hemoglobin, about 200 times greater than oxygen. When CO is inhaled, it combines with hemoglobin (an iron-protein component of red blood cells) producing carboxyhemoglobin (COHb), which greatly reduces oxygen uptake and transport to vital organs like the heart and brain. Exposure to CO can cause various health problems, including 1) at low levels: fatigue in healthy people and chest pain in people with heart disease; 2) at moderate levels: angina, impaired vision, reduced brain function; 3) at higher levels: impaired vision and coordination, headaches, dizziness, confusion, nausea, flu-like symptoms, and death at very high concentrations. At the level above 800 ppm the fatal effects occur within 1-hour exposure.

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**Nitrogen dioxide ($NO_2$)**

Among the $NO_x$ present in the atmosphere, $NO_2$ is of most concern from the point of view of human health. The toxicity of exposure to $NO_2$ to humans is not yet well understood, especially at low levels commonly found in the ambient air (WHO, 2021). Acute exposures at high $NO_2$ levels can worsen respiratory diseases, i.e., asthma and cause various respiratory problems, and increase hospital admissions. Chronic exposures to elevated $NO_2$ enhance the development of asthma and increase susceptibility to respiratory infections. People with asthma, as well as children and the elderly are generally at greater risk for the health effects of $NO_2$.

**Sulphur dioxide ($SO_2$)**

This gas is emitted from the combustion of sulfur-containing fossil fuels such as coal and fuel oil in industrial boilers, thermal power plants, cookstoves, and vehicle engines, as well as from natural sources of volcanoes and ocean. Acute exposure to this strong acidic gas causes respiratory effects in humans by making breathing difficulty, especially people with asthma and children.

**Volatile organic compounds (VOC)**

VOCs are released from incomplete combustion of fuel in cookstoves, vehicle engines and biomass burning, tobacco smoking, as well as fugitive emissions from fuel distribution, e.g., gasoline stations. In homes, VOCs are released from household products such as paints, varnishes, and wax, as well as household chemicals (cleaning, disinfecting, cosmetic, etc.). Concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. Exposures to VOC can lead to a range of health effects, including irritation of eye, nose and throat, headaches, loss of coordination, nausea, damage to liver, kidney, and nervous system, and cancers. The extent of health effects highly depends on type of VOC compounds, exposure dose, exposure time, and susceptibility people. For example, benzene is a carcinogen that is released from the gasoline stations, vehicle exhausts, cooking and biomass burning, etc.

**Semi-volatile organic compounds (SVOC)**

These species present in the air partly as gaseous airborne chemicals and partly as chemicals adsorbed on airborne particles. Examples of SVOC prevalent in the air include PAHs, dioxins, chlorinated pesticides which are acutely toxic and carcinogenic compounds hence of great health concern. PAHs are released from incomplete combustion of fuel in vehicle engines, cookstoves, and open burning of solid waste and biomass. Dioxins have many sources including the open burning of solid waste and crop residue. Some pesticides may be carcinogens, some affect the nervous system while others may irritate the skin or eyes.

**Short-lived climate forcers**

Some pollutants have climate forcing effects and because they have shorter lifetime than carbon dioxide ($CO_2$) they are called short-lived climate forcers (UNEP-WMO, 2011) or short-lived climate pollutants (SLCF/P). Thus, besides having health effects, these species also have climate impacts, some are warming (BC, $CH_4$, CO) while others are cooling ($SO_2$, $NO_x$, OC) agents. Especially, BC particles can absorb solar radiation and warm the atmosphere (Bond et al. 2013).

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## 2.2 Indoor air pollution

Indoor air pollution levels depend on several factors including the presence of indoor sources and the emission rate, ventilation rate, penetration of outdoor pollutants into the indoor environment, and pollutant sink or removal rate on indoor surfaces. Many sources, related to both combustion and non-combustion activities, emit air pollution indoors. In poorly ventilated homes, indoor fine PM concentrations can exceed the limits, which are set for outdoor air, by dozens to hundred times. Exposure is particularly high among women and children in rural areas, who spend most of the time near fireplaces in homes. Children are affected more by indoor air pollution than ambient air pollution. On a global scale, indoor air pollution is responsible for the death of 2.31 mil. people in 2019 (HEI, 2020). Of all neonatal deaths attributable to air pollution, household air pollution (from burning solid fuels for cooking) accounts for about 64%, while the rest are attributable to ambient $PM_{2.5}$.

The indoor air pollutants are originated from indoor sources can be grouped in 4 categories: i) combustion pollutants (residential combustion, tobacco smoke), ii) non-combustion VOC (building materials, household products, paints, or from contaminated soil), and iii) hazardous chemicals used indoor (pesticides, asbestos containing materials), iv) biological agents (mildew, molds, fungus, or bacteria, house dust mites, etc.) as seen in Table 2.

**Table 2. Air pollutants predominantly indoor and sources** (Kim Oanh and Hung, 2005)

| **Pollutants** | **Sources** |
|---|---|
| Radon | Building materials, soil, water |
| Asbestos, mineral wools, synthetic fibers | Insulation, fire-retardant, ACM |
| VOC | Adhesives, solvents, cooking, cosmetics, smoking |
| Formaldehyde | Particleboard, insulation, smoking, combustion sources |
| Nicotine aerosols | Tobacco smoking |
| Hg | Fungicides in paints, lab., thermometer breakage |
| Biological pollutants viable PM/allergens | Infected organisms, house dust mites, animal debris |

In Asian developing countries, cooking and space heating using dirty fuels are the leading cause of indoor air pollution. Solid fuels such as wood, agricultural waste, cattle dung, or low-quality smoky coal are still commonly used in rural and peri-urban areas to release large amounts of pollutants indoors (Huy et al., 2021). Poorly ventilated kitchens lead to a high build-up of combustion pollutants indoors during cooking periods. Space heating with open fires is done with reduced ventilation to keep in the warmth in cold winters, which leads to even higher exposures.

