Subject Name & Code: Environmental Sciences (NESV101)

Sl. No.	Faculty	Topics
1	Prof S Das **(Course Instructor: Section-)**	Solid and e-Waste Management: Characteristics and Sources of Solid Waste/e-Waste, Environmental Issues related to Solid Waste, Waste Management, Basics of Solid Waste Treatment Methods, Solid Waste Transformation through Thermochemical and Biological Methods and Different Disposal Techniques for e-Waste. **Environmental Impact Assessment (EIA):** Introduction to Basic EIA Structure and Overview on Impacts of Air, Water, Biological and Socio-economical Aspects
2	Prof. Vittal H **(Course Instructor: Section-)**	**Global Atmospheric Change:** Atmospheric System, Atmospheric Circulations, Introduction to Climate and Weather, Global Energy Balance, Greenhouse Effect, and Radiative Forcing of Climate Change and Global Warming Potential. **Natural Resources:** Water resources, Mineral Resources, Land Resources, Forest Resources, Energy Resources. **Other Environmental Pollution:** Marine pollution, Nuclear Pollution, Thermal Pollution etc.
3	Prof Sheeja Jagadevan **(Course Instructor: Section-)**	**Water & Wastewater Pollution:** Introduction to Water Pollution, Characteristics/Source/Types/Analysis of Water and Wastewater, Drinking Water and Basic Treatments Process, Industrial Wastewater and Basic Treatments Process, Municipal Wastewater and Basic Treatments Process, Prevention and Control of Water Pollution and Standards for Drinking Water and Effluents. **Ecosystems:** Definition, Scope, and Importance of Ecosystems. Biogeochemical cycles, Eutrophication, Bioaccumulation and Biomagnification, ecosystem value, services and carrying capacity. **Biodiversity:** Introduction, Definition, Value of biodiversity, Threats and conservation of biodiversity, Biodiversity Indices, National Biodiversity Act.
4	**Prof. Brijesh Kumar Mishra** **(Course Instructor: Section-)**	**Air Pollution:** Types and Sources of Air Pollution, Effects of Air Pollution, Controlling Air Pollutants, Indoor Air Pollution, Ozone Depletion in the Stratosphere, Acid Deposition and **Noise Pollution.** **Environmental Policy & Legislation:** Environmental Protection act, Legal aspects Air Act, Water Act, Forest Act, Wildlife Act, Municipal Solid Waste Management and Handling Rules.

AIR POLLUTION

UNDERSTANDING CAUSES, TYPES, AND EFFECTS

Introduction to Air Pollution

- **Definition:** Air pollution refers to the presence of **harmful or excessive substances** in the atmosphere that pose risks to human health, ecosystems, and climate.
- **Key Pollutants**

- **Gaseous Pollutants:**
  - **Sulfur Dioxide (SO_2)** – from coal burning
  - **Nitrogen Oxides (NO_x)** – from vehicles and power plants
  - **Carbon Monoxide (CO)** – from incomplete combustion
  - **Ozone (O_3)** – secondary pollutant formed via photochemical reactions
- **Particulate Matter (PM):**
  - **PM2.5** – fine particles ≤ 2.5 µm (can penetrate deep into lungs)
  - **PM10** – coarse particles ≤ 10 µm
- **Other Pollutants:**
  - **Volatile Organic Compounds (VOCs)**
  - **Heavy metals (e.g., Pb, Hg)**
  - **Biological molecules** – pollen, mold spores, bacteria

Types of Air Pollution

On the basis of origin

1. Natural Pollution
2. Anthropogenic Pollution

On the basis of chemical composisiton

1. Primary Pollutants
2. Secondary Pollutants

On the basis of spatial characteristtics

1. Point Source
2. Line Source
3. Area Source

On the basis of physical state

1. Particulate Air Pollutants
2. Gaseous Air Pollutants

Types of Air Pollution
(On the basis of Origin)

1.Natural Air Pollution

- Volcanic eruptions: SO_2, CO_2, ash
- Forest fires: PM, CO, NO_x
- Dust storms: PM
- Sea spray: Salt particles
- Biological decay: CH_4
- Pollen and spores

1. Natural Air Pollution

Source	Pollutants	Mechanism/Remarks
Volcanic Eruptions	SO_2, CO_2, ash, H_2S	Emit large quantities of gases and particulate ash; major contributors to stratospheric aerosol load.
Forest Fires	$PM_{2.5}$, PM_{10}, CO, NO_x, VOCs	Release both primary (PM) and secondary pollutants (ozone precursors); intensified by climate change.
Dust Storms	Coarse PM (PM_{10})	Windblown dust from arid/semi-arid regions; contributes to transboundary pollution.
Sea Spray	NaCl, Mg^{2+}, Cl^- aerosols	Oceanic turbulence forms saline aerosols influencing coastal air quality.
Biological Decay	CH_4, NH_3	Anaerobic decomposition in wetlands, swamps, and soils.
Pollen & Spores	Bioaerosols	Allergens and natural particulates; seasonally variable.

2.Anthropogenic (Man-Made)

Occurs especially in urban and industrial areas

- Combustion of Fossil Fuels.
- Agricultural Activities.
- Waste Disposal and Treatment.
- Residential Sources.

2.Anthropogenic (Man-Made)

Fossil Fuel Combustion	Agricultural Activities
Transportation: Cars, trucks, buses, and airplanes burn gasoline or diesel, releasing CO, NOx, hydrocarbons (HC), and particulate matter.	Use of Fertilizers and Pesticides: Release ammonia (NH_3) and VOCs.
Power Plants: Coal, oil, and natural gas-fired plants emit sulfur dioxide (SO_2), nitrogen oxides (NOx), CO_2, and particulate matter.	**Livestock:** Emit methane (CH_4) and ammonia (NH_3) through enteric fermentation and manure management.
Industrial Processes: Factories produce emissions from chemical reactions, fuel combustion, and material handling.	**Crop Burning:** Produces smoke, particulate matter, and carbon monoxide.

2.Anthropogenic (Man-Made)

Waste Disposal and Treatment	Residential Sources
Landfills: Generate methane (CH_4) from decomposition of organic waste.	Cooking and Heating: Burning biomass, coal, or kerosene releases CO, particulate matter, and other pollutants.
Open Burning of Waste: Releases toxic gases, particulate matter, and heavy metals..	Use of Solvents: Paints and cleaning agents emit volatile organic compounds (VOCs).
Sewage Treatment: May emit gases like hydrogen sulfide (H_2S) and methane.	Poor ventilation and accumulation of indoor pollutants : Traps harmful indoor emissions from cooking, cleaners, and materials, raising pollution levels.

Other Contributing Factors to Air Pollution

1. Deforestation contributes to air pollution through the following mechanisms:

- **Increase in particulate matter (PM_{10} and $PM_{2.5}$)** due to soil erosion and dust suspension in the absence of tree cover.
- **Reduction in carbon sequestration**, leading to higher atmospheric CO_2 levels, which contributes to greenhouse gas accumulation.
- **Biomass burning** during forest clearing emits air pollutants such as CO, NO_x, and VOCs, which contribute to smog and ozone formation.

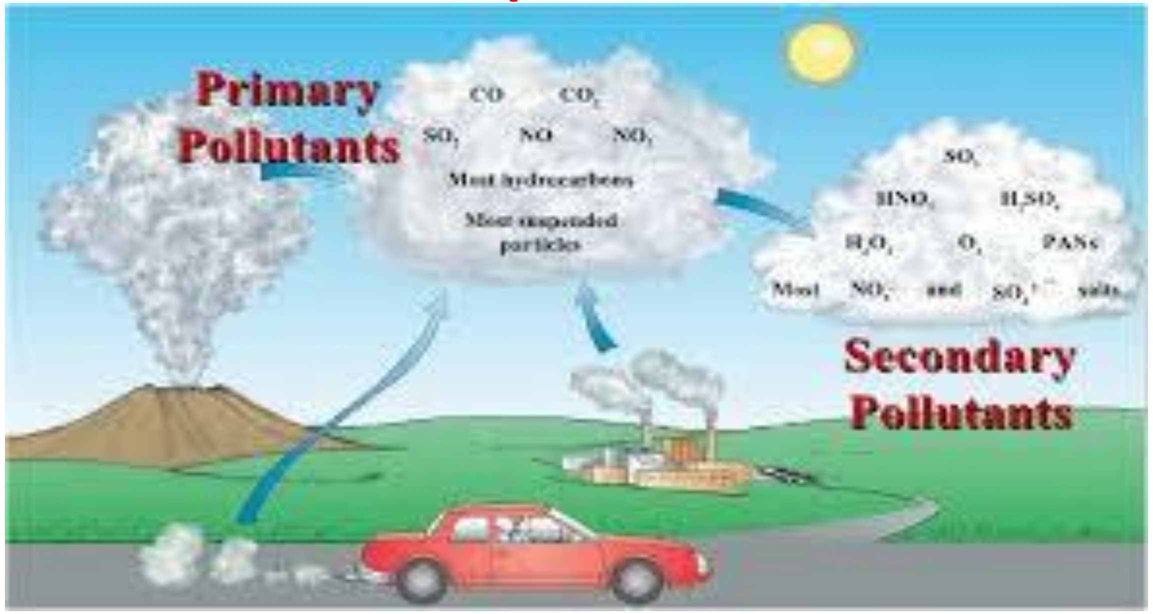
2. Urbanization accelerates air quality degradation in multiple ways:

- **Urban Heat Island effect** raises temperatures, intensifying ground-level ozone (O_3) formation via photochemical reactions involving NO_x and VOCs.
- **High concentration of emission sources**, such as vehicles and industries, increases pollutants like SO_2, NO_x, CO, and black carbon.
- **Loss of vegetation and airflow obstruction** limits natural dispersion of pollutants, causing their accumulation and increased human exposure.

3. Industrial accidents pose sudden and severe threats to air quality through:

- **Acute release of hazardous gases** such as ammonia, chlorine, and methyl isocyanate, which cause respiratory and systemic toxicity.
- **Emission of persistent organic pollutants (POPs)** like dioxins and furans, which remain in the environment and pose long-term health risks.
- **Formation of secondary pollutants**, including smog and acid rain, due to atmospheric chemical reactions following the release of precursor gases.

