Environmental Sustainability

Comprehensive Academic Textbook

& Full PYQ Solved Bank

Course Code: DI02000051
Program: Diploma in Engineering (All Branches)
Semester: 2nd **Category:** Mandatory Course
Credits: 2 (L:2 + T:0) **Marks:** 100

Papers Covered in PYQ Solutions:

Summer 2022 · Winter 2022 · Summer 2023 · Winter 2023
Summer 2024 · Winter 2024 · Summer 2025 · Winter 2025

Gujarat Technological University
Diploma Engineering Programme
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Compiled for Diploma Engineering students

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Environmental Sustainability

A Comprehensive Textbook with Solved Previous Year Questions

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Dedicated to

My family and mentors,

whose support and guidance made this work possible.

Contents

Preface

About This Textbook

Environmental Sustainability is one of the most critically important subjects for modern engineers. As the world grapples with resource depletion, pollution, and climate change, engineers are uniquely positioned — and morally obligated — to design systems and adopt practices that protect the planet for future generations.

This textbook has been designed with a dual purpose. First, it provides a thorough and pedagogically sound explanation of every topic in the GTU syllabus for DI02000051. Each chapter builds upon previous concepts, ensuring that a student starting from zero can develop a comprehensive understanding of environmental systems, pollution mechanisms, energy alternatives, climate science, and environmental governance.

Second, it functions as a complete answer reference for the Previous Year Question (PYQ) bank. Each solved PYQ is presented in a structured, exam-oriented format — directly after the conceptual explanation it draws from — so that students understand *why* an answer is correct, not just *what* the answer is.

How to Use This Book

1. **First reading:** Read the theory sections and `keyconcept` boxes carefully to build your understanding. Do not skip examples.

2. **Second pass:** Study the solved PYQs (highlighted in red boxes) while covering the answer with your hand — attempt an answer first, then compare.

3. **Before exams:** Use the mock papers at the end of the book as timed exam simulations.

Course Outcomes

After completing this course, students will be able to:

1. Understand the principles of ecosystem functioning, biodiversity, and natural biogeochemical cycles.

2. Analyse different forms of pollution and evaluate appropriate control technologies.

3. Compare renewable and conventional energy systems and evaluate their environ-

mental trade-offs.

4. Assess the scientific evidence for climate change and articulate global strategies for its mitigation.

5. Apply principles of environmental law, sustainable design, and cleaner production to engineering decisions.

Teaching and Examination Scheme

Teaching Scheme			Credits	Assessment		Total
L	**T**	**P**		**ESE (Theory)**	**PA/CA**	
2	0	0	2	70 Marks	30 Marks	100 Marks

Acknowledgments

I would like to express my sincere gratitude to everyone who contributed to the development of this textbook.

Special thanks to:

- **Academic Mentors**: For their guidance and technical feedback during the writing process.
- **Student Reviewers**: For their valuable insights that helped simplify complex mathematical concepts.
- **Family and Friends**: For their unwavering support and encouragement throughout this journey.
- **Claude Sonnet 4.6**: For advanced AI assistance in content structuring, formatting, and refining explanations.

Ultimately, this book exists to serve the student community, and I am grateful for the opportunity to contribute to their learning.

About the Author

Milav Jayeshkumar Dabgar is an engineering educator and R&D professional with over 9 years of experience in electronics hardware development, embedded systems, AI/ML, and full-stack software engineering. He currently serves as a **Lecturer (Class - II) & Innovation Leader** at Government Polytechnic, Palanpur, under the Education Department of the Government of Gujarat.

Milav holds a Master of Engineering (ME) in Communication Systems from L.D. College of Engineering and a Bachelor of Engineering (BE) in Electronics & Communication. He is also currently pursuing a **BS in Data Science and Applications from IIT Madras**, where he has completed both the **Diploma in Programming** and the **Diploma in Data Science** with distinction.

Most recently, he completed the **AICTE QIP PG Certificate Program in Deep Learning from SVNIT Surat** with a **perfect 10/10 CGPA**, topping his batch.

A dedicated mentor, Milav has guided numerous student teams in securing over **45 lakhs** in innovation funding, including 25 lakhs from Shark Tank India and 20 lakhs through iHub Gujarat, resulting in two student patents. He is recognized as an **NPTEL Evangelist** and **NPTEL Discipline Star** in Computer Science, reflecting his commitment to continuous learning and academic excellence.

His technical expertise spans from embedded systems (8051, STM32, Arduino) to modern web technologies (Next.js, Python, PostgreSQL) and Data Science (TensorFlow, PyTorch). Through this textbook, he aims to simplify complex Applied Mathematics concepts by integrating industry rigor with academic excellence.

Milav is also an active content creator, running a popular **YouTube channel** (@milav.dabgar) where he shares technical tutorials and academic resources. He maintains a personal blog and resource hub at milav.in and can be reached for professional collaborations on LinkedIn.

Chapter 1

Environmental Sustainability: Ecosystems and Biodiversity

1.1 What is Environmental Sustainability?

The word *sustainability* comes from the Latin *sustinere*, meaning "to hold up" or "to support." In an environmental context, sustainability refers to the ability of natural systems to remain diverse and productive indefinitely, so that they can continue to provide the ecosystem services on which all life depends.

The most widely quoted definition comes from the **Brundtland Report (1987, Our Common Future)**, published by the United Nations World Commission on Environment and Development:

Brundtland Definition of Sustainable Development

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

This definition rests on two key concepts:

1. **Needs:** Particularly the essential needs of the world's poor, which should be given overriding priority.

2. **Limits:** The idea that technology and social organisation must not impose limits on the environment's ability to meet present and future needs.

1.1.1 The Three Pillars of Sustainability

Modern sustainability thinking is organised around three mutually reinforcing pillars, sometimes depicted as three overlapping circles:

The Three Pillars

1. **Environmental Sustainability:** Maintaining the integrity of natural systems — clean air, clean water, fertile soil, stable climate, and thriving biodiversity.
2. **Social Sustainability:** Ensuring that human communities have equitable access to education, health, food, and a decent quality of life.
3. **Economic Sustainability:** Enabling economies to grow and develop in ways that do not destroy the natural capital on which they depend.

True sustainability is achieved only when all three pillars are balanced simultaneously. Economic development that destroys forests (environmental) or displaces communities (social) is not genuinely sustainable.

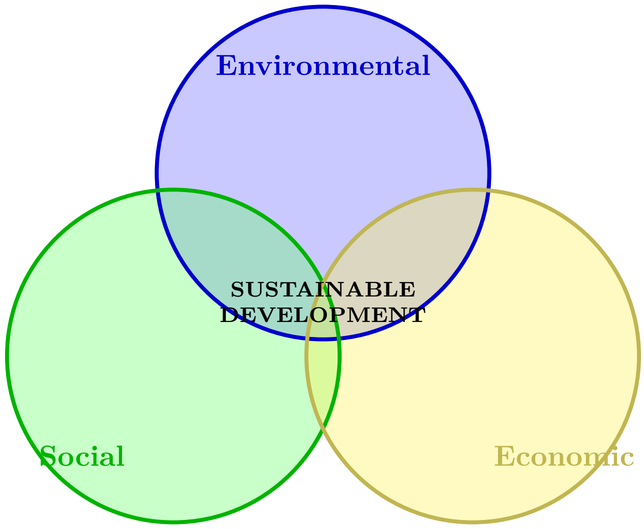


Figure 1.1: The Three Pillars (Circles) of Sustainable Development — True sustainability lies at the intersection of all three.

Pillar	Core Focus	Key Indicators
Environmental	Protect ecosystems, conserve resources, reduce pollution	Air quality, water quality, biodiversity index, CO_2 levels
Social	Equity, health, education, community well-being	HDI, literacy rate, poverty index, life expectancy
Economic	Growth without depleting natural capital	GDP, employment, resource productivity, innovation rate
Intersection	True Sustainable Development	All indicators balanced simultaneously

Table 1.1: Three Pillars of Sustainability — Focus Areas and Key Indicators

1.1.2 Historical Context

Human civilizations have always interacted with their natural environment. For most of history, these interactions were local and their impacts relatively small. The Industrial Revolution of the eighteenth and nineteenth centuries changed this fundamentally:

- Fossil fuels (coal, oil, gas) became the primary energy source, releasing carbon dioxide that had been trapped underground for millions of years.
- Industrial production vastly expanded the throughput of raw materials, creating large volumes of waste.
- The global human population, which stood at about one billion in 1800, reached eight billion by 2022, multiplying resource demands.

As environmental damage became visible — acid rain, smog, pesticide contamination of food chains, deforestation — governments and scientists began to respond with research, legislation, and international agreements. Environmental sustainability emerged as a formal discipline from this context.

1.2 Fundamentals of Ecology

Ecology

Ecology is the branch of biology that studies the relationships between living organisms (including humans) and their physical environment. The word was coined by German zoologist Ernst Haeckel in 1866 from the Greek *oikos* (house) and *logos* (study). Ecology examines how organisms interact with each other and with the abiotic (non-living) components of their environment such as temperature, sunlight, water, and soil.

Ecology operates at multiple levels of organization:

Level	Description
Individual	A single organism and how it responds to its environment.
Population	A group of individuals of the same species living in the same area.
Community	All populations of different species sharing a habitat and interacting.
Ecosystem	A community plus all its abiotic (non-living) surroundings.
Biome	A large geographic region with a characteristic type of vegetation (e.g., tropical rainforest, tundra).
Biosphere	The global sum of all ecosystems; the zone of life on Earth.

Table 1.2: Levels of Ecological Organization

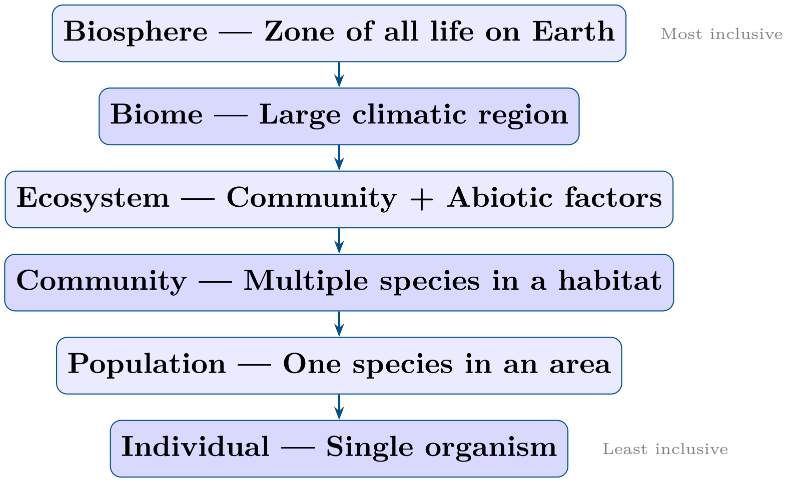


Figure 1.2: Hierarchy of Ecological Organization — from the individual level to the global biosphere

1.3 The Ecosystem: Definition and Structure

Ecosystem

An **ecosystem** is a functional unit of nature in which living organisms (plants, animals, microorganisms) interact with each other and with the non-living physical environment (sunlight, water, soil, air, temperature), forming a system through which energy flows and materials cycle. The term was first coined by British ecologist Arthur Tansley in 1935.

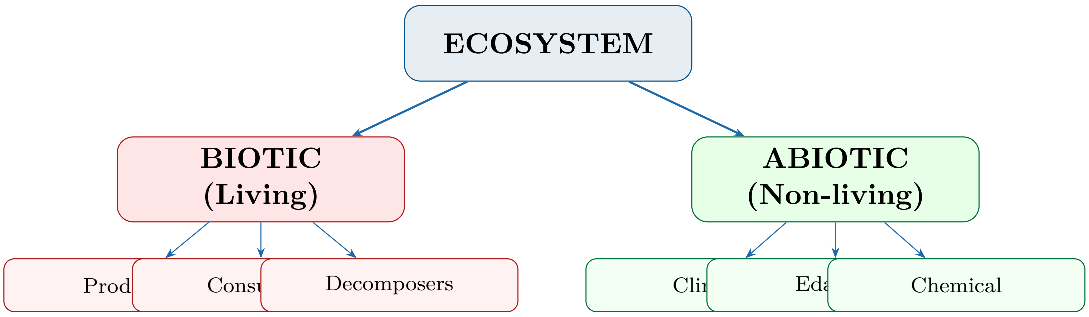


Figure 1.3: Components of an Ecosystem — Biotic (living) and Abiotic (non-living) elements

1.3.1 Components of an Ecosystem

Every ecosystem is made up of two broad categories of components:

1. Abiotic Components (Non-living)

These are the physical and chemical factors of the environment:

- **Climatic factors:** Sunlight (intensity, duration), temperature (range, seasonality), precipitation (rainfall, snowfall), wind, humidity.

- **Edaphic (soil) factors:** Soil texture, mineral content, pH, organic matter content, water-holding capacity.
- **Chemical factors:** Atmospheric gases (O_2, CO_2, N_2), dissolved minerals in water (nitrates, phosphates), salinity.

2. Biotic Components (Living)

The living world is organized into three functional groups based on how organisms obtain energy:

- **Producers (Autotrophs):** Organisms that manufacture their own food from inorganic raw materials using an external energy source. Green plants, algae, and cyanobacteria use *photosynthesis*:

  $$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

  Chemoautotrophic bacteria (found in deep-sea vents) oxidize inorganic chemicals instead of using sunlight.

- **Consumers (Heterotrophs):** Organisms that cannot make their own food and must consume other organisms. They are grouped into:
  - *Primary (1st-order) consumers:* Herbivores that eat plants (grasshoppers, cows, deer).
  - *Secondary (2nd-order) consumers:* Carnivores that eat herbivores (frogs, small fish, foxes).
  - *Tertiary (3rd-order) consumers:* Carnivores that eat secondary consumers (snakes, large fish, eagles).
  - *Omnivores:* Organisms that eat both plants and animals (bears, humans, pigs).

- **Decomposers (Saprotrophic Organisms):** Microorganisms — primarily bacteria and fungi — that break down dead organic matter (detritus) into simpler inorganic compounds (CO_2, water, minerals), which are then returned to the soil and atmosphere for reuse by producers. Without decomposers, nutrients would remain locked in dead bodies and the cycling of matter would halt entirely.

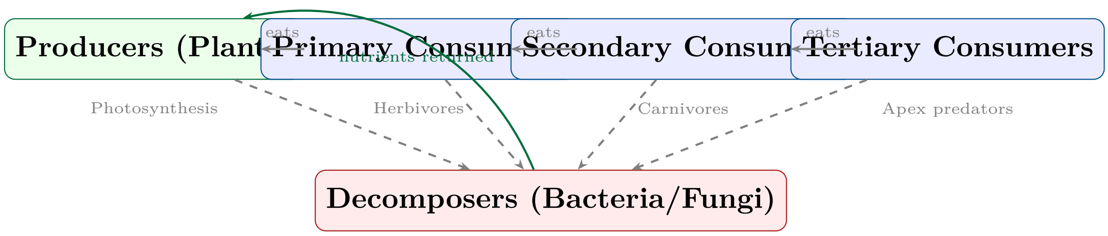


Figure 1.4: Biotic Components of an Ecosystem — Energy flow from producers through consumers to decomposers (dashed = death pathway)

Component	**Type**	**Examples**	**Function**
Producers	Autotrophs	Plants, algae, cyanobacteria	Fix solar energy via photosynthesis
Primary Consumers	Herbivores	Grasshopper, cow, deer	Eat plants
Secondary Consumers	Carnivores	Frog, fox, small fish	Eat herbivores
Tertiary Consumers	Apex carnivores	Eagle, hawk, shark	Top of food chain
Omnivores	Both	Bear, human, pig	Eat plants and animals
Decomposers	Saprotrophs	Bacteria, fungi, earthworms	Break down dead organic matter

Table 1.3: Biotic Components of an Ecosystem — Classification and Functions

PYQ: Define Ecology and Ecosystem. (W'21 – Q.1)

Ecology: The scientific study of the relationships and interactions between living organisms and their physical environment, including interactions among organisms themselves.
Ecosystem: A structural and functional unit of nature comprising a community of living organisms (biotic components) interacting with their non-living (abiotic) environment as a system. Energy flows through an ecosystem (one-way) and nutrients cycle within it (cyclically).
Key distinction: A *habitat* is simply the physical place where an organism lives. An *ecosystem* is the habitat *plus* all the organisms living in it *plus* all the interactions among them and the abiotic factors.

1.4 Classification of Ecosystems

Ecosystems vary enormously in structure, climate, and species composition. They are classified at the broadest level into **Natural** and **Artificial** ecosystems.

1.4.1 Natural Ecosystems

Natural ecosystems exist without direct human creation or management. They are further divided into:

A. Terrestrial Ecosystems

Type	Climate / Location	Key Characteristics
Tropical Rainforest	Near the equator; hot and very wet (>200 cm rain/yr).	Highest biodiversity on Earth; 4 canopy layers; nutrient-poor soils.
Temperate Forest	Mid-latitudes; 4 seasons; 75–150 cm rain/yr.	Deciduous trees (oak, maple) that shed leaves; rich soil.
Boreal Forest (Taiga)	Sub-arctic; very cold; low rainfall.	Dominated by conifers (pine, spruce); permafrost.
Grassland (Savanna)	Tropical; seasonal; 50–130 cm rain.	Few trees; grasses dominant; large grazing mammals.
Desert	Very low rainfall (<25 cm/yr); extreme temperatures.	Sparse vegetation; animals adapted to water scarcity.
Tundra	Polar and alpine; frozen subsoil.	No trees; mosses, lichens; extreme cold; permafrost.

Table 1.4: Types of Terrestrial Ecosystems

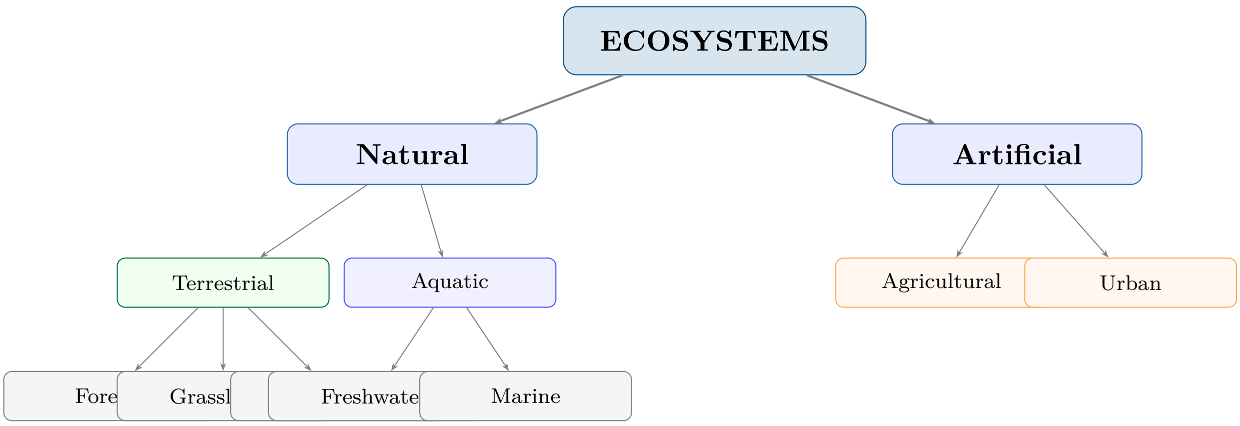


Figure 1.5: Classification of Ecosystems — Natural (Terrestrial and Aquatic) and Artificial

B. Aquatic Ecosystems

- **Freshwater:**
  - *Lotic (running water):* Rivers, streams, springs. High oxygen content; current shapes organisms.
  - *Lentic (standing water):* Lakes, ponds, swamps. Thermally stratified; distinct depth zones.
  - *Wetlands:* Marshes, bogs, floodplains. Transition between land and water; extremely productive and important for water filtration.

- **Marine:**
  - *Open Ocean (Pelagic Zone):* Covers 70% of Earth's surface. Dominated by phytoplankton (microscopic algae) that are responsible for ∼50% of global oxygen production.
  - *Coral Reefs:* Found in warm, shallow, clear tropical waters. Called the "rainforests of the sea" for their exceptional biodiversity despite covering only 0.1% of the ocean floor.
  - *Deep-sea / Benthic Zone:* Permanent darkness, high pressure; organisms depend on the rain of organic detritus from above or chemosynthesis at hydrothermal vents.
  - *Estuaries:* Where rivers meet the sea; mixing of fresh and salt water; highly productive nursery habitats for many commercial fish species.

1.4.2 Artificial (Human-made) Ecosystems

These are created and maintained by human activity:

- **Agricultural Ecosystems (Agroecosystems):** Croplands and plantations. They have very low biodiversity (monocultures), require constant human inputs (fertilizer, irrigation, pesticides), and are highly productive but fragile.
- **Urban Ecosystems:** Cities and towns. Dominated by concrete, roads, and buildings; artificially managed green spaces; high human population density; significant waste and energy flows.
- **Aquaria / Managed Ponds:** Controlled water systems; used for research, aquaculture, or recreation.

Feature	Natural Ecosystem	Artificial Ecosystem
Origin	Formed naturally without human help	Created and managed by humans
Biodiversity	High — many species coexist	Low — monocultures common
Self-sufficiency	Self-sustaining; recycles nutrients	Requires external inputs (fertilizer, etc.)
Stability	High; many species provide redundancy	Low; vulnerable to disease/pest attack
Energy source	Sunlight (solar)	Solar + fossil fuel inputs
Examples	Forest, ocean, river, grassland	Cropland, fish pond, city park, zoo

Table 1.5: Natural vs. Artificial (Human-made) Ecosystems — Key Differences

PYQ: Classify ecosystems. Describe the marine and forest ecosystems in detail. (W'22, Su'22)

Classification: Ecosystems are classified into Natural (Terrestrial, Aquatic) and Artificial (Agricultural, Urban). Natural terrestrial ecosystems include forests, grasslands, and deserts. Natural aquatic ecosystems include freshwater (rivers, lakes, wetlands) and marine (open ocean, coral reefs, estuaries) types.

Marine Ecosystem: The marine ecosystem encompasses all saltwater bodies covering approximately 71% of Earth's surface. It is the largest ecosystem on the planet.

- *Producers:* Phytoplankton (microscopic algae) and seaweeds/kelp near shores perform photosynthesis and form the base of the food chain.
- *Consumers:* Range from microscopic zooplankton to large whales and sharks.
- *Significance:* Regulates global climate by absorbing CO_2 and heat; produces 50% of Earth's oxygen; supports enormous biodiversity and provides food (fish, shellfish) for billions of people.
- *Major threats:* Overfishing, ocean acidification, plastic pollution, oil spills, rising sea temperatures causing coral bleaching.

Forest Ecosystem: Forests are terrestrial ecosystems dominated by trees and woody vegetation. They cover approximately 31% of Earth's land surface.

- *Types:* Tropical rainforests (Amazon, Congo), temperate deciduous forests, boreal forests (taiga).
- *Functions:* Largest terrestrial carbon sinks (storing carbon in wood and soil); regulate the water cycle through evapotranspiration; prevent soil erosion; provide habitat for over 80% of terrestrial biodiversity.
- *Effects of deforestation:* Loss of biodiversity; increased atmospheric CO_2; disruption of local and regional rainfall patterns; increased flood risk and soil erosion; displacement of indigenous communities.

1.5 Energy Flow: Food Chains and Food Webs

One of the most fundamental questions in ecology is: *How does energy move through an ecosystem?* The answer lies in understanding feeding relationships.

1.5.1 Food Chains

Food Chain

A **food chain** is a linear sequence showing the transfer of energy and nutrients from one organism to the next as each one is eaten by the next. Each step in a food chain is called a **trophic level** (from the Greek *trophe*, meaning "nourishment").

Example of a Grassland Food Chain:

$$\text{Grass} \xrightarrow{\text{eats}} \text{Grasshopper} \xrightarrow{\text{eats}} \text{Frog} \xrightarrow{\text{eats}} \text{Snake} \xrightarrow{\text{eats}} \text{Hawk}$$

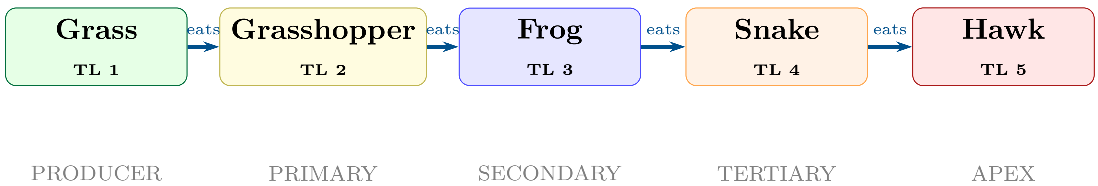


Figure 1.6: A Grassland Food Chain showing five trophic levels and the direction of energy flow

Trophic Level Assignment:

Level	Organism	Role
TL 1	Grass	Producer (autotroph)
TL 2	Grasshopper	Primary (herbivore) consumer
TL 3	Frog	Secondary consumer (carnivore)
TL 4	Snake	Tertiary consumer
TL 5	Hawk	Apex predator (quaternary consumer)

Types of food chains:

- **Grazing Food Chain:** Begins with a living green plant (as above). Common in terrestrial and aquatic ecosystems.
- **Detritus Food Chain:** Begins with dead organic matter (detritus). Bacteria and fungi decompose the detritus, which is then eaten by detritivores (earthworms, millipedes, woodlice), which are in turn eaten by predators. This type is extremely important in nutrient recycling.

1.5.2 Food Webs

In reality, most organisms eat more than one type of food and are eaten by more than one type of predator. A food chain is a simplification. A **food web** is a more realistic, interconnected picture.

Food Web

A **food web** is a network of interconnected food chains within an ecosystem, showing all the feeding relationships between different populations. It represents the actual complexity of who eats whom.

Significance of Food Webs:

- **Stability:** A food web provides *redundancy*. If one prey species declines, a predator that is connected to the web can switch to an alternative food source, providing ecosystem stability. A simple food chain is more vulnerable — if one link breaks, the entire chain collapses.
- **Trophic cascades:** Removing a top predator from a food web can have dramatic downstream effects. For example, removing wolves from Yellowstone allowed deer populations to explode, which over-grazed riverbank vegetation, leading to bank erosion and altered river flow — effects that cascaded through the entire ecosystem.
- **Bioaccumulation:** Persistent toxic chemicals (like DDT or mercury) enter food webs at low trophic levels and become increasingly concentrated at each higher level — a process called **biomagnification**.

PYQ: Explain food chain and food web. Compare them. (W'21, W'22, Su'25)

Food Chain: A food chain is a linear sequence of organisms in which each member feeds on the one before it. It shows a single, direct pathway of energy transfer. Example:

$$\text{Phytoplankton} \rightarrow \text{Zooplankton} \rightarrow \text{Small Fish} \rightarrow \text{Large Fish} \rightarrow \text{Osprey}$$

Food Web: A food web is a complex network of multiple, interconnected food chains within an ecosystem. It is a more realistic representation of feeding relationships because most organisms eat several types of food.
Comparison:

Food Chain	**Food Web**
Linear, single pathway	Network of multiple pathways
Simplified model	Realistic model
Less stable — collapse of one level collapses the whole chain	More stable — alternative pathways exist
Easier to study but less accurate	Complex but accurately represents nature
Shows feeding of one organism	Shows all feeding relationships in a community

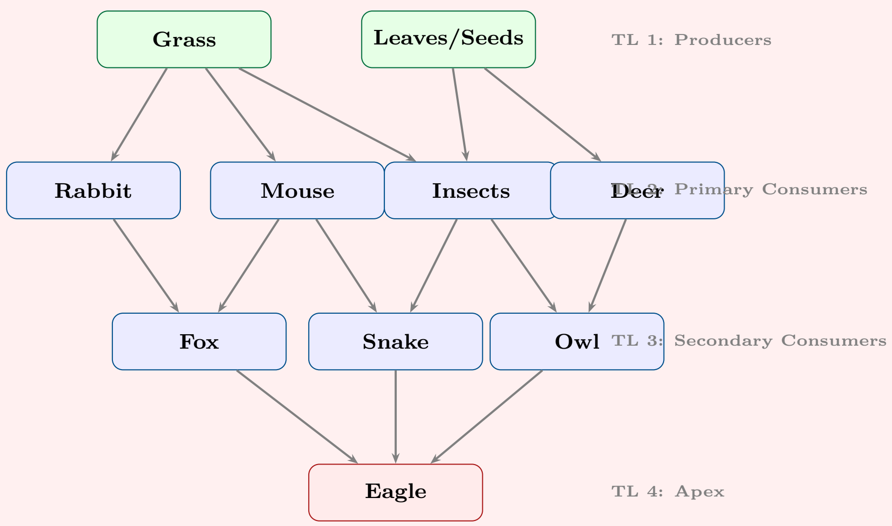


Figure 1.7: A Food Web — multiple interconnected food chains showing real-world feeding relationships in a grassland ecosystem

1.6 Ecological Pyramids

When we think about the biomass, numbers, and energy at each trophic level in a food chain, a striking pattern emerges — the amounts always decrease as we move from producers to apex predators. This is represented visually as an **ecological pyramid** (also called an *Eltonian Pyramid*, named after the ecologist Charles Elton who first described them in 1927).