## 2.3 Transboundary pollution

Air pollutants emitted at a location may widely disperse and circulate the globe within a few days to weeks depending on the meteorological conditions hence the impacts of human activities are felt from local to global scale. In the transboundary events, the emissions within a state/country can introduce adverse effects in other states/countries. The pollutants that have been observed and model predicted to have a high potential for long range transport include fine particles, acidifying substances ($SO_2$, $NO_x$), $O_3$ and its precursors, heavy metals (e.g., Hg) and persistent organic pollutants (POP). Major transboundary air pollution issues in the Asian continent include the Southeast Asian haze (ASEAN

Haze), ABC, Northeast Asian dust storm and acid deposition. It is noted that POP as well as the trace elements from coal combustion, particularly Hg, also have a high potential for long range transport in Asia, hence more comprehensive studies are required to analyze the issues.

*SEA haze*: Smoke from big forest fire events, that frequently occur during the dry season in Southeast Asia (SEA), causes severe transboundary haze pollution problems. The smoke contains high levels of toxic gases (VOC, PAH, CO) and fine particles. The fine haze particles can affect the atmospheric visibility and climate forcing. The ASEAN HAZE agreement (ASEAN, 2016) entered into force in 2003, aims to tackle transboundary haze pollution resulting from land and forest fires.

*Atmospheric brown cloud (ABC)*: The ABC appears as large air masses which are a few km thick and contain pollution at levels similar to those found in polluted air in heavily populated regions. There are several ABC hotspots in the world including those in South, Southeast and East Asia. It consists of a mixture of aerosols (BC, OC, sulfates, nitrates, etc.) and is thought to mainly originate from burning of fossil fuels and biomass over the entire Asia. ABC is transported far from the source regions hence can introduce multiple effects on regional air quality, air temperature, precipitation, agriculture, and health (UNEP, 2008).

*Asian dust storm*: The yellow-sand or the dust storm that occurs frequently over arid desert areas of East Asia, mainly over the Gobi Desert and arid areas of China and Mongolia, is reported to deteriorate the PM air quality in China, Hong Kong, Taiwan, Korea, Japan, Mongolia and even passes over the Pacific to reach the Western coast of America (Wu et al., 2021). The highest occurrence frequency is in spring (March-May) when the soil in the arid areas has thawed but is not yet covered by vegetation. Large particles settle out near the source while the fine dust particles may be lifted up as high as 1-3 km and remain in the air for a period of 5-10 days to transport over a large distance.

*Acid deposition:* The major anthropogenic precursors of acid deposition are $SO_2$ and $NO_x$ which are emitted primarily from fossil fuel combustion. During their atmospheric residence time of several days, they travel over thousands of kilometers while transforming into acidic compounds by a complex series of chemical reactions. They may be deposited from the atmosphere as dry or wet (with precipitation) acid deposition causing acidifying effects on the Earth surface. The term ‘acid rain’ is frequently used and it is normally perceived as the wet acid deposition that has pH lower than that of the pure rainwater (pH = 5.6). Acid deposition kills aquatic life, trees, crops and other vegetation, damages buildings and monuments, corrodes metals, reduces soil fertility, and can leach toxic metals into underground drinking water sources. The impact of acid deposition on an ecosystem depends on its assimilation capacity of the excess of acidity.

## 3. Major anthropogenic emission sources

Air pollutants are released from both natural and man-made sources. Natural sources include for example, the geogenic processes (volcano eruption, earthquakes, oil and gas seeps, sea spray), biogenic processes releasing pollutants from plant (VOC, pollens, bacteria, fungus spores, etc.) and soil, or weather-related processes (lightning, wildfires, etc.). Among the man-made sources, fuel combustion is the largest contributor to the air pollution burden which tends to increase along with population and economic growth. Fuel type is a useful indicator of potential emissions: coal and biomass as high emitting solid fuels, gasoline/diesel, kerosene as medium emitting liquid fuels, while Liquified

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petroleum gas (LPG) and natural gas (NG) as low emitting gaseous fuels. Major anthropogenic combustion sources of air pollution in Asia include mobile sources (on-road and off-road), stationary sources (power plants, large industries, small industries, waste incinerators, residential, etc.) and open burning (forest fire, grassland, agricultural residue, solid waste). With the current intrusion trend of clean fuels, such as NG, for combustion in all scales (power plant, industry, residential) the air pollution emissions are expected to reduce. The renewable energy, such as solar, wind, etc., has an increasing trend hence would reduce the atmospheric emissions, both air pollution and GHGs and SLCP (e.g., BC).

### 3.1. Mobile sources

The fast growth in the number of vehicles in Asian cities lead to the increased emissions of toxic air pollutants. Exposure to traffic emissions in cities is of greater concern as the pollutants are released at the breathing level in populated areas, especially during congestions. Uncontrolled vehicle exhausts are the largest sources of air pollution in many Asian urban areas.

In particular, the use of second-hand, high mileage, and poorly maintained vehicles results in large emissions per unit of fuel consumed in many Asian cities. Leaded gasoline has been successfully phased out worldwide in 2021 after 19-year campaign (UNEP, 2021). However, high VOC emissions from incomplete combustion of unleaded gasoline in old engines that are not equipped with a proper control device (catalytic converters) would be another issue (Kim Oanh et al., 2018a).

The efforts to control mobile source emissions are detailed in Section 5.5. However, the focus is still on on-road vehicles while the off-road vehicles remain largely unregulated. These polluting diesel-powered construction and agricultural machineries and boats, continue pollute the air in urban areas, while the shipping activities may significantly affect air quality in the coastal areas.