Classification of Air Pollutants
(Based on Chemical Composition)



- **Primary Pollutants:** Emitted directly
- Definition- Primary pollutants are emitted directly from a source into the atmosphere.
- Ex- CO, SO_2, NOx, PM, VOCs

- **Secondary Pollutants:** Formed in atmosphere
- They form in the atmosphere through chemical reactions between primary pollutants and other atmospheric components.
- Ex- O_3, H_2SO_4 & HNO_3, Peroxyacetyl Nitrate (PAN), Secondary Particulate Matter

Classification of Air Pollutants (Based on Physical State)

1. Particulate Air Pollutants (Solid or Liquid Phase)

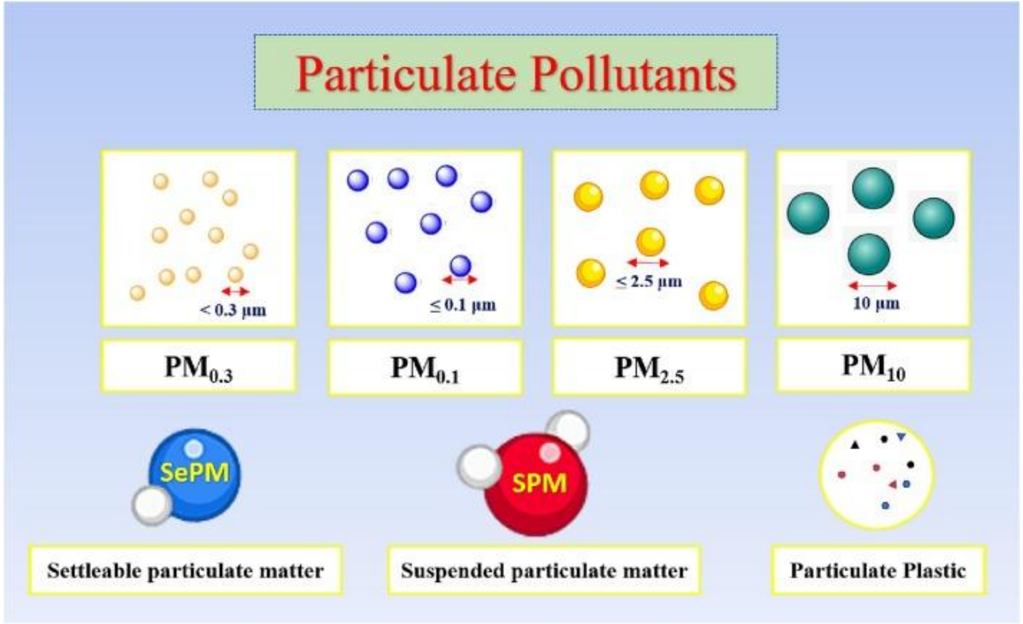
Particulate pollutants are **tiny solid particles or liquid droplets** suspended in the air, often referred to as **aerosols**.

Types:

- Dust – Solid particles from soil, mining, roads.
- Smoke – From combustion (wood, coal, fossil fuels).
- Soot – Carbon-rich fine black particles from incomplete combustion.
- Fumes – Fine solid particles formed by condensation of vapors (e.g., metals).
- Mist – Tiny liquid droplets suspended in air (e.g., sulfuric acid mist).
- Fog – Water droplets mixed with pollutants (industrial smog).
- PM2.5 and PM10 – Particles with diameters <2.5 µm and
- <10 µm, respectively.

Sources:

- Vehicle exhaust
- Construction and demolition
- Road dust
- Industrial emissions
- Biomass and crop burning
- Volcanic eruptions and natural dust storms



Classification of Air Pollutants (Based on Physical State)

2. Gaseous Air Pollutants

- These are pollutants that exist in the gaseous phase under normal atmospheric conditions.

Types:

- Carbon monoxide (CO) – Incomplete combustion of fuels
- Sulfur dioxide (SO_2) – Coal/oil combustion
- Nitrogen oxides (NO and NO_2) – Vehicle and power plant emissions
- Ozone (O_3) – Secondary pollutant formed by photochemical reactions
- Volatile Organic Compounds (VOCs) – From fuels, solvents, paints (e.g., benzene, formaldehyde)
- Ammonia (NH_3) – From agriculture and waste

Sources:

- Vehicle emissions
- Power plants and refineries
- Industrial processes
- Household cleaning products and paints
- Agricultural activities

Classification Of Air Pollution (On the basis of spatial characteristics)

1. Point Source: A point source refers to a single, identifiable and localized origin of pollution. These sources emit pollutants from a specific, fixed location.

➢ **Key Features:**

- Easy to monitor and regulate due to fixed location.
- Emissions are traceable to a specific source.
- Typically involves large-scale industrial or ---

energy production facilities.

➢ **Examples:**

- Factory smokestacks
- Power plant chimneys
- Incinerators

➢ **Environmental Relevance:**

Point sources are often regulated under pollution control laws due to their concentrated emissions and significant impact on **local air quality**.

2.Line Source: A line source is characterized by pollution emitted along a continuous linear path. These are typically associated with transportation corridors.

➢ **Key Features:**

- Emissions are distributed along a line rather than at a single point.
- Pollution intensity may vary along the path based on traffic density and movement.

➢ **Examples:**

- **Highways** with vehicle exhaust emissions
- **Railway lines** due to diesel engines
- **Runways at airports** during aircraft taxiing, takeoff,

and landing

➢ **Environmental Impact:**

Significant contribution to **urban air pollution** and **ground-level ozone** formation due to vehicular NO_x and VOC emissions.

3. Area Source: An **area source** emits pollutants over a **broad surface area**, with no distinct single emission point. Emissions are **diffuse, intermittent**, and often **difficult to monitor.**

- **Key Features:**

- Wide spatial coverage
- Emissions result from collective, scattered activities
- Often seasonal or weather-dependent

- **Examples:**

- Agricultural fields using fertilizers and pesticides
- Construction sites
- Open burning areas

- **Environmental Impact:**

Area sources contribute to **ambient particulate pollution**, **groundwater contamination** (via deposition), and **seasonal smog**.

Units Of Air Pollution Concentration

1. Micrograms per Cubic Meter (μg/m^3)

- **Definition:** This unit measures the **mass of pollutant particles or gases** contained in **one cubic meter of air**.
- **Application:** Commonly used for **particulate matter (PM2.5, PM10)** and certain gaseous pollutants like **SO_2**, **NO_2**, etc.
- **Example:** A PM2.5 concentration of **35 μg/m^3** means that **35 micrograms** of fine particulate matter are present in **1 m^3** of air.
- **Used For:** Suspended particulate matter, Heavy metals, Dust, smoke, etc.

2. Parts per Million (ppm)

- **Definition:** A **volume-based ratio**, representing the number of pollutant gas molecules **per million molecules of air**.
- **Application:** Used mainly for **gaseous pollutants** such as **CO**, **NOx**, **O_3**, etc.
- **Example:** 1 ppm of CO implies **1 molecule of carbon monoxide** per **1,000,000 molecules** of air.
- **Conversion Note:** Ppm can be converted to μg/m^3 using molecular weight, temperature, and pressure for detailed analysis.

- A sample of air analyzed at 25°C and 1 atm pressure is reported to contain 0.04 ppm of SO_2. Atomic mass of S = 32, O = 16. The equivalent SO_2 concentration (in $\mu g/m^3$) will be?

Calculation:

T_1 = 273 K and T_2 = 273 + 25 = 298 K

Since n and R are constant for a given gas, thus∴

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{1\times22.4}{273} = \frac{1\times V_2}{298}$$

V = 24.45 ltr.

This means that 1 mole of SO_2 occupies 24.45 ltrs. at 25^0 C and 1 atm.

{SO_2} = 0.04 ppm à this means that

10^6 cum air has 0.04 cum SO_2

Or

10^6 cum air à 0.04 × 1000 = 40 ltrs. SO_2

1 mole of SO_2 occupies 24.45 liters. Therefore, 10^6 cum air à 40/24.45 = 1.636 moles of SO_2

The molecular weight of SO_2 = 32 + 2 × 16 = 64 gm.

10^6 cum air has 1.636 × 64 = 104.7 gm SO_2

Or

1 cum air has $\frac{104.7\times10^6}{10^6}$ **µg/m³** SO_2

∴ SO_2 in µg/m³ = 104.7 µg/m³

Particulate Matter (PM)

1. Definition and Classification of Particulate Matter (PM):

- **Particulate Matter (PM)** is a complex mixture of very small solid particles and liquid droplets suspended in the air.
- It is classified by size into **PM_{10} (≤10 µm)** and **$PM_{2.5}$ (≤2.5 µm)**, with $PM_{2.5}$ being more harmful due to deeper lung penetration.
- These fine particles can **impair respiratory health** and **carry toxic substances**, posing major health and environmental risks.

2. Sources and Formation of PM (Brief):

- Major PM sources include vehicle exhaust, industrial emissions, dust, and combustion activities.
- Secondary PM forms in the atmosphere through chemical reactions involving SO_2, NO_x, and NH_3.
- Natural sources include dust storms, sea spray, and biological debris.

3. Chemical Composition and Characteristics of PM:

- PM is a **heterogeneous mixture** of inorganic substances like **sulfates, nitrates, ammonium, heavy metals (e.g., lead)**, and trace elements.
- It also contains **organic compounds**, including **polycyclic aromatic hydrocarbons (PAHs)** and various hydrocarbons, mainly from combustion sources.
- Biological materials such as **pollen, mold spores, bacteria**, and **black carbon** from diesel and biomass burning enhance **toxicity and climate impact**.

Sulfur Dioxide (SO_2)

1. Definition and Properties of Sulfur Dioxide (SO_2):

- **Sulfur Dioxide (SO_2)** is a **colorless, pungent, and highly reactive gas** composed of one sulfur atom and two oxygen atoms.
- It is **water-soluble**, forming **sulfurous acid (H_2SO_3)** upon contact with moisture, contributing to **acid rain**.
- SO_2 is a **precursor to fine particulate matter ($PM_{2.5}$)** and **sulfate aerosols**, impacting **air quality, visibility, and climate**.

2. Natural Sources of SO_2:

- **Volcanic eruptions** are the most significant natural source, releasing large amounts of SO_2 during activity.
- **Geothermal activities** like **hot springs and geysers** emit smaller quantities.
- **Oceans and decaying organic matter** contribute trace levels of biogenic SO_2 under anaerobic conditions.

3. Anthropogenic (Human-Made) Sources of SO_2:

- Primarily produced by the **combustion of sulfur-containing fossil fuels** (coal, oil) in **power plants, industrial boilers**, and **refineries**.
- Emitted during the **smelting of metal ores** (e.g., copper, lead, zinc) that contain sulfur compounds.
- Additional sources include **vehicle exhaust (especially diesel)** and **residential fuel burning** (coal and biomass stoves).

Carbon Monoxide (CO)

1. Definition and Properties of Carbon Monoxide (CO):

- **Carbon Monoxide (CO)** is a **colorless, odorless, tasteless, and highly toxic gas** formed from the incomplete combustion of carbon-containing fuels.
- It consists of one carbon atom and one oxygen atom.
- CO has a strong affinity for hemoglobin, forming **carboxyhemoglobin**, which **reduces oxygen-carrying capacity** of blood, leading to hypoxia.
- Exposure to CO is especially dangerous in **enclosed or poorly ventilated areas**.