Ecological Pyramid

An **ecological pyramid** is a diagrammatic representation of the numerical relationship, biomass, or energy content of organisms at successive trophic levels of a food chain. The base represents producers (largest quantity) and the apex represents the highest-order consumers (smallest quantity).

1.6.1 Types of Ecological Pyramids

1. Pyramid of Numbers

Shows the number of individual organisms at each trophic level.

- **Usually upright:** Many grass plants (10^6) → fewer grasshoppers (10^5) → even fewer frogs (10^3) → very few snakes (10^2) → one hawk (10^0).
- **Can be inverted:** In a forest, one large oak tree supports thousands of caterpillars. The number of producers (one tree) is less than the number of primary consumers.
- **Limitation:** Treats a bacterium and an elephant as equivalent "numbers" — ignores body size and biomass.

2. Pyramid of Biomass

Shows the total dry mass of living tissue at each trophic level, usually measured in grams per square metre (g/m²).

- **Usually upright on land:** Large mass of vegetation supports smaller mass of herbivores, which supports smaller mass of carnivores. Example (grassland): Grass (500 g/m²) → Insects (50 g/m²) → Birds (5 g/m²) → Hawks (0.5 g/m²).
- **Can be inverted in aquatic systems:** In some marine ecosystems, the producers (phytoplankton) have a very small standing biomass at any given moment, yet they reproduce so rapidly that they can support a larger biomass of zooplankton. The pyramid appears inverted.

3. Pyramid of Energy

Shows the rate of energy flow (energy per unit area per unit time, measured in kJ/m²/year) at each trophic level.

The Ten Percent Law (Lindeman's Law, 1942)

When energy is transferred from one trophic level to the next, only approximately **10%** of the energy is retained and stored as biomass. The remaining **90%** is lost as:

- Heat dissipated during cellular respiration.
- Energy used for the organism's own bodily functions (growth, movement, reproduction).
- Undigested material passed in feces.

This is why the Pyramid of Energy is **always upright** — energy is perpetually lost at each level. It also explains why food chains rarely have more than 4–5 trophic levels: after 5 levels, so little energy remains that sustaining a population becomes impossible.

Example Calculation: If 10,000 kJ of solar energy is fixed by plants:

- 1,000 kJ available to herbivores (10%)

- 100 kJ available to primary carnivores (10% of 1,000)
- 10 kJ available to secondary carnivores (10% of 100)
- 1 kJ available to apex predator (10% of 10)

PYQ: Write a short note on the Ecological (Eltonian) Pyramid. Explain all three types. (Su'22, Su'25, W'23)

Ecological / Eltonian Pyramid: A graphical representation of the number, biomass, or energy content of organisms at each trophic level of a food chain. Named after ecologist Charles Elton.
Three types:
1. Pyramid of Numbers: Shows the count of individual organisms at each trophic level. Usually upright (many producers → fewer consumers) but can be inverted in forest ecosystems (one tree supports thousands of insects).
2. Pyramid of Biomass: Shows the total dry organic mass per unit area at each trophic level. Generally upright on land; may be inverted in aquatic systems where phytoplankton (small standing biomass but rapid reproduction) supports larger biomass of zooplankton.
3. Pyramid of Energy: Shows the rate of energy flow or productivity at each trophic level. Always upright because energy is always lost at each transfer. Only ∼10% of energy passes from one level to the next (Lindeman's 10% rule). This pyramid is the most universally valid and scientifically accurate of the three types.

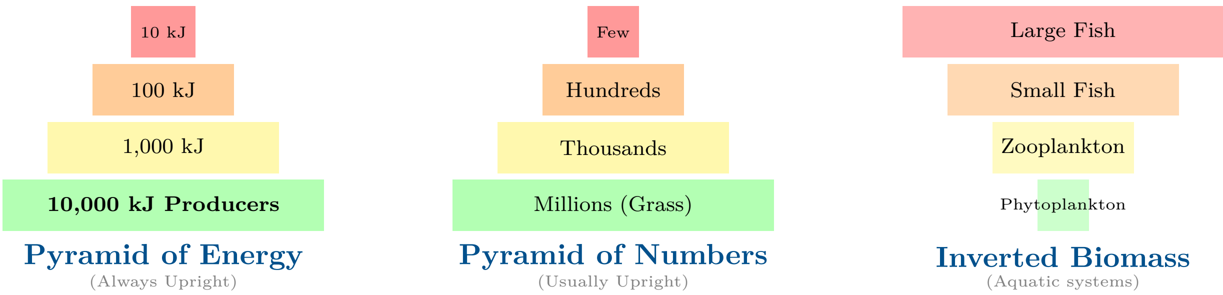


Figure 1.8: Three Types of Ecological Pyramids: (left) Pyramid of Energy always upright, (centre) Pyramid of Numbers usually upright, (right) Inverted Pyramid of Biomass in aquatic ecosystems

Feature	**Pyramid of Numbers**	**Pyramid of Biomass**	**Pyramid of Energy**
What it shows	Count of organisms	Total dry mass (g/m^2)	Energy flow ($kJ/m^2/yr$)
Unit	Number of individuals	g/m^2	$kJ/m^2/yr$
Can be inverted?	Yes (forest ecosystem)	Yes (aquatic)	Never — always upright
Limitation	Ignores body size	Time-dependent measurement	Most difficult to measure
Scientific accuracy	Low	Medium	Highest — universally valid

Table 1.6: Comparison of Three Types of Ecological Pyramids

1.7 Ecological Footprint and Carrying Capacity

1.7.1 Carrying Capacity

Every environment has a finite amount of resources — food, water, space, light. The **carrying capacity** (K) is the maximum population size that a given environment can sustainably support over the long term without degradation of the resource base.

When a population grows logistically (as most real populations do), its growth rate slows as the population approaches K:

$$\frac{dN}{dt} = rN\left(\frac{K-N}{K}\right)$$

where N is the population size, r is the intrinsic rate of natural increase, and K is the carrying capacity.

1.7.2 Ecological Footprint

Ecological Footprint

The **ecological footprint** is a measure of how much biologically productive land and water area an individual, city, country, or humanity as a whole requires to produce the resources it consumes and to absorb the waste it generates, using prevailing technology. It is expressed in **global hectares (gha)**.

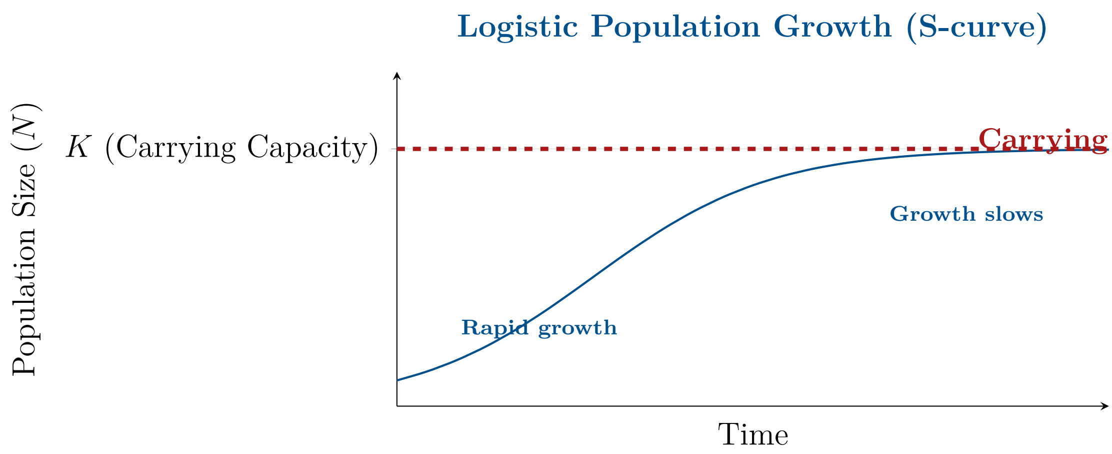


Figure 1.9: Logistic (S-curve) Population Growth — growth slows as population approaches the carrying capacity K of the environment

The ecological footprint concept was developed by Mathis Wackernagel and William Rees in the early 1990s at the University of British Columbia.

Components of an ecological footprint:

- **Carbon footprint:** Land required to absorb CO_2 emissions (forest area needed as a carbon sink).
- **Cropland:** Area required to grow food and plant-based products.
- **Grazing land:** Area required to raise livestock.
- **Forest land:** Area required for timber and wood products.
- **Fishing grounds:** Aquatic area required to support fish consumption.
- **Built-up land:** Area occupied by roads, buildings, and infrastructure.

PYQ: What is ecological overshoot? When does it occur? (Su'22, W'22, W'23)

Ecological Overshoot: Ecological overshoot occurs when humanity's demand on the natural world — the ecological footprint — exceeds what the biosphere can regenerate and what the atmosphere can safely absorb as waste. In other words, we are consuming natural capital faster than nature can replenish it.
When does it occur? Globally, Earth Overshoot Day (calculated annually by the Global Footprint Network) marks the date by which humanity has used all the biological resources that Earth can regenerate in an entire year. In recent decades, this day has consistently fallen in late July or August, meaning humanity is living on "ecological credit" for the remaining 4–5 months of the year.
Signs of Overshoot:

- Shrinking forests, fish stocks, and fresh water supplies.
- Accumulating waste products (greenhouse gases, plastic, chemical pollution)

faster than natural systems can absorb them.

- Loss of biodiversity as species cannot adapt fast enough to habitat loss.

Consequences: If overshoot continues unchecked, it leads to a degraded natural resource base, reduced ecosystem services, and ultimately, a crash in the carrying capacity of the Earth — reducing what future generations can sustain.

1.8 Biodiversity

Biodiversity

Biodiversity (biological diversity) refers to the variety of all living organisms on Earth, including the diversity within species (genetic diversity), between species (species diversity), and of ecosystems (ecosystem diversity). The term was popularised by biologist Edward O. Wilson in 1986.

1.8.1 Three Levels of Biodiversity

1. **Genetic Diversity:** The variation in the genetic makeup (genes and alleles) within a single species. Genetically diverse populations are better able to adapt to environmental changes and resist diseases. Example: Different varieties of rice (basmati, jasmine, arborio) represent genetic diversity within *Oryza sativa*.

2. **Species Diversity:** The variety and relative abundance of species in a given area. A species-rich community (e.g., a tropical rainforest with thousands of species) has higher species diversity than a species-poor one (e.g., an arctic tundra). Measured by indices like the **Shannon–Wiener Index**.

3. **Ecosystem Diversity:** The variety of habitats, biological communities, and ecological processes in the biosphere. A landscape containing forests, grasslands, wetlands, rivers, and coastal zones has high ecosystem diversity.

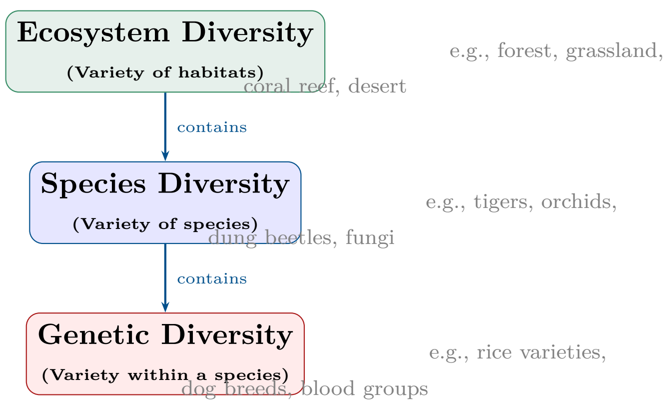


Figure 1.10: Three Levels of Biodiversity — Genetic, Species, and Ecosystem Diversity (nested from most specific to most broad)

1.8.2 Importance of Biodiversity

Biodiversity provides an extraordinary range of services:

Category	Services Provided
Provisioning	Food (crops, livestock, fish, wild plants), fresh water, wood, fibre, genetic resources for medicine.
Regulating	Climate regulation, flood control, disease control, water purification, pollination of crops.
Cultural	Recreational, spiritual, artistic, and educational value; eco-tourism.
Supporting	Soil formation, nutrient cycling, photosynthesis — these underpin all other services.

Table 1.7: Ecosystem Services Provided by Biodiversity

1.8.3 Threats to Biodiversity — The HIPPOE Framework

- **H**abitat Destruction: Deforestation, wetland draining, urbanisation — the single largest driver of biodiversity loss.
- **I**nvasive Species: Non-native species introduced (accidentally or deliberately) that out-compete or prey on native species. Example: Nile Perch introduced to Lake Victoria wiped out hundreds of endemic cichlid fish.
- **P**ollution: Chemical contamination of air, water, and soil directly kills organisms and disrupts reproduction and immune systems.
- **P**opulation Growth: Rising human populations demand more land, water, and resources, directly encroaching on wildlife habitats.
- **O**verexploitation: Overfishing, illegal wildlife trade (poaching), unsustainable logging.
- **E**ntopic change (Climate Change): Shifting temperature and rainfall patterns exceed the adaptive capacity of many species, causing range shifts, phenological mismatches, and local extinctions.

Letter	**Threat**	**Mechanism**	**Example**
H	Habitat Destruction	Loss of living space for species	Amazon deforestation
I	Invasive Species	Out-compete or predate native species	Cane toads in Australia
P	Pollution	Kills or impairs reproduction	DDT thinning bird eggshells
P	Population Growth	Increases demand for land and resources	Urban sprawl eating forests
O	Overexploitation	Species harvested faster than they reproduce	Atlantic cod collapse
E	Entopic/Climate Change	Shifts habitats, disrupts seasonal cues	Coral bleaching from warming

Table 1.8: The HIPPOE Framework — Six Major Threats to Biodiversity and Examples

1.8.4 Conservation Strategies

In-Situ vs. Ex-Situ Conservation

In-Situ Conservation (on-site) is the protection of species within their natural habitat:

- National Parks: Areas strictly protected from human exploitation (e.g., Jim Corbett, Kaziranga in India).
- Wildlife Sanctuaries: Areas where animals are protected but some human activities are permitted.
- Biosphere Reserves: Large, zonated areas (core protected zone, buffer zone, transition zone) that balance conservation with sustainable human use. India has 18 biosphere reserves.
- Community Reserves and Sacred Groves.

Ex-Situ Conservation (off-site) is the protection of species outside their natural habitat:

- Zoological parks (zoos) and botanical gardens.
- Seed banks: Controlled-temperature storage facilities that preserve seeds of thousands of plant varieties (e.g., Svalbard Global Seed Vault in Norway).
- Cryopreservation: Preservation of tissues, sperm, eggs, or embryos at very low temperatures for endangered species.
- Gene banks and cell culture collections.

Aspect	In-Situ Conservation	Ex-Situ Conservation
Meaning	Protection in natural habitat	Protection outside natural habitat
Location	Wild, in the field	Zoo, botanical garden, seed bank
Examples	National parks, biosphere reserves, wildlife sanctuaries	Zoos, gene banks, cryopreservation, botanical gardens
Advantage	Preserves natural behaviour and ecological relationships	Can save critically endangered species from extinction
Limitation	Vulnerable to poaching, fire, floods	Artificial environment; may not preserve all traits
India examples	Kaziranga NP, Sundarbans, Silent Valley	Nehru Zoological Park, Gene banks at NBPGR New Delhi

Table 1.9: In-Situ vs. Ex-Situ Conservation — Comparison

PYQ: What is biodiversity? Give its types and explain its importance. (W'21, N-W'25)

Biodiversity: The total variability of life on Earth at three levels — genetic, species, and ecosystem.

Types:

1. **Genetic diversity:** Variation in genes within a species, enabling adaptation. Example: Pest-resistant strains of wheat are genetically distinct from ordinary wheat.
2. **Species diversity:** Variety of species in an ecosystem. Tropical rainforests have the highest species diversity on Earth.
3. **Ecosystem diversity:** Variety of ecosystems from deserts to coral reefs to boreal forests across the biosphere.

Importance:

- **Ecological stability:** Diverse communities are more resilient to disturbances and species loss.
- **Food security:** Agricultural biodiversity provides the genetic base for crop improvement.
- **Medicine:** Approximately 25% of modern drugs are derived from plants; many undiscovered cures exist in biodiversity-rich habitats.
- **Ecosystem services:** Pollination, water purification, flood control, and climate regulation all depend on biodiversity.
- **Cultural and aesthetic value:** Biodiversity supports livelihoods, tourism, art, and spiritual traditions worldwide.

1.9 Biogeochemical Cycles

Life depends on a small set of chemical elements — primarily carbon, nitrogen, phosphorus, sulfur, and water (hydrogen and oxygen). Unlike energy, which flows through ecosystems in one direction and is eventually lost as heat, these elements cycle continuously between the biotic (living) and abiotic (non-living) components of the Earth. These cyclic movements are called **biogeochemical cycles**.

Biogeochemical Cycle

A **biogeochemical cycle** is the cyclical pathway through which a chemical element or molecule moves through the biotic components of an ecosystem (plants, animals, microorganisms) and the abiotic environment (atmosphere, hydrosphere, lithosphere). The rates at which elements cycle can be altered by human activities, with major environmental consequences.

The major cycles we study are:

- The **Hydrologic Cycle** (Water Cycle)
- The **Carbon Cycle**
- The **Nitrogen Cycle**
- The **Phosphorus Cycle** (brief overview)

Cycle	**Key Element**	**Main Reservoirs**	**Key Processes**
Water / Hydrologic	H_2O	Ocean (97%), glaciers, groundwater	Evaporation, transpiration, precipitation, runoff
Carbon	C (as CO_2, organic C)	Lithosphere, ocean, atmosphere, biosphere	Photosynthesis, respiration, combustion, fossilisation
Nitrogen	N (as N_2, proteins)	Atmosphere (78% N_2), soil, organisms	Fixation, nitrification, assimilation, denitrification
Phosphorus	P (as phosphate)	Rocks/sediments, soil, water	Weathering, absorption by plants, decomposition

Table 1.10: Overview of Major Biogeochemical Cycles

1.9.1 The Hydrologic (Water) Cycle

Water is the medium of life. It constitutes 60–90% of the mass of all living cells and is the solvent in which virtually all biochemical reactions occur. The hydrologic cycle describes the continuous movement of water on, above, and below the surface of the Earth.

Processes in the Hydrologic Cycle

1. **Evaporation:** Solar energy heats surface water in oceans, lakes, and rivers, converting liquid water into water vapour, which rises into the atmosphere. Oceans account for approximately 86% of all evaporation. This process is driven by temperature and wind speed.

2. **Transpiration:** Plants absorb water from the soil through their roots and release it as water vapour through tiny pores (stomata) in their leaves. A single large tree can transpire hundreds of litres of water per day. The combined process of evaporation and transpiration is called **evapotranspiration**.

3. **Condensation:** As water vapour rises, it cools and condenses around tiny particles (dust, sea salt, smoke) called condensation nuclei, forming tiny liquid water droplets or ice crystals that make up clouds and fog. The temperature at which this occurs is the **dew point**.

4. **Precipitation:** When cloud droplets combine and grow heavy enough, they fall back to Earth as **rain**, **snow**, **sleet**, or **hail**, depending on temperature. Global average precipitation is roughly 990 mm per year, but it is very unevenly distributed — tropical regions receive far more than deserts.

5. **Interception:** Some precipitation is caught by vegetation (leaves, branches) before it reaches the ground. This water either evaporates directly or slowly drips to the soil.

6. **Surface Runoff:** Water that falls on the land flows over the surface into streams, rivers, and eventually into the ocean. The rate of runoff depends on slope, soil type, and vegetation cover. Deforestation drastically increases runoff, causing flooding and soil erosion.

7. **Infiltration and Groundwater Recharge:** Some water penetrates the soil surface and moves downward through soil and rock until it reaches the **water table** — the top of the saturated zone. This water is stored in **aquifers** (underground permeable rock layers) and moves slowly as **groundwater**. It may resurface as springs or be extracted by wells for human use.

Human Impacts on the Hydrologic Cycle

- **Deforestation** reduces transpiration and increases surface runoff, altering local rainfall patterns and increasing flood risk.

- **Urbanisation** replaces permeable soil with impermeable concrete, drastically reducing infiltration and groundwater recharge, while increasing flash flood risk.

- **Over-extraction of groundwater** depletes aquifers faster than they are recharged, causing land subsidence and water shortages.
- **Climate change** intensifies the cycle: a warmer atmosphere holds more water vapour (about 7% more per °C of warming), making wet regions wetter and dry regions drier, and intensifying extreme weather events.

PYQ: What are biogeochemical cycles? Explain the hydrologic (water) cycle in detail. (Su'22, W'21)

Biogeochemical Cycles: Pathways through which chemical elements or compounds continuously cycle between the living (biotic) and non-living (abiotic) components of the Earth system. They include the water cycle, carbon cycle, nitrogen cycle, and phosphorus cycle.

Hydrologic Cycle (Water Cycle): The hydrologic cycle is the continuous, natural circulation of water through the Earth system — from the surface (oceans, lakes, rivers) into the atmosphere and back to the surface.

Key stages:

1. **Evaporation and Transpiration:** Solar energy causes water to evaporate from water bodies. Plants also release water vapour through transpiration. Both processes drive water vapour into the atmosphere.
2. **Condensation:** Rising water vapour cools and condenses around dust particles, forming clouds.
3. **Precipitation:** Accumulated cloud droplets fall as rain, snow, or hail onto land and water surfaces.
4. **Surface Runoff:** Water flows over land into rivers and streams, returning to the ocean.
5. **Infiltration and Groundwater:** Part of the water percolates through soil into underground aquifers, from which it may re-emerge as springs or be extracted by wells.

Importance: The water cycle distributes fresh water across the Earth, regulates temperature, supports all biological processes, and erodes and shapes the landscape. Human actions (deforestation, over-irrigation, urbanisation) disrupt the cycle and reduce fresh water availability.

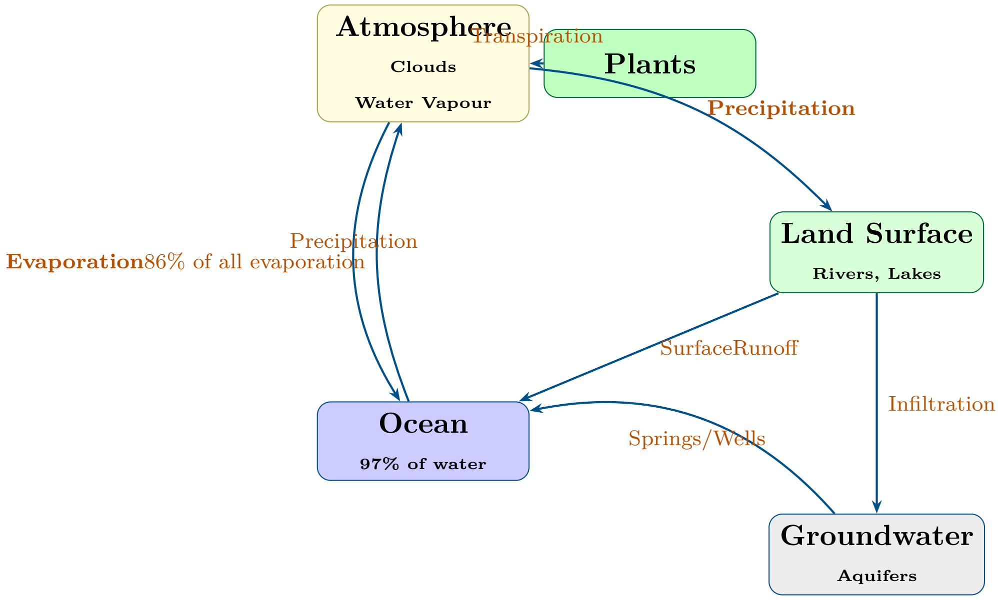


Figure 1.11: The Hydrologic (Water) Cycle — continuous movement of water between the ocean, atmosphere, land, and groundwater

Process	**Description**	**Direction**
Evaporation	Solar energy converts liquid water to vapour	Surface → Atmosphere
Transpiration	Plants release water vapour through stomata	Land (plants) → Atmosphere
Condensation	Water vapour cools and forms clouds/droplets	Atmosphere (cloud formation)
Precipitation	Water falls as rain, snow, hail, sleet	Atmosphere → Land/Ocean
Surface Runoff	Water flows over land into rivers/ocean	Land → Ocean
Infiltration	Water soaks into soil, recharges groundwater	Land surface → Underground
Transpired back	Groundwater emerges as springs or is pumped	Underground → Surface

Table 1.11: Processes in the Hydrologic Cycle — Description and Direction of Water Movement

1.9.2 The Carbon Cycle

Carbon is the chemical backbone of life — the basis of all organic molecules including carbohydrates, proteins, fats, and DNA. Carbon moves between the atmosphere (as

CO_2), the oceans (as dissolved CO_2 and carbonate), the land (as organic matter and limestone rock), and living organisms.

Major Carbon Reservoirs

Carbon Reservoir	**Approx. Carbon Stock**
Oceans (dissolved inorganic + organic)	38,000 Gt C
Lithosphere (sediments, rocks, fossil fuels)	>60,000,000 Gt C
Terrestrial biosphere (soil + vegetation)	2,500 Gt C
Atmosphere (as CO_2)	∼860 Gt C

Table 1.12: Major Carbon Reservoirs (Gt C = gigatonnes of carbon)

Processes in the Carbon Cycle

1. **Photosynthesis:** The primary mechanism by which atmospheric carbon enters living systems. Green plants, algae, and cyanobacteria use solar energy to convert CO_2 and water into glucose:

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$$

Globally, photosynthesis fixes approximately 120 Gt of carbon per year.

2. **Respiration:** All living organisms (including plants) release CO_2 back into the atmosphere through cellular respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy (ATP)}$$

Respiration returns approximately 60 Gt of carbon per year to the atmosphere.

3. **Decomposition:** When organisms die, bacteria and fungi break down their organic matter, releasing CO_2 (and CH_4 in anaerobic conditions). This returns approximately 56 Gt C/year.

4. **Combustion:** Burning of wood, grass, or fossil fuels converts stored carbon rapidly into CO_2:

$$\text{Biomass/Fossil fuel} + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

Human fossil fuel combustion currently releases approximately **10 Gt C/year** — a geologically instantaneous pulse of carbon that took millions of years to store underground.

5. **Ocean Exchange:** The ocean surface exchanges CO_2 with the atmosphere continuously. Cooler water absorbs more CO_2; warmer water releases it. Oceans have absorbed about 30% of human CO_2 emissions, but this causes **ocean acidification**.

6. **Fossilisation:** Over millions of years, organic matter buried under sediments is transformed by heat and pressure into coal, oil, and natural gas — locking carbon away in long-term geological storage.

PYQ: Explain the carbon cycle with a neat diagram. (W'21, W'22, Su'25, N-W'25)

Carbon Cycle: The continuous movement of carbon atoms between the atmosphere, living organisms, soils, oceans, and geological formations.

Key processes:

1. **Photosynthesis:** Plants absorb atmospheric CO_2 and water, using solar energy to synthesise glucose ($C_6H_{12}O_6$) while releasing O_2. Carbon enters the biotic component.
2. **Respiration:** Plants and animals break down glucose for energy, returning CO_2 to the atmosphere.
3. **Consumption:** Animals eat plants and incorporate carbon into their own tissues.
4. **Decomposition:** Bacteria and fungi decompose dead organisms, releasing CO_2 (aerobic) or CH_4 (anaerobic) back into the atmosphere.
5. **Combustion:** Burning of fossil fuels and biomass releases stored carbon rapidly as CO_2.
6. **Fossilisation:** Over geological time, buried organic matter becomes fossil fuels, removing carbon from the active cycle for millions of years.

Human disruption: Burning fossil fuels and deforestation together release approximately 11 Gt of carbon per year into the atmosphere, far exceeding natural uptake rates. This has raised atmospheric CO_2 from ∼280 ppm (pre-industrial) to over 420 ppm today, driving climate change.