### 3.2. Stationary sources

*Industry/power plants:* The heavy reliance on coal as a cheap fuel in power plants and in large scale industrial boilers causes significant air pollution emissions in most Asian countries (Huy and Kim Oanh, 2017). Fortunately, these sources are increasingly regulated for emissions reduction. Much less attention is being paid to small and medium industries/workshops (in many cases on the family scale) which are typically based on backward and heavily polluting facilities. These industries are often found scattered in populated areas of developing Asia hence these intensive emissions would lead to high risks of population exposure.

*Domestic:* Residential heating and cooking with dirty fuels are very important pollution sources in Asian rural and peri-urban areas (Huy et al., 2021). In particular, high emission of products of incomplete combustion including fine particles, CO, VOC, semi-VOC from residential combustion in Asia implies high indoor exposure and health risks.

*Other stationary sources:* Other important stationary point sources include municipal solid waste incinerators and hospital waste (bio-infectious hazardous wastes) incinerators. Many of them are of small scale with limited emission control hence would emit substantially. Unstable power supply in

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many Asian cities prompts operations of numerous diesel-powered generators installed in hotels, supermarkets, institutions, and even private homes which emit intensively.

### 3.3. Open burning

*Crop residue field burning*: In agrarian countries of Asia, the crop residue field burning can contribute substantially to air pollution. This field burning activity, being uncontrolled and incomplete combustion in nature, emits a large amount of toxic air pollutants and GHGs (Kim Oanh et al., 2018b). The field burning smoke causes widespread ambient pollution not only in rural and peri-urban areas but also in nearby urban areas.

*Solid waste*: municipal solid waste open burning is a major source of toxic air pollutants in many places in Asia (Pansuk et al., 2018). Smoldering conditions of this burning type, especially of landfill fires, release substantial amounts of toxic air pollutants. Better solid waste collection and management would minimize the emissions. In some Asian countries, the solid waste backyard burning is officially banned but the effectiveness of enforcement is still an issue.

## 4. Air quality management

### 4.1. Integrated air quality management

The integrated AQM program should be based on the principles of air quality objectives, the use of sound science, the analysis of mitigation options, and the involvement of all key organizations and stakeholders in the public decision-making process. The ultimate goal of AQM is to ensure that ambient air pollution concentrations do not exceed the defined target levels, and that human health and the environment are protected. AQM requires a careful balancing of the cost of source control measures against health, environmental and economic benefits. AQM issues also need to be prioritized within the context of other local influences on public health and the environment, such as the contribution of indoor air pollution, unsafe water, and sanitation conditions. The main components of an AQM framework include the establishment of appropriate air quality goals/targets, development of clean air implementation plans, implementation, and enforcement of efficient actions to realize the plans, establishment of institutional arrangements to achieve the clean air goals (Fig. 2).

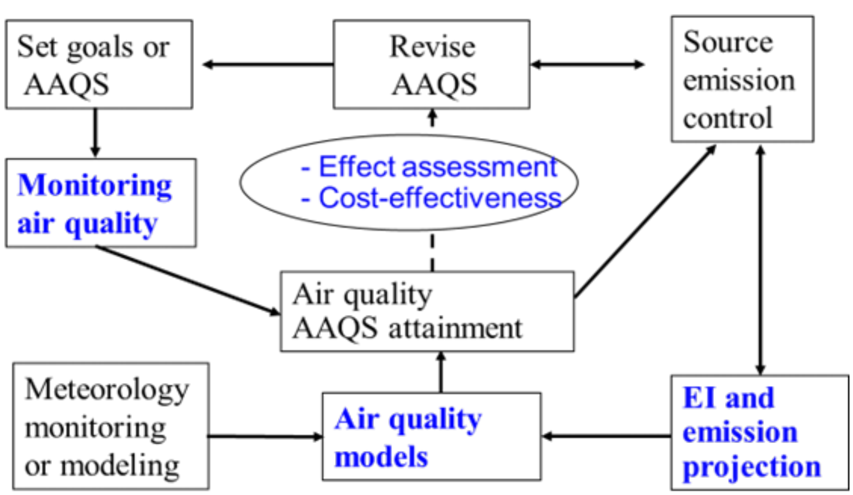


**Fig. 2. Framework of integrated air quality management**

Integrated AQM thus requires the use of both technical tool and management tool. The technical tool used to provide information on air quality includes the air quality monitoring, emission inventory, air quality modeling and the combined monitoring and modeling approach for

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assessment of effects of air pollution. Measures applied for source emission control, technical and policy, are however the key to reduce air pollution in a domain.

### 4.2. Air quality monitoring

Air quality monitoring involves measurements of air pollutant concentrations by using traditional standard equipment (sampling and subsequent analysis), advanced methods for in-situ monitoring with the aid of remote sensing (satellite) or on-line sensor systems, or a combination of several of these techniques (Loi et al., 2020). The monitoring data are used to assess the exposure and associated risks to human health and ecosystems due to air pollution so that necessary regulatory activities can be taken to reduce the pollution levels and associated effects. Regulatory monitoring, conducted by governmental agencies, is done to determine whether air quality in an area is complying with the NAAQS so that regulatory actions can be taken to deal with non-compliance.

Therefore, spatially, a network consisting of multiple monitoring sites is required to provide information on the status of air pollution in a geographical domain. Temporally, monitoring should also be done at fine resolution (hourly) and continuously over a long period of many years to provide the information on the air pollution trend and to assess the efficacy of interventions.

The monitoring activity thus generates large air quality datasets to be properly managed to ensure the data quality, archive and retrieval, and publicizing. Good data management strategies are therefore required to handle and process and share the information where cloud computing plays important roles. Monitoring data should be timely disseminated to ensure a timely flow of the air quality information to relevant stakeholders, e.g., to the public to avoid excessive exposure during pollution episodes or to authority to enforce control measures.