2. Anthropogenic (Human-Made) Sources of CO:

- **Motor vehicles**, especially those using petrol and diesel (incomplete combustion).
- **Residential heating and cooking** using **solid fuels**, kerosene, wood, or gas.
- **Industrial processes** such as **steel and cement manufacturing**.
- **Power plants** using coal or other fossil fuels.
- **Tobacco smoke** (including cigarettes and hookah).
- **Open burning** of garbage, crop residue, and municipal waste.

3. Natural Sources of CO:

- **Forest and bushfires**, especially during dry seasons.
- **Volcanic eruptions** (minor source).
- **Decomposition of organic matter** under anaerobic conditions in wetlands and soils.
- **Lightning-induced oxidation** of methane and other hydrocarbons in the atmosphere.

Problem: An adult breathes 10 m^3 of air/day. If indoor CO concentration is 20 ppm, estimate how much CO the person inhales per day (in mg) at different temperatures.

(Molar mass of CO = 28 g/mol; Use ideal gas law to estimate molar volume at each temperature.)

Where:

Symbol	Meaning	Value (atmosphere units)
R	Universal gas constant	0.0821 L·atm/mol·K
T	Temperature in Kelvin	(e.g., 273 K, 298 K, 323 K, etc.)
P	Pressure	1 atm (for standard or NTP conditions)
V_m	Molar volume (L/mol)	What we are solving for

Solution:

T (K)	Molar Volume $V_m = \frac{RT}{P}$	CO Concentration $\text{mg/m}^3 = 20 \times \frac{28}{V_m}$	CO Inhaled per Day $\text{mg/day} = \text{mg/m}^3 \times 10$
273	$22.40\,\text{L/mol}$	$20 \times \frac{28}{22.4} = 25.00$	$25.00 \times 10 = 250.0$
298	$24.45\,\text{L/mol}$	$20 \times \frac{28}{24.45} = 22.90$	$22.90 \times 10 = 229.0$
323	$26.53\,\text{L/mol}$	$20 \times \frac{28}{26.53} = 21.12$	$21.12 \times 10 = 211.2$

Key Notes (for slide):

- Molar Volume increases with temperature → CO concentration in mg/m^3 decreases.
- So, same ppm leads to lower CO mass inhaled at higher temperatures.

Nitrogen Oxides (NOx)

1. Definition and Properties of Nitrogen Oxides (NO_x):

- **Nitrogen Oxides (NO_x)** primarily refer to **Nitric Oxide (NO)** and **Nitrogen Dioxide (NO_2)**; occasionally, other oxides like **Nitrous Oxide (N_2O)** are included.
- They are **highly reactive gases** formed during **high-temperature combustion** of fossil fuels.
- NO_x plays a critical role in the formation of **ground-level ozone**, **photochemical smog**, and **acid rain**.
- NO is relatively **harmless** at low concentrations, but it rapidly oxidizes to **NO_2**, a **toxic and irritating gas**.

2. Anthropogenic (Human-Made) Sources of NO_x:

- **Motor vehicle emissions**, especially from **diesel engines**.
- **Power plants** burning **coal, oil, or natural gas**.
- **Industrial furnaces, kilns, and boilers** (e.g., cement and steel manufacturing).
- **Residential combustion** (stoves, fireplaces, space heaters using fuel).
- **Heavy transport**: ships, aircraft, locomotives.

3. Natural Sources of NO_x:

- **Lightning strikes** (convert atmospheric **N_2** and **O_2** into **NO**).
- **Forest fires** and **volcanic eruptions** release thermal NO_x.
- **Soil microbial activity** (especially nitrifying and denitrifying bacteria under aerobic/anaerobic conditions).

Hydrocarbons

1. Definition and Classification of Hydrocarbons (HCs):

- **Hydrocarbons** are organic compounds composed solely of **carbon (C)** and **hydrogen (H)**.
- In air pollution studies, hydrocarbons are often referred to as **Volatile Organic Compounds (VOCs)**—substances that easily evaporate into the atmosphere and **react with NO_x to form ground-level ozone and photochemical smog**.
- Hydrocarbons are classified into:
  - **Alkanes** (e.g., methane, ethane) – saturated HCs
  - **Alkenes** (e.g., ethylene, propylene) – unsaturated HCs with double bonds
  - **Aromatic hydrocarbons** (e.g., benzene, toluene, xylene) – contain benzene rings and are **carcinogenic**

2. Anthropogenic (Human-Made) Sources of HCs:

- **Motor vehicle emissions**, especially from **incomplete combustion** and **fuel evaporation**.
- **Industrial processes** such as chemical manufacturing, painting, printing, and petroleum refining.
- **Petroleum refineries and fuel storage facilities**.
- Use of **solvents** in **paints, adhesives, thinners, and dry-cleaning operations**.
- **Domestic sources**: aerosol sprays, cooking (especially using oils at high temperatures), and space heating.
- **Open burning** of municipal waste, biomass, or agricultural residue.

3. Natural Sources of HCs:

- **Plants and vegetation**, particularly trees that emit **terpenes** and other **biogenic VOCs**.
- **Methane** from **wetlands**, **termite activity**, and **oceanic biological processes**.
- **Forest fires** and **volcanic eruptions**, which emit a wide range of hydrocarbons.

Lead (Pb)

1. Overview

- **Lead** is a **toxic heavy metal** that occurs naturally in the Earth's crust.
- It becomes a **hazardous air pollutant** when released into the atmosphere from **human activities**, especially industrial processes.
- Lead is **non-biodegradable**, **bioaccumulates** in organisms, and poses serious **health and environmental risks**, especially for children.

2. Anthropogenic (Human-Made) Sources:

- **Combustion of leaded gasoline** (historically major; largely phased out globally)
- **Metal smelting and refining** (especially non-ferrous metal industries)
- **Battery manufacturing and recycling** (particularly **lead-acid batteries**)
- **Lead-based paints and pigments**
- **Coal combustion** in thermal power plants
- **Burning of electronic waste** and improper disposal of e-waste
- **Ceramics and pottery** industries using lead-based glazes

3. Natural Sources (Minor):

- **Volcanic eruptions** (release trace amounts of lead-containing ash)
- **Wind-blown soil and dust** (containing naturally occurring lead deposits)

Benzene and Benzo[a]pyrene

1. Benzene

- **Benzene** is a **volatile organic compound (VOC)**, widely present in ambient air due to **vehicle exhaust**, **petrochemical industries**, **gasoline evaporation**, and **fuel combustion**.
- It is also found in **tobacco smoke**, **household products** (e.g., paints, adhesives), and **solvents**.
- Benzene is **highly flammable** and easily **vaporizes**, contributing significantly to **urban air pollution**.
- **Health Effects**:
  - **Carcinogenic** (linked to leukemia)
  - Affects **bone marrow**, **nervous system**, and causes **immune system suppression** upon chronic exposure.

2. Benzo[a]pyrene (BaP)

- **BaP** is a **polycyclic aromatic hydrocarbon (PAH)** released mainly through **incomplete combustion** of **coal, wood, fossil fuels, biomass**, and **organic matter**.
- Sources include: **Motor vehicle exhaust; Industrial emissions; Cigarette smoke; Grilled/charred foods**
- BaP is a **carcinogenic compound** often found in **soot and tar**, and tends to **adhere to particulate matter**, increasing its **persistence** and **distribution** in the air.
- **Health Effects**:
  - **Highly mutagenic and carcinogenic**
  - Linked to **lung and skin cancers, developmental toxicity**, and **DNA damage**

Ozone

1. Overview

- Ground-level **ozone** is a **harmful air pollutant**, distinct from the **beneficial ozone layer** in the stratosphere.
- It is a **secondary pollutant**: not directly emitted but formed by a **photochemical reaction** involving **nitrogen oxides (NO_x)** and **volatile organic compounds (VOCs)** in the presence of **sunlight**.
- Elevated levels are common in **urban environments** during **warm, sunny weather**, especially in summer.

2. Formation Mechanism

- **Photochemical Reaction:** $$\mathrm{NO}_x + \mathrm{VOCs} + \mathrm{Sunlight} \rightarrow \mathrm{O}_3$$
- Ozone levels are influenced by the **balance between NO_x and VOCs**:
  - In **VOC-limited environments** (like urban centers), reducing NO_x can **increase ozone**.
  - In **NO_x-limited environments** (rural/suburban), reducing NO_x **reduces ozone**

3. Sources of Precursors

- **NO_x:** Vehicle exhaust; Power plants; Industrial combustion
- **VOCs:** Solvents and chemical manufacturing; Gasoline vapors; Vegetation (biogenic VOCs)

Photochemical Smog

1. Overview

- A type of air pollution formed when **sunlight** reacts with **nitrogen oxides (NO_x)** and **volatile organic compounds (VOCs)**.
- Produces a mix of **secondary pollutants**:
  - **Ozone (O_3)**
  - **Peroxyacyl nitrates (PANs)**
  - **Aldehydes** and other **oxidants**

2. Formation Mechanism

- **NO_2 + sunlight → NO + O** ----(Nitrogen dioxide is broken down by UV rays.)
- **$O + O_2 \rightarrow O_3$** ------(Atomic oxygen reacts with O_2 to form ozone)
- **O_3 + VOCs + NO_x → PANs, aldehydes, more oxidants** ------ (VOCs and NOx in sunlight react to form complex secondary pollutants.)

3. Key Conditions for Formation

- Urban areas with high vehicle traffic
- Regions with strong sunlight (e.g., summer months)
- Cities in basins or valleys (e.g., Los Angeles, Delhi, Mexico City)
- Dry and warm climates enhance smog formation.