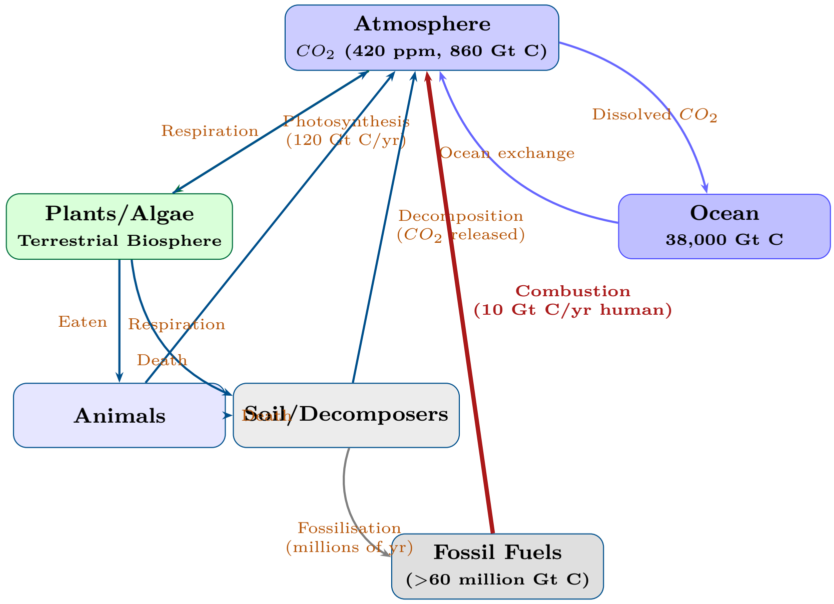


Figure 1.12: The Carbon Cycle — showing natural fluxes and the large pulse of carbon from human fossil fuel combustion

Process	**Description**	**Flux (Gt C/yr)**
Photosynthesis	Plants and algae fix CO_2 into organic molecules	~120
Plant respiration	Plants release CO_2 via cellular respiration	~60
Decomposition	Bacteria/fungi release CO_2 from dead matter	~56
Ocean uptake	Ocean surface dissolves atmospheric CO_2	~2–3
Human combustion	Burning fossil fuels + deforestation	~10–11
Fossilisation	Burial of organic matter over geological time	Near zero (current)

Table 1.13: Key Processes in the Carbon Cycle and Their Annual Fluxes

1.9.3 The Nitrogen Cycle

Nitrogen (N_2) makes up 78% of the atmosphere but is chemically inert in its molecular form — virtually no organism can use atmospheric nitrogen directly. The nitrogen cycle describes how nitrogen is converted between its various chemical forms through the action of specialised microorganisms, making it available to living organisms.

Processes in the Nitrogen Cycle

1. **Nitrogen Fixation:** The conversion of atmospheric N_2 into biologically usable ammonia (NH_3) or ammonium (NH_4^+). Performed by:

- *Biological fixation:* Specialised bacteria such as free-living *Azotobacter* (soil) and symbiotic *Rhizobium* (root nodules of legumes like peas and soybeans) carry out this reaction: $N_2 + 8H^+ + 8e^- \rightarrow 2NH_3 + H_2$
- *Lightning fixation:* A small amount of N_2 is fixed by the energy of lightning, forming nitric oxide (NO), which reacts with water to form nitric acid (HNO_3) that falls with rain.
- *Industrial (Haber-Bosch) fixation:* Humans synthesise ammonia-based fertilisers at the rate of ∼120 Mt/year — approximately doubling the natural rate of fixation and greatly altering the nitrogen cycle.

2. **Nitrification:** The conversion of ammonia (NH_3) into nitrite (NO_2^-) and then into nitrate (NO_3^-) by specialised aerobic soil bacteria:

   - *Nitroso*- bacteria: $2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$
   - *Nitro*- bacteria: $2NO_2^- + O_2 \rightarrow 2NO_3^-$

   Nitrate is water-soluble and is the form most readily absorbed by plant roots.

3. **Assimilation:** Plants absorb ammonium (NH_4^+) or nitrate (NO_3^-) from the soil and incorporate them into organic nitrogen compounds — particularly amino acids and proteins. Animals obtain nitrogen by consuming plants or other animals.

4. **Ammonification (Mineralisation):** When organisms die or excrete wastes, decomposers (bacteria and fungi) break down organic nitrogen compounds back into ammonia (NH_3) and ammonium (NH_4^+) — the process of ammonification. This returns nitrogen to a form that can re-enter the cycle.

5. **Denitrification:** Anaerobic bacteria (e.g., *Pseudomonas denitrificans*) in waterlogged soils convert nitrate (NO_3^-) back into nitrogen gas (N_2) or nitrous oxide (N_2O), which is released into the atmosphere, closing the cycle:

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$$

Human Impacts on the Nitrogen Cycle

- Excessive use of synthetic nitrogen fertilisers leads to **nitrate leaching** into waterways, causing **eutrophication** — explosive growth of algae that depletes oxygen and kills aquatic life.
- Nitrous oxide (N_2O) released by agricultural soils is a potent greenhouse gas, nearly 300 times more warming than CO_2 over 100 years.
- Atmospheric nitrogen deposition (from burning fuels and agriculture) is altering the species composition of sensitive ecosystems like heathlands and boreal forests.

PYQ: Explain the nitrogen cycle. (W'23)

Nitrogen Cycle: The biogeochemical pathway by which nitrogen is converted into its various chemical forms and circulated through atmospheric, terrestrial, and aquatic ecosystems.

Stages:

1. **Nitrogen Fixation:** Atmospheric N_2 is converted to ammonia (NH_3) by nitrogen-fixing bacteria (*Rhizobium* in legume root nodules, *Azotobacter* in soil) or by lightning. Industrial Haber-Bosch process: $N_2 + 3H_2 \rightarrow 2NH_3$.
2. **Nitrification:** Soil bacteria convert ammonia (NH_3/NH_4^+) first to nitrite (NO_2^-) and then to nitrate (NO_3^-), the form most usable by plants.
3. **Assimilation:** Plant roots absorb nitrate or ammonium and incorporate nitrogen into amino acids, proteins, and DNA. Animals get nitrogen by consuming plants.
4. **Ammonification:** Decomposers break down dead organic matter and waste products, releasing ammonia back into the soil.
5. **Denitrification:** Anaerobic bacteria convert nitrate back to N_2 gas, returning it to the atmosphere and completing the cycle.

Importance: Nitrogen is essential for proteins and nucleic acids — the very molecules of life. Without the nitrogen cycle, nutrients locked in dead organisms could not be recycled, and ecosystems would collapse.

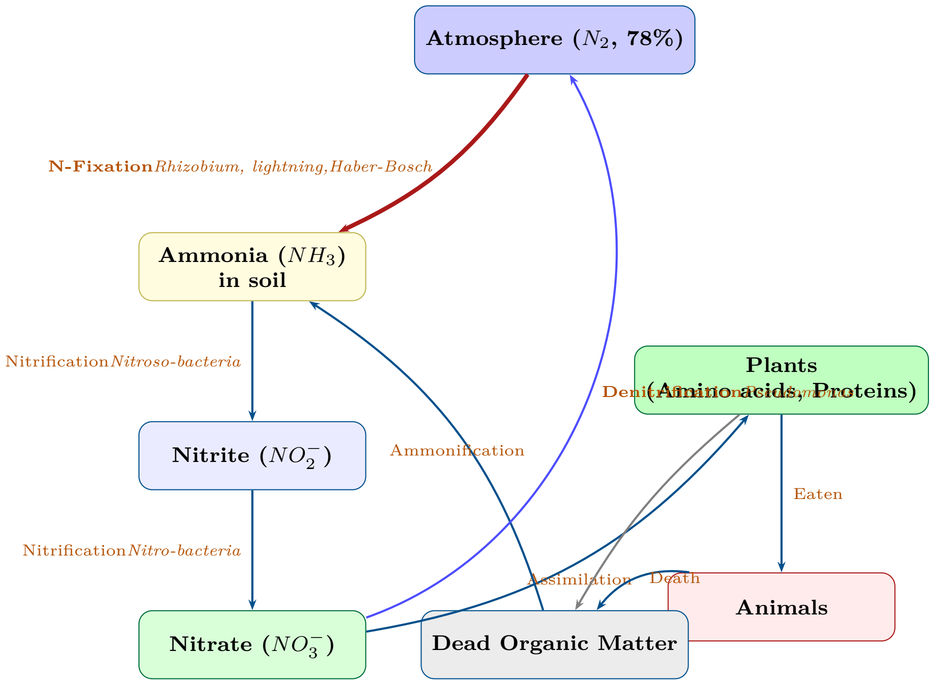


Figure 1.13: The Nitrogen Cycle — showing fixation from atmosphere, nitrification in soil, assimilation by plants, and denitrification returning N_2 to atmosphere

Process	**Description**	**Microorganism Involved**
Nitrogen fixation	$N_2 \rightarrow NH_3$ (inert gas made usable)	*Rhizobium*, *Azotobacter*, lightning, Haber-Bosch
Nitrification	$NH_3 \rightarrow NO_2^- \rightarrow NO_3^-$ (oxidation)	*Nitrosomonas*, *Nitrobacter*
Assimilation	Plants absorb NO_3^- or NH_4^+ into proteins	Plants (not a microorganism)
Ammonification	Dead matter $\rightarrow NH_3$ returned to soil	Bacteria and fungi (decomposers)
Denitrification	$NO_3^- \rightarrow N_2$ (returned to atmosphere)	*Pseudomonas denitrificans*

Table 1.14: Five Processes of the Nitrogen Cycle

Phase	**The Phosphorus Cycle (Sedimentary Cycle)**	**Human Perturbation**
Rock Weathering	Slow release of PO_4^{3-} from rocks to soil over millennia.	Mining ancient rocks speeds this up drastically.
Plant Uptake	Roots absorb phosphates; it enters the food web.	Fertilisers add massive excess causing run-off.
Decomposition	Dead matter releases phosphorus back to soil.	Animal waste (manure) concentrated on farms.
Sedimentation	Phosphates flow to oceans, sink, and form new rock over millions of years.	Accelerated eutrophication in lakes/oceans before sinking.

Table 1.15: The Phosphorus Cycle — A typical sedimentary cycle without an atmospheric component, heavily altered by human mining for fertiliser

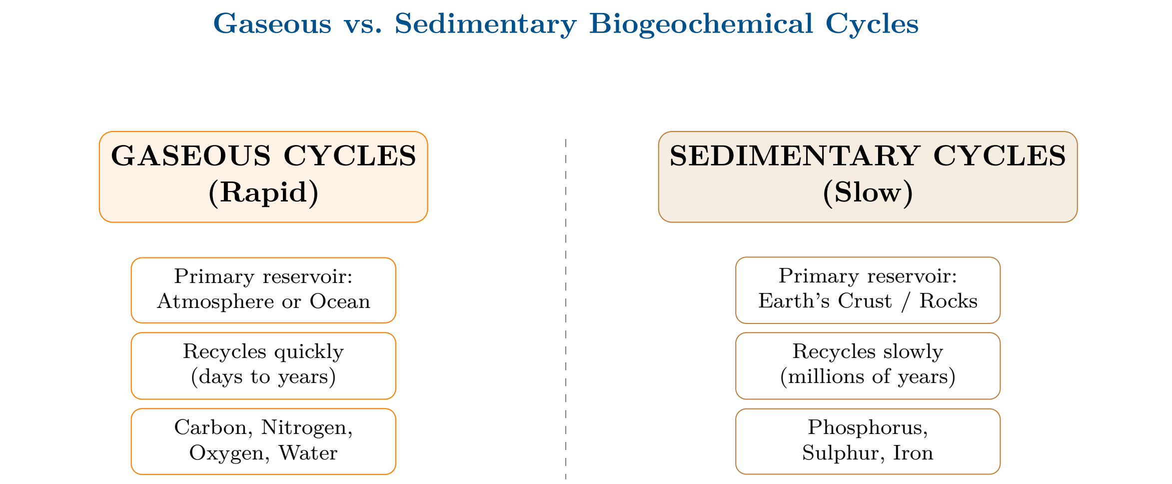


Figure 1.14: Comparison of Gaseous and Sedimentary Cycles — Gaseous cycles adjust quickly to perturbations, while sedimentary cycles adjust over geological time

Chapter 2

Waste Management and Pollution Control

2.1 Introduction to Environmental Pollution

Pollution and Pollutant

Environmental Pollution is the introduction of contaminants into the natural environment that cause adverse changes. It is the process by which the physical, chemical, or biological characteristics of air, water, soil, or other components of the environment are altered to a level that is harmful to human beings, other living organisms, or cultural resources.

A **pollutant** is any agent — physical, chemical, or biological — that is introduced into the environment in quantities that harm living organisms or disrupt natural processes. The concept is dose-dependent: even naturally occurring substances (like CO_2 or nitrogen) become pollutants when their concentrations exceed certain thresholds.

2.1.1 Classification of Pollutants

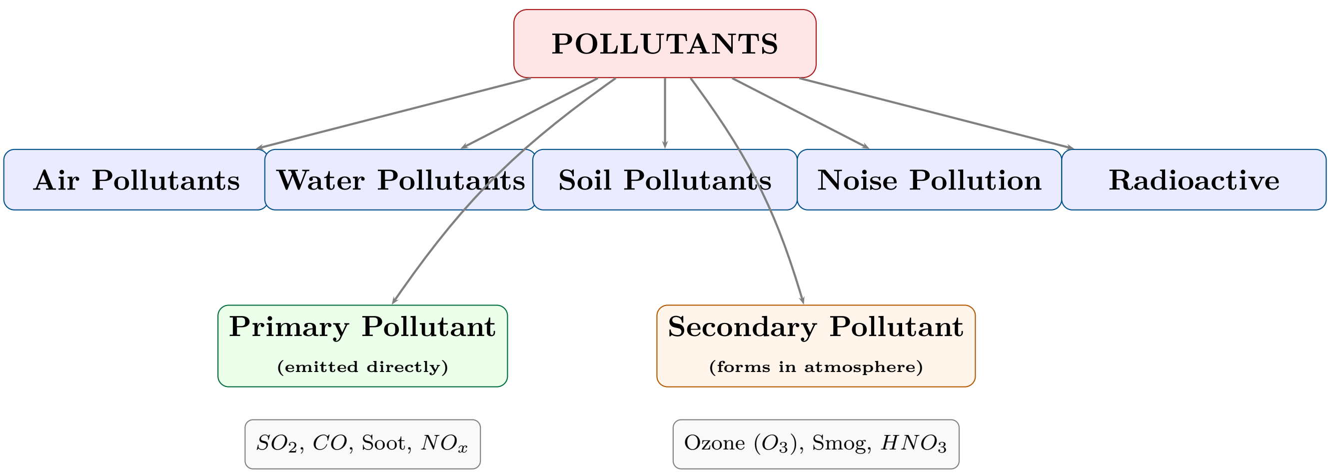


Figure 2.1: Classification of Environmental Pollutants by medium and origin

Pollutants can be classified in several ways:

By Origin

- **Natural Pollutants:** Arise from natural events — volcanic ash and gases (SO_2, H_2S), forest fires, wind-blown dust, decomposition gases (CH_4, H_2S), pollen.
- **Anthropogenic (Man-made) Pollutants:** Arise from human activities — combustion of fossil fuels, industrial effluents, agricultural chemicals (pesticides, fertilisers), municipal sewage, electronic waste.

By Degradability

- **Biodegradable pollutants:** Can be broken down by microorganisms into harmless compounds over time (e.g., food waste, manure, untreated sewage). These become problematic only when they accumulate faster than they can be broken down.
- **Non-biodegradable pollutants:** Cannot be broken down biologically and persist in the environment for very long periods (years to millennia). Examples: DDT, heavy metals (lead, mercury, cadmium), plastic polymers, radioactive isotopes.

By Physical Form

- **Gaseous:** CO_2, SO_2, NO_x, O_3, CH_4, VOCs (volatile organic compounds).
- **Particulate:** Dust, smoke, soot, aerosols, mist, fumes.
- **Liquid:** Industrial effluents, agricultural run-off, oil spills.
- **Solid:** Municipal solid waste, e-waste, mining tailings, hazardous waste.

2.1.2 Air Pollution Terminology

PYQ: Define Mist, Aerosol and Dust; classify air pollutants (N-W'25, N-Su'25)

Dust: Solid particles, typically between 1–100 micrometres (μm) in diameter, suspended in the atmosphere. Generated by mechanical processes — crushing, grinding, blasting, drilling, and wind erosion of soil. Coarse dust (>10 μm) settles quickly; fine dust (<2.5 μm, termed $PM_{2.5}$) remains airborne for hours or days and penetrates deep into the lungs.
Mist: Consists of tiny liquid droplets suspended in the atmosphere, formed by condensation of water vapour or by mechanical breakup of liquid. Mist reduces visibility and can carry dissolved pollutants. Acid mist (formed from SO_2 or NO_x dissolving in water droplets) is particularly harmful to vegetation and lungs.
Aerosol: A colloid system in which fine solid or liquid particles are dispersed in a gas. Examples include smoke (solid particles in air), fog (water droplets in air), smog (air pollution from smoke and fog), and sprayed agricultural chemicals. Aerosols affect climate by scattering or absorbing solar radiation and by acting as cloud condensation nuclei.

Fumes: Solid particles formed by condensation from the vapour state, usually after volatilisation of metals. Example: welding fumes contain metallic oxides that are hazardous.

Classification of Air Pollutants (Primary vs. Secondary):

- **Primary pollutants:** Emitted directly into the atmosphere from a source. Examples: carbon monoxide (CO) from incomplete combustion, sulfur dioxide (SO_2) from coal burning, particulate matter (PM) from industrial processes, ammonia (NH_3) from agriculture.
- **Secondary pollutants:** Formed in the atmosphere by chemical reactions between primary pollutants or between primary pollutants and other atmospheric constituents. Examples: ground-level ozone (O_3) formed from reactions of NO_x and VOCs in sunlight; photochemical smog; sulfuric acid (H_2SO_4) aerosol from $SO_2 + H_2O$; peroxyacetyl nitrates (PANs).

2.2 Air Pollution: Sources and Health Effects

2.2.1 Major Sources of Air Pollution

Pollutant	Type	Major Sources	Health/Environmental Effects
Particulate Matter (PM)	Physical	Road dust, combustion, mining	Respiratory disease, lung cancer, reduced visibility
Sulfur Dioxide (SO_2)	Chemical	Coal burning, smelting	Acid rain, bronchitis, corrosion of buildings
Nitrogen Oxides (NO_x)	Chemical	Vehicle exhaust, power plants	Photochemical smog, acid rain, respiratory irritation
Carbon Monoxide (CO)	Chemical	Incomplete combustion	Binds haemoglobin, reduces O_2 transport, death at high conc.
Ozone (O_3) tropospheric	Secondary	NO_x + VOCs + sunlight	Respiratory damage, crop damage
Lead (Pb)	Heavy metal	Leaded fuel (historic), batteries, paint	Neurotoxic, especially harmful to children

Table 2.1: Major Air Pollutants — Types, Sources, and Effects

2.2.2 Health Impacts of Air Pollution

Air pollution is the world's largest environmental health risk, responsible for approximately 7 million premature deaths globally per year (WHO, 2022).

Health Effects of Air Pollution on Humans and Plants

Effects on Human Health:

- **Respiratory system:** Short-term exposure causes coughing, wheezing, and asthma attacks. Long-term leads to chronic bronchitis, emphysema (Chronic Obstructive Pulmonary Disease, COPD), and lung cancer.
- **Cardiovascular system:** Fine particles ($PM_{2.5}$) and ozone enter the bloodstream, increasing risk of heart attack, stroke, and arrhythmia.
- **Neurological effects:** Lead and mercury cause neurotoxicity — reduced IQ in children, peripheral neuropathy, cognitive decline.
- **Reproductive effects:** Some air pollutants (dioxins, PAHs) disrupt hormonal function, impairing fertility and foetal development.

Effects on Plants and Vegetation:

- SO_2 and NO_2 enter leaves through stomata and dissolve in cell water, forming acids that destroy chloroplasts and cause necrosis (tissue death), bleaching, and leaf drop.
- Ozone (O_3) above background levels inhibits photosynthesis and damages crops — it is estimated to reduce global wheat and soybean yields by 5–10%.
- Acid rain (pH <5.6) leaches calcium, magnesium, and potassium from soil, stunting plant growth, and mobilises aluminium ions that are directly toxic to plant roots.
- Fluoride compounds from brick kilns and fertiliser factories cause fluorosis in vegetation — mottling and necrosis of leaves.

2.3 Acid Rain

Acid Rain

Acid rain (more precisely, acid deposition) refers to any form of precipitation (rain, snow, fog, sleet) with a pH lower than 5.6 — the natural pH of rainwater in equilibrium with atmospheric CO_2. It is caused by the atmospheric dissolution of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3).

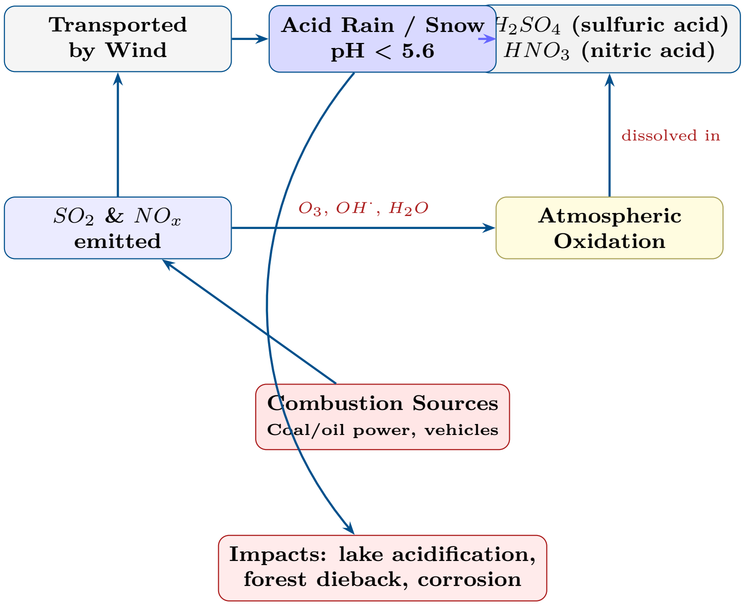


Figure 2.2: Acid Rain Formation — from combustion emissions of SO_2/NO_x through atmospheric chemistry to deposition and impacts

2.3.1 Formation of Acid Rain

Acid rain forms through two primary chemical pathways in the atmosphere:

Sulfuric acid pathway:

$$SO_2 + \frac{1}{2}O_2 \xrightarrow{\text{oxidation}} SO_3$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \text{ (sulfuric acid)}$$

Nitric acid pathway:

$$NO + \frac{1}{2}O_2 \rightarrow NO_2$$

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO \text{ (nitric acid)}$$

These acids dissolve in cloud water and fall as acid precipitation.

2.3.2 Effects of Acid Rain

- **Freshwater ecosystems:** As lake pH falls below 5.0, most fish species cannot survive. Acids also mobilise heavy metals (aluminium, lead, cadmium) from soil into lakes and rivers, creating secondary toxic effects. Scandinavia's lakes turned biologically dead ("fish-less lakes") due to sulphurous emissions from UK industry in the 1970s–80s.

- **Forests:** Acid rain leaches calcium and magnesium from soils (nutrients essential for trees), weakening trees and making them vulnerable to frost, drought, and insect attack. The Black Forest in Germany and Appalachian forests in the USA have suffered significant acid rain damage.

- **Soils:** Acidification reduces microbial activity, impairs nitrogen fixation by bacteria, and destroys humus structure — reducing soil fertility.

- **Buildings and monuments:** Acids react with limestone ($CaCO_3$) and marble ($CaCO_3$) in historic buildings and sculptures: $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2$. The resulting gypsum ($CaSO_4$) is water-soluble and washes away. The Taj Mahal, Acropolis, and many European cathedrals suffer irreversible acid rain damage.
- **Human health:** Acid aerosols (H_2SO_4, HNO_3 droplets) penetrate deep into the lungs, worsening respiratory diseases. Aluminium and lead mobilised into drinking water supplies are neurotoxic.

2.3.3 Control of Acid Rain

- **Flue gas desulfurisation (FGD):** Scrubbers in power plant chimneys react SO_2 with limestone ($CaCO_3$) to produce gypsum and capture it before emission: $SO_2 + CaCO_3 + \frac{1}{2}O_2 \rightarrow CaSO_4 + CO_2$.
- **Catalytic converters:** In vehicle exhausts, platinum-group catalysts convert NO_x to harmless N_2 and CO to CO_2.
- **Low-sulphur coal / fuel switching:** Using coal with lower sulphur content, or switching from coal to natural gas (which contains negligible sulphur).
- **Liming:** Adding powdered limestone to acidified lakes and soils to neutralise acidity and restore biological activity (symptomatic treatment, not a source cure).

PYQ: What is acid rain? Explain its formation and negative effects. (Su'22, W'22, W'21)

Acid Rain: Precipitation (rain, snow, fog) with pH significantly below normal (<5.6) due to the presence of sulfuric acid (H_2SO_4) and nitric acid (HNO_3) formed by SO_2 and NO_x emissions reacting with atmospheric water.
Formation: SO_2 from coal-burning power plants and metal smelting is oxidised to SO_3, which reacts with water to form H_2SO_4. NO_x from high-temperature combustion (vehicle engines, furnaces) reacts with water to form HNO_3. Both acids dissolve into cloud water and fall as acid rain.
Effects:

- **Aquatic life:** Lakes become acidic (pH < 5); fish cannot reproduce. Aluminium mobilised from soil enters water, further killing aquatic organisms.
- **Forests:** Leaches vital nutrients (Ca, Mg) from soil; weakens trees, killing millions of hectares of European and North American forest.
- **Agricultural soils:** Reduces soil fertility and destroys soil microorganism communities (including nitrogen-fixing bacteria).
- **Monuments and buildings:** Dissolves limestone and marble in historic structures (Taj Mahal, Acropolis).

Control: Install flue gas desulfurisation (FGD) scrubbers; use catalytic converters; switch to low-sulphur fuels; renewable energy to phase out coal.

2.4 Soil Pollution

Soil Pollution

Soil pollution (land pollution) is the degradation of the physical, chemical, and biological properties of soil due to the introduction of contaminants — xenobiotic substances, waste materials, or excessive quantities of natural compounds — that reduce its productive capacity and render it hazardous to human health and ecosystems.

2.4.1 Sources of Soil Pollution

1. **Agricultural chemicals:** Excessive or improper use of synthetic pesticides (organochlorines like DDT, organophosphates), herbicides, and synthetic nitrogen/phosphorus fertilisers. These chemicals persist in soil, bioaccumulate, and disrupt soil ecology.

2. **Industrial effluents and solid waste:** Factories release heavy metals (lead, cadmium, mercury, chromium, arsenic) in process wastewater or slag. Mining operations leave behind mine tailings rich in acid-generating sulphide minerals.

3. **Municipal solid waste:** Indiscriminate dumping of garbage, biomedical waste, and e-waste in open landfills. Leachate (rainwater contaminated by waste) percolates into soil and groundwater.

4. **Oil spills and petroleum contamination:** Fuel leaks from underground storage tanks and pipeline spills contaminate soil with polycyclic aromatic hydrocarbons (PAHs) and BTEX compounds (benzene, toluene, ethylbenzene, xylene).

5. **Acid rain deposition:** Acidic precipitation leaches nutrients from soil and mobilises toxic metals.

6. **Radioactive waste:** Improper disposal of radioactive materials from nuclear power plants, medical centres, and research facilities contaminates soil with long-lived radionuclides.

2.4.2 Effects of Soil Pollution

- **Loss of soil fertility:** Destruction of soil microorganism communities (bacteria, fungi, earthworms) that drive nutrient cycling, decomposition, and nitrogen fixation — reducing the productive capacity of agricultural land.

- **Food chain contamination:** Crops grown on contaminated soil absorb pollutants. Heavy metals and persistent organic pollutants enter the food chain and bioaccumulate, ultimately reaching high concentrations in humans.

- **Groundwater contamination:** Pollutants leach through soil into aquifers, contaminating drinking water wells with heavy metals, nitrates, and organic compounds.

- **Human health:** Direct contact, inhalation of contaminated soil dust, or ingestion through food and water causes poisoning, neurological damage, cancer, and reproductive problems.

- **Ecosystem impacts:** Reduction in plant diversity; disappearance of soil fauna; loss of ecosystem function (water retention, carbon storage, nutrient cycling).

PYQ: Causes and effects of soil pollution. What are the control measures? (W'22, N-W'25, N-Su'25)

Soil Pollution: Contamination of soil by industrial, agricultural, and domestic waste that reduces its fertility and makes it hazardous to living organisms.

Causes:

1. Overuse of synthetic pesticides and fertilisers in agriculture.
2. Indiscriminate disposal of industrial effluents, mining waste, and e-waste.
3. Open dumping of municipal solid waste.
4. Oil spills and underground petroleum tank leaks.
5. Acid rain depositing toxic metals.