*Conventional monitoring:* Traditionally, air pollution situation is monitored by conventional air pollution monitoring systems with stationary monitors. These monitors are highly reliable, accurate and able to measure a wide range of pollutants by using conventional analytical instruments that can be divided into two principal approaches: 1) manual air quality monitoring and 2) automatic continuous monitoring.

*Low-cost sensors:* To resolve the limitations of conventional air monitoring instruments, sensors of small size and low cost are a promising alternative. The sensors for PM commonly use the optical method (light scattering, light obstruction, etc.) while several types of gas sensors are available, such as electrochemical sensors, metal oxide sensor, or photo ionization detector (Loi et al., 2020). Optical sensors can also detect gases like CO and $CO_2$ by measuring the absorption of infrared light. Hundreds of sensors may be deployed in a domain which produces a big data set to characterize the air quality.

However, measurement with low-cost sensors is facing issues of data quality, if solved, various applications such as monitoring air pollution, traffic management, personal exposure and health assessment, citizen science, etc. will be significantly expanded. There are multiple error sources for low-cost sensors which can be divided into two groups: internal errors and external errors. Internal errors are related to sensor working principle, poor sensitivity in low concentration environments, systematic measuring error, nonlinear correlation with standard measurement, and sensor sensitive drift after a certain time of operation. External errors are caused by the effect of environmental factors such as temperature and humidity, the diversity and complexity of substances in the air leading to the "confusion" of the sensor. The main challenge of monitoring using low-cost sensors is the data quality. Therefore, the low-cost sensors are required to be calibrated with standard devices accuracy which is done in two phases: pre-calibration and post-calibration. The air quality data is provided in real-time to publicity via web or mobile applications. Improvement of the accuracy of these monitoring data is however the largest challenge. The data science technology may help calibrate the sensors to improve the data quality.

*Satellite monitoring:* Satellite remote sensing technologies provide an alternative for monitoring air quality and especially useful in areas where no ground-based monitoring network exists. The satellite data also provide long-term monitoring to assess the trends of ambient pollutant concentrations (Duncan et al., 2014). Satellite data could support to identify the location of peak concentration which may be associated with emission source apportionment or to understand pollutants from long distance transport at national and regional scales. Besides, satellite data can provide a visualization tool, effective for communicating to nontechnical audiences. To date, the use of satellite data together with ground measurement and modeling tool enable scientific understanding of air quality for policy making than either method alone.

Several satellites have been launched to space which provide huge amounts of data for air quality assessment. Satellite data have been presented in various levels corresponding to degree of processing. Level 0 (L0) contains the raw data obtained from the sensor/instrument. L1 data are produced from L0 by applying the instrument pre- and post-launch calibrations to produce radiances and then geolocating these data. Level 2 (L2) and Level 3 (L3) data, main products for air pollution monitoring, are processed from L1 to a geophysical parameter, such as Aerosol Optical Depth (AOD) to characterize the PM pollution or Vertical Column Density (VCD) for $NO_2$. The spatial resolution of satellite data varies with the instrument and data level of processing. The temporal resolution is determined by several factors, including the satellite orbit, the orbital swath width, and the degree of snow cover and cloud cover. Most data are from instruments on polar-orbiting satellites (e.g., Terra, Aqua) that have 90-min sequential orbits, thus achieving global coverage in a day or two. The "near-real-time" products are available on the website within a few hours for operational use, while the final products are processed carefully and provided later. The satellite products for air quality are provided for specific pollutant products (e.g. $NO_2$, $SO_2$, CO, $O_3$, $CH_4$, $CO_2$) or aerosols (Pham et al., 2020), fire and smoke products, and true color imagery. The satellite data, however, are vertically integrated hence there is a need to relate the satellite data to the air quality at the breathing level.

### 4.3. Emissions inventory

Emission inventory (EI) is a comprehensive list of emissions from various sources of air pollutants and/or greenhouse gases (GHGs) in a defined area during a specific time. The emission sources covered in an EI may include both man-made, and the natural sources. For GHGs, the EI also covers the land-use and land-cover changes (IPCC, 2006). EI can be developed for a specific pollutant such as $SO_2$ or BC, a group of atmospheric substances or multi-pollutants depending on the intended uses of the dataset. The key air pollutants include PM, CO, $SO_2$, $NO_x$ and VOC while key GHGs include $CO_2$, $CH_4$, nitrous oxide ($N_2O$) and F-gases. SLCP/F are included as they are of interest from the toxic effects and climate forcing points of view. The overall framework of EI is presented in Fig. 3.

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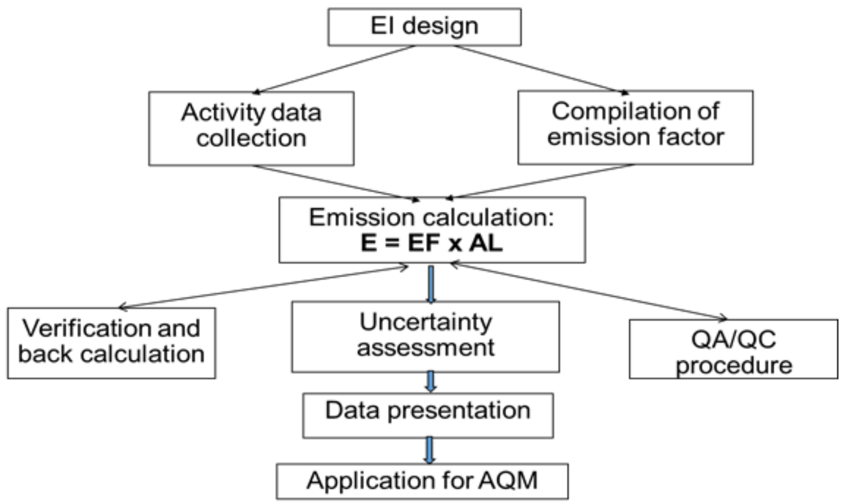