Revised National Ambient Air Quality Standards (NAAQS)

[NAAQS Notification dated 18th November, 2009]

S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air: Industrial, Residential, Rural and other Areas	Concentration in Ambient Air: Ecologically Sensitive Area (notified by Central Government)	Methods of Measurement
1	Sulphur Dioxide (SO_2), µg/m^3	Annual*	50	20	1. Improved West and Gaeke 2. Ultraviolet Fluorescence
		24 Hours**	80	80	
2	Nitrogen Dioxide (NO_2), µg/m^3	Annual*	40	30	1. Modified Jacob & Hochheiser 2. Chemiluminescence
		24 Hours**	80	80	
3	Particulate Matter (Size <10µm) or PM_{10} µg/m^3	Annual*	60	60	1. Gravimetric 2. TEOM 3. Beta attenuation
		24 Hours**	100	100	
4	Particulate Matter (Size <2.5 µm) or $PM_{2.5}$ µg/m^3	Annual*	40	40	1. Gravimetric 2. TEOM 3. Beta attenuation
		24 Hours **	60	60	
5	Ozone (O_3), µg/m^3	8 hours**	100	100	1. UV photometric 2. Chemiluminescence 3. Chemical Method
		1 hours **	180	180	
6	Lead (Pb), µg/m^3	Annual *	0.50	0.50	1. AAS/ICP Method after sampling using EPM 2000 or equivalent filter paper 2. ED-XRF using Teflon filter
		24 Hour**	1.0	1.0	
7	Carbon Monoxide (CO), mg/m^3	8 Hours **	02	02	Non dispersive Infra Red (NDIR) Spectroscopy
		1 Hour**	04	04	
8	Ammonia (NH_3), µg/m^3	Annual*	100	100	1. Chemiluminescence 2. Indophernol blue method
		24 Hour**	400	400	
9	Benzene (C_6H_6) , µg/m^3	Annual *	05	05	1. Gas chromatography based continuous analyzer 2. Adsorption and Desorption followed by GC analysis
10	Benzo(a)Pyrene (BaP)- particulate phase only, ng/m^3	Annual*	01	01	Solvent extraction followed by HPLC/GC analysis
11	Arsenic (As), ng/m^3	Annual*	06	06	AAS/ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel (Ni), ng/m^3	Annual*	20	20	AAS/ICP method after sampling on EPM 2000 or equivalent filter paper

** Annual Arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform interval.** 24 hourly 08 hourly or 01 hourly monitored values, as applicable shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.*

NOTE: Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigation.

Effects Of Air Pollution

- Air pollution exerts profound impacts on environmental health, human well-being, and climate systems by releasing harmful pollutants such as particulate matter (PM), NO_x, SO_2, CO, benzene, and formaldehyde into the atmosphere.
- It accelerates ecosystem degradation through contamination of air, water, and soil, promotes acid rain, and disrupts biogeochemical cycles, affecting agriculture and aquatic biodiversity.
- Elevated greenhouse gases from pollution exacerbate global warming, intensify extreme weather events, and destabilize climatic equilibrium.
- Reduced visibility from smog and haze impairs transportation, lowers urban livability, and diminishes scenic and tourism value.
- Chronic exposure corrodes infrastructure and heritage structures via chemical weathering (e.g., sulphation), while VOCs and industrial odours degrade indoor and outdoor air quality.

Effect Of Air Pollution On Human Health

1. Respiratory Effects

- Irritation of the nose, throat, and lungs.
- Increased cases of **asthma (breathing difficulty)**, **bronchitis (chest congestion/cough with mucus)**, and **chronic obstructive pulmonary disease – COPD (long-term airflow blockage)**.
- Reduced lung function, especially in children and the elderly.
- Aggravation of pre-existing respiratory conditions such as **sinusitis (nasal inflammation)** and **allergic rhinitis (seasonal allergies)**.

2. Cardiovascular Effects

- Increased risk of **heart attacks (sudden chest pain)** and **strokes (brain clot or bleed)**
- Elevated **blood pressure (high BP)**
- Inflammation and damage to **blood vessels (artery damage)**, increasing the risk of circulatory diseases.

3. Neurological Effects 🧠

- **Cognitive decline (mental slowing)** and memory impairment due to chronic exposure to air pollutants.
- Developmental delays in children, including **reduced IQ (learning difficulties)** and **attention deficit (difficulty focusing)**.
- **Neurotoxicity** caused by inhalation or ingestion of heavy metals such as **lead (brain damage risk)** and **mercury (nerve toxin)**, which affect both central and peripheral nervous systems.

4. Cancer Risk 🧬

- Elevated risk of **lung cancer (cancer of lungs)** and **bladder cancer (urinary tract cancer)** due to exposure to carcinogens like **benzene, formaldehyde**, and **polycyclic aromatic hydrocarbons (PAHs)**.
- Fine particulate matter ($PM_{2.5}$) is classified as a **Group 1 carcinogen** by the World Health Organization (WHO), indicating sufficient evidence of cancer-causing potential in humans.

5. Effects on Children and Pregnant Women 👶

- Increased incidence of **preterm births** and **low birth weight** due to maternal exposure to pollutants.
- Impaired **lung growth** and **neurodevelopment (brain development issues)** in infants and children.
- Elevated risk of **childhood asthma (breathing difficulty)** and frequent **respiratory infections** due to immature immune systems.

6. Effects on Elderly and Vulnerable Groups 👴

- Exacerbation of existing **chronic diseases** such as COPD, cardiovascular disease, and diabetes.
- Higher rates of **hospitalization** and **mortality** during pollution episodes (e.g., smog events).
- Declined **immune response** and slower recovery, making elderly more prone to complications.

7. Mortality and Morbidity ☠️

- Air pollution is linked to **millions of premature deaths** globally each year (as per WHO and Lancet reports).
- Long-term exposure increases the risk of **non-communicable diseases (NCDs)** like stroke, cancer, respiratory, and heart diseases, reducing life expectancy and quality of life.

Size-Dependent Deposition of Particulate Matter in the Human Respiratory System

- The diagram explains how **particles of varying sizes** deposit in different sections of the **respiratory tract**, helping to identify **which size fraction** is responsible for **specific health outcomes**.
- **Large Particles (>10 µm):**
  - Deposited in the **nasopharyngeal region** (nose and throat
  - Cause **sneezing**, **coughing**, and **upper respiratory irritatio**
- **Medium Particles (1–10 µm):**
  - Penetrate to the **tracheobronchial region** (airways).
  - Associated with **bronchitis**, **asthma**, and airway inflammation.
- **Fine and Ultrafine Particles (<1 µm):**
  - Reach the **pulmonary/alveolar region** (deep lungs).
  - Can **cross into the bloodstream**, affecting the **heart**, **brain** and triggering **chronic diseases** such as cardiovascular and neurodegenerative disorders.
- **Smaller particles** penetrate **deeper** into the lungs.
- **Ultrafine particles (<0.1 µm)** are **most hazardous** as they-

bypass natural respiratory defenses and reach vital organs- via circulation.

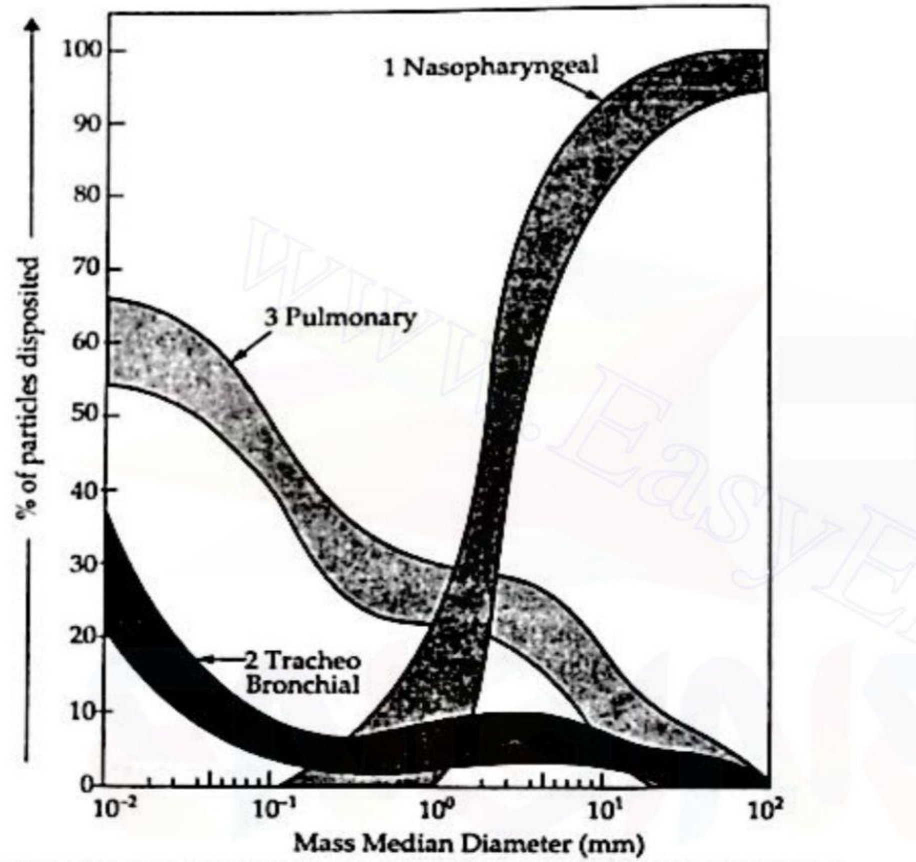


Fig. 18.2. Percentage of particles of different sizes deposited in the *respiratory tract*—consisting of (*i*) nose and throat region—called *nasopharyngeal*; (*ii*) tubes leading to lungs—called *tracheobronchial*; and (*iii*) lung regions—called pulmonary.

S. No.	Pollutant	Health Effects
1.	Particulate Matter (PM_{10}, $PM_{2.5}$)	- Penetrates deep into lungs; $PM_{2.5}$ reaches alveoli and bloodstream. - Triggers asthma, bronchitis, and COPD.- Impairs respiratory and cardiovascular function. - Causes lung tissue damage, promotes carcinogenic changes. - Contributes to premature birth, infant mortality, and cognitive decline in children. - Elderly and immunocompromised are at higher risk of morbidity and mortality. - Long-term exposure associated with stroke, heart disease, and diabetes.
2.	Sulfur Dioxide (SO_2)	- Irritates mucous membranes of the nose, throat, and lungs. - Causes tightness in chest, shortness of breath, and wheezing. - Triggers asthmatic attacks and aggravates chronic lung conditions. - Long exposure leads to lung inflammation and reduced lung function. - May contribute to acid rain, indirectly affecting food and water safety.

S. No.	Pollutant	Health Effects
3.	Carbon Monoxide (CO)	- Binds with hemoglobin, reducing oxygen transport. - Leads to hypoxia (oxygen deficiency), impairing brain and heart function. - Symptoms: headache, dizziness, confusion, and fainting.- High levels cause neurological damage, unconsciousness, and death.- Dangerous to fetuses, infants, and those with heart disease.
4.	Nitrogen Oxides (NO_x)	- NO_2 aggravates asthma, bronchitis, and respiratory infections. - Causes inflammation of airways, especially in children. - Decreases lung function and increases sensitivity to allergens. - Involved in photochemical smog formation, reducing visibility and increasing ozone exposure.
5.	Lead (Pb)	- Affects central nervous system, especially in children.- Causes learning disabilities, behavioral disorders, and lower IQ.- Associated with hypertension, kidney damage, and reproductive issues in adults.- Chronic exposure leads to mental retardation and developmental delays.