Effects:

- Reduced soil fertility and agricultural productivity.
- Contamination of food crops with heavy metals and pesticide residues.
- Groundwater contamination as pollutants leach through soil.
- Destruction of soil microorganisms, earthworms, and soil structure.
- Human health problems: lead poisoning, cancer, neurological disorders from contaminated food and water.

Control Measures:

- **Bioremediation:** Using bacteria, fungi, or plants (phytoremediation) to break down or absorb soil contaminants in situ.
- **Soil washing:** Excavating contaminated soil and washing with chemical solutions to extract contaminants.
- **Reduce chemical inputs:** Promote integrated pest management (IPM) and organic/biological fertilisers to reduce chemical application.
- **Proper waste management:** Sanitary landfills with leachate collection, rather than open dumping; hazardous waste treatment before disposal.
- **Legislation:** Enforce regulations on industrial effluent and agricultural chemical use.

Type	Definition	Examples	In Environment
Primary pollutant	Emitted directly from source	CO, SO_2, NO, SPM, Pb	Present as emitted
Secondary pollutant	Formed by reactions in environment	Ozone (O_3), PAN, H_2SO_4	Forms after emission

Table 2.2: Primary vs. Secondary Pollutants — Key Distinction

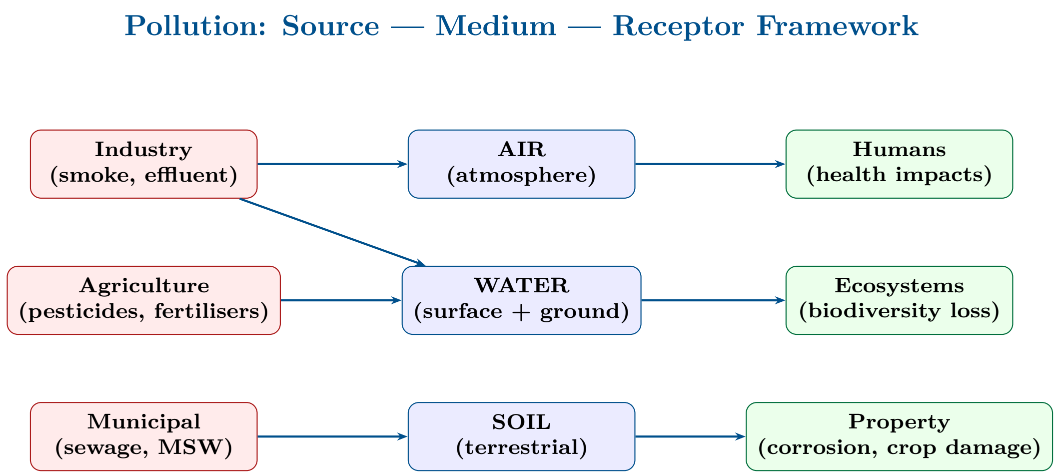


Figure 2.3: Pollution Pathway: Source – Medium – Receptor — Pollutants originate from sources, travel through environmental media (air, water, soil), and affect human and ecological receptors

Type of Pollution	Key Pollutants	Main Sources	Key Impact
Air pollution	SO_2, NO_x, CO, SPM, O_3, VOCs	Vehicles, industries, power plants	Respiratory disease, acid rain
Water pollution	Heavy metals, BOD, pathogens, nitrates	Sewage, agriculture, industry	Waterborne disease, eutrophication
Soil pollution	Pesticides, heavy metals, plastics	Agriculture, landfill, industry	Crop contamination, infertility
Noise pollution	High decibel levels (>85 dB)	Traffic, construction, industry	Hearing loss, stress
Thermal pollution	Hot water discharge	Power plant cooling	Kills aquatic life
Radioactive pollution	Alpha, Beta, Gamma radiation	Nuclear plants, mining, medical	Cancer, genetic damage

Table 2.3: Classification of Environmental Pollution — Types, Key Pollutants, Sources, and Impacts

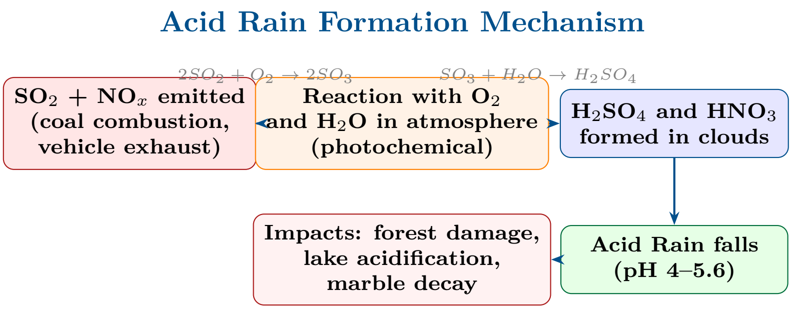


Figure 2.4: Acid Rain Formation — from SO_2/NO_x emission through atmospheric reaction to acidic precipitation and ecological impacts

Pollutant	Type	Sources	Effects
Sulphur dioxide (SO_2)	Gas, primary	Coal power plants, smelters	Acid rain, lung disease, plant damage
Nitrogen oxides (NO_x)	Gas, primary	Vehicles, power plants	Smog, acid rain, ozone formation
Carbon monoxide (CO)	Gas, primary	Incomplete combustion, vehicles	Binds haemoglobin; lethal at high conc.
Ozone (O_3)	Gas, secondary	Photochemical smog	Lung irritant; damages crops; at stratosphere: beneficial
SPM/$PM_{2.5}$	Particulate	Factories, vehicles, construction	Deep lung penetration; cardiovascular disease
Lead (Pb)	Heavy metal	Leaded petrol (historical), batteries	Neurotoxin; IQ reduction in children

Table 2.4: Major Air Pollutants — Type, Sources, and Health/Environmental Effects

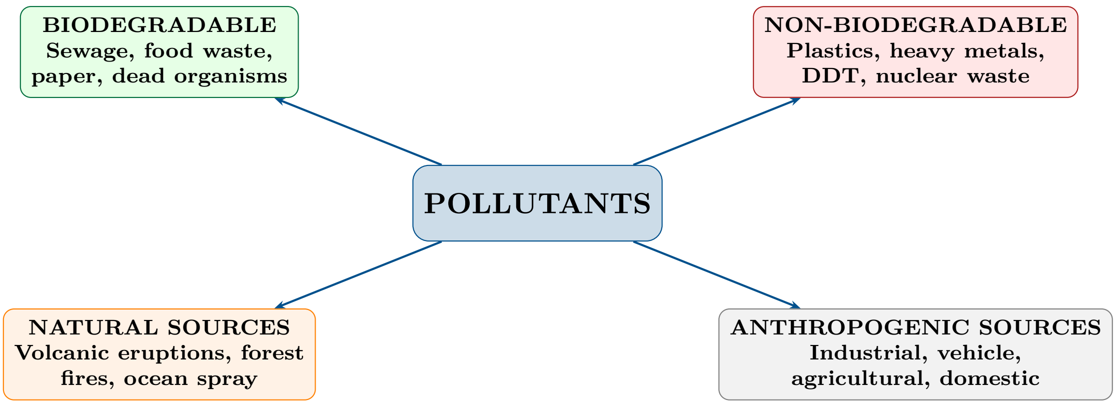


Figure 2.5: Pollutant Classification Mindmap — by biodegradability and by origin (natural vs. anthropogenic)

pH value	Category	Examples	Ecological Impact
<4.0	Very strong acid	Battery acid	Fatal to virtually all aquatic life
4.0–5.6	Acid rain range	Polluted rain, some lakes	Fish eggs fail; biodiversity loss
5.6–6.5	Slightly acidic	Many natural streams	Some sensitive species affected
7.0	Neutral	Pure water	Optimal for most aquatic life
7.5–8.5	Slightly alkaline	Natural seawater	Normal marine ecosystem
>9.0	Alkaline	Industrial effluent	Toxic to aquatic organisms

Table 2.5: pH Scale and Ecological Impact — Acid Rain Reference Range Highlighted

2.5 Air Pollution Control Equipment

Removing particulate matter and gaseous pollutants from flue gases (exhaust from industrial processes and power plants) before they are released into the atmosphere is a fundamental engineering challenge. There are four main categories of dust/particulate collectors:

Device	Operating Principle	Particle Size Removed	Efficiency
Gravitational Settling Chamber	Gravity causes particles to fall as gas velocity is reduced	$> 50\ \mu$m	Low (50–70%)
Cyclone Separator	Centrifugal force separates particles from gas stream	$> 10\ \mu$m	Medium (70–90%)
Electrostatic Precipitator (ESP)	Electric charge causes particles to migrate to plates	$> 0.01\ \mu$m	Very High ($> 99\%$)
Wet Scrubber	Water spray washes particles and gases out	$> 0.5\ \mu$m	High (90–99%)

Table 2.6: Overview and Comparison of Air Pollution Control Equipment

2.5.1 Gravitational Settling Chamber

The simplest and oldest type of particle collector. It exploits Newton's law of gravitation: any particle denser than air will naturally fall if the horizontal velocity is low enough to allow settling before the gas exits.

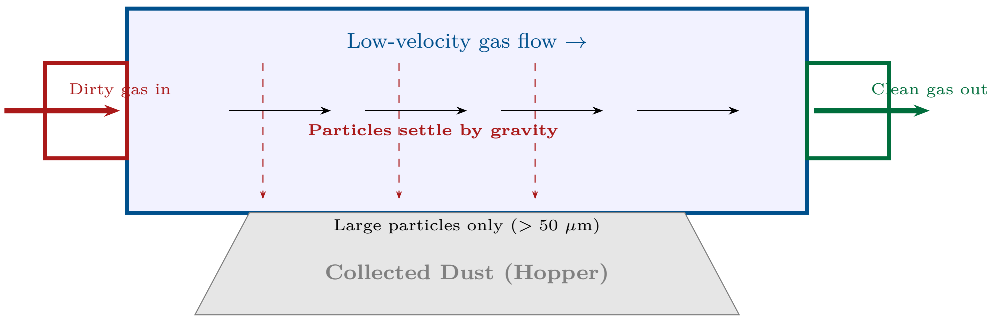


Figure 2.6: Gravitational Settling Chamber — Dirty gas enters at low velocity; heavy particles ($> 50\ \mu$m) settle into the hopper by gravity; cleaned gas exits

Principle

Particulate matter has a settling velocity that depends on the particle's size, density, and shape, as well as the viscosity of the gas. For large, dense particles, gravitational force is sufficient to pull them out of a slow-moving gas stream.

The settling velocity v_s of a spherical particle under Stokes' law is:

$$v_s = \frac{(\rho_p - \rho_g) \cdot d_p^2 \cdot g}{18\mu}$$

where ρ_p = particle density, ρ_g = gas density, d_p = particle diameter, g = acceleration due to gravity, and μ = dynamic viscosity of the gas.

Construction

A gravitational settling chamber is simply a large, horizontal rectangular box:

- The **inlet** brings dirty gas in at one end at a relatively high velocity.
- The large cross-sectional area of the **chamber** causes the gas velocity to drop dramatically.
- Horizontal **baffles** (shelves) may be installed inside to reduce the vertical distance particles must fall, improving efficiency for smaller particles.
- The **floor** (or hoppers at the bottom) collects the settled dust.
- Clean gas exits through the **outlet** at the opposite end.

Working

1. Gas laden with dust particles enters the inlet.
2. As the gas enters the large chamber, its velocity drops significantly (velocity is inversely proportional to cross-sectional area).
3. With reduced gas velocity, gravitational force acts on particles: heavy, large particles ($>$50 μm) settle to the chamber floor within the length of the chamber.
4. Settled dust accumulates in the hopper and is periodically removed via a screw conveyor or manually.
5. Cleaned exhaust gas exits at the outlet.

Performance, Advantages and Disadvantages

Advantages	Disadvantages
Simple construction; low capital cost.	Only removes particles $> 40–50\ \mu m$; fails on fine dust.
Very low pressure drop (low energy cost).	Requires very large floor area.
No moving parts; low maintenance.	Cannot handle sticky or hygroscopic (moisture-absorbing) particles.
Can handle high-temperature gas streams.	Low overall collection efficiency (50–70%).
Collected particles remain dry (easy disposal).	Must be cleaned periodically; cannot operate continuously.

PYQ: Explain construction and working of a Gravitational Settling Chamber. (Su'25, N-Su'25, Su'22)

Gravitational Settling Chamber: A large, horizontal rectangular box used to remove coarse dust particles from exhaust gases by gravity.
Construction: An inlet pipe brings contaminated gas into one end of a wide, low-velocity chamber. Internal baffles (horizontal shelves) may be fitted inside to improve efficiency. Collection hoppers at the bottom collect settled dust. The cleaned gas exits at the other end.
Working Principle:

1. Polluted exhaust gas enters the large chamber.
2. Because the chamber cross-section is much larger than the inlet pipe, gas velocity falls sharply.
3. The low velocity gives gravity time to act: large, heavy particles (diameter > 50 micrometres) lose their inertia and fall to the chamber floor.
4. Finer particles remain entrained and exit with the gas.
5. Settled dust is periodically removed from the collection hopper.

Advantages: Simple, cheap, low maintenance, handles hot gases.
Disadvantages: Only effective for large particles; requires large space; low efficiency (~50-70%).

2.5.2 Cyclone Separator

A cyclone separator (also called a centrifugal collector) removes particles from a gas stream using centrifugal force — a much stronger separating force than gravity.

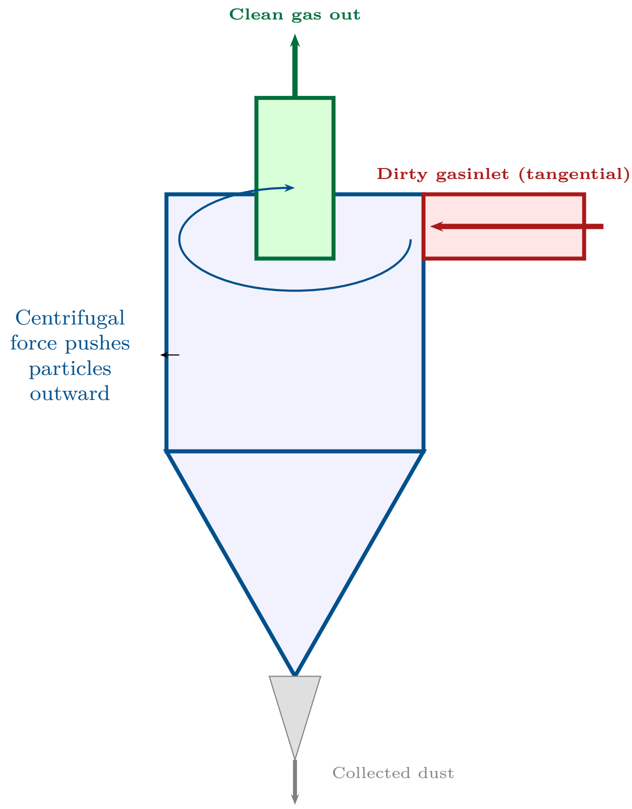


Figure 2.7: Cyclone Separator — Gas enters tangentially creating a downward spiral; centrifugal force throws particles to the wall, they fall into the hopper; clean gas exits via central pipe

Principle

When a gas stream is made to rotate, any particles in the gas experience centrifugal force that pushes them outward towards the wall. The centrifugal force on a particle is:

$$F_c = \frac{mv^2}{r}$$

where m = mass of particle, v = tangential velocity, and r = radius of rotation. This force is many times stronger than gravity, allowing cyclones to separate particles as small as 5–15 μm.

Construction and Working

1. Dirty gas enters tangentially at the top of a cylindrical chamber, creating a spinning vortex.
2. The spinning motion creates centrifugal force that drives particles outward to the cylinder wall.
3. Particles lose velocity, fall down the wall into the conical bottom section, and collect in the hopper below.
4. The now-cleaned gas spirals inward and upward, exiting through a central outlet pipe at the top.

Advantages: No moving parts; handles high temperatures and pressures; more efficient than settling chambers (effective for 5–50 μm particles); relatively compact.
Disadvantages: Poor efficiency for particles <5 μm; high pressure drop; abrasion from hard particles.

2.5.3 Electrostatic Precipitator (ESP)

The Electrostatic Precipitator is among the most effective and widely used devices for controlling particulate air pollution from large industrial sources such as coal-fired power plants, steel mills, and cement factories.

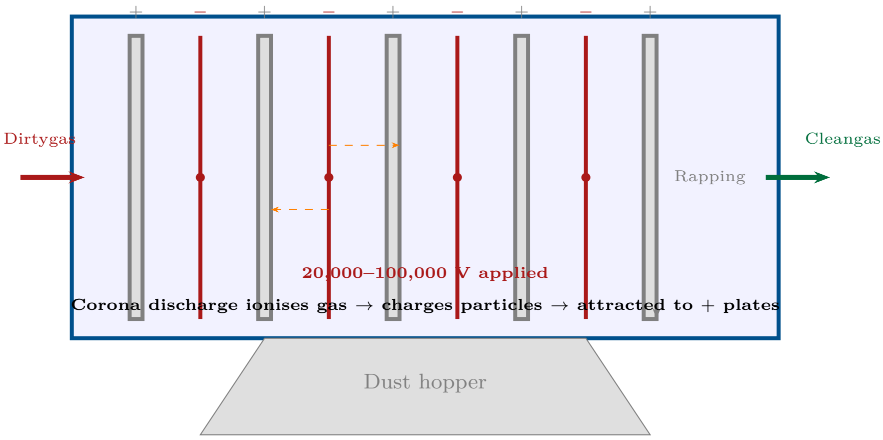


Figure 2.8: Electrostatic Precipitator (ESP) — Discharge electrodes (−) create corona discharge charging particles; charged particles migrate to grounded collection plates (+); rapping dislodges dust into hopper

Principle

ESP exploits the fact that electrically charged particles are attracted towards a plate or surface of opposite polarity. By imparting a strong negative charge to particles and providing a grounded positive collection plate, even the finest particles (<1 μm) can be captured efficiently.

Construction

- **Discharge electrodes:** High-voltage wires or rods (typically at −20,000 to −100,000 V DC) suspended between collecting plates.
- **Collecting plates:** Large, parallel metal plates (usually steel) at ground (zero) potential, spaced about 25–30 cm apart.
- **Rapper mechanism:** Mechanical hammers that periodically strike the collecting plates to dislodge accumulated dust.
- **Dust hopper:** Located at the bottom to collect the dislodged particles.
- **Casing:** The entire assembly is enclosed in a steel shell through which the gas flows horizontally from inlet to outlet.

Working

1. **Ionisation (Corona discharge):** A high voltage is applied to the discharge wires. This creates an intense electric field that ionises the surrounding gas, forming a corona — a visible glow of plasma. The corona generates millions of negative ions (predominantly O_2^- and O^-).

2. **Charging of particles:** Particles in the gas stream pass through the ion cloud and become negatively charged by ion attachment.

3. **Collection:** The negatively charged particles experience an electrostatic force towards the grounded (positive) collecting plates. They migrate through the gas and adhere to the plate surface.

4. **Removal:** The rapper mechanism periodically vibrates the collecting plates. The accumulated dust cake breaks off and falls into the dusthopper below.

5. **Gas outlet:** Clean gas (removal efficiency $> 99\%$ for PM) exits through the outlet.

PYQ: Explain the construction and working of an Electrostatic Precipitator (ESP). (W'23)

Electrostatic Precipitator (ESP): A pollution control device that uses electrical forces (electrostatic attraction) to remove fine particles from an industrial exhaust gas stream.

Construction: An ESP consists of:

- High-voltage discharge wires (at −20,000 to −100,000 V) suspended in the gas stream.
- Grounded metal collecting plates on either side of the wires.
- Rapper mechanisms attached to the plates.
- Bottom hopper to collect removed dust.

Working Principle — Four Stages:

1. **Ionisation:** High voltage on the discharge wire creates a corona discharge that ionises the surrounding gas, generating massive numbers of negative ions.
2. **Particle Charging:** As dirty gas flows through, dust particles collide with the negative ions and acquire a negative charge.
3. **Electrostatic Collection:** Negatively charged particles are strongly attracted to the grounded (positive) collecting plates; they migrate and stick to the plate surface, forming a dust layer.
4. **Dust Removal:** Mechanical rappers periodically shake the plates; the dust layer falls into the hoppers below and is removed.

Advantages: Very high collection efficiency (>99%); handles very fine particles (<1 μm); can treat large volumes of gas; low pressure drop; can handle high-temperature exhaust.

Disadvantages: Very high capital cost; not suitable for highly combustible gases; efficiency drops for high electrical resistivity dust.

2.5.4 Wet Scrubbers

Wet scrubbers use a liquid (usually water) to both capture particulate matter and absorb soluble gaseous pollutants (such as SO_2, HCl, NH_3) simultaneously.

Working

1. Contaminated gas enters the scrubber from the bottom.
2. Scrubbing liquid is sprayed from nozzles at the top, creating a fine mist or a turbulent liquid curtain that the gas must pass through.
3. Particles collide with water droplets, become wetted, and are entrained in the water.
4. Soluble gaseous pollutants dissolve into the water.
5. The dirty scrubbing slurry (water + captured pollutants) falls to the sump at the bottom and is drained for treatment.
6. Cleaned gas exits from the top.

Advantage: Can simultaneously remove both particulate matter and soluble gases; useful for sticky or hygroscopic particles.
Disadvantage: Produces contaminated wastewater that itself requires treatment; risk of corrosion; high operating cost.

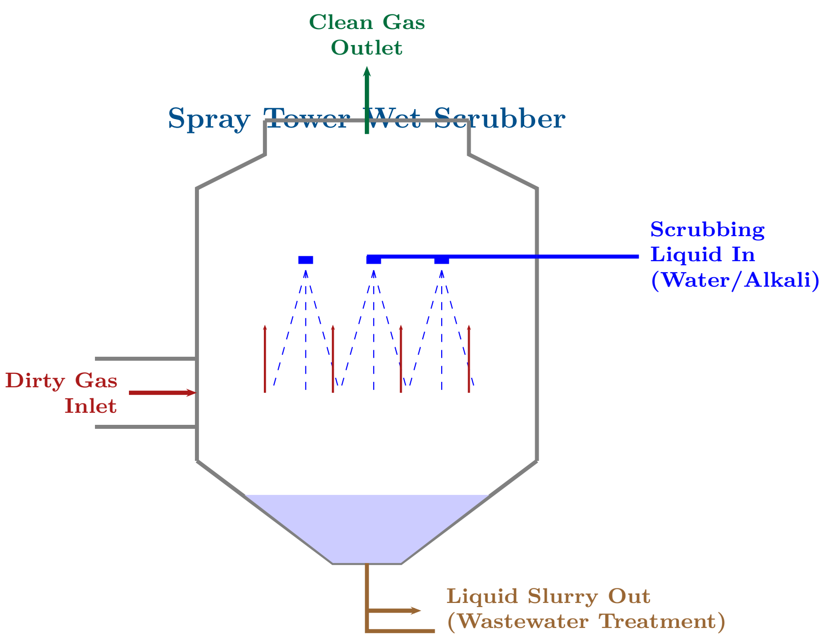


Figure 2.9: Wet Scrubber (Spray Tower) — Dirty gas flows upwards while water/chemical droplets are sprayed downwards, knocking out particles and absorbing soluble gases like SO_2

Control Device	**Suitable For**	**Typical Efficiency**
Gravity Settling Chamber	Large particles (>50 μm)	Low (∼50%); used as pre-cleaner
Cyclone Separator	Medium to large particles (>10 μm)	Moderate (70–90%); handles high dust loads
Fabric Filter (Baghouse)	Fine particles (>0.1 μm)	Very High (>99%); sensitive to temp/moisture
Electrostatic Precipitator	Fine particles (>0.1 μm), high volumes	Very High (>99%); high capital cost
Wet Scrubber	Particles & soluble gases (SO_2, NH_3)	High (>95%); creates water pollution issue

Table 2.7: Comparison of Particulate Emission Control Devices

Smog Formation (Photochemical Smog)

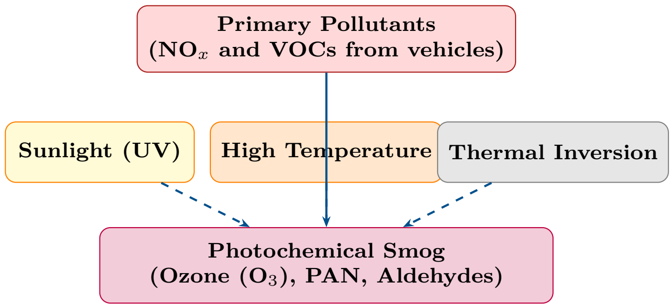


Figure 2.10: Photochemical Smog Formation — A complex mix of secondary pollutants formed when nitrogen oxides and volatile organic compounds react in the presence of strong sunlight

Aspect	Industrial Smog (London Smog)	Photochemical Smog (LA Smog)
Primary Source	Coal burning (industries, power plants)	Vehicle exhaust (petrol/diesel)
Key Pollutants	SO_2 and particulate matter (soot)	NO_x, VOCs, Ozone, PAN
Weather Required	Cold, damp, foggy conditions	Hot, sunny, dry conditions
Chemical Nature	Reducing smog (high SO_2)	Oxidising smog (high O_3)
Time of Occurrence	Usually winter mornings	Usually summer afternoons

Table 2.8: Differences between Classical/Industrial Smog and Photochemical Smog

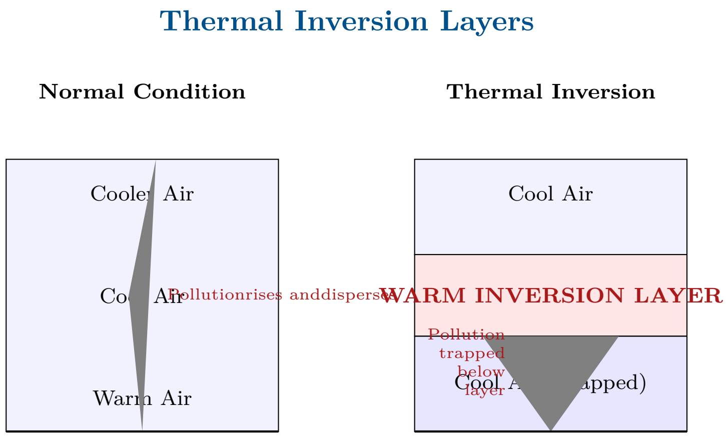


Figure 2.11: Thermal Inversion — Normally, warm air at the surface rises and disperses pollutants. During an inversion, a layer of warm air traps cooler air below it, trapping pollutants near the surface and causing severe smog episodes

2.6 Water Pollution

Water Pollution

Water pollution is the contamination of water bodies (rivers, lakes, groundwater, oceans) with substances that alter the physical, chemical, or biological properties of water to the extent that it becomes harmful to human beings, aquatic organisms, or the environment. Unlike air, water cannot be "replaced" locally — what is polluted remains in the system until actively cleaned.

2.6.1 Sources of Water Pollution

Water pollution sources are classified as:

1. **Point Sources:** Pollution that enters a water body from a single, identifiable location, such as a discharge pipe from a factory or sewage treatment plant. Point sources are relatively easier to regulate because they can be monitored and controlled at the pipe.

2. **Non-Point Sources (Diffuse Sources):** Pollution that comes from many dispersed sources over a large area, with no single identifiable point of entry. Examples:

   - Agricultural run-off carrying fertilisers (nitrates, phosphates) and pesticides into rivers.
   - Urban stormwater run-off carrying oil, heavy metals, and debris from road surfaces.
   - Atmospheric deposition of acidic compounds into lakes and reservoirs.

   Non-point sources are far harder to control and regulate.

Major Categories of Water Pollutants

Category	Examples and Effects
Pathogens	Bacteria (*E. coli*), viruses, protozoa from sewage. Cause cholera, typhoid, hepatitis A, dysentery.
Organic matter	Sewage, food processing waste. Depletes dissolved oxygen (DO) through microbial decomposition.
Nutrients	Nitrates and phosphates from agriculture and sewage. Cause eutrophication.
Heavy metals	Lead, mercury, cadmium, arsenic from industrial effluents and mining. Bioaccumulate; highly toxic.
Synthetic organics	Pesticides (DDT, endosulfan), industrial solvents, plasticisers. Endocrine disruptors; carcinogenic.
Thermal pollution	Hot water discharged from power plant cooling systems. Lowers dissolved oxygen; kills aquatic life.
Radioactive waste	Nuclear power plant discharge, medical isotopes. Can cause cancer and genetic mutations.
Sediment	Soil erosion from construction, mining, deforestation. Smothers aquatic habitats; reduces light penetration.