**Fig. 3. Framework of emissions inventories development**. Source: Kim Oanh et al. (2020)

Two main inputs for the EI calculation are emission factors (EF) and activity data (AL). The AL includes, for example, the fuel consumption rate per year in industry and power plant (for point source category), number of vehicles and the average traveling distance per year (for on-road mobile source category), or fuel consumption rate for domestic cooking or amount of biomass subjected to open burning (for area source category). The EFs, the emission amount per unit of AL, should be a relevant value for the sources in the domain. For the sources having emission control devices, the portion of the pollutants removed by the device should be excluded. Emission calculation is done with QA/QC procedures to ensure the accuracy of the EI database (Shrestha et al., 2013).

### 4.4. Air quality modeling

Air pollution modelling is a technical tool used to establish a quantitative relationship between emissions and concentrations/depositions that is used to analyze and assess the efficacy of abatement strategies.

*Numerical air quality model:* Two main types of numerical air quality models or chemical transport models (CTM) exist, namely the Eulerian and Lagrangian models. Eulerian model type is most currently used. These models use a fixed reference/observer with respect to the earth and calculate the pollutant concentration in each grid cell by using a system of equations (Kim Oanh and Permadi, 2009). Examples of the web-based information of these CTM include Comprehensive Air quality Model with extensions (CAMx, https://www.camx.com/), Community Multiscale Air Quality Model (CMAQ, https://www.epa.gov/cmaq), Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem, https://www2.acom.ucar.edu/wrf-chem).

Comprehensive input data of emissions, meteorology and topography are required to run CTM to simulate the processes of formation of atmospheric pollutants and their dispersion and accumulation in a domain (Fig.4). CTM can be used for historical simulations to provide comprehensive spatial coverage for air pollution data that are especially useful for the locations where the monitoring data are insufficient. Interactions between air quality and climate change can also be investigated using the modelling approach and this helps to analyze the potential co-benefits (to air quality and climate) resulting from different interventions while health benefits can also be quantified along with.

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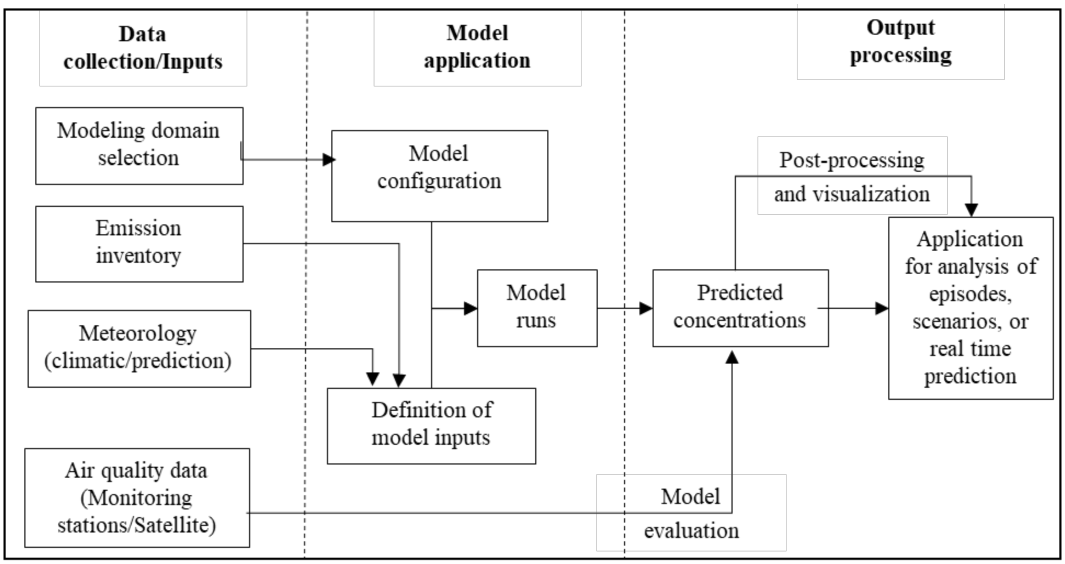


**Fig. 4. Framework of air quality dispersion model application with data flows**

Source: Kim Oanh and Permadi (2009)

*Statistical model:* Different from the numeric models, statistical and machine learning methods exploit relations and rules from multi-source air quality datasets to create air quality models which are commonly used for mapping (Nguyen et al., 2020) and time series forecasting (Espinosa et al., 2021). The air quality mapping use regression methods, such as multiple variable regressions, mixed effect models, support vector regression, neural network etc., to estimate ground air pollutants, such as $PM_{2.5}$, $PM_{10}$, $NO_2$, etc., from input datasets including satellite-derived air pollution, meteorological factors, and land use information (e.g., population density, traffic density, etc.). First, the statistical models are trained using short-/long-term historical ground measurements and input datasets for regional, national, and global scales. The geo-statistical methods, e.g., inverse distance weighting, kriging, are used to interpolate air pollution mapping for urban areas where many air quality stations are located. The time series forecasting application focuses on predicting air pollutants from hours to days, and even a month ahead using machine learning methods such as multi-layer perceptron (MLP), support vector regression (SVR) and autoregressive integrated moving average (ARIMA) models, or deep learning models, e.g. Long Short Term Memory (LSTM), deep recurrent neural networks (DRNN), geo-context based diffusion convolutional recurrent neural network (GC-DCRNN), or a combined those learning methods.