S. No.	Pollutant	Health Effects
6.	Ozone (O_3)	- Reduces lung capacity and causes chest pain, coughing, and wheezing.- Triggers respiratory inflammation and aggravates COPD and asthma.- Long exposure linked with lung aging, immune dysfunction, and cardiovascular strain.- Dangerous to both healthy individuals and those with respiratory vulnerabilities.
7.	Carbon Dioxide (CO_2)	- Not toxic at ambient levels but contributes to climate change.- Indirectly affects human health by increasing heat waves, vector-borne diseases, and food insecurity.- Causes ocean acidification, disrupting marine food chains and affecting nutrition.
8.	Nuclear Radiation / Waste	- Leads to genetic mutations, cancer, and radiation sickness.- Damages bone marrow, thyroid, lungs, and reproductive organs.- Long-term exposure increases risk of leukemia, birth defects, and early mortality.- Contaminates air, water, and soil for decades.

🧮 Numerical 5 (Revised): Estimating Lifetime Cancer Risk from Benzo[a]pyrene (BaP)

🔹 **Given:**

- Ambient BaP concentration = 3 ng/m^3
- Inhalation rate = 10 m^3/day
- Lifetime = 70 years
- Body weight = 75 kg
- Cancer Slope Factor (CSF) for BaP = 1.1 $(\mu g/kg\text{-}day)^{-1}$

Step-by-Step Calculation:

✅ **1. Total BaP inhaled over a lifetime**

$$\text{Total air inhaled per year} = 10 \times 365 = 3650\,\text{m}^3/\text{year}$$

$$\text{BaP per year} = 3\,\text{ng}/\text{m}^3 \times 3650 = 10,950\,\text{ng}/\text{year}$$

$$\text{BaP over 70 years} = 10,950 \times 70 = 766,500\,\text{ng} = 0.7665\,\text{mg} = 0.0007665\,\text{g}$$

✅ **2. Average Daily Dose (ADD)**

$$\text{ADD} = \frac{\text{Total BaP dose } (\mu\text{g})}{\text{Body weight} \times \text{Lifetime in days}} = \frac{766.5\,\mu g}{75 \times 70 \times 365} = \frac{766.5}{1,912,500} \approx 4.007 \times 10^{-4}\,\mu g/kg - day$$

✅ **3. Lifetime Cancer Risk**

$$\text{Risk} = \text{ADD} \times \text{Cancer Slope Factor} = 4.007 \times 10^{-4} \times 1.1 \approx 4.41 \times 10^{-4}$$

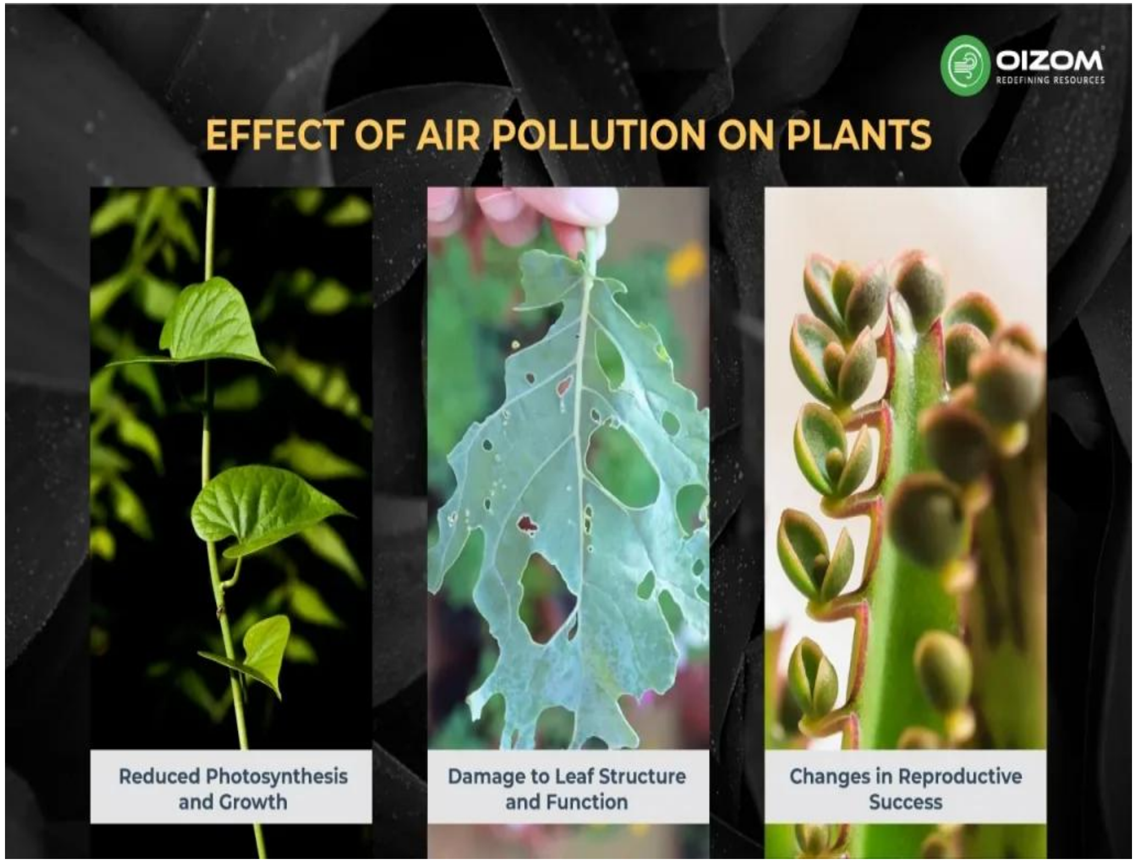
🎯 **Final Answer:**

$$\boxed{\text{Estimated Lifetime Cancer Risk} \approx 4.41 \times 10^{-4} \text{ or } 0.044\%}$$

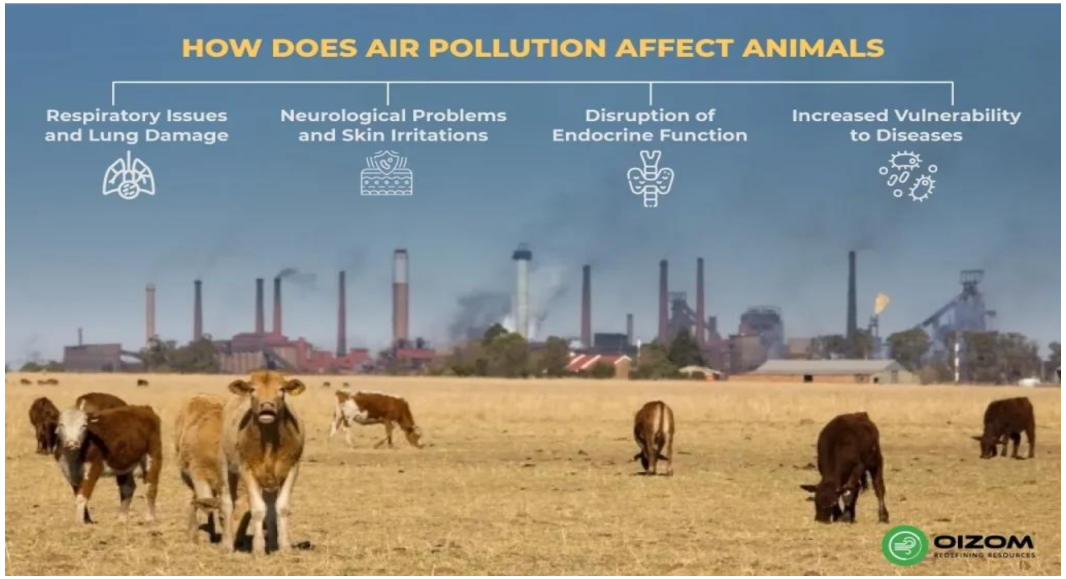
➡️ This means **out of 10,000 people**, about **44 may develop cancer** due to lifetime BaP inhalation at this exposure level.

Effect Of Air Pollution On Plant Health

- **Leaf Damage**
  - Yellowing (chlorosis), browning (necrosis), and visible spots.
  - Caused by ozone, sulfur dioxide, and nitrogen oxides.
- **Reduced Photosynthesis**
  - Damage to chlorophyll and stomatal blockage.
  - Leads to lower energy production and stunted growth.
- **Growth Suppression**
  - Slower germination, shorter roots and shoots.
  - Caused by long-term exposure to pollutants.
- **Yield Reduction**
  - Decreased crop quantity and quality.
  - Affects flowering, fruiting, and seed development.
- **Increased Disease Susceptibility**
  - Pollutants weaken plant immunity.
  - Makes plants more vulnerable to pests and pathogens.
- **Soil and Nutrient Effects**
  - Acid rain alters soil pH and reduces nutrient uptake.
  - Affects plant metabolism and root health.



Effect Of Air Pollution On Live-Stock Animals



- **Respiratory Problems**
  - Coughing, wheezing, and lung infections from gases like ammonia and particulate matter.
- **Reduced Productivity**
  - Decreased milk, meat, and egg production due to poor air quality.
- **Lower Feed Intake & Weight Gain**
  - Pollutants suppress appetite and slow growth rates.
- **Reproductive Issues**
  - Fertility decline, miscarriages, and low birth weight in offspring.
- **Increased Disease Risk**
  - Weakened immunity makes animals more vulnerable to infections.
- **Neurological Effects**
  - Gases like CO and H_2S may cause disorientation and behavioral changes.
- **Mortality and Stress**
  - High pollutant levels in enclosed spaces can cause death and stress-related issues.
- **Contamination of Animal Products**
  - Toxins may accumulate in milk, meat, and eggs, affecting food safety.

Effects Of Air Pollutants On Material and Services

1. Structural Damage

- **Acid rain** (from SO_2 and NO_x) corrodes **buildings,- bridges, and monuments**.
- Materials like **limestone, marble, and metals** degrade- faster in polluted air.

2. Surface Discoloration and Staining

- **Particulate matter (PM)** causes **blackening or soiling-** of surfaces (walls, statues, signage).
- Affects the **aesthetic value** of public and private- buildings.

3. Metal Corrosion

- Pollutants like **SO_2, NO_x, and ozone (O_3)** accelerate **rusting and corrosion** of metals (iron, steel, copper).
- Increases **maintenance costs** in industries and infrastructure.

Effects Of Air Pollution On Aquatic Life and Global and Regional Environment

1. On Aquatic Life

Acid rain lowers the pH of water bodies, making them more acidic. This harms fish and aquatic organisms by:

- Damaging gills and reducing reproduction.
- Killing sensitive species like trout and amphibians.
- Disrupting food chains and reducing biodiversity.

2. On Global and Regional Environment

- Climate Change: CO_2 and CH_4 increase global temperatures.
- Ozone Depletion: CFCs reduce ozone, raising UV exposure.
- Acid Rain: Transboundary SO_2 and NO_x cause ecosystem damage.
- Smog: O_3 and NO_x cause photochemical smog in cities.
- Acid Rain: Local emissions damage soil, water, and vegetation.
- Weather Changes: Aerosols alter regional rainfall and temperature.