Table 2.9: Categories of Water Pollutants and Effects

Category	Examples	Primary Effect
Organic (oxygen-demanding)	Sewage, food processing waste	Depletes dissolved oxygen (DO); kills aquatic life
Inorganic	Heavy metals (Pb, Hg, As), acids, salts	Toxic to aquatic organisms and humans
Nutrients	Nitrates, phosphates from fertilisers	Eutrophication; algal blooms; hypoxia
Thermal	Hot water from power plant cooling	Reduces DO; affects breeding of fish
Pathogens	Bacteria, viruses, parasites in sewage	Waterborne disease: typhoid, cholera, dysentery
Sediments	Silt, clay from erosion/construction	Destroys aquatic habitat; reduces light penetration
Synthetic chemicals	Pesticides, pharmaceuticals, plastics	Persistent; bioaccumulate in food chains

Table 2.10: Classification of Water Pollutants — Categories, Examples, and Primary Effects

2.6.2 Eutrophication

Eutrophication

Eutrophication is the process by which a water body becomes increasingly enriched with nutrients (primarily nitrogen and phosphorus), leading to explosive growth of algae (algal bloom). When the algae die, their decomposition by bacteria consumes massive amounts of dissolved oxygen, creating hypoxic dead zones where aquatic life cannot survive.

PYQ: What is eutrophication? How does it affect aquatic ecosystems? (W'22, Su'22)

Process:

Excess nutrients → Algal bloom → Algae die → Decomposers consume DO → Hypoxic dead zon

Effects: Algae block sunlight from submerged plants; oxygen depletion creates dead zones; some algae produce cyanotoxins; loss of recreational value and biodiversity.

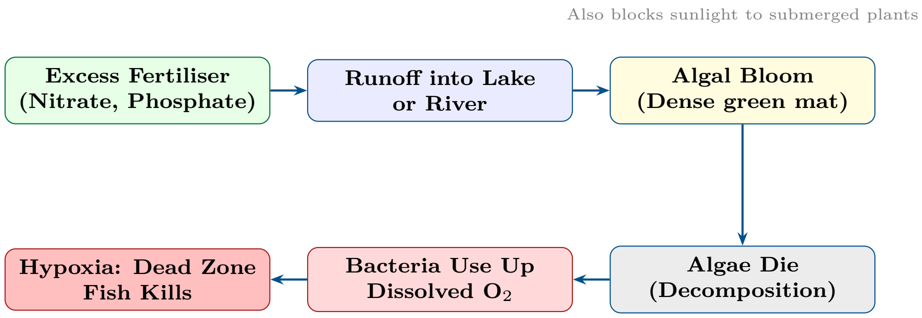


Figure 2.12: Eutrophication Chain — How excess nutrient input leads to algal bloom, oxygen depletion, and fish kills

Why BOD Matters

- **High BOD** indicates a heavy organic load in the water — large amounts of organic waste that bacteria are consuming. As bacteria multiply and consume DO, the oxygen level in the water drops sharply.
- When DO falls below approximately 4–5 mg/L, fish and other sensitive aquatic organisms begin to die.
- When DO approaches zero, anaerobic decomposition takes over, producing malodorous gases (H_2S, CH_4) and turning water black (septic water).
- Clean river water typically has a BOD of < 1–2 mg/L. Slightly polluted water: 2–8 mg/L. Raw sewage: 200–300 mg/L. Industrial effluent can exceed 5,000 mg/L.

Oxygen Sag Curve

When an organic effluent is discharged into a river, dissolved oxygen first rapidly drops (as bacteria consume it), then gradually recovers downstream as reaeration (absorption of oxygen from the atmosphere) and reduced organic load allow the ecosystem to recover. This characteristic pattern is called the **oxygen sag curve** or **Streeter-Phelps curve**.

2.6.3 Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD)

COD is the total amount of oxygen required to chemically oxidise all organic and inorganic substances present in a water sample using a strong chemical oxidising agent (typically potassium dichromate, $K_2Cr_2O_7$, in acidic solution). Results are expressed in **mg/L** of O_2 equivalent.

COD vs. BOD: Comparison

Parameter	BOD	COD
Full form	Biological Oxygen Demand	Chemical Oxygen Demand
What it measures	Oxygen used by *microorganisms* to decompose organic matter biologically.	Oxygen equivalent needed to *chemically* oxidise all organic and inorganic matter.
Test duration	5 days (BOD_5)	2–4 hours
Method	Biological (microbial incubation)	Chemical (dichromate oxidation)
Measures	Only biodegradable organic matter	All oxidisable matter (biodegradable + non-biodegradable + inorganic)
Relationship	COD $\geq$ BOD always	COD $\geq$ BOD always
Use	Measures organic biodegradable pollution load; indicator of impact on dissolvedoxygen.	Faster test; total pollution load; measures even non-biodegradable toxic organics.

Table 2.11: Comparison of BOD and COD

PYQ: Define BOD and COD. Distinguish them. Explain their importance. (Su'22, N-W'25, Su'25)

BOD (Biological Oxygen Demand): The quantity of dissolved oxygen (mg/L) consumed by aerobic microorganisms in decomposing organic matter in water at 20°C over 5 days. It is a measure of the amount of *biodegradable* organic pollution in water.
COD (Chemical Oxygen Demand): The quantity of oxygen (mg/L) required to completely oxidise all organic and some inorganic pollutants in water using a strong chemical reagent (potassium dichromate). It measures both biodegradable and non-biodegradable pollution.
Key distinctions:

- BOD is a biological test taking 5 days; COD is a chemical test taking 2–4 hours.
- BOD only measures organic matter that bacteria can decompose; COD measures everything that can be chemically oxidised.
- COD is always $\geq$ BOD because COD includes non-biodegradable compounds that BOD ignores.
- For domestic sewage, COD/BOD ratio is approximately 1.5–2; for industrial effluent containing non-biodegradable toxic organics, this ratio can be very high.

Importance:

- BOD directly indicates the risk of oxygen depletion and fish kills in rivers.
- COD gives a faster, more complete picture of total pollution load and is used to design industrial treatment systems.
- Both are key parameters in environmental regulatory compliance monitoring.

2.7 Sewage Treatment

Sewage (municipal wastewater) contains pathogens, organic matter, nutrients, and suspended solids. Releasing untreated sewage into water bodies is a primary cause of water pollution in developing countries. Sewage Treatment Plants (STPs, also known as Wastewater Treatment Plants, WWTPs) process sewage through a series of physical, chemical, and biological stages before discharge.

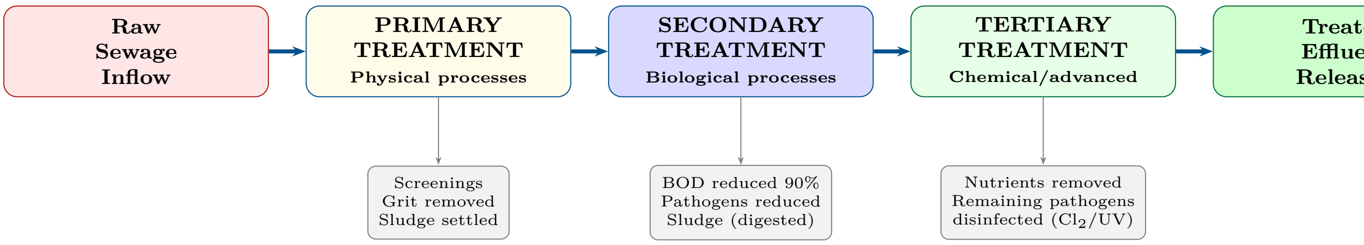


Figure 2.13: Sewage Treatment Plant (STP) — Three-stage process: primary (physical), secondary (biological), and tertiary (chemical/advanced) treatment

Stage	Type	Processes	Pollutants Removed
Primary	Physical	Screening, grit chamber, sedimentation tank	Floating debris, grit, 50–60% suspended solids, 30% BOD
Secondary	Biological	Activated sludge, trickling filter, aeration tank	90%+ BOD, organic matter, most pathogens
Tertiary	Chemical / Advanced	Coagulation, filtration, chlorination / UV / ozone	Nutrients (N&P), residual pathogens, colour, odour

Table 2.12: Three Stages of Sewage Treatment — Processes and Pollutants Removed

2.7.1 Primary Treatment (Physical)

The goal is to remove large solids and reduce suspended matter physically.

1. **Screening:** Sewage passes through bar screens (coarse and fine metal grids) that trap large objects — rags, plastics, sticks, paper.

2. **Grit Chamber:** A slightly enlarged channel where the sewage velocity is reduced enough to allow heavy inorganic particles (sand, gravel, eggshells) to settle out, while keeping lighter organic solids in suspension.

3. **Primary Sedimentation (Settling) Tank:** A large circular or rectangular tank where the sewage remains undisturbed for 2–4 hours. Organic suspended solids settle to the bottom as **primary sludge**; fats and oils float to the top as **scum** and are skimmed off. The clarified liquid (primary effluent) passes on to secondary treatment.

After primary treatment, approximately 50–70% of total suspended solids and 30–40% of BOD are removed.

2.7.2 Secondary Treatment (Biological)

The goal is to remove dissolved and colloidal organic matter using microbial action.

Activated Sludge Process (Most Common)

1. Primary effluent flows into a large **aeration tank**.

2. Air is vigorously pumped into the tank (or mechanical agitators stir the mixture). This aerates the liquid and keeps a dense population of aerobic bacteria (termed *activated sludge*) suspended.

3. Bacteria consume dissolved organic matter (BOD) vigorously, breaking it down into CO_2, water, and new bacterial biomass.

4. The mixed liquid (effluent + bacteria) flows into a **secondary clarifier (settling tank)** where the bacteria flocculate and settle as **secondary sludge**.

5. A portion of the settled sludge is returned to the aeration tank to maintain the active bacterial population (**return activated sludge, RAS**).

6. Clarified secondary effluent (BOD reduced by 85–95%) flows to tertiary treatment.

Trickling Filter

An alternative biological process where primary effluent is sprinkled over a bed of coarse media (crushed rock, plastic rings). A biofilm of bacteria and other microorganisms forms on the media surface and feeds on the organic matter in the percolating wastewater.

2.7.3 Tertiary Treatment (Advanced)

Tertiary treatment polishes the secondary effluent to a very high quality — sometimes to drinking water standards.

- **Filtration:** Passing effluent through sand filters to remove remaining suspended solids.

- **Disinfection:** Adding chlorine (Cl_2), chloramine, ozone (O_3), or ultraviolet (UV) radiation to kill remaining pathogens.
- **Nutrient Removal:** Chemical precipitation (adding lime for phosphorus removal) or biological nitrification/denitrification to reduce nitrogen and phosphorus and prevent eutrophication.
- **Carbon adsorption:** Passing effluent through activated carbon filters to remove trace organic micropollutants and colour.

PYQ: Sketch the flow diagram of a sewage water treatment plant. (Su'25)

A Sewage Treatment Plant (STP) treats wastewater in three stages:
Primary (Physical) Treatment: Raw sewage → Bar Screen (removes large solids) → Grit Chamber (removes sand/gravel) → Primary Settling Tank (removes 50-70% suspended solids, 30-40% BOD; produces primary sludge and scum).
Secondary (Biological) Treatment: Primary effluent → Aeration Tank with activated sludge (aerobic bacteria consume dissolved organic matter over 6-8 hours) → Secondary Clarifier (bacteria settle as sludge; return activated sludge recycled back). BOD removal: 85-95%.
Tertiary (Advanced) Treatment: Secondary effluent → Sand Filtration → Chlorination/UV Disinfection → Nutrient removal → Treated water discharged to river or reused for irrigation/industry.
Sludge Handling: Primary and secondary sludge is pumped to an **anaerobic digester** where bacteria decompose the sludge under oxygen-free conditions, producing **biogas** (used for plant energy) and stabilised sludge (used as agricultural fertiliser or landfilled).

2.8 Noise Pollution

Noise Pollution

Noise pollution is defined as any unwanted, disturbing sound that disrupts the activity, rest, or equilibrium of human or animal life. Sound level is measured in **decibels (dB)**; the decibel scale is logarithmic, so an increase of 10 dB represents a tenfold increase in sound intensity.

2.8.1 Sources

- **Transportation:** Road vehicles, aircraft, trains — the dominant source in urban areas.
- **Industrial:** Compressors, generators, forges, textile mills.
- **Construction:** Drilling, blasting, pile driving.
- **Domestic:** Loudspeakers, home appliances, neighbourhood dogs.

- **Agricultural:** Tractors, threshers, water pumps.

2.8.2 Effects of Noise Pollution

Effect Category	Specific Effects
Hearing damage	Noise-Induced Hearing Loss (NIHL): prolonged exposure to > 85 dB causes permanent hair cell damage in the cochlea.
Psychological	Anxiety, stress, anger, irritability, cognitive impairment, sleep disturbance.
Cardiovascular	Increased blood pressure, heart rate, and risk of hypertension from chronic exposure.
Interference	Disrupts communication, concentration, and learning (especially in schools near airports or highways).
Wildlife	Disrupts communication, mating calls, navigation (whale sonar affected by shipping noise).

Legislation: enforce noise standards (e.g., maximum permissible noise limits in residential zones at 55 dB during the day, 45 dB at night in India under the Noise Pollution Rules, 2000).

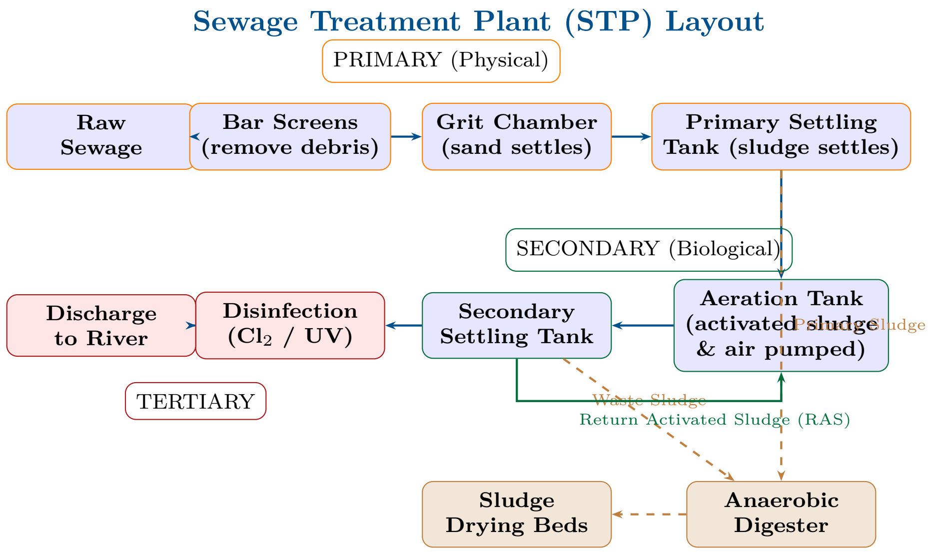


Figure 2.14: Process Flow Diagram of a typical Sewage Treatment Plant (STP) using the Activated Sludge Process

Zone/Area	Day limit (dB) [6 AM – 10 PM]	Night limit (dB) [10 PM – 6 AM]
Industrial Area	75	70
Commercial Area	65	55
Residential Area	55	45
Silence Zone (Hospitals, Schools)	50	40

Table 2.13: Ambient Air Quality Standards in respect of Noise in India (Noise Pollution Rules, 2000)

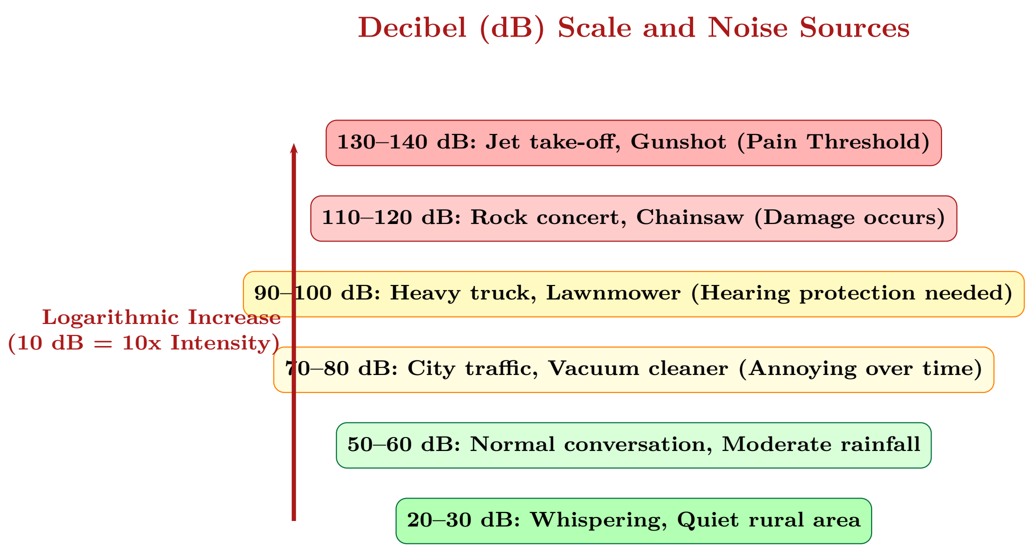


Figure 2.15: The Decibel Scale — Noise levels above 85 dB for prolonged periods can cause permanent hearing loss (NIHL)

2.9 Solid Waste Management

Solid waste is any unwanted solid material that society discards. As global production and consumption grow, solid waste generation has become one of the most pressing environmental challenges, particularly in rapidly urbanising countries like India.

Solid Waste

Solid waste encompasses any garbage, refuse, or sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material (including solid, liquid, semi-solid, or contained gaseous material) resulting from industrial, commercial, mining, and agricultural operations and from community activities.

2.9.1 Classification of Solid Waste

Category	Examples	Characteristics
Municipal Solid Waste (MSW)	Food scraps, paper, glass, textiles, garden waste.	Mix of organic (biodegradable) and inorganic (non-biodegradable).
Industrial Waste	Factory rejects, slag, ash from power plants.	May contain toxic chemicals; needs careful disposal.
Hazardous Waste	Chemical solvents, paint, batteries, pesticide containers.	Flammable, corrosive, toxic, or reactive; strictly regulated.
Electronic Waste (E-waste)	Computers, phones, TVs, batteries, circuit boards.	Contains toxic heavy metals; requires specialised recycling.
Biomedical Waste	Syringes, blood-soaked bandages, surgical tools.	Risk of infection; must be segregated and sterilised.
Construction & Demolition Waste	Concrete rubble, bricks, wood, steel, tiles.	Bulky; can be recycled as aggregate fill.
Agricultural Waste	Crop residues, animal dung, decayed produce.	Largely biodegradable; can produce biogas or compost.

Table 2.14: Classification of Solid Waste

2.10 Electronic Waste (E-Waste)

Electronic Waste (E-Waste)

E-waste (electronic waste, or Waste Electrical and Electronic Equipment — WEEE) refers to any discarded electrical or electronic device that has reached the end of its useful life. This includes everything from large appliances (refrigerators, washing machines, air conditioners) to small consumer electronics (mobile phones, laptops, cameras, LED bulbs, circuit boards, batteries, and printers).

2.10.1 Composition and Hazardous Content

Electronic devices are manufactured from a complex mixture of materials:

Material	**Found In**	**Health / Environmental Risk**
Lead (Pb)	Solder, CRT monitors, batteries.	Neurotoxin; causes brain damage especially in children; kidney damage.
Mercury (Hg)	Fluorescent tubes, flat screens, switches.	Neurotoxin; bioaccumulates as methylmercury in fish; causes Minamata disease.
Cadmium (Cd)	Rechargeable NiCad batteries, semiconductors.	Carcinogen; accumulates in kidneys; chronic lung disease.
Hexavalent Chromium	Metal casings, dyes, anti-corrosion coatings.	Carcinogen; causes skin ulcers and respiratory damage.
PBDEs/BFRs	Plastic casings, circuit boards (flame retardants).	Endocrine disruptors; persist in environment.
PVC (plastics)	Cables, insulation.	When burned, releases dioxins and furans — highly toxic carcinogens.
Beryllium	Motherboards, connectors.	Inhalation of dust causes berylliosis (chronic lung disease).

Table 2.15: Hazardous Materials in E-Waste and Their Health Effects

2.10.2 E-Waste Generation

India is one of the world's largest producers of e-waste, generating approximately 3.2 million metric tonnes per year (2023). Globally, about 62 million tonnes of e-waste were generated in 2022, with only 22% formally recycled.

2.10.3 Impacts of E-Waste

- **Environmental contamination:** Heavy metals leach from landfills into groundwater and soil. In the vicinity of informal e-waste processing sites, concentrations of lead in soil can be 10–100 times safe limits.
- **Air pollution:** Informal burning of e-waste cables to recover copper releases toxic gases (dioxins, furans, polyaromatic hydrocarbons) and heavy metal aerosols.
- **Water pollution:** Acid leaching of circuit boards releases heavy metals directly into water. Informal processing sites near rivers cause aquatic toxicity.
- **Human health:** Workers in informal e-waste yards (often in developing countries, including women and children) suffer chronic lead and mercury poisoning leading to neurological impairment, kidney failure, respiratory disease, and increased cancer risk.

2.10.4 Formal E-Waste Recycling Process

1. **Collection:** E-waste is deposited at authorised collection centres or collected from consumers by certified recyclers.
2. **Manual dismantling:** Trained workers separate components by type — batteries (hazardous), circuit boards (valuable metals), plastic casings, cables, glass panels.
3. **Shredding:** Non-hazardous components are mechanically shredded to release materials.
4. **Material recovery:**
   - *Metal recovery:* Smelting and hydrometallurgical processes recover gold, silver, copper, palladium, and aluminium.
   - *Plastic separation:* Plastics are separated by type and sent to plastic recyclers.
   - *Hazardous materials:* Mercury, lead, and cadmium are extracted using dedicated processes and disposed of safely according to hazardous waste regulations.
5. **Documentation:** Certified recyclers maintain records for regulatory compliance under India's E-Waste (Management) Rules, 2016.

PYQ: What is e-waste? Write its effects and methods of management. (W'22, Su'25, N-W'25)

E-waste (Electronic Waste): Discarded electrical and electronic equipment (EEE) including computers, mobile phones, televisions, refrigerators, and any device with a power or battery. It is the world's fastest growing solid waste stream, with over 50 million tonnes generated globally per year.

Hazardous Materials in E-waste:

- **Lead (Pb):** In CRT monitors, solder. Neurotoxic.

- **Mercury (Hg):** In fluorescent backlights. Neurological and kidney damage.
- **Cadmium (Cd):** In NiCd batteries. Kidney damage; carcinogenic.
- **Brominated Flame Retardants (BFRs):** In circuit boards. Release dioxins when burned.
- **Arsenic, Chromium VI, Beryllium:** Various circuit components. Carcinogenic.
- **Rare Earth Elements:** Valuable materials (gold, silver, copper, palladium) recoverable through formal recycling.

Management (Formal Recycling Steps):

1. **Collection:** Take-back programmes, e-waste bins, authorised collection centres.
2. **Manual Dismantling:** Trained workers remove batteries, toners, screens safely.
3. **Shredding and Sorting:** Automated sorting of metals, plastics, and glass.
4. **Precious Metal Recovery:** Hydrometallurgical or pyrometallurgical processes recover Au, Ag, Cu, etc.
5. **Safe Disposal:** Non-recyclable materials sent to secure landfill or incineration.

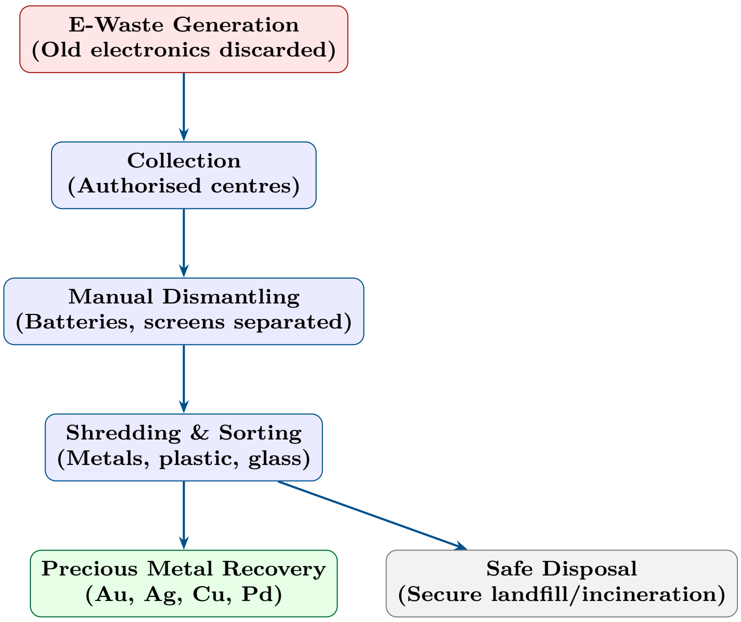


Figure 2.16: Formal E-Waste Recycling Process — from collection through dismantling to precious metal recovery

2.11 Plastic Waste

Plastic Waste

Plastic waste refers to any discarded synthetic polymer material derived from petrochemicals. Plastics are valued for their durability, versatility, and low cost — but these same properties make them an environmental catastrophe, as they resist biological degradation for decades to centuries.

2.11.1 Types of Plastic and Degradation

Type	Uses	Degradation Time
PET	Water bottles, food containers.	450–500 years
HDPE	Milk jugs, pipes, bags.	100–500 years
PVC	Pipes, cables, flooring.	Centuries; releases toxic HCl when burned.
LDPE	Plastic bags, film wraps.	10–1,000 years
PP	Bottle caps, food packaging.	20–30 years
PS	Styrofoam, disposable cups.	50 years to indefinite

Table 2.16: Common Plastic Types and Degradation Times

2.11.2 Impacts of Plastic Pollution

- **Marine pollution:** The ocean contains an estimated 170 trillion plastic particles (2023 estimate). The "Great Pacific Garbage Patch" is a swirling accumulation of plastic debris spanning an area twice the size of Texas.
- **Wildlife:** Marine animals (sea turtles, whales, seabirds) mistake plastic for food, causing intestinal blockage and death. Entanglement in plastic nets and rings kills millions of marine animals annually.
- **Microplastics:** Plastics photodegrade into tiny fragments (<5 mm) called **microplastics**. These are now found in drinking water, food (fish, sea salt, honey), human blood, the placenta, and even the top of Mount Everest. Health effects are under active investigation but include potential endocrine disruption.
- **Soil pollution:** Plastic films in agricultural soil block water and air penetration, reducing crop yields and harming earthworms and soil microorganisms.

PYQ: Write about the effects of plastic waste on the environment. (W'21, W'22)

Plastic waste is a major global environmental crisis because plastics are non-biodegradable — bacteria and other organisms largely cannot break them down, so they persist in the environment for centuries.

Effects:

1. **Marine ecosystem destruction:** Approximately 8–10 million tonnes of plastic enter the oceans annually. Whales, sea turtles, and seabirds ingest plastic, causing internal injuries, starvation, and death. Coral reefs choked by plastic debris suffer bleaching and disease.
2. **Soil contamination:** Plastic mulch films and single-use bags in agricultural land impede soil structure, reduce water absorption, and release toxic plasticisers (such as BPA) into the soil.
3. **Microplastic contamination:** As macroplastics break down by UV and mechanical action into microplastics (<5 mm) and nanoplastics (<1 µm), they enter the food chain. Humans consume an estimated 5 grams of plastic per week through food and water.
4. **Air pollution:** Open burning of plastic waste (common in low-income countries) releases dioxins, furans, and heavy metals that cause cancer, respiratory disease, and neurological damage.
5. **Clogging of drainage systems:** Plastic bags block drains and sewers, causing urban flooding and providing breeding sites for disease vectors (mosquitoes, rodents).