## 5. Emission control technologies

To improve the air quality in a domain, the foremost requirement is to reduce emissions from both local and distant sources affecting the domain. Both policy and technology measures are used to reduce the emissions. The policy measures include those related to land-use (urban planning, relocation of polluting industries, zoning, etc.), compliance policy (emission standards, ambient air quality standards, etc.), traffic management (public transport, non-motorized, rush hour management, etc.). The technical measures include, for example, the fuel quality improvement, cleaner production, end-of-the pipe control, etc. which impose regulatory mandates on processes, fuels, and emission treatment. The common emission reduction approaches include:

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- Command-and control (CAC): this is the traditional approach which is primarily based on environmental standards. CAC is straightforward and has produced better air quality at initial stages in many countries.
- Market-based (economic) instruments (MBI): it is based on the "polluter pays" principle and uses the emission charge, emission trading, congestion pricing (e.g., charge vehicles entering city center, etc.). MBI is cost effective and flexible which provides incentives to "polluters" to reduce emissions even below the regulatory limits, i.e., to the lowest possible levels.
- Participatory approach: it mobilizes the participation of the community, i.e., all the stakeholders to individually reduce emissions though educative/persuasive, awareness raising, public participatory, etc.

This section mainly focuses on the control technologies, more on the end-of-pipe devices, which remove the emissions from anthropogenic sources.

### 5.1. Control technologies of particulate matters

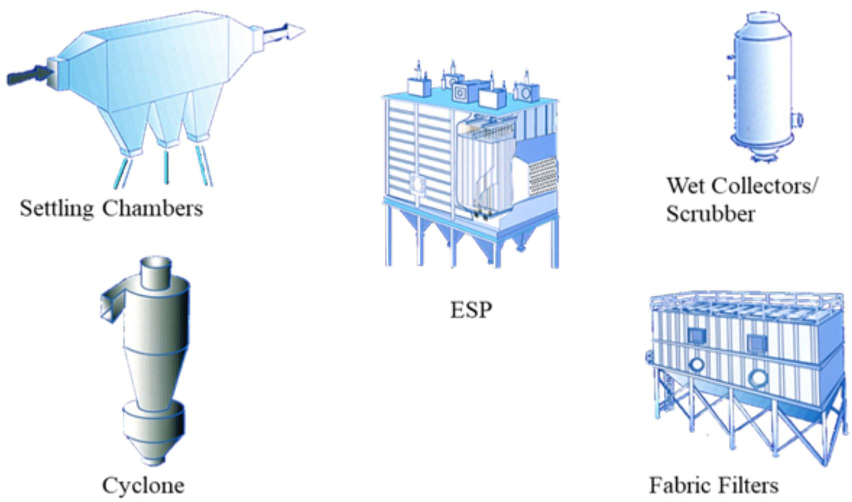


**Fig. 5. PM control devices**

Cyclones, scrubbers, gravity settling chambers, electrostatic precipitators, and fabric filters (Fig. 5) are used to remove PM from the emission streams, mainly from the stationary sources.

- Gravity settling chambers (GSC) are one of the most basic and oldest technologies for particle collection. GSC principle is to ensure that contaminated gas passes slowly through a long chamber. Large particles settle to the bottom due to gravity. This device has low removal efficiencies even for large particles, i.e., 50-60% for particles with size >40-60 µm.
- Cyclone: its operation mechanism is to force the gaseous suspension to flow spirally inside a constrained space. The particles are thrown against the cylinder walls by centrifugal forces created by the swirling action.
- Wet scrubber is a common device for PM removal which uses liquid to remove particles from emission streams. Its principle is similar to the absorption tower used for gaseous treatment but with different optimum operation conditions.
- Electrostatic precipitators (ESP) use a high voltage to produce gas ions which subsequently charge particles in the emission stream. The charged particles are collected on the oppositely charged collecting plates.

- Fabric filters (baghouse) work by retaining particles while sieving through the filter cloth and the filter cakes hence can achieve high removal efficiencies for very small particles.

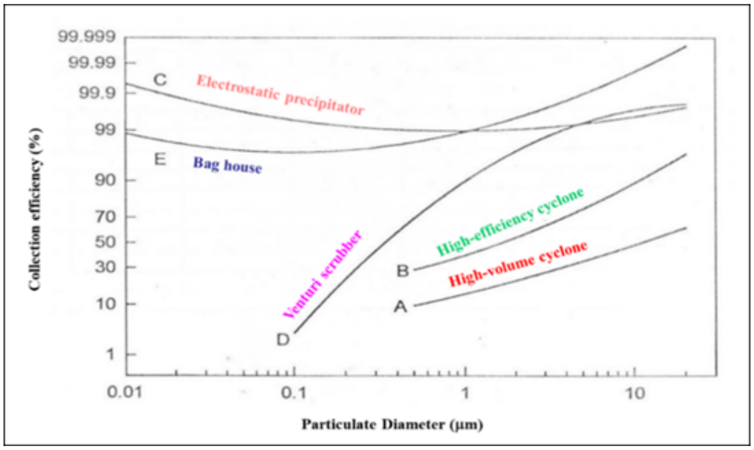


**Fig. 6. Removal efficiency of PM control devices.** Source: Hesketh (1981)

In general, the mechanical collectors of GSC and cyclones have lower removal efficiencies hence they are used as pre-cleaning devices, upstream of the high-efficiency control devices of scrubbers, ESP, or baghouse. The typical removal efficiencies of the PM control devices are shown in Fig. 6.