Dispersion of Air Pollutants into the Atmosphere

- **Definition:** The **dispersion of air pollutants** refers to the process by which airborne pollutants emitted from sources such as industrial stacks, motor vehicles, biomass burning, or volcanic eruptions spread and dilute in the atmosphere. This determines the **downwind concentration**, **exposure level**, and **impact area** of the pollutants.

  Dispersion is governed by **atmospheric dynamics**, **topography**, **chemical transformations**, and **meteorological parameters** such as wind speed, temperature, turbulence, and humidity.

- **Lapse Rate:** The lapse rate refers to the rate at which air temperature decreases with an increase in altitude in the atmosphere.

Why Does Air Cool When It Rises?

- Rising air expands due to lower pressure at high altitudes
- Expanding air loses heat and cools down
- Cooling rate depends on moisture content

Key Applications of Lapse Rate and Dispersion

- **Air Quality Modeling** – Lapse rate helps predict how pollutants disperse in the atmosphere using models like AERMOD and CALPUFF.
- **Urban Planning and Zoning** – Knowledge of lapse rate guides the placement of industries to reduce pollution exposure in residential areas.
- **Weather Forecasting** – Lapse rate is used to assess atmospheric stability and forecast phenomena like clouds, storms, and inversions.

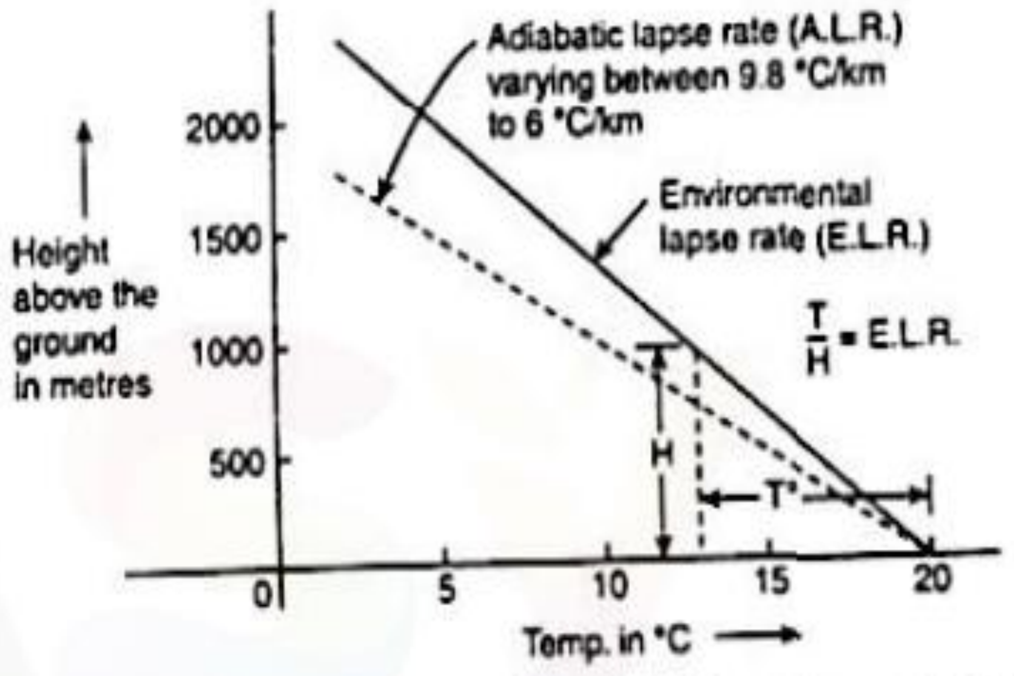
1.Environmental Lapse Rate (ELR)

•The actual rate of temperature decrease in the atmosphere at a given time and place.

•Varies with weather, time, and location.

•Average: **6.5°C per 1000 meters**

Application:Stability assessment, pollution--dispersion, aviation



18.3. The change of temperature with height in the environment, called E.L.R.

2.Dry Adiabatic Lapse Rate (DALR)

•The rate at which **dry (unsaturated)** air--cools as it rises.

•Constant: **9.8°C per 1000 meters**

Application: Parcel theory, mountain weather, dry air convection

3.Moist Adiabatic Lapse Rate (MALR)

•The rate at which **saturated** air cools as it rises.

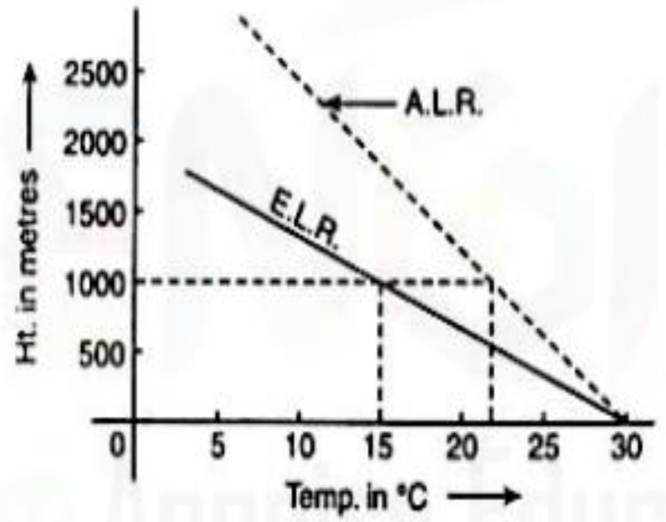
•Lower than DALR due to latent heat release during condensation.

•Variable: **4°C to 7°C per 1000 meters**

Application: Cloud formation, thunderstorms, moist convection

Condition 1: ELR > ALR ⇒ Unstable Atmosphere

- Rising air parcel stays warmer than surrounding air.
- Warm air is less dense, so it continues to rise freely.
- Promotes vertical mixing, cloud formation, and pollutant dispersion.
- Air rises, cools more slowly than the surroundings, and keeps rising → unstable air.



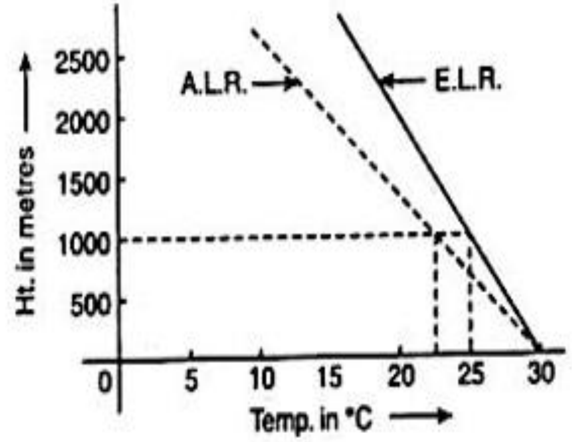
- ELR > ALR ⇒ Unstable atmosphere ⇒ Vertical motion enhanced ⇒ Better pollutant dispersion

➢ **Example:** On a hot sunny afternoon, the surface heats up rapidly. The temperature drops quickly with height, making ELR steep.

➢ Indian States Where This Commonly Occurs: Rajasthan, Gujarat, Madhya Pradesh, Telangana, Maharashtra, etc.

Condition 2: ELR < ALR ⇒ Stable Atmosphere

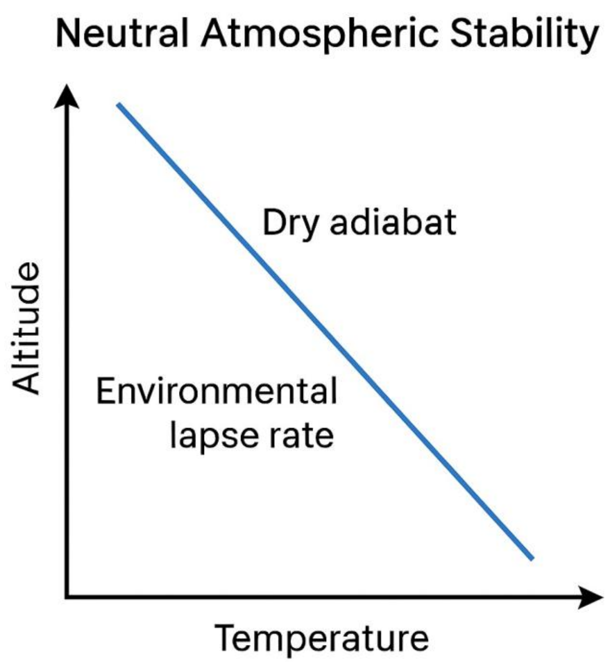
- A **rising air parcel cools faster** than the surrounding air.
- So it becomes **colder and denser** than the air around it.
- As a result, the air parcel **sinks back** to its original level.
- **Vertical motion is suppressed**, and **pollutants remain trapped** near the surface.
- **Cool air near the surface** is trapped by **warmer air above**
- Common during **winter nights**, especially in **valleys**
- Leads to **smog**, fog, and **severe air pollution episodes**
- ELR < ALR ⇒ Stable atmosphere ⇒ No vertical movement ⇒ Pollutants stay trapped near surface.



Example: Stable atmospheric conditions (ELR < ALR) often occur in: Delhi (NCR), Bangalore, Pune, Punjab, Haryana and Dehradun

Condition 3: ELR = ALR ⇒ Neutral Atmosphere

- When the **Environmental Lapse Rate (ELR)** is **equal to** the **Adiabatic Lapse Rate (ALR)** (usually the **Dry Adiabatic Lapse Rate**), the atmosphere is said to be **neutrally stable** or in a **neutral state**.
- A **rising air parcel** cools at the **same rate** as the surrounding environment.
- The **temperature inside and outside the parcel remains the same** at every altitude.
- There is **no buoyant force** pushing the air parcel upward or pulling it downward.

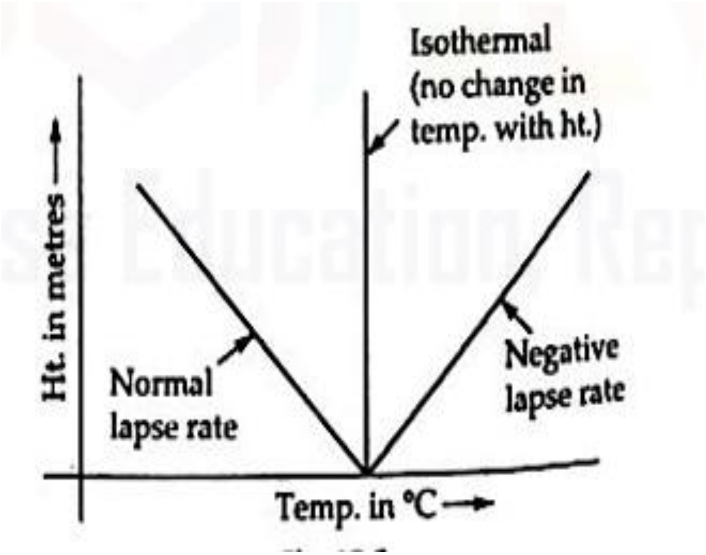


- **Mixing layers** in the lower atmosphere may become **neutrally stable** during:
  - Late **afternoon**, after peak surface heating subsides.
  - Days with **consistent cloud cover** that limits solar heating.
  - Urban areas with **constant mechanical turbulence** (from buildings, traffic).