Waste Class	Hazard	Examples & Sources
Ignitable	Fire risk	Solvents, waste oils, paint thinners (Industrial)
Corrosive	Dissolves	Battery acid, alkaline cleaners, rust removers (Industrial)
Reactive	Explosive	Cyanides, sulphides, old munitions (Military/Chemical)
Toxic	Poisonous	Heavy metals (Pb, Hg), pesticides (Agriculture/Mining)
Infectious	Disease	Used bandages, syringes, surgical waste (Hospitals)
Radioactive	Radiation	Spent nuclear fuel, medical isotopes (Power/Hospitals)

Table 2.17: Classification of Hazardous Wastes and Examples

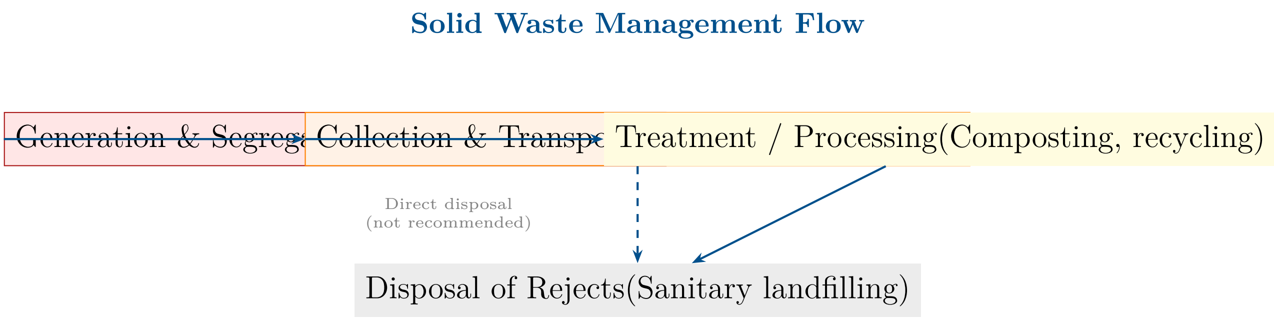


Figure 2.17: Solid Waste Management Flow Schematic

Method	Advantages	Disadvantages
Sanitary Landfill	Can handle large volumes, cheap	Requires land, risk of leachate & CH_4
Incineration	Reduces volume by 90%, energy recovery	High cost, toxic emissions (dioxins)
Composting	Yields fertiliser, organic waste solution	Requires segregation, slow process
Recycling	Resource recovery, saves energy	High collection/sorting costs, market dependent

Table 2.18: Solid Waste Disposal Methods — Advantages and Disadvantages Comparison

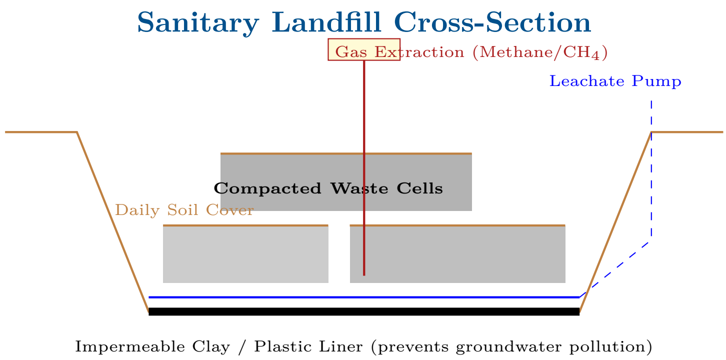


Figure 2.18: Cross-section of a Sanitary Landfill — showing impermeable base liner, leachate collection system, compacted waste cells with daily soil cover, and gas extraction

Colour Code	Type of Biomedical Waste (BMW Recovery Pattern)
Yellow Bin	Human anatomical waste, animal waste, soiled waste, expired medicine
Red Bin	Contaminated waste (recyclable) like tubing, bottles, IV tubes, syringes (without needles)
White (Translucent)	Waste sharps including needles, syringes with fixed needles, scalpels
Blue Bin	Broken glassware, metallic body implants

Table 2.19: Biomedical Waste Segregation Colour Coding (India Standard Guidelines)

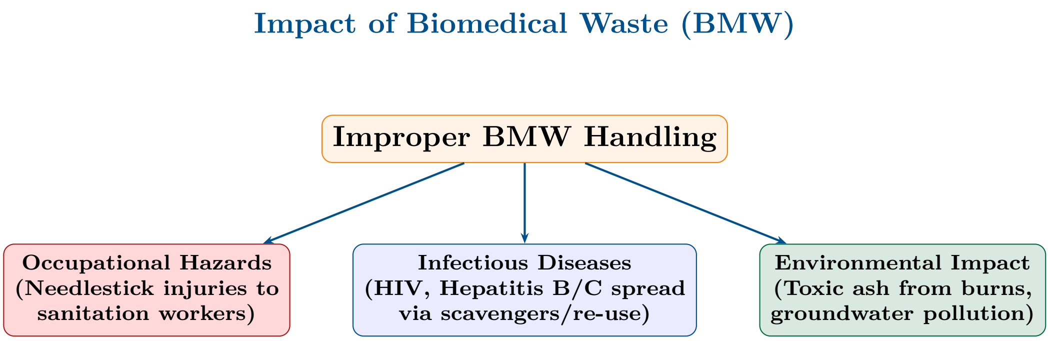


Figure 2.19: Consequences and Impacts of Improper Biomedical Waste Management

Chapter 3

Renewable Energy Technologies

3.1 Energy: Conventional vs. Non-Conventional Sources

Energy is the foundation of modern civilisation. Every industrial process, every transport vehicle, every hospital, and every household requires energy. How we produce and consume energy profoundly shapes the environment.

Conventional (Non-Renewable) Energy

Conventional energy sources are those that have been in use for a long time and currently account for the bulk of global energy supply. They are derived from fossil fuels — coal, petroleum, and natural gas — which were formed from the remains of prehistoric organisms over millions of years under high pressure and temperature. They are characterised by:

- Finite geological reserves that cannot be replenished on a human timescale.
- High energy density (large amount of energy per unit mass or volume).
- Significant environmental pollution upon combustion.
- Well-developed, mature infrastructure.

Non-Conventional (Renewable) Energy

Non-conventional or renewable energy sources are those that are naturally replenished on a human timescale and are essentially inexhaustible. They include solar energy, wind energy, hydropower, tidal energy, geothermal energy, and biomass/biogas. They are characterised by:

- Originating from natural flows of energy (sunlight, wind, water cycle).
- Near-zero or zero direct carbon emissions during operation.
- Lower energy density than fossil fuels but rapidly improving technology and cost competitiveness.

PYQ: Compare Conventional and Non-Conventional Energy Sources in detail. (Su'22, N-Su'25, W'22)

Parameter	Conventional (Non-Renewable)	Non-Conventional (Renewable)
Availability	Finite reserves; will eventually be exhausted.	Virtually inexhaustible; continuously replenished.
Examples	Coal, petroleum, natural gas, nuclear uranium-235.	Solar, wind, tidal, geothermal, biomass.
Pollution	Burns to produce CO_2, SO_2, NO_x, PM — causes climate change, acid rain.	Zero or minimal emissions during operation.
Energy density	Very high (coal: ∼24 MJ/kg; diesel: ∼45 MJ/kg).	Lower; requires large collection areas.
Capital cost	Lower initial plant cost (except nuclear).	High initial cost, especially solar PV and wind.
Running cost	High and volatile fuel costs.	Very low (fuel is free — sun, wind).
Infrastructure	Highly developed; global supply chains.	Rapidly developing; increasingly grid-integrated.
Reliability	24/7 on-demand power possible.	Intermittent (solar/wind depend on weather); storage needed.
Environmental impact	Habitat destruction (mining), oil spills, greenhouse gas emissions, acid rain.	Land use, visual impact, bird strikes (wind), manufacturing emissions.

3.2 Solar Energy

Solar Energy

Solar energy is the radiant light and heat from the Sun that is harnessed using a range of technologies, including photovoltaic (PV) cells, solar thermal collectors, and solar ponds. The Sun radiates approximately 3.8×10^{26} W of power; the amount intercepted by Earth is 1.36 kW/m^2 (the solar constant). India, with its tropical climate, receives an average of 5–7 kWh/m^2/day of solar irradiance.

Feature	Conventional (Fossil) Fuels	Solar Energy
Source	Underground (formed millions of years ago)	Sun (effectively infinite)
Renewability	Non-renewable; will be depleted	Renewable; replenished daily
CO_2 Emissions	Very high (coal > oil > gas)	Zero (at point of use)
Environmental impact	Air, water, soil pollution; land degradation	Minimal; land use at installation site
Energy security	Dependent on geopolitical supply	Domestic, decentralised
Cost trend	Volatile; generally rising	Falling rapidly (90% drop since 2010)
Availability	24/7 if fuel is available	Intermittent; depends on sunlight

Table 3.1: Conventional vs. Solar Energy — Comparison

The Earth receives approximately 1.74×10^{17} watts of solar power — more energy in one hour than the entire human civilisation uses in a year. Harnessing even a small fraction of this resource can meet humanity's energy needs sustainably.

3.2.1 Solar Photovoltaic (PV) Cells

Photovoltaic Cell

A **photovoltaic (PV) cell** (also called a solar cell) is a semiconductor device that converts sunlight directly into electricity through the **photovoltaic effect**. Based on the same p-n junction physics as a diode, a PV cell generates an electromotive force (emf) when photons from sunlight have sufficient energy ($E = h\nu$) to excite electrons across the band gap of the semiconductor.

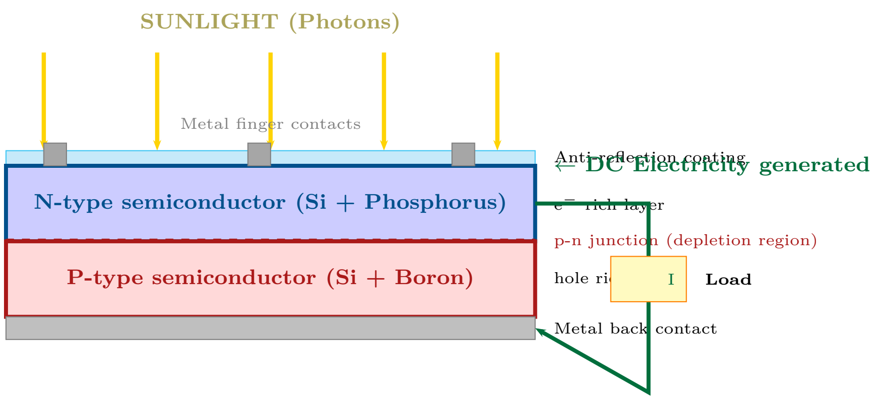


Figure 3.1: Cross-section of a Silicon Solar PV Cell — Photons strike n-type layer, exciting electron-hole pairs; built-in electric field at p-n junction drives electrons through external circuit, generating DC electricity

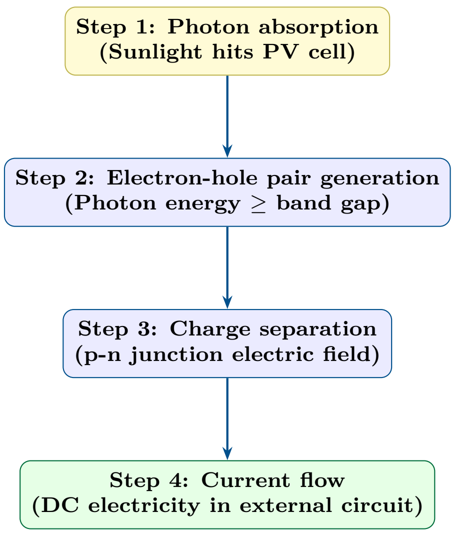


Figure 3.2: Working of a Solar PV Cell — 4-step process from photon absorption to DC electricity generation

Principle: The Photovoltaic Effect

The photovoltaic effect is the generation of an electric voltage (and thus current) in a material when it is exposed to light. It was first observed by French physicist Edmond Becquerel in 1839.

In a solar cell, photons of light interact with electrons in a semiconductor material (silicon), providing them with enough energy to become free charge carriers. These free electrons are then directed through an external circuit by the internal electric field of a p-n junction, constituting a useful electric current.

Construction of a Silicon PV Cell

A basic silicon solar cell consists of:

1. n-type semiconductor layer (top): Silicon doped with phosphorus atoms, which have 5 valence electrons. The extra electron becomes a free carrier. This layer is thin (to allow light to pass through).

2. **p-n junction:** The boundary between the n-type and p-type layers. At this junction, free electrons from the n-side and "holes" (positive vacancies) from the p-side diffuse across and recombine, creating a built-in electric field that points from n to p.

3. **p-type semiconductor layer (bottom):** Silicon doped with boron (3 valence electrons), creating *holes* (electron vacancies) as the dominant positive charge carriers. This layer is thicker.

4. **Metal contacts:** A metal grid on the front (grid fingers to minimise light blockage) and a solid metal back contact collect the current and connect to the external circuit.

5. **Anti-reflection coating:** A thin layer of silicon nitride (Si_3N_4) on the front surface reduces reflection losses, allowing more light to be absorbed.

Working

1. A photon of sunlight strikes the n-type surface and penetrates to the p-n junction region.

2. If the photon has sufficient energy (greater than the silicon bandgap of 1.12 eV), it transfers its energy to an electron in the crystal lattice, freeing it from its covalent bond (this creates an *electron-hole pair*).

3. The built-in electric field at the p-n junction separates the pair: the free electron is swept towards the n-side, and the hole migrates to the p-side.

4. Electrons accumulate at the n-type front contact; holes accumulate at the p-type back contact. This creates a potential difference (voltage) across the cell — typically about 0.5–0.6 V per silicon cell.

5. When the cell is connected to an external load (a resistor, battery, or motor), electrons flow from the negative (n-side) terminal through the external circuit, performing work, and return to the positive (p-side) terminal. This flow of electrons is direct current (DC) electricity.

6. Multiple cells are connected in series (to increase voltage) and in parallel (to increase current) to form a **solar module (panel)**, and multiple panels form a **solar array**.

PYQ: Explain the working of a solar photovoltaic (PV) cell. (Su'25, N-W'25, W'23)

Solar PV Cell: A semiconductor device that converts sunlight directly into electrical energy using the photovoltaic effect.
Construction: Made of two layers of silicon:

- *n-type layer* (phosphorus-doped; extra free electrons) on top.

- *p-type layer* (boron-doped; extra holes) at the bottom.
- A *p-n junction* forms at their boundary, creating a built-in electric field.
- Metal contacts collect current; anti-reflection coating maximises light absorption.

Working (four steps):

1. **Photon absorption:** Sunlight photons strike the silicon, transferring energy to bound electrons.
2. **Electron-hole pair generation:** Energised electrons break free from covalent bonds, leaving behind positive holes.
3. **Charge separation:** The p-n junction's electric field separates electrons (to n-side) from holes (to p-side), preventing immediate recombination.
4. **Current flow:** Electrons flow through the external circuit from the n-contact (negative terminal) to the p-contact (positive terminal), delivering DC electricity to the load.

Key values: A single silicon cell produces ~0.5 V and 1–4 W. Cells are combined in series-parallel to form modules (typically 250–400 W for standard residential panels).

3.2.2 Solar Flat Plate Collectors

Where PV cells convert sunlight to electricity, flat plate collectors convert sunlight to **heat** — primarily for domestic water heating and space heating.

3.2.3 Flat Plate Solar Collector

Flat Plate Collector

A **flat plate solar collector** is a solar thermal device that collects and converts solar radiation into heat, which is then transferred to a fluid (usually water or a water-glycol mixture) flowing through tubes attached to the absorber. The design is simple and maintenance-free, making it the most widely deployed solar thermal technology worldwide for domestic water heating.

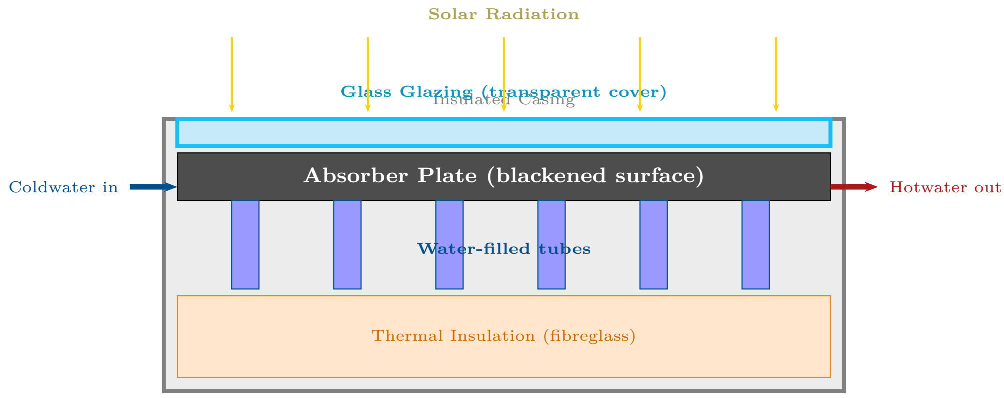


Figure 3.3: Flat Plate Solar Collector cross-section — Sunlight passes through glass glazing, is absorbed by blackened absorber plate, heats water in tubes; insulation minimises heat loss

PYQ: Explain working of a liquid flat plate collector. (W'21)

Liquid Flat Plate Collector: A solar thermal device that uses sunlight to heat a liquid (usually water or a water-antifreeze mixture) for domestic or industrial heating applications.

Construction:

- **Absorber plate:** A flat, blackened metal plate (usually copper or aluminium) that absorbs incident solar radiation and converts it to heat. The black coating is often selective — high absorptivity for shortwave solar radiation but low emissivity for longwave infrared re-radiation.
- **Flow tubes (risers):** Copper or stainless steel tubes bonded to the absorber plate through which the heat transfer fluid flows.
- **Transparent cover:** One or two sheets of low-iron glass or transparent plastic over the absorber plate. The cover allows shortwave solar radiation to pass in but traps longwave re-radiation (greenhouse effect), reducing convective and radiative heat loss from the absorber.
- **Insulated housing:** A metal or plastic box with mineral wool or polyurethane foam insulation on the sides and back to minimise conductive heat losses.

Working:

1. Solar radiation passes through the transparent cover and is absorbed by the black absorber plate.
2. The plate heats up and transfers heat by conduction to the fluid flowing through the bonded tubes.
3. Heated fluid (water or glycol solution) circulates from the collector to a well-insulated storage tank.
4. Cold water enters the bottom of the collector; hot water exits from the top. This can be driven by natural convection (thermosyphon system) or by a pump (active system).

5. Hot water in the storage tank is available on demand for bathing, washing, or space heating.

Applications: Widely used in hotels, hospitals, residential buildings, and industries (food processing, dairy, textile dyeing) where hot water or process heat is needed up to ∼80°C.

3.2.4 Solar Pond

A solar pond is a remarkable and ingenious technology that uses the natural properties of salinated (salt) water to collect and store solar energy as heat, without the need for any mechanical pumps or moving parts.

Why Ordinary Ponds Don't Retain Heat

In a freshwater pond heated by sunlight, the warm surface water has lower density than the cooler water below. This creates convection currents — the warm water rises to the surface and loses its heat to the atmosphere through evaporation and radiation. Thus, a normal pond cannot store significant solar heat.

The Salinity Gradient Principle

A solar pond breaks this convective cycle by exploiting the **salinity gradient**:

- The **lower zone (LCZ)** contains a highly concentrated salt solution (e.g., ∼25% NaCl). This dense, heavy brine absorbs sunlight at the bottom.
- The **non-convective gradient zone (NCZ)** lies above the LCZ. Salt concentration decreases from bottom to top. Although the lower water warms up, the high salinity makes it denser than the cooler but less salty water above it — so warm water cannot rise. Convection is suppressed. This zone acts as a transparent insulating layer.
- The **upper convective zone (UCZ)** is a thin, fresh or low-salinity surface layer kept well-mixed by wind. It is nearly transparent to solar radiation and allows sunlight to penetrate into the gradient zone below.

Heat accumulates in the LCZ and can reach temperatures of 80–90°C, even approaching 100°C in well-maintained ponds.

Energy Extraction

Heat is extracted from the lower convective zone by pumping the hot brine through a heat exchanger. The extracted heat drives an organic Rankine cycle (ORC) turbine for electricity generation, or is used directly for industrial process heat, space heating, desalination, or drying agricultural products.

PYQ: Explain the Solar Pond with its working principle. State its advantages. (W'22, W'23)

Solar Pond: A body of saltwater that collects and stores solar heat energy using a salinity gradient to suppress convective heat loss.
Principle: In a normal pond, heated surface water becomes less dense and rises, losing heat. In a solar pond, the lower zone contains highly concentrated brine (high density). Although this lower zone is heated by absorbed sunlight, its high salt content keeps it denser than the cooler but less salty water above — so it cannot rise. Heat is trapped at the bottom.
Three Zones:

1. **Upper Convective Zone (UCZ):** Thin, low-salinity layer near the surface; transparent; allows sunlight to pass through.
2. **Non-Convective Zone (NCZ):** The insulating layer; salt concentration increases with depth; convection is suppressed.
3. **Lower Convective Zone (LCZ):** High-salinity, very hot (80–90°C) brine where solar heat is stored.

Energy use: Hot brine is pumped from the LCZ through a heat exchanger to extract heat for electricity (via ORC turbine), industrial process heat, or desalination.
Advantages:

- Simultaneously collects *and* stores heat — acts as its own thermal energy storage.
- No mechanical moving parts in the pond itself — very low maintenance.
- Can supply heat continuously, even during cloudy periods (due to thermal mass of brine).
- Low capital cost — just a paddock and common salt.
- Can be built in flat, arid, coastal areas where land is cheap and sunshine is abundant.

3.2.5 Types of Solar PV Cells

Not all solar cells are made alike. Several generations of PV technology exist, each with different efficiency, cost, and application profiles:

Type	**Characteristics**	**Efficiency**
Monocrystalline Silicon	Made from a single silicon crystal (high purity). Uniform dark colour. Best efficiency; most widely used for rooftop solar.	20–26%
Polycrystalline Silicon	Made from multiple silicon crystals melted together. Blue, speckled appearance. Slightly lower efficiency but lower cost.	15–20%
Amorphous (Thin-film) Silicon	Non-crystalline silicon deposited as a thin film on glass or flexible substrate. Lower efficiency but flexible; works in low light; used in calculators, building-integrated PV.	6–12%
Cadmium Telluride (CdTe)	Second-generation thin film; low cost, fast payback; cadmium is toxic (disposal concern).	11–15%
Copper Indium Gallium Selenide (CIGS)	Thin film; high efficiency for thin film; flexible. Used in specialised applications.	13–23%
Perovskite (Emerging)	Novel halide perovskite absorbers; very rapid efficiency improvement in labs; commercial stability still being resolved.	25–33% (lab)

Table 3.2: Types of Solar PV Cells and Their Characteristics

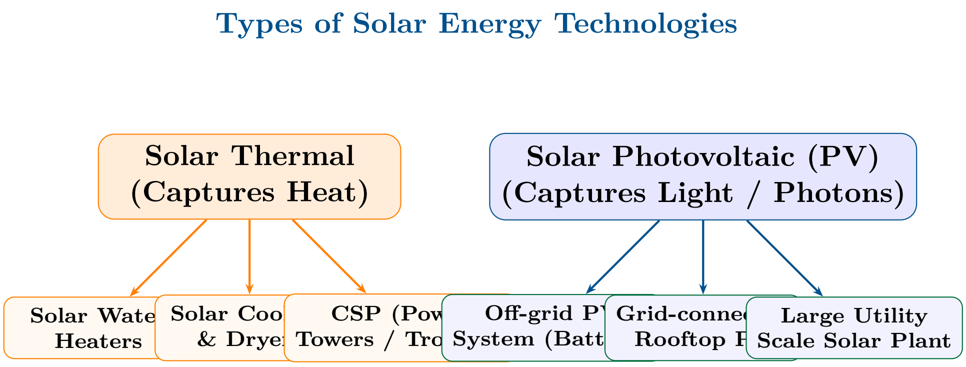


Figure 3.4: Broad Classification of Solar Energy Technologies — Distinguishing between thermal (heat) and photovoltaic (light) applications

Feature	**Solar Thermal Energy**	**Solar Photovoltaic (PV)**
Operating Principle	Converts sunlight directly into heat.	Converts sunlight directly into electricity via the photoelectric effect.
Energy Collected	Infrared and visible spectrum.	Visible and UV spectrum (photons).
Storage	Cheap and easy (hot water/molten salts).	Expensive (requires batteries).
Typical Uses	Water heating, industrial process heat, solar cooking.	Powering homes, electronics, feeding electrical grid.
Overall Efficiency	High (thermal efficiency up to 70-80%).	Lower (electrical efficiency 15-25%).

Table 3.3: Comparison of Solar Thermal and Solar PV Technologies

Hierarchy of Solar PV Systems

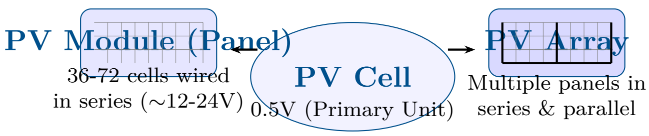


Figure 3.5: Hierarchy of Solar PV Systems — Individual cells are wired together to form modules (panels), which are combined to form arrays of required voltage and current

Component	**Grid-Connected PV System**	**Stand-Alone (Off-Grid) PV System**
Battery Bank	Not required (the grid acts as storage).	Essential (stores energy for night/cloudy days).
Charge Controller	Not required.	Essential (prevents battery overcharging).
Inverter Type	Grid-tie inverter (syncs to grid frequency).	Stand-alone inverter (creates its own 50Hz sine wave).
Net Metering	Yes (sells excess power back to grid).	No (excess power is wasted once batteries are full).
Reliability	Power shuts down if grid fails (anti-islanding safety feature).	Independent power supply, unaffected by grid blackouts.

Table 3.4: Comparison of Grid-Connected versus Stand-Alone Solar PV Systems

3.3 Wind Energy

Wind Energy

Wind energy is the kinetic energy of moving air masses that is converted into electrical energy using a wind turbine. Wind is generated by the differential heating of Earth's surface by the Sun (creating pressure gradients), modified by the Coriolis effect and local topography. Wind power is one of the fastest-growing renewable energy technologies globally.

Feature	HAWT (Horizontal Axis)	VAWT (Vertical Axis)
Rotor axis	Horizontal (parallel to wind direction)	Vertical (perpendicular to ground)
Working	Must face into wind (yaw control needed)	Works with wind from any direction
Efficiency	Higher (40–45%, closer to Betz limit)	Lower (25–35%)
Start-up wind speed	Self-starting above ∼3 m/s	May need assistance to start
Maintenance	Harder (high altitude nacelle)	Easier (generator at ground level)
Noise	More noise from blades	Generally quieter
Wind farm suitability	Large utility-scale farms	Urban, rooftop and decentralised
Examples	GE Haliade-X 14 MW, Vestas V162	Darrieus turbine, Savonius rotor

Table 3.5: HAWT vs. VAWT — Comparison of Horizontal-Axis and Vertical-Axis Wind Turbines

3.3.1 Basic Wind Turbine Principles

Wind turbines extract kinetic energy from the wind and convert it into rotational mechanical energy, which is then converted to electrical energy by a generator.

The power available in a stream of wind is:

$$P = \frac{1}{2}\rho A v^3$$

where ρ = air density (kg/m^3), A = swept area of the rotor blades (m^2), and v = wind speed (m/s).

Key observations:

- Power increases with the **cube** of wind speed — doubling the wind speed increases power by a factor of 8. This is why locating turbines in high-wind areas is critical.
- Power increases linearly with swept area — doubling the blade length quadruples the swept area and the power.
- There is a theoretical maximum efficiency (Betz Limit) of 59.3% for any wind turbine — no device can extract more than 59.3% of the kinetic energy from wind.

3.3.2 Horizontal Axis Wind Turbines (HAWT)

HAWT

HAWT are the dominant technology for commercial electricity generation. The rotor axis is parallel to the ground and the wind direction.

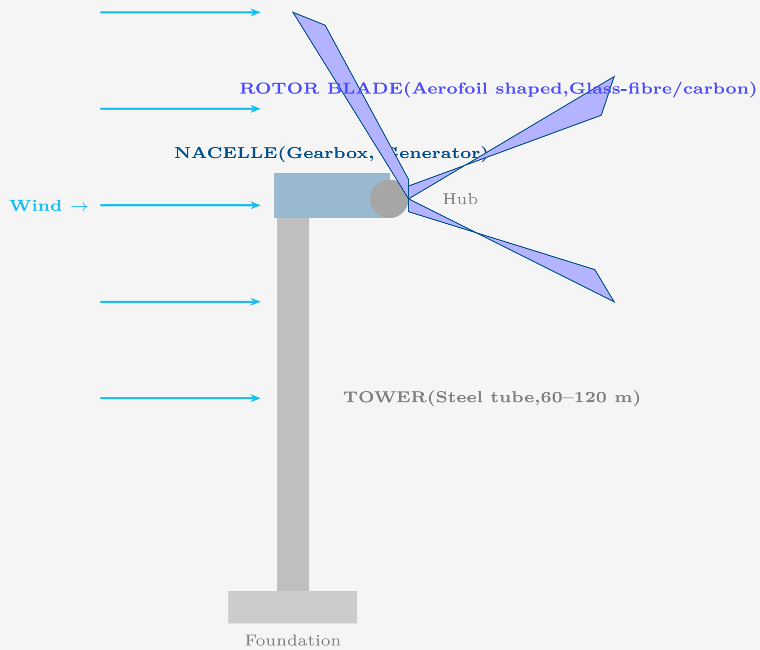


Figure 3.6: Horizontal Axis Wind Turbine (HAWT) construction — three-blade upwind configuration with labelled components

Construction of a HAWT

- **Rotor blades:** Usually three, made of fibreglass-reinforced plastic or carbon fibre composite. They are aerodynamically shaped as aerofoils — the same principle as aircraft wings. Wind flowing over the curved upper surface creates lift (a pressure difference), which spins the rotor. Blade length ranges from 20 m (small turbines) to over 100 m (offshore turbines).
- **Nacelle:** The large housing at the top of the tower containing the gearbox (which steps up the slow rotor rotation of ∼10–20 RPM to ∼1,500 RPM for the generator), the generator, brake, control electronics, and cooling systems.
- **Yaw system:** An electric motor-driven mechanism that rotates the entire nacelle

and rotor to face into the wind. Wind direction sensors (wind vanes) continuously send data to the yaw control system.