### 5.2. Control technologies of nitrogen oxides

At high combustion temperatures, i.e., above 1000°C, $N_2$ in the air reacts with oxygen ($O_2$) to form $NO_x$ (thermal $NO_x$). If fuel contains nitrogen, it also readily reacts to form $NO_x$ (prompt $NO_x$) but in a much smaller amount as compared to the thermal $NO_x$. $NO_x$ emitted from combustion devices consists of mostly NO (about 90%) and $NO_2$ (about 10%). $NO_x$ emissions are usually controlled using two approaches: during combustion control (Low-$NO_x$ burner technologies) and post-combustion control (deNOx). During combustion, $NO_x$ control is achieved through reduction of the thermal $NO_x$ by altering the combustion conditions, e.g., lowering peak combustion temperature (e.g., exhaust gas circulation), regulating the air-to-fuel ratio (A/F, e.g., two-stage of stoichiometric combustion) or reducing the amount of time in which oxidizing conditions exist, etc.

DeNOx technologies remove $NO_x$ from the flue gas. Selective catalytic reduction (SCR) technologies are most commonly used to treat the emissions from fossil fuel combustion devices (Muralikrishna and Manickam, 2017). SCR device uses a reactant, commonly ammonia ($NH_3$), to selectively react with $NO_x$ in the presence of suitable catalysts to convert $NO_x$ to $N_2$ and $O_2$, which may reach 90% efficiency at optimum conditions. Selective non-catalytic reduction (SNCR) is an alternative which has the reactant ($NH_3$) injected in a high temperature zone for activation hence no need for any catalyst. SNCR has lower conversion efficiencies than SCR and are also less commonly used.

### 5.3. Control technologies of sulfur oxides

$SO_2$, produced predominantly from combustion of sulfur-containing fossil fuels such as coal and fuel oil. $SO_2$ emission control may be achieved using one or a combination of the following approaches:

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- Pre-combustion: selection of low sulfur (S) fuel, i.e., Liquefied natural gas (LNG), Compressed natural gas (CNG), LPG contain less S than coal and oil, and removal of S from the fuel (coal and oil desulfurization).
- During combustion control technologies: mixing limestone with coal for burning to form $CaSO_4$ (solid) hence reducing $SO_2$ gas in the emissions.
- Post-combustion control: flue gas desulfurization (FGD).

FGD technologies use a sorbent, in wet or dry form, to remove $SO_2$ emissions. FGD is commonly applied to treat the stack gas of coal-fired boilers and industrial processes. In the dry process, dry sorbent is injected (lime or pebble lime) into a rising flue gas to react with $SO_2$. It is used in combination with PM control devices to finally remove $SO_2$ absorbed on the sorbent particles. The wet FGD applies the reagent in slurry and produces slurry wastes. The common reagents used in wet FGD are lime, limestone, magnesium oxide and other alkali solutions and may have $SO_2$ removal efficiency reaching 90-95%.

### 5.4. Control technologies of volatile organic compounds (VOC)

Adsorption, absorption thermal and catalytic oxidation, condensation and biofilters are some of the control methods used to treat VOC emissions (Cheremisinoff, 2002). Emission streams having moderate to high VOC concentrations can be more cost-effectively treated using incineration or condensation (Parmar and Rao, 2008). At lower concentrations, VOCs are removed by adsorption or absorption which actually do not destroy VOCs but just transfer to another media, solid or liquid, respectively. Biofilters use microorganisms to digest VOCs and tune them to $CO_2$, water, and biomass. Biofilters effectively reduce VOC at low concentration at low cost but need more extended treatment time.

### 5.5. Vehicle emissions control approaches

Vehicular emissions are the product of the travel distance (km), the fuel consumption per km (fuel/km) and the EF of the pollutants (g/L fuel). Therefore, vehicular emissions strategies aim to: 1) reduce the travel distance by restraining traffic volume and reducing traveling of each vehicle, 2) increase the fuel efficiency, and 3) reduce the EF. Urban planning, public transport system and travel behavior changes are important to achieve the first objective. The second and third objectives require technical measures such as engine and fuel improvement, i.e., progressive Euro standards, and emissions control devices. Electric vehicles in principle have zero exhaust emissions but the concern should be on clean production of the electricity which is used to power the vehicles.

The state-of-the-art exhaust control device for gasoline-powered vehicles is the three-way-catalytic converter (TWC), which can simultaneously remove $NO_x$, CO, and hydrocarbon (HC) emission by 85-90%. To optimize performance of TWC, a strict control of A/F ratio is required. Besides, S content in fuel affects the performance of the catalytic converters hence low S fuel is important.

Diesel-powered vehicles in principle have high concentrations of HC, $NO_x$, and PM in the exhaust gas. Besides, if the S content in diesel is high then $SO_2$ concentrations in the exhaust will be high. The higher S content in diesel the higher PM emissions. Both PM and $SO_2$ in the exhaust adversely affect the catalyst performance. Hence it is mandatory to have low S content of diesel to reduce the emissions from diesel vehicles. PM emissions are controlled by various types of diesel particulate filters (DPF) which have removal efficiency of around 90%. If the oxidation catalysts are coated on the filters, then the removal of CO, HC, and PAH may be as high as 85%. $NO_x$ emissions from diesel exhaust in principle may be controlled using absorption (still in the development) and SCR with $NH_3$ as reactant.

## 6. Special Topics of Air Environment Management

### 6.1 Noise pollution and management

Noise is a form of physical pollution and is generally defined as an unwanted sound. When the sound level increases it becomes harmful to human and other living organisms. The common sources of noise are transportation (vehicle, airplane, railway, etc.), construction activity, entertainment events, etc. The longer the exposure to the loud noise, the higher risk of hearing loss, loss of focus, stress, high blood pressure, etc. The WHO guideline recommended that the noise should be kept below 70 dBA over 24-hour or 75 dBA over 8-hour of exposure (CDC, 2021).