  Neutral atmospheric environment occurs in : Chennai or Kochi

Negative Lapse Rate and Inversion

- A **negative lapse rate**—more commonly known as a **temperature inversion**—occurs when temperature increases with height, which creates a “lid” of warm air above cooler surface air.
- This effectively traps pollutants close to the ground.
- Under normal conditions, warm air rises and carries pollutants upward, dispersing them.
- But during an inversion, vertical mixing is suppressed.
- Pollutants such as $PM_{2.5}$, nitrogen oxides, sulfur dioxide, volatile organic compounds, carbon monoxide, and soot accumulate in this shallow mixing layer.



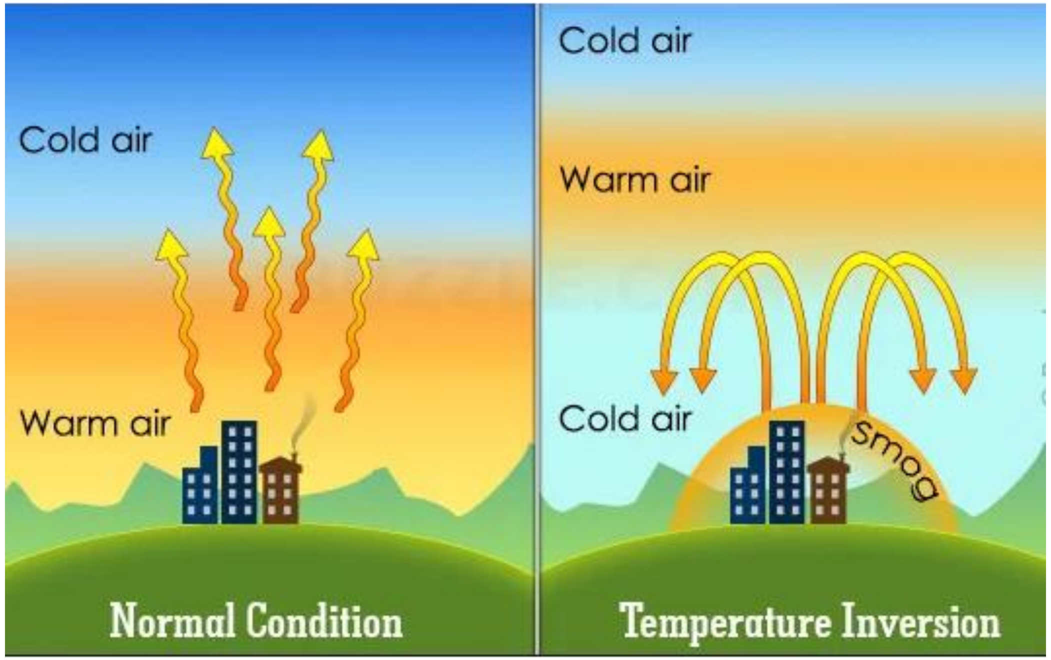
Types of Inversions

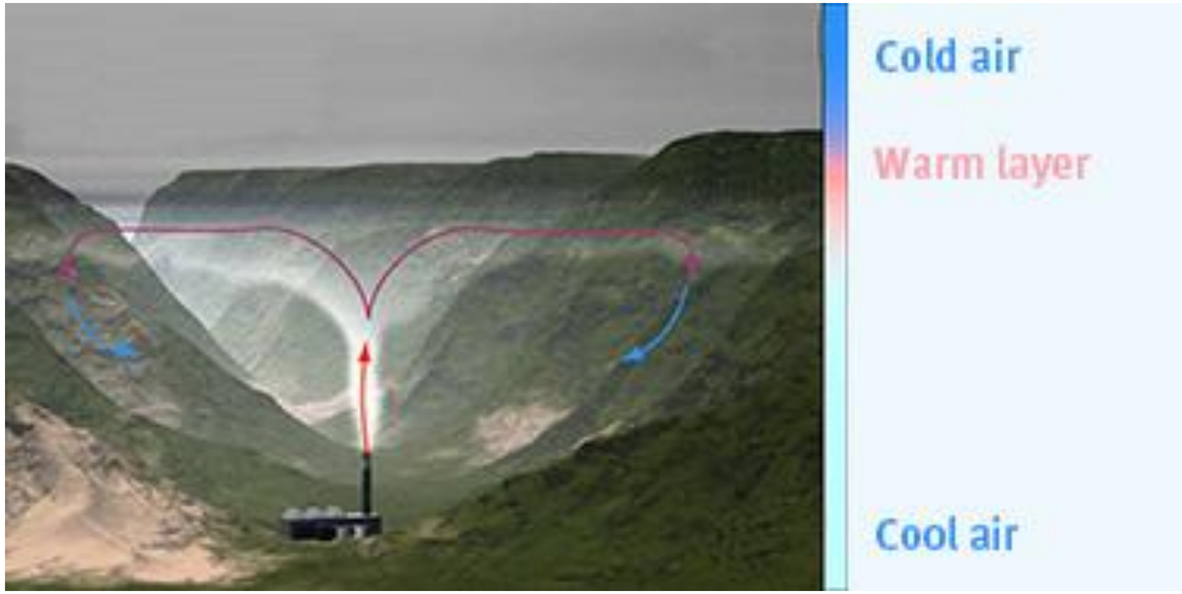
1.Radiation Inversion

- Occurs under clear night skies and calm winds when the ground loses heat via long-wave radiation, cooling surface air below warmer air aloft.
- This creates a stable, shallow inversion near the ground that quickly dissolves after sunrise.
- The shallow but strong inversion traps pollutants from road traffic, heating, and industry close to the surface, sharply increasing $PM_{2.5}$ and other emissions within a thin layer.

2. Subsidence Inversion

- Occurs under a high-pressure/anticyclone setup: large-scale descent of air aloft warms by compression, forming a warm inversion layer above cooler boundary air, typically at 1,000–2,000 m altitude.
- Though weaker stratification than radiation inversion, subsidence inversions suppress vertical mixing and can transport polluted air downward from aloft into the boundary layer—intensifying surface pollution.


Cold air
Warm air
Normal Condition
Cold air
Warm air
Cold air
Smog
Temperature Inversion


Cold air
Warm layer
Cool air

Case Study of Inversion Condition

1. Great Smog of London (December 1952)

Type: Subsidence inversion combined with stagnant anticyclonic conditions over a cold industrial city.

Context: A high-pressure system blocked dispersion of coal-burning emissions during a cold spell.

A thick inversion layer formed, locking in sulfurous smoke and particulates.

Impact: Estimated **10,000–12,000** deaths, massive disruptions in visibility, and stoppages in transit.

2. Delhi, Indo-Gangetic Plain (Winter smog dominance)

Type: A combination of **radiation inversions** near the surface and **subsidence inversions** aloft, creating a **composite inversion structure**

Context: During winter, clear skies and calm winds cause the ground to cool rapidly—forming a shallow radiation inversion near the surface.

Above it, a subsidence inversion forms under high-pressure systems.

Meanwhile emissions from crop residue burning, vehicles, industry, and construction add to pollution.

Impact: AQI often climbs above **1,000**; peak levels reaching nearly **1,400–1,700**, forcing school closures and heavy health alerts.

This seasonal inversion fosters severe haze episodes in December–January.

Problem:

During winter, an inversion traps pollutants between surface temperature **15°C** and a temperature of **20°C** at the inversion top.

If the **Environmental Lapse Rate (ELR)** is **6°C/km**, estimate the **height of the inversion layer**.

Solution:

$$\Delta T = 20 - 15 = 5^{\circ}C$$

$$\text{Height} = \frac{\Delta T}{\text{ELR}} = \frac{5}{6} = 0.833\,\text{km} = 833\,\text{m}$$

Problem:

A radiation inversion layer traps pollutants within **50 m** height.

If **SO_2 emission** is **1.2 tons/day** from an industrial area of **5 km²**, calculate:

(a) Volume of trapped air

(b) SO_2 concentration in μg/m³

Solution:

(a) Volume = 5×10^6 m² × 50 = $2.5 \times 10^8\,\text{m}^3$

(b)

$$SO_2\text{ mass} = 1.2 \times 10^6\,\text{g} = 1.2 \times 10^9\,\mu g \Rightarrow \text{Concentration} = \frac{1.2 \times 10^9}{2.5 \times 10^8} = 4.8\,\mu g/m^3$$

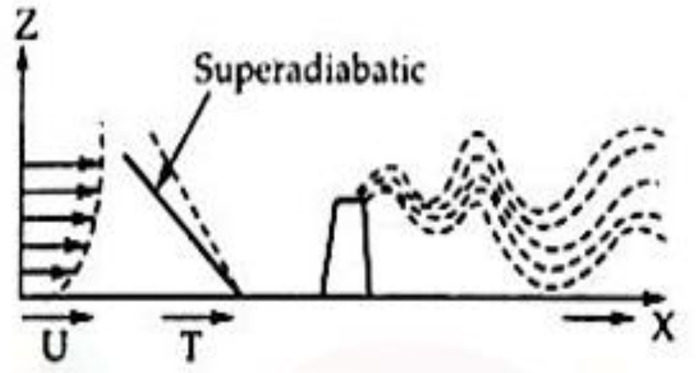
Impacts of wind on dispersion of pollutants

- Wind plays a vital role in dispersing air pollutants: **strong winds foster dilution**, **horizontal transport**, and **vertical mixing**, whereas **calm winds and directional misalignment can trap pollutants near their source**.
- Research shows that when wind speed exceeds a critical threshold—about **1.2 m/s above rooftop level**—pollutant concentrations decline sharply, entering a wind-dependent regime where turbulence and eddies enhance vertical mixing.
- Below this threshold, concentrations remain high regardless of wind direction, as traffic-driven turbulence dominates.
- In **urban street canyons**, wind blowing **parallel to the street axis** promotes ventilation and reduces $PM_{2.5}$ levels, while **perpendicular or oblique winds** induce vortex circulation that traps pollutants, especially along leeward sidewalks.
- Complex terrain and urban roughness further reduce near-surface wind speeds and suppress mixing—intensifying stagnation under calm conditions .