- **Pitch control system:** Actuators that can rotate each blade around its long axis to adjust the angle of attack (pitch) — optimising energy capture at varying wind speeds and feathering (turning blade parallel to wind) during storms to prevent damage.
- **Tower:** A tall steel or concrete tower (50–180 m) that supports the nacelle and rotor, elevating the turbine to where wind speeds are higher and more consistent.

Working

1. Wind strikes the rotor blades at an angle. The aerofoil shape creates a pressure difference (higher pressure on the windward side, lower on the leeward side), resulting in a lift force that causes the blades to rotate.
2. The slow rotation of the main shaft (~15 RPM) is stepped up to 1,500 RPM by the gearbox.
3. The high-speed shaft drives the electrical generator, producing AC electricity (or DC in some designs, then inverted to AC).
4. The yaw system continuously tracks wind direction and adjusts the nacelle orientation.
5. Pitch control optimises efficiency at different wind speeds: minimum pitch at low wind speeds for maximum energy capture; increasing pitch (feathering) at dangerously high wind speeds to protect the turbine.
6. Electricity is sent down cabling inside the tower through a transformer to the grid.

3.3.3 Vertical Axis Wind Turbines (VAWT)

VAWT

A **Vertical Axis Wind Turbine (VAWT)** is a wind turbine whose main rotor shaft runs vertically, perpendicular to the ground. The generator and gearbox are located at the base (ground level), and the blades are arranged around the vertical shaft.

Key Design Types

- **Darrieus Turbine:** Features curved, egg-beater shaped blades that generate lift from their aerofoil profile. More efficient than Savonius but not self-starting.
- **Savonius Turbine:** Features S-shaped or half-cylinder scoops (drag-type, not lift-type). Self-starting even at very low wind speeds. Lower efficiency than Darrieus. Used for pumping water, small-scale electricity generation, and anemometers.

- **H-rotor (H-Darrieus):** Straight vertical blades connected to the shaft by horizontal arms.

PYQ: Compare HAWT and VAWT with a neat sketch. (Su'25, W'21, W'23, N-W'25)

Comparison of HAWT and VAWT:

Parameter	HAWT	VAWT
Rotor axis orientation	Horizontal (parallel to ground and wind).	Vertical (perpendicular to ground).
Generator location	Inside nacelle, on top of tall tower.	At ground level — more accessible for maintenance.
Wind direction sensitivity	Requires yaw mechanism to face into wind.	Omnidirectional — works from any wind direction.
Self-starting	Yes (some designs).	Savonius: Yes; Darrieus: No (needs auxiliary start).
Efficiency (Cp)	Higher (∼35–45%).	Lower (∼20–30%).
Blade design	Long, slender aerofoil blades.	Curved (Darrieus), S-shaped (Savonius), or straight (H-rotor).
Tower height	Must be tall (50–180 m) to access faster winds.	Can be low-profile, suitable for rooftops and urban areas.
Installation	Requires large, open, high-wind areas. More complex to install.	Compact; can be installed closer together; low visual impact in cities.
Scale	Very large-scale commercial use (1–15+ MW).	Typically small-scale (<100 kW); urban/off-grid applications.
Examples	GE, Vestas, Siemens-Gamesa turbines in commercial wind farms.	Building-integrated turbines, water pumps, signage power.

Conclusion: HAWTs dominate commercial electricity generation due to their superior efficiency. VAWTs are preferred for urban, small-scale, and applications where the wind direction is variable or the installation height is limited.

PYQ: Explain the Savonius Wind Turbine (windmill) with a neat sketch. (W'21)

Savonius Rotor: A drag-type VAWT invented by Finnish engineer Sigurd Johannes Savonius in 1922.

Construction:

- Two (or more) half-cylinder buckets or scoops are arranged around a vertical central shaft.
- The scoops face opposite directions, forming an S-shape when viewed from above.
- The rotating assembly is supported on bearings at the top and bottom.
- A generator or pump is connected directly to the bottom of the shaft.

Working Principle — Drag Force:

1. Wind strikes the open (concave) face of one bucket — this cupped face has high aerodynamic drag, generating a large force that pushes it away from the wind.
2. The wind also strikes the convex (back) face of the opposing bucket — this presents lower drag.
3. The net torque from the differential drag forces causes the shaft to rotate continuously.
4. As the shaft turns, the generator converts mechanical rotation into electricity.

Advantages:

- Self-starting — begins rotating even in gentle breezes (∼2 m/s).
- Omnidirectional — operates with wind from any direction.
- Very simple, robust construction; very low maintenance.
- Suitable for pumping water in remote agricultural areas and for low-power applications (small instrumentation, rural electrification).

Disadvantages: Low efficiency (15–25%) compared to HAWT; generates relatively small amounts of electricity per unit of rotor area; not suitable for large-scale power generation.

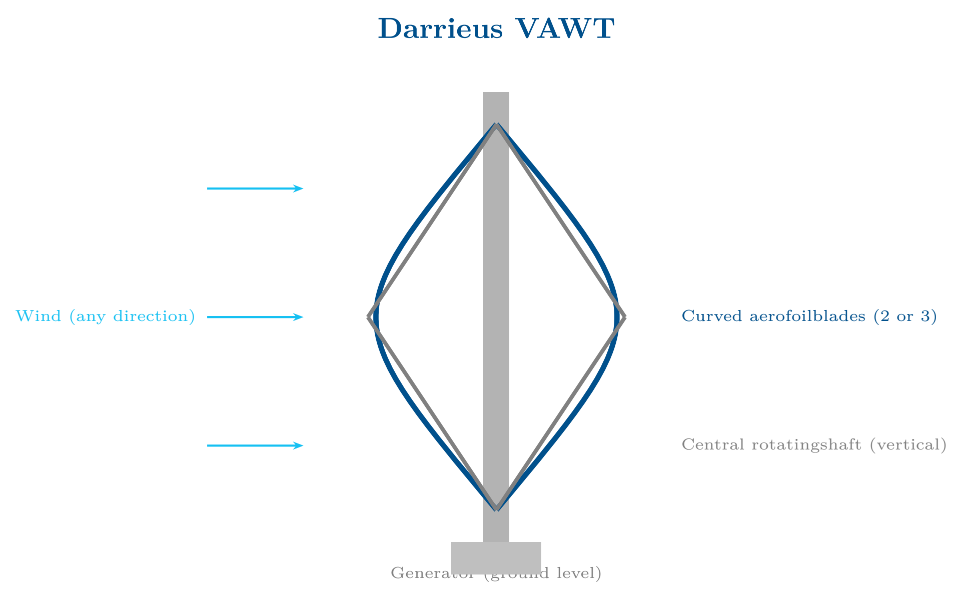
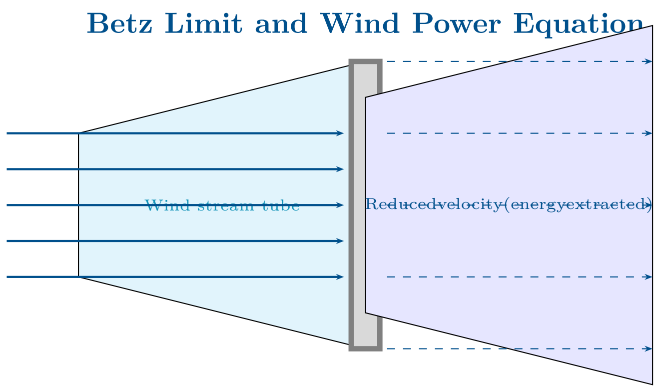


Figure 3.7: Darrieus Vertical Axis Wind Turbine (VAWT) — accepts wind from any direction; generator located at ground level for easy maintenance; lower efficiency than HAWT

Component	**Function**
Rotor blades (3)	Aerofoil-shaped; capture wind kinetic energy and convert to rotational motion
Hub	Connects blades to the low-speed shaft; transfers rotational force
Low-speed shaft	Rotates at 10–22 rpm (blade rotation speed)
Gearbox	Steps up rotation speed from ∼15 rpm to ∼1500 rpm for generator
High-speed shaft	Drives the generator at high speed
Generator	Converts mechanical rotation to AC electricity (typically 690 V, 3-phase)
Yaw mechanism	Rotates nacelle to face into prevailing wind direction
Pitch control	Adjusts blade angle to optimise energy capture at different wind speeds
Nacelle	Houses gearbox, generator, and control systems; sits atop tower
Tower	Steel tubular structure (60–120 m); raises rotor to higher, steadier wind

Table 3.6: HAWT Major Components and Their Functions



$$P = \frac{1}{2}\rho A v^3 \quad \text{(theoretical max)}$$
$$P_{max} = 0.593 \times \frac{1}{2}\rho A v^3 \quad \text{(Betz limit: 59.3\%)}$$

Figure 3.8: Wind Power Equation and Betz Limit — Maximum 59.3% of wind kinetic energy can theoretically be extracted; real turbines achieve 40–45%

Wind Speed (m/s)	**Description**	**Turbine Status**
<3 m/s	Below cut-in wind speed	Turbine does not generate
3–4 m/s	Cut-in wind speed	Turbine starts generating
8–12 m/s	Rated wind speed	Rated (maximum) power output
>25 m/s	Cut-out wind speed	Turbine shuts down to prevent damage

Table 3.7: Wind Turbine Cut-in, Rated, and Cut-out Wind Speeds

Country/State	Installed Capacity	Notable Feature
China	∼400 GW (world #1)	Largest wind power capacity globally
USA	∼148 GW (world #2)	Texas is the top wind state
Germany	∼66 GW	Pioneer in offshore wind development
India	∼45 GW (world #4)	Tamil Nadu, Gujarat, Rajasthan are leaders
Tamil Nadu	∼10 GW	Largest wind capacity in India
Gujarat	∼8 GW	Offshore wind potential in Gujarat coast

Table 3.8: Global Wind Energy Leaders and India's Top Wind States (Approximate 2024 Data)

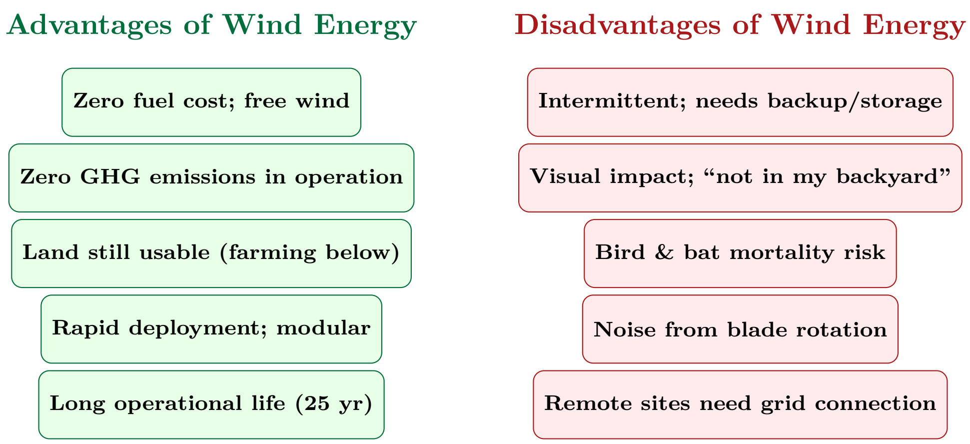


Figure 3.9: Advantages and Disadvantages of Wind Energy

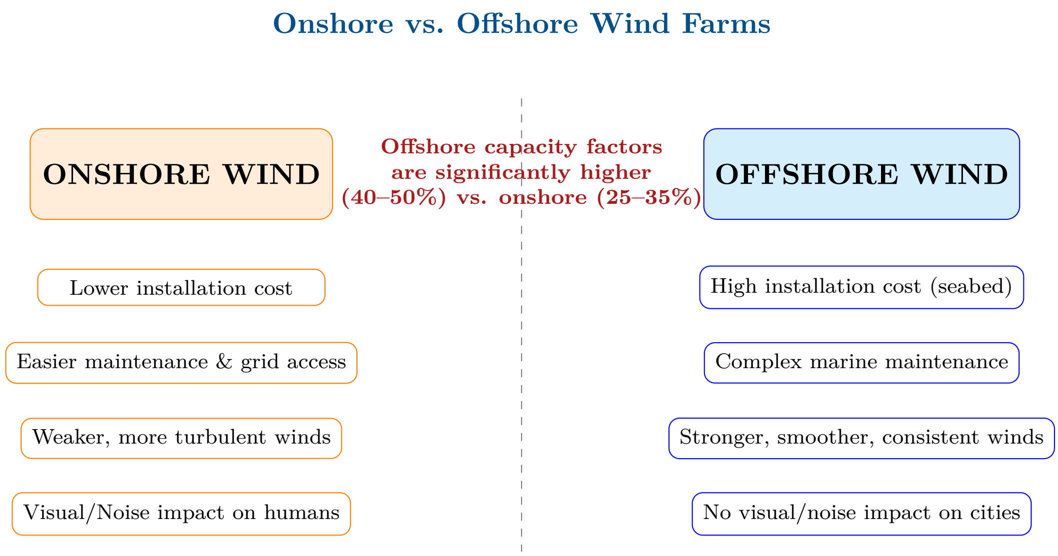


Figure 3.10: Comparison of Onshore and Offshore Wind Farms — Offshore wind offers much higher energy yield though at a higher initial capital cost and maintenance difficulty

3.4 Bioenergy (Biomass Energy)

Bioenergy

Bioenergy is energy derived from biological materials (biomass) — organic matter from plants, animals, and microorganisms. Biomass stores solar energy captured by photosynthesis. When burned or converted to fuels, this stored chemical energy is released. Unlike fossil fuels, biomass is considered renewable because new plant material can be grown to replace what was used.

Energy Source	Type	Key Advantage	Limitation
Solar PV	Renewable	Zero emissions, falling cost	Intermittent; needs storage
Wind	Renewable	Land-efficient; offshore potential	Intermittent; noise
Biomass/Biogas	Renewable	Dispatchable (24/7); waste utilisation	Land use; CO_2 if not managed
Geothermal	Renewable	Baseload (24/7), constant power	Limited to specific regions
Tidal / Wave	Renewable	Predictable; high power density	High capital cost; few viable sites
Hydropower	Renewable	Reliable, low-cost, dispatchable	Large land area; ecosystem disruption
Hydrogen (Green)	Renewable carrier	Versatile; zero-emission when burnt	Expensive electrolysis; storage challenges

Table 3.9: Renewable Energy Sources — Key Advantages and Limitations

Biomass is converted to useful energy through several pathways:

- **Direct combustion:** Burning biomass to generate heat or electricity. The least efficient but simplest method.
- **Anaerobic digestion (Biogas):** Microorganisms break down organic matter in the absence of oxygen, producing biogas (∼60% CH_4, ∼40% CO_2).
- **Fermentation (Bioethanol):** Yeast ferments sugars from crops (sugarcane, corn) to produce bioethanol — a liquid biofuel used in vehicles.
- **Transesterification (Biodiesel):** Vegetable oils or animal fats are chemically reacted with methanol to produce biodiesel.
- **Gasification / Pyrolysis:** Heating biomass with limited oxygen (gasification) or without oxygen (pyrolysis) produces syngas or bio-oil.

3.4.1 Biogas Plant (Anaerobic Digester)

The biogas plant (also called a gobar gas plant in India or an anaerobic digester) converts wet organic waste — primarily cattle dung — into a mixture of methane, carbon dioxide, and trace gases (collectively "biogas") through anaerobic digestion.

Microbiology of Anaerobic Digestion

Anaerobic digestion occurs in four sequential stages carried out by different groups of microorganisms:

1. **Hydrolysis:** Complex organic polymers (cellulose, proteins, lipids) are broken down by hydrolytic bacteria into simple monomers (sugars, amino acids, fatty acids).
2. **Acidogenesis:** Acidogenic bacteria ferment the monomers into volatile fatty acids (mainly acetic, propionic, and butyric acid), alcohols, CO_2, and H_2.
3. **Acetogenesis:** Acetogenic bacteria further convert the volatile fatty acids and alcohols into acetic acid (CH_3COOH), CO_2, and H_2.
4. **Methanogenesis:** Methanogens (strict anaerobes) convert acetic acid and H_2/CO_2 into methane and CO_2:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad \text{(acetoclastic methanogenesis)}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \text{(hydrogenotrophic methanogenesis)}$$

PYQ: Explain construction and working of a biogas plant with a diagram. (W'21, W'22, W'23, Su'25)

Biogas Plant: A biogas plant produces biogas (∼60% CH_4, 40% CO_2) through anaerobic digestion of organic waste.
Key components: Mixing tank (dung + water 1:1); underground digester; fixed dome (gas holder); outlet/compensation chamber; gas pipe and tap.
Working: Fresh slurry is fed daily. Anaerobic bacteria decompose organic matter over 40–50 days. Biogas accumulates in the dome and is piped to the kitchen. Spent digestate is used as biofertiliser.
Advantages: Clean cooking fuel; reduces deforestation; reduces indoor air pollution; produces biofertiliser; reduces CH_4 emissions from open dung.

3.5 Other Renewable Energy Sources

3.5.1 Geothermal Energy

Geothermal Energy

Geothermal energy is heat derived from the natural radioactive decay of elements (primarily uranium, thorium, and potassium) deep within the Earth's interior and from residual heat left over from the planet's formation. The interior of the Earth reaches temperatures of over 5,000°C at the core. This heat conducts outward, maintaining a geothermal gradient of approximately 25–30°C per kilometre of depth.

Working of a Geothermal Power Plant

1. Wells (1–3 km deep) are drilled into hot rock formations or natural geothermal reservoirs (hot water or steam trapped in porous rock).
2. Steam or hot water under pressure is extracted from the reservoir via production wells.
3. The steam (direct use) or heat (via a heat exchanger for binary cycle plants) drives a turbine connected to a generator.
4. Used steam is condensed back to water and reinjected into the reservoir via injection wells to sustain the resource.

Significant geothermal sites: Iceland (uses geothermal for ∼90% of heating), Larderello (Italy, world's first geothermal plant, 1904), The Geysers (California, USA), Krakatau (Indonesia).

Advantages: Reliable baseload power (24/7, independent of weather); very low emissions; small surface footprint; long plant life.
Disadvantages: Geographically limited (effective only near tectonic plate boundaries, volcanic zones); risk of induced seismicity; potential release of H_2S gas.

3.5.2 Tidal Energy

Tidal Energy

Tidal energy is derived from the gravitational forces between the Earth, Moon, and Sun, which cause the periodic rise and fall of sea levels (tides). The kinetic energy of these massive moving water bodies can be captured and converted to electricity.

Tidal Barrage

The most common approach is the tidal barrage (a dam-like structure built across a tidal estuary):

1. At high tide, the seawater gate is opened. Water flows through sluice gates into the estuary and through turbines, generating electricity.

2. At low tide, the gate is closed trapping water inside. As the external sea level falls, the head difference between inside (high) and outside (low) drives water back out through turbines, generating electricity again.

Example: La Rance Tidal Barrage (France, 240 MW, operational since 1966); Sihwa Lake Plant (South Korea, 254 MW).

Advantages: Predictable and reliable (tides follow a precise astronomical schedule); zero fuel cost; very long operational life; no greenhouse gas emissions.
Disadvantages: Very high construction cost; limited to coastal estuaries with large tidal range (>5 m); ecological impact on estuarine habitats.

3.5.3 Small Hydropower

Hydropower

Hydropower converts the gravitational potential energy of water stored at elevation into kinetic energy (as it falls) and then into electrical energy via a turbine-generator system. It is the world's largest source of renewable electricity (∼17% of global generation).

Working of a Run-of-River Micro-Hydropower Plant

1. Water from a river is diverted through a weir and intake structure.
2. It flows through a penstock (a pressurised pipe) down an elevation drop.
3. The high-pressure, high-velocity water jet strikes the Pelton wheel or Kaplan turbine blades, converting hydraulic energy to rotational energy.
4. The turbine drives a generator to produce electricity.
5. Water exits through a draft tube and returns to the river.

3.5.4 Hydrogen Energy

Hydrogen (H_2) is the lightest and most abundant element in the universe. As an energy carrier (not a primary energy source), hydrogen can store and deliver energy efficiently:

- **Green hydrogen:** Produced by electrolysis of water using renewable electricity — zero carbon during production.
- **Grey hydrogen:** Produced from natural gas (steam methane reforming) — significant CO_2 emissions.
- **Blue hydrogen:** Grey hydrogen with Carbon Capture and Storage (CCS).

Applications: Fuel cells (power electric vehicles and buildings), steelmaking (replace coal-based reduction), ammonia synthesis, aviation fuel.

PYQ: Write a short note on Geothermal and Tidal Energy. (N-Su'25, W'22)

Geothermal Energy: Energy derived from heat within the Earth (from radioactive decay and primordial heat). Geothermal power plants drill wells (1–3 km) into hot rock or steam reservoirs. The extracted steam or hot water drives turbines to generate electricity. It is a reliable, 24/7 baseload renewable energy source but is geographically limited to volcanic and tectonic zones. Countries like Iceland generate over 30% of their electricity from geothermal sources.
Tidal Energy: Energy harvested from the rise and fall of ocean tides caused by the gravitational attraction of the Moon and Sun. The primary technology is the *tidal barrage* — a dam built across a tidal estuary with turbines in the gate openings. As tide rises, water flows in through turbines (generating electricity); as tide falls, water flows out again through turbines (generating electricity again). Tidal energy is highly predictable (tidal schedules are known centuries in advance) and emission-free. Disadvantages: very high construction cost; limited to locations with a tidal range exceeding 5 metres.

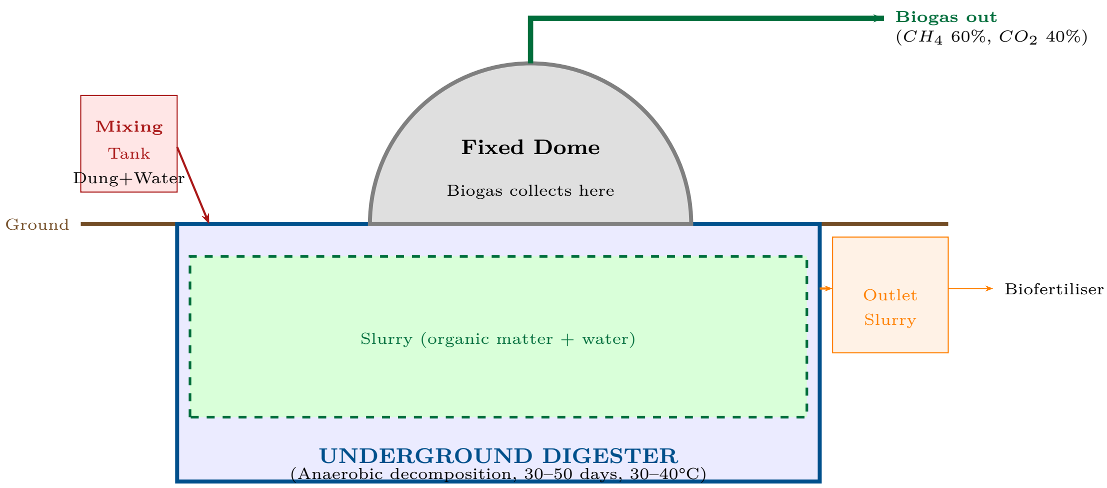


Figure 3.11: Fixed-Dome Biogas Plant (KVIC/Deenbandhu Model) — Cross-section showing mixing tank, underground anaerobic digester, fixed dome gas collector, gas outlet pipe, and biofertiliser outlet

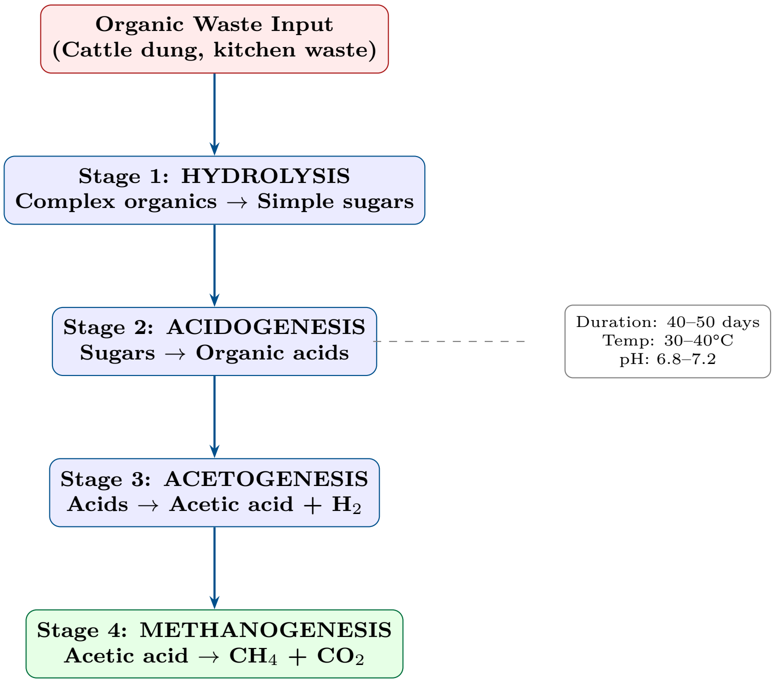


Figure 3.12: Four-Stage Anaerobic Digestion Process — Sequential microbial decomposition from raw organic waste to biogas

Type	**Floating Drum Plant**	**Fixed Dome Plant (KVIC/Deenbandhu)**
Gas holder	Metal drum that floats on slurry	Fixed brick/concrete dome, underground
Gas pressure	Constant (drum weight provides pressure)	Variable (slurry level varies)
Maintenance	Higher (metal drum corrodes)	Lower (no moving parts, no corrosion)
Cost	Higher initial cost	Lower, uses local materials
Lifespan	15–20 years	20–30+ years
Suitability	Small household scale	Community and household scale

Table 3.10: Floating Drum vs. Fixed Dome Biogas Plant — Comparison

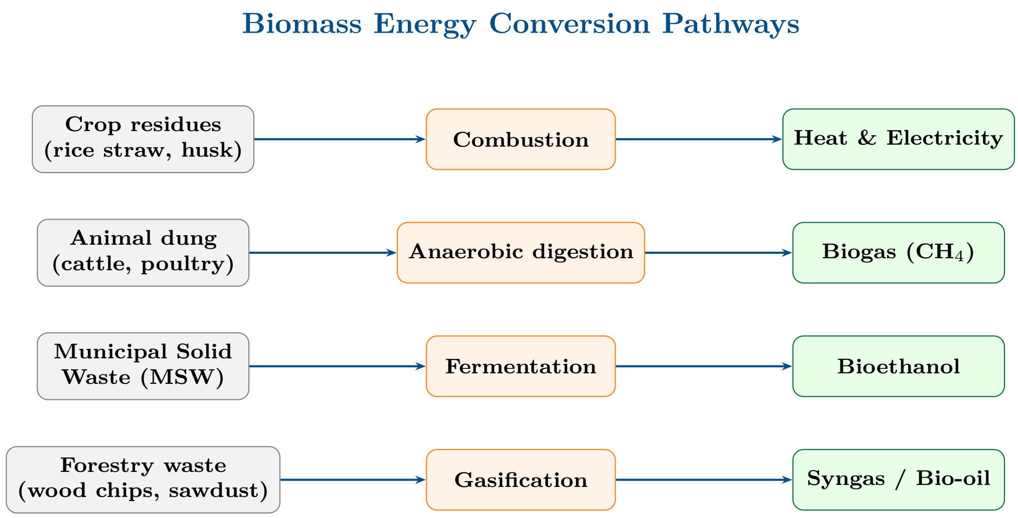


Figure 3.13: Biomass Energy Conversion Pathways — four main conversion routes from organic feedstocks to usable energy products