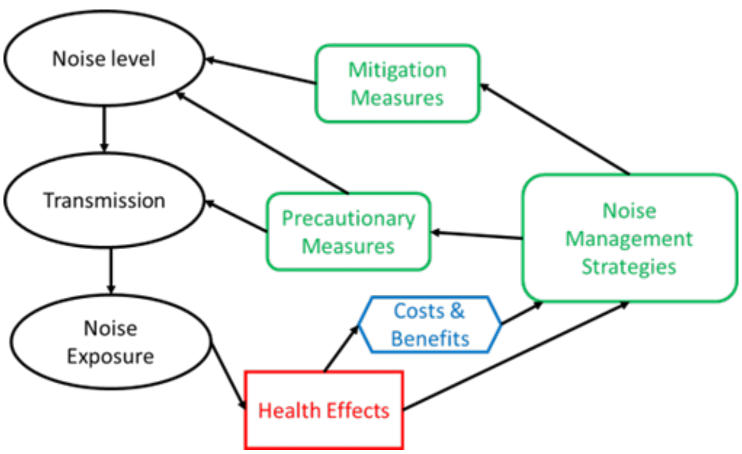


**Fig. 7. Stages involved in development of a noise abatement strategy**. Adapted from WHO (1999)

The goal of noise management is to maintain low noise exposures so that human health and well-being are protected. Fig. 7 shows components involved in development of a noise control strategy which is similar to AQM strategies presented in Fig. 2. The "mitigation measures" for noise pollution involve the sources control, e.g., the use of quiet road surfaces, use the equipment with sound labeling and "precautionary measures" through careful planning to avoid hence can continuously reduce noise level.

### 6.2 Odor pollution and management

Odor is a mixture of substances that can trigger the olfactory system. Various gases, e.g., VOCs (benzene), $NH_3$, etc. are odorous. Odors are more subjective to individuals, and different persons have different perceptions of different odors. In general, humans can smell with very low concentration of substances, called "Odor Threshold Values" (OTV) which is much lower than the levels at which the substance starts to cause toxic health effects. However, an unpleasant odor can lead to different impacts such as headaches, nausea or even vomiting. In some cases, long-term exposure to odor can lead to chronic respiratory problems such as allergy.

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The most common sources of odor are landfills, food processing factories, sewage systems, animal farms and chemical factories. The most effective method to control odor is to control at sources before it releases to the atmosphere, including preventive control of accidental release and leakage. The odor control methods generally follow the gas control technologies including the four approaches listed below (Capelli, et al. 2019):

- End-of-pipe control techniques: these are similar to the VOC control devices above. Besides, chemical reactions such as oxidizing VOC by $O_3$ may also be used.
- Cover/enclosure: the surface is covered to block VOCs from releasing into the atmosphere.
- Enhance emission dispersion capability: the odorous substance in the atmosphere is diluted before it reaches a receptor, e.g., by increasing stack height, collecting and releasing all odorants to the stack (no ground-level release).
- Nebulization of de-odorizing: nebulizing nozzles are installed at the stack outlet, composting piles, landfills, etc. to nebulize and reduce odor level of the emission by masking with a pleasant odor.

### 6.3 Photochemical smog management

Photochemical smog is a mixture of pollutants that are formed from the photochemical reaction (reaction with the present of sunlight) (USEPA, 2021). The major precursors (or primary pollutants) in the reaction which are $NO_x$ and VOCs will create a cloud (smog) of brown haze of secondary pollutants in the presence of sunlight. $O_3$ is the main component of the photochemical smog along with hazardous pollutants (peroxyacetyl nitrate, PAN) and fine particles. Photochemical smog and $O_3$ problems happen when strong solar radiations present, during the afternoon of a hot summer day.

$NO_x$ and VOCs can originate from both natural and anthropogenic sources. Especially, a large amount of VOCs is of biogenic nature. The management of photochemical smog pollutants, including $O_3$, can be done through the control of the precursors, i.e., $NO_x$ and VOCs. However, the relationship between the amount of $O_3$ formed and the concentrations of $NO_x$ and VOCs, respectively, is not linear. To effectively manage the $O_3$ air quality in a domain, one should first determine its predominant $O_3$ formation regime, i.e., $NO_x$-limited or VOC-limited. The regime is established using the ratio of VOC/$NO_x$ as seen in Fig. 8. If the domain falls in the VOC-limited region (left side of Fig. 8), reducing $NO_x$ may lead to an increase in $O_3$ concentration hence the VOC emission control should be of priority. On the other hand, if the domain has a $NO_x$-limited regime (right side of Fig. 8), then policies on reducing $NO_x$ should be prioritized.

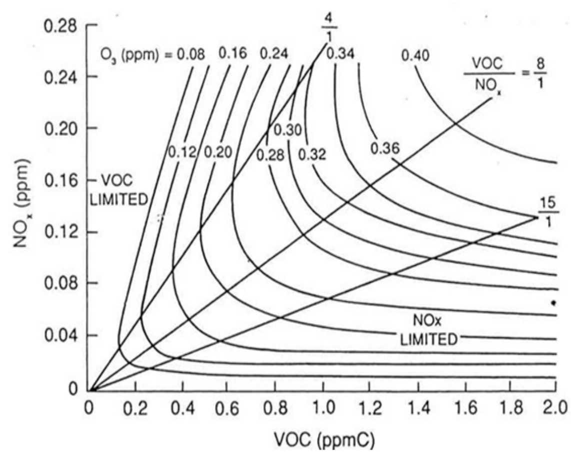


**Fig. 8. Typical ozone isopleths used in USEPA's EKMA.** Source: Dodge (1977)

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*This document was produced within the MONTUS project financed by the European Union in the framework of Erasmus + Capacity Building 598264-EPP-1-2018-1-FR-EPPKA2-CBHE-JP.*

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