Lapse Rates and Dispersion of Air Pollutants

1. Looping Plume

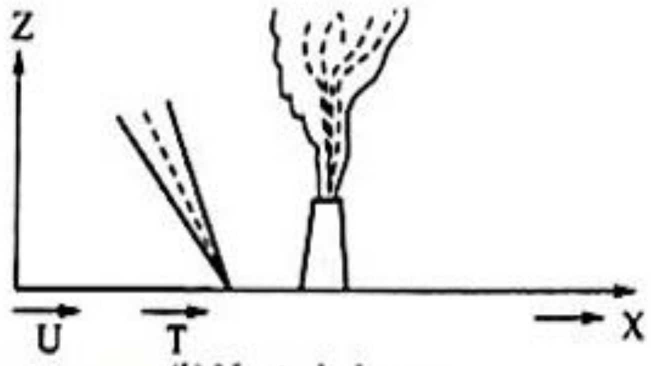
- A **looping plume** occurs under **very unstable atmospheric conditions**, where the **environmental lapse rate (ELR)** exceeds the **dry adiabatic lapse rate (DALR)** (i.e. super-adiabatic environment).
- In this state, the atmosphere promotes vigorous vertical motion, causing the plume to oscillate in a looping or wave-like path.



(a) Looping plume

2. Neutral Plume

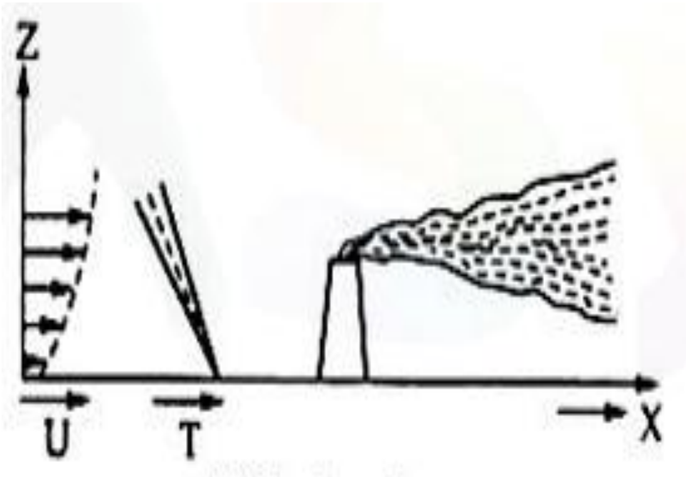
- A **neutral plume** forms under **neutral atmospheric stability**, when the **environmental lapse rate (ELR)** equals the **dry adiabatic lapse rate (DALR)**—i.e., the atmosphere is neither stable nor unstable.
- In this scenario, the released plume rises due to buoyancy initially, but vertical motion is neither enhanced nor suppressed by the ambient temperature gradient.



(b) Neutral plume

3. Coning Plume

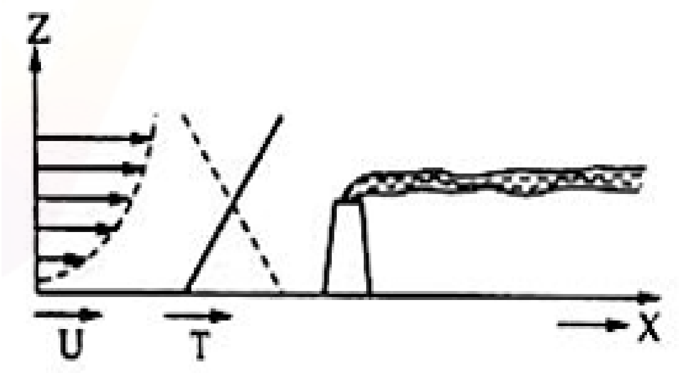
- A **coning plume** forms when the atmosphere is in **neutral or slightly stable conditions**, typically where the **environmental lapse rate (ELR)** is just below the **dry adiabatic lapse rate (DALR)**—forming a **sub-adiabatic** profile.
- In such conditions, turbulence evenly spreads the plume vertically and horizontally, creating a roughly symmetrical cone shape around the emission axis.
- This plume shape indicates moderately efficient dispersion.



(c) Coning plume

4. Fanning Plume

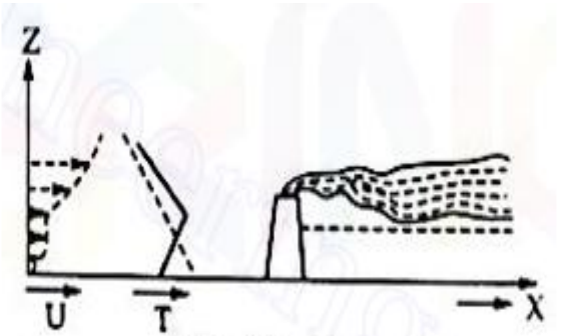
- A **fanning plume** occurs when the atmosphere is **stably stratified**—in other words, under **temperature inversion conditions** (i.e., a negative lapse rate).
- In such a scenario, vertical motion is strongly suppressed, so the plume spreads almost exclusively **horizontally**, remaining at the emission level without vertical mixing or descent toward the ground.
- The plume visually resembles an **oriental fan**—a wide, shallow shape that travels downwind in nearly a flat plane.



(d) Fanning plume

5. Lofting Plume

- A **lofting plume** forms when a **surface inversion (negative lapse rate)** exists just below the stack exit, while the layer immediately above the plume exhibits **super-adiabatic lapse conditions** (high instability).
- This structure prevents downward mixing but encourages a rapid upward rise and turbulent mixing above the inversion.



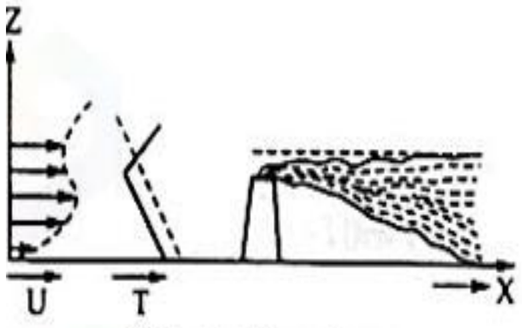
(e) Lofting plume

6.Fumigating Plume

- A **fumigating plume**—or **fumigation plume**—occurs when there is a **temperature inversion layer just above a smokestack** and **very unstable turbulence or heating below the stack exit**.

Under these conditions:

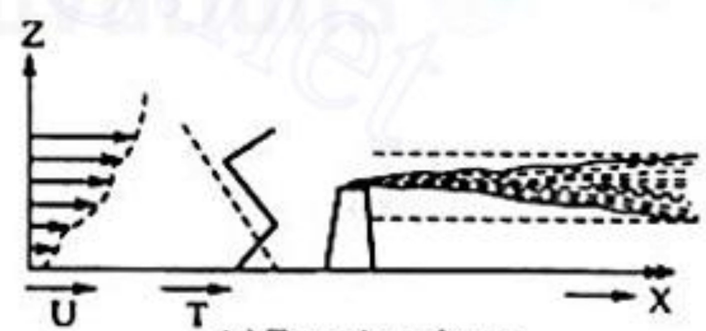
- Pollutants **cannot rise above the inversion** layer.
- Instead, turbulent mixing beneath the inversion **pushes contaminant-rich air downward**, delivering it to ground level.
- This is the opposite of a lofting plume, which lifts pollutants aloft and reduces ground-level exposure.



(f) Fumigating plume

7. Trapping Plume

- A **trapping plume** occurs when a vertical temperature inversion exists **both above and below** the emission source (e.g. a smokestack), creating a “sandwich” of stable layers that **confines the plume within a limited vertical zone**.
- Neither upward nor downward movement is possible, causing the pollutants to be trapped in place.



(g) Trapping plume

Plume Type	Stability / Lapse Rate	Typical Wind / Conditions	Dispersion Behavior	Ground-Level Impact
Looping	Super-adiabatic (ELR > DALR; very unstable)	Strong solar heating, wind > 10 m/s (≈ 36 km/h)	Wavy, oscillating plume; rapid vertical mixing	May touch ground ⇒ high local spikes
Funnels/Neutral	Neutral (ELR = DALR)	Moderate winds, neutral stability	Straight vertical rise balanced with lateral spread	Moderate; predictable mixing
Coning	Slightly stable or sub-adiabatic (ELR < DALR but near neutral)	Wind > 32 km/h (~9 m/s), overcast or windy	Symmetrical cone; balanced vertical & horizontal mixing	Moderate; delayed ground arrival
Fanning	Stable inversion (negative lapse rate)	Light winds, clear night or early morning	Fan-shaped horizontal spread at stack-height; minimal vertical mixing	Low near source; remains aloft
Lofting	Inversion below stack + unstable layer above	Typically early night residual turbulence	Plume rises above inversion and disperses aloft	Low ground impact; favorable dispersion
Fumigation	Inversion above stack + super-adiabatic layer below	Clear skies, light winds, mid-morning inversion breakup	Plume pushed downward into mixing layer ⇒ spreads to ground	Very high; worst-case exposure
Trapping	Inversion layers both above & below stack	Very stable air, often in valleys	Plume confined within a “sandwich” layer, no vertical mixing	Pollutants remain trapped; surface or layer zone

Impact of Atmospheric Pressure on Dispersion of Air Pollutants

➢ High-Pressure Systems (Anticyclones)

- Air sinks and creates clear skies.
- Forms temperature inversions that **trap pollutants near the surface**.
- **Reduces vertical mixing** and wind speed, leading to **pollution build-up**.

➢ Low-Pressure Systems

- Air rises and causes **clouds, wind, and rain**.
- Enhances **vertical and horizontal mixing**.
- **Improves air quality** by dispersing or washing out pollutants.

➢ Interaction with Other Factors

- Pressure alone doesn’t determine pollution levels.
- It **interacts with wind, temperature, and stability** to influence dispersion.

Impact of Moisture and Precipitation on Dispersion of Air Pollutants

➢ Positive Impacts:

•**High humidity** makes fine particles (like $PM_{2.5}$) absorb moisture, become heavier, and settle faster—reducing air suspension.

•**Rainfall** helps clean the air:

- **Rainout**: Pollutants are incorporated into cloud droplets before rain.
- **Washout**: Falling raindrops collide with and remove particles and gases from the air.

➢ Negative Impacts:

- **High humidity** increases haze and visibility reduction by enhancing particle growth and secondary aerosol formation.
- **Humidity at night** can lead to **temperature inversions**, trapping pollutants near the surface.
- **Low humidity** keeps particles smaller and lighter, allowing them to stay airborne longer and increasing $PM_{2.5}/PM_{10}$ levels.
- In dry conditions, **pollutant removal is less effective**, and **dust resuspension** can raise pollution, especially in arid areas.