Source	**Technology**	**Product**	**India Example**
Cattle dung	Fixed/floating dome biogas plant	Biogas (CH_4)	Millions of household plants
Sugarcane	Fermentation	Bioethanol	Blended with petrol (EBP)
Vegetable oils	Transesterification	Biodiesel	Jatropha, soyabean
Rice paddy straw	Combustion in power plant	Electricity	Punjab biomass plants
MSW	Gasification / incineration	Syngas / heat	Delhi, Mumbai WtE plants
Sewage sludge	Anaerobic digestion	Biogas + biofertiliser	STPs across India

Table 3.11: Bioenergy Sources, Technologies, Products, and Indian Examples

Feature	**Biogas**	**LPG (Liquefied Petroleum Gas)**
Source	Renewable (organic waste)	Fossil fuel (non-renewable)
Composition	55–65% CH_4, 35–45% CO_2	Propane (C_3H_8) + Butane (C_4H_{10})
Calorific value	20–25 MJ/m^3	45–50 MJ/kg (much higher)
CO_2 impact	Carbon-neutral (bioganic cycle)	Fossil CO_2 emissions
Cost	Very low (after construction)	Market-linked, volatile
By-product	Biofertiliser (valuable)	None
Rural benefit	Decentralised, local production	Supply chain needed

Table 3.12: Biogas vs. LPG — Comparison for Rural Energy Applications

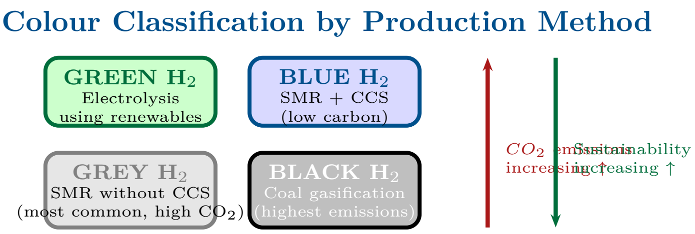


Figure 3.14: Hydrogen Colour Classification — from green (renewable, zero-emission) to black (coal-based, highest CO_2)

Feature	Geothermal Energy	Tidal Energy
Source	Earth's internal heat (radioactive decay)	Moon/Sun gravitational forces
Technology	Wells, steam turbines, binary cycle plants	Tidal barrage, tidal stream turbines
Availability	24/7 baseload; independent of weather	Predictable (tidal schedule known in advance)
Capacity factor	High (>90%)	Moderate (40–60%)
Geographic limit	Tectonic zones, volcanic regions	Estuaries with >5 m tidal range
Environmental impact	Minimal; some H_2S release risk	Habitat change in estuaries
India relevance	Limited (Manikaran, HP)	Limited (Gulf of Khambhat potential)

Table 3.13: Geothermal vs. Tidal Energy — Comparison of Two Non-Solar Renewables

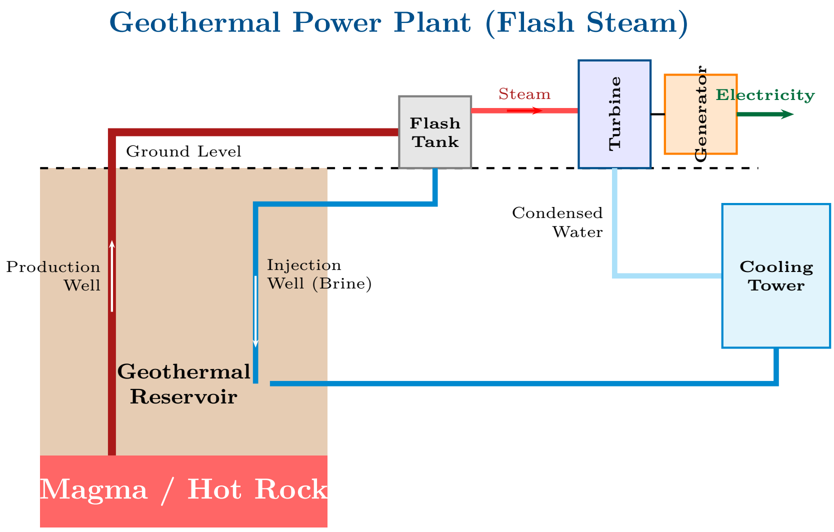


Figure 3.15: Flash Steam Geothermal Power Plant — High pressure hot water from deep underground flashes to steam at the surface to drive a turbine; the condensed water and leftover brine are reinjected into the reservoir to maintain pressure

Chapter 4

Climate Change: Science and Solutions

4.1 The Science of Climate Change

Global Warming and Climate Change

Global warming refers specifically to the long-term rise in Earth's average surface temperature, primarily driven by the increase in atmospheric concentrations of greenhouse gases (GHGs) due to human activities since the Industrial Revolution.
Climate change is a broader term encompassing all the long-term changes in Earth's climate system — including global warming, but also changes in precipitation patterns, sea level rise, ocean acidification, glacier retreat, changes in the frequency and intensity of extreme weather events, and disruptions to biological systems.

4.1.1 Evidence for Climate Change

The scientific evidence for human-caused climate change is unequivocal. The Intergovernmental Panel on Climate Change (IPCC) synthesises thousands of scientific studies. Key observations include:

- **Rising temperatures:** The global average surface temperature has increased by approximately **1.1°C** since the pre-industrial period (∼1850). The last decade (2011–2020) was the warmest on record.
- **Atmospheric CO_2:** Pre-industrial atmospheric CO_2 concentration was ∼280 ppm. By 2024, it reached **424 ppm** — higher than at any point in the past 3 million years.
- **Sea level rise:** Global mean sea level has risen by approximately 20 cm since 1900, with the rate accelerating to over 4 mm/year currently.
- **Arctic sea ice decline:** Arctic summer sea ice extent has declined by ∼40% since

satellite records began in 1979.

- **Glacier and ice sheet melt:** The Greenland and Antarctic ice sheets are losing mass at accelerating rates, contributing to sea level rise. Mountain glaciers worldwide are retreating.
- **Ocean warming and acidification:** More than 90% of the excess heat trapped by greenhouse gases has been absorbed by the oceans. Ocean pH has dropped from ∼8.2 to ∼8.1 (a 26% increase in acidity on the logarithmic pH scale).

4.2 The Greenhouse Effect

The greenhouse effect is the natural process by which certain atmospheric gases trap heat near the Earth's surface, making the planet warm enough to support life. Without any greenhouse effect, Earth's average temperature would be approximately −18°C instead of the current +15°C.

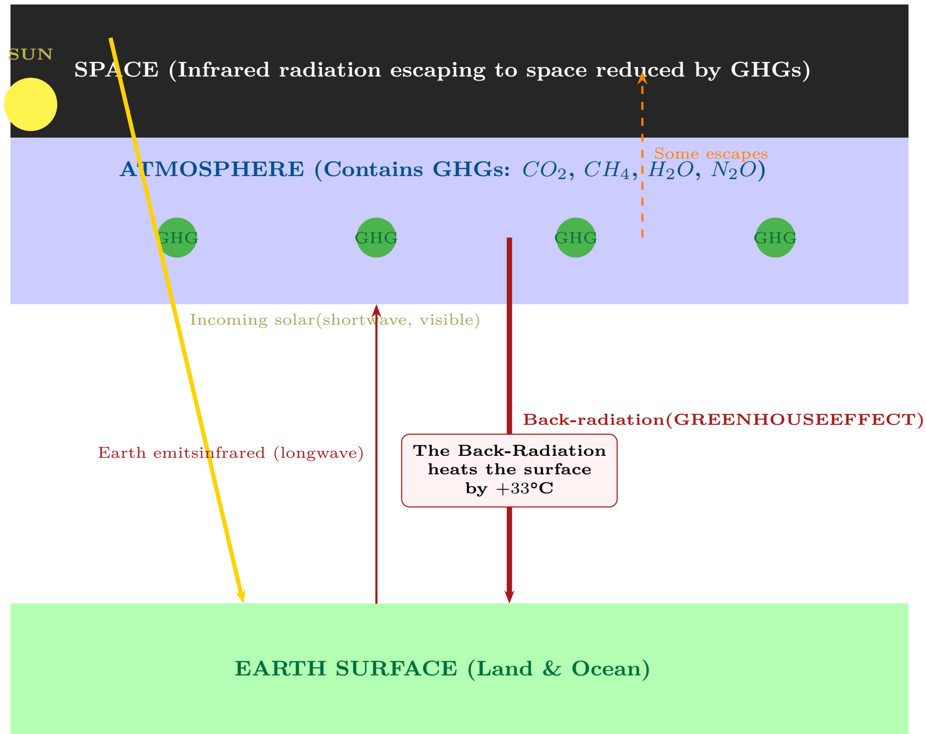


Figure 4.1: The Greenhouse Effect — Incoming solar shortwave radiation passes through the atmosphere; Earth emits infrared; GHG molecules absorb and re-emit this back toward Earth, warming the surface

4.2.1 Natural vs. Enhanced Greenhouse Effect

Aspect	**Natural Greenhouse Effect**	**Enhanced (Anthropogenic) Greenhouse Effect**
Cause	Natural concentrations of GHGs (water vapour, CO_2, CH_4, N_2O) in the atmosphere.	Human addition of extra GHGs through fossil fuel combustion, deforestation, agriculture, industrial processes.
Effect	Keeps Earth's average temperature at a life-supporting +15°C.	Increases the amount of heat trapped, raising temperatures beyond natural variability.
Consequence	Essential for life as we know it.	Global warming, climate change, extreme weather, sea level rise.

4.2.2 Mechanism of the Greenhouse Effect

1. **Solar (shortwave) radiation** ($\lambda \approx 0.2$–$4\ \mu$m) from the Sun passes through the atmosphere largely unimpeded and is absorbed by the Earth's land and ocean surfaces.
2. The warmed surface emits **thermal (longwave) infrared radiation** ($\lambda \approx 5$–$50\ \mu$m) upward towards space.
3. Greenhouse gas molecules in the atmosphere absorb this longwave radiation — they resonate at infrared frequencies corresponding to their molecular vibration modes (bending and stretching of chemical bonds).
4. The energised GHG molecules re-emit radiation in all directions — including back downward towards Earth's surface.
5. This *back-radiation* provides additional heating to the surface and lower atmosphere — the greenhouse effect.

PYQ: Explain the Greenhouse Effect. List major greenhouse gases and their sources. (Su'22, N-W'25, W'22, W'23)

The Greenhouse Effect: The process by which atmospheric gases (greenhouse gases) trap infrared radiation emitted by Earth's warm surface, preventing it from escaping directly to space, and re-radiating it back to Earth — warming the surface.

Process:

1. Solar shortwave radiation passes through the atmosphere and warms the Earth.

2. The warmed Earth radiates longwave infrared radiation upward.
3. Greenhouse gas molecules absorb this infrared radiation (they cannot pass through the atmosphere freely).
4. GHG molecules re-emit radiation in all directions, including back toward Earth.
5. This "back radiation" supplements the direct solar heating, maintaining a higher surface temperature.

Major Greenhouse Gases and Their Sources:

GHG	**Sources**	**GWP (100-yr)**
CO_2	Fossil fuel combustion, deforestation, cement production.	1 (reference)
CH_4	Cattle/livestock, rice paddies, landfills, natural gas leaks, coal mines.	84
N_2O	Agricultural fertilisers, livestock waste, industrial processes.	273
HFCs, PFCs, SF_6	Refrigerants, air-conditioners, aluminium production, electrical equipment.	1,000–24,000

GWP = Global Warming Potential relative to CO_2 over 100 years.

4.3 Ozone Layer Depletion

The Ozone Layer

The **ozone layer** is a region of the stratosphere (approximately 15–35 km altitude) where ozone (O_3) molecules are present at elevated concentrations, reaching ∼10 parts per million (compared to a background of ∼0.1 ppm in the troposphere). The ozone layer absorbs 97–99% of the Sun's harmful ultraviolet B (UV-B, 280–315 nm) radiation — protecting life on Earth from its mutagenic and carcinogenic effects.

Figure 4.2: Atmospheric Layers and the Ozone Layer — The ozone layer in the stratosphere at 15–35 km is the critical UV-B shield for life on Earth

4.3.1 Mechanism of Ozone Depletion

Chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances (ODS) accumulate in the stratosphere. Under intense UV radiation:

1. UV-C radiation cleaves a chlorine atom from the CFC molecule:

$$CFCl_3 + h\nu \rightarrow CFCl_2^{\cdot} + Cl^{\cdot}$$

2. The highly reactive chlorine radical destroys an ozone molecule:

$$Cl^{\cdot} + O_3 \rightarrow ClO^{\cdot} + O_2$$

3. The chlorine monoxide radical ($ClO^{\cdot}$) reacts with a free oxygen atom to regenerate the chlorine radical:

$$ClO^{\cdot} + O^{\cdot} \rightarrow Cl^{\cdot} + O_2$$

4. The regenerated chlorine radical (Step 4 → Step 2) repeats the cycle. A single chlorine atom can destroy up to **100,000 ozone molecules** before being permanently incorporated into a stable molecule.

Effects of Ozone Depletion

- **Increased UV-B at Earth's surface:** A 1% decrease in stratospheric ozone increases UV-B by ~2%.
- **Human health:** Increased risk of skin cancer (basal cell, squamous cell, and melanoma), cataracts, and suppression of the immune system.
- **Marine ecosystems:** UV-B damages phytoplankton, the base of marine food chains; disrupts early life stages of fish, shrimp, and crab.

- **Agriculture:** Reduces yields of key crops (wheat, rice, soybeans) and damages forest seedlings.
- **Materials:** UV-B degrades plastics, rubber, and wood, reducing product lifespans.

4.3.2 The Montreal Protocol

The **Montreal Protocol on Substances that Deplete the Ozone Layer** (1987) is widely considered the most successful international environmental treaty in history. It phased out the production and consumption of over 100 ODS (CFCs, HCFCs, halons, methyl bromide). As a result, stratospheric chlorine concentrations have been declining since the mid-1990s, and the ozone layer is slowly recovering.

PYQ: Explain ozone layer depletion and its effects on the environment. (W'22, Su'25, W'23)

Ozone Layer: A region of the stratosphere (15–35 km altitude) containing ozone (O_3) that absorbs ~99% of the Sun's harmful UV-B radiation.
Depletion Mechanism: Chlorofluorocarbons (CFCs) from refrigerants, aerosols, and foam blowing drift into the stratosphere. UV radiation cleaves chlorine atoms from CFCs:

$$CFCl_3 + h\nu \rightarrow CFCl_2^{\cdot} + Cl^{\cdot}$$

Each chlorine atom destroys ozone in a catalytic chain reaction:

$$Cl^{\cdot} + O_3 \rightarrow ClO^{\cdot} + O_2 \quad ; \quad ClO^{\cdot} + O^{\cdot} \rightarrow Cl^{\cdot} + O_2$$

A single Cl atom can destroy 100,000 ozone molecules before deactivation.
Effects:

- **Skin cancer and cataracts:** Increased UV-B at the surface raises skin cancer incidence by ~2% for every 1% ozone loss.
- **Marine ecosystem damage:** UV-B reduces phytoplankton productivity, undermining ocean food chains.
- **Agricultural losses:** Reduced yields of wheat, rice, soybean, and other crops.
- **Immune suppression:** UV-B weakens the immune response, increasing susceptibility to infectious diseases.

Solution: The Montreal Protocol (1987) successfully phased out ODS production globally. The ozone hole over Antarctica has been slowly recovering and is expected to fully heal by ~2065.

Gas	Pre-industrial Conc.	Current Conc. (2024)	Key Sources
CO_2	280 ppm	∼424 ppm	Fossil fuels, deforestation, cement
CH_4	722 ppb	∼1923 ppb	Livestock, rice paddies, landfills, natural gas
N_2O	270 ppb	∼336 ppb	Agriculture (fertilisers), wastewater
HFCs	0	Rising	Refrigerants (replaced CFCs)

Table 4.1: Key Greenhouse Gases — Pre-industrial vs. Current Concentrations and Sources

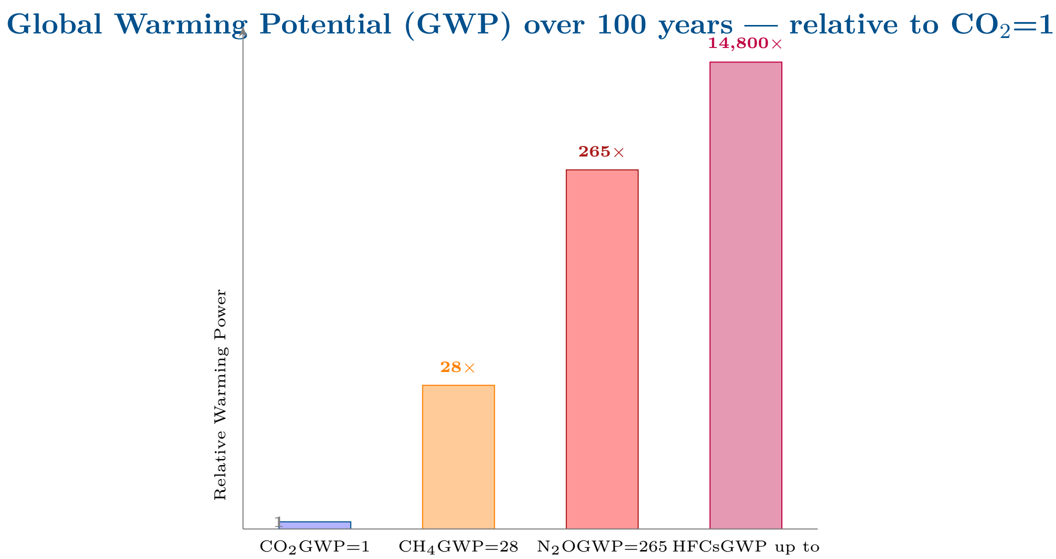


Figure 4.3: Global Warming Potential (GWP) of Major Greenhouse Gases over 100 years — CH_4 is 28×, N_2O is 265×, and some HFCs are up to 14,800× more potent than CO_2

Warming	Sea level rise	Arctic ice loss	Projected impacts by 2100
+1.5°C	+26–77 cm	40–60% reduction	Coral reef bleaching; limited food security risks
+2.0°C	+30–93 cm	>60% reduction	Far greater risks; more extreme events
+3.0°C	>1 m possible	>90% reduction	Catastrophic; many regions uninhabitable
+4.0°C	1–2 m possible	Near ice-free summer	Civilisation-scale disruptions

Table 4.2: IPCC Warming Scenarios — Projected Impacts at Different Global Temperature Rise Levels

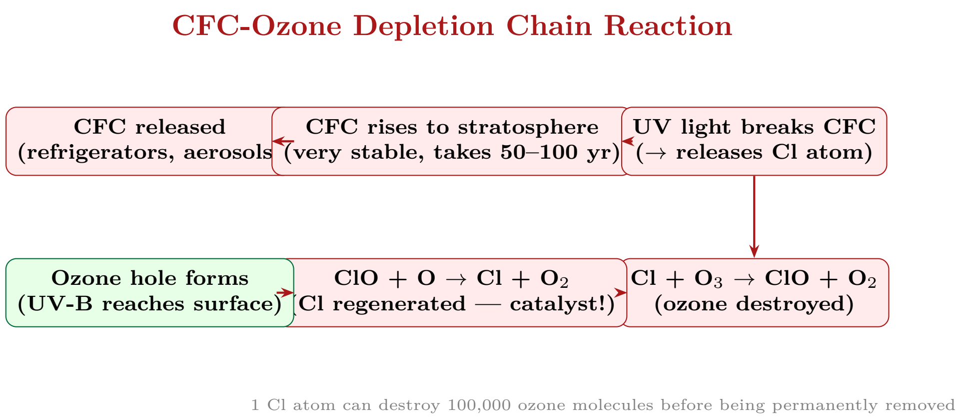


Figure 4.4: CFC-Ozone Depletion Catalytic Chain — One chlorine atom from CFCs acts as a catalyst, destroying up to 100,000 ozone molecules in a chain reaction

Agreement	Year	Key Provision
Vienna Convention	1985	Framework for ozone layer protection; international cooperation
Montreal Protocol	1987	Phase-out of CFCs, HCFCs, Halons; most successful environmental treaty
Kigali Amendment	2016	Extended Montreal Protocol to phase-down HFCs (potent greenhouse gases)
Kyoto Protocol	1997	First binding GHG reduction targets for developed countries
Paris Agreement	2015	Limit warming to 1.5–2°C; nationally determined contributions (NDCs)

Table 4.3: Key International Environmental Agreements on Ozone and Climate

UV Type	Wavelength	Effect / Blocked By
UV-A (320–400 nm)	Longest, least harmful	Not absorbed by ozone; causes skin aging
UV-B (280–315 nm)	Medium; most damaging of reaching UV	97–99% absorbed by ozone layer; causes skin cancer, cataracts, immune suppression
UV-C (100–280 nm)	Shortest, most energetic	Completely absorbed by atmosphere (O_2 and O_3); does not reach surface

Table 4.4: Types of Ultraviolet Radiation — Wavelengths, Effects, and Ozone Absorption

4.4 Impacts of Climate Change

Climate change is not a future threat — it is a present reality. Its impacts are already being felt across every region of the world and every sector of the economy. Understanding these impacts is critical for engineers and planners who must design infrastructure and systems for a changing world.

Impact Area	Key Changes	Example/Evidence
Sea Level Rise	+20 cm since 1900; +4 mm/yr currently	Maldives, Mumbai coastal flooding
Extreme Weather	Heavier rain, longer droughts, stronger cyclones	India heatwaves reaching 48–50°C
Biodiversity	Coral bleaching, habitat loss, phenological mismatch	50% of Great Barrier Reef bleached
Food Security	Lower yields of wheat, rice, maize in tropics	500 million at risk by 2050
Water Scarcity	Glacial melt reduces freshwater to river-dependent billions	Indus, Ganges river flow reducing
Human Health	Vector-borne diseases spread to new regions	Malaria, dengue expanding to higher latitudes

Table 4.5: Key Impacts of Climate Change Across Multiple Sectors

4.4.1 Rising Sea Levels

Sea level rise has two primary causes:

1. **Thermal expansion (Steric rise):** As ocean water warms, it expands. This accounts for approximately 42% of observed sea level rise.

2. **Melting of land ice:** Ice sheets (Greenland, Antarctica) and mountain glaciers melt, adding water to the ocean. This accounts for the remaining 58%.

Projected impacts by 2100 (under high emission scenario):

- Sea levels could rise by 0.6–1.0 metres (or more, if ice sheet instability triggers faster melting).
- Low-lying coastal cities (Mumbai, Dhaka, Jakarta, Miami, Shanghai) face chronic flooding.
- Small island nations (Maldives, Marshall Islands, Tuvalu) risk complete submergence.
- Saltwater intrusion into coastal freshwater aquifers threatens drinking water supplies and agriculture.

- Increased coastal erosion destroys beaches and natural protective barriers (mangroves, barrier islands).

4.4.2 Extreme Weather Events

A warmer atmosphere holds more water vapour (Clausius-Clapeyron relation: $\sim$7% more per °C of warming), intensifying the water cycle and leading to:

- **Intensified precipitation:** When storms do occur, they produce heavier rainfall and flooding. India is already seeing more intense monsoon cloudburst events causing flash floods.
- **Droughts:** In regions where precipitation decreases or evaporation increases, prolonged droughts become more common. The Mediterranean, southwestern USA, and parts of Africa and Australia are already experiencing this.
- **Heatwaves:** More frequent, longer, and more intense heatwaves kill thousands of people annually. India's heatwaves (reaching 48–50°C) have become more common.
- **Tropical cyclones:** While the total number may not increase, the most intense storms (Category 4 and 5) are becoming more frequent, with higher wind speeds and storm surge.
- **Wildfires:** Hotter, drier conditions increase wildfire frequency and severity (California, Australia, Siberia).

4.4.3 Impact on Biodiversity and Ecosystems

Ecosystem	Climate Impact
Coral Reefs	Ocean warming (>1°C above average) causes coral bleaching (expulsion of symbiotic algae); ocean acidification weakens coral skeletons. 50% of the Great Barrier Reef has bleached since 2016.
Arctic / Polar	Sea ice loss destroys habitat for polar bears, seals, walruses. Permafrost thaw releases stored CH_4 (a feedback loop).
Forests	Shifting climate zones push species to higher latitudes and altitudes; species too slow to migrate face extinction. Bark beetle outbreaks (favoured by warmer winters) kill millions of acres of boreal forest.
Fresh Waters	Warmer water holds less oxygen; glacial-fed rivers see reduced summer flows as glaciers shrink; lake stratification and eutrophication worsen.
Wetlands & Mangroves	Sea level rise and increased storm surge erode coastal wetlands and mangrove forests, which are critical carbon sinks and storm barriers.

Table 4.6: Climate Change Impacts on Major Ecosystems

PYQ: Discuss the impacts of climate change on biodiversity, sea levels, and weather. (N-W'25, W'21)

Impacts of Climate Change:
1. Sea Level Rise: Global average sea levels have already risen ∼20 cm since 1900 due to (a) thermal expansion of warming seawater and (b) melting glaciers and ice sheets. Low-lying coastal cities and small island nations face chronic flooding and saltwater intrusion. By 2100, sea levels may rise a further 0.6–1 m under business-as-usual emissions.
2. Extreme Weather: A warmer atmosphere holds more water vapour, intensifying precipitation events (floods, intense monsoons) whilst simultaneously worsening droughts in arid regions. Tropical cyclones are becoming more intense. Heatwaves are more frequent, longer, and deadlier.
3. Impact on Biodiversity:

- **Coral bleaching:** Ocean warming of just 1–2°C above normal causes corals to expel their symbiotic zooxanthellae algae and bleach white; prolonged bleaching leads to coral death.
- **Ocean acidification:** The ocean absorbs ∼30% of human CO_2 emissions, lowering pH (from 8.2 to 8.1 since pre-industrial times). This weakens the shells of molluscs, echinoderms, and corals.
- **Habitat loss:** Polar species (polar bear, penguin) lose sea-ice habitat. Moun-

tain species are pushed further upslope until there is no further habitat. Many species cannot migrate fast enough and face local extinction.

- **Phenological mismatch:** Warming shifts the timing of seasonal events (plant flowering, insect emergence, bird migration) at different rates, disrupting the synchronised chains of ecological relationships (e.g., chicks hatching before peak caterpillar abundance).

4.4.4 Impact on Human Health and Society

- **Food security:** Higher temperatures, shifting rainfall, and more frequent droughts reduce yields of major staples (wheat, maize, rice). An estimated 500 million people in tropical regions could face food insecurity by 2050 under high-emission scenarios.
- **Water scarcity:** Changes in precipitation and glacial melt alter freshwater availability. Billions of people depend on glacier-fed rivers (Indus, Ganges, Yangtze) for irrigation and drinking water.
- **Vector-borne disease:** Warmer temperatures expand the geographic range of disease vectors — malaria mosquitoes and dengue-carrying *Aedes aegypti* are expanding into higher latitudes and altitudes.
- **Climate migration:** Sea level rise, desertification, and crop failure may displace hundreds of millions of people, creating massive waves of climate refugees by mid-century.
- **Economic costs:** The Swiss Re Institute (2021) estimated that unchecked climate change could reduce global GDP by up to 18% by 2050.

PYQ: What is climate change? What are its causes? Write reasons for climate change. (W'23, Su'25, N-Su'25)

Climate Change: Long-term shifts in the statistical distribution of weather patterns (temperature, precipitation, wind, sea levels, and storm intensity) over periods ranging from decades to millions of years. In modern usage, it specifically refers to the rapid, human-driven changes occurring since the Industrial Revolution.

Natural Causes of Climate Change:

1. **Milankovitch cycles:** Slow, predictable changes in Earth's orbital shape (eccentricity), axial tilt (obliquity), and wobble (precession) over tens of thousands of years alter the seasonal distribution of solar energy received by Earth — driving ice ages and warm interglacial periods.
2. **Solar activity:** Variations in the Sun's energy output (sunspot cycles, solar flares) cause small fluctuations in the energy reaching Earth. These have been measured by satellite and ruled out as the primary driver of the current warming trend.
3. **Volcanic eruptions:** Major eruptions inject large quantities of sulfur dioxide

(SO_2) into the stratosphere, where it forms reflective aerosols that temporarily cool the climate (e.g., Mount Pinatubo 1991 cooled global temperatures by ∼0.5°C for 1–2 years). Long-term, massive volcanic events (flood basalts) have triggered mass extinctions.

4. **Continental drift:** Over millions of years, plate tectonics rearrange the continents, altering ocean circulation, atmospheric circulation patterns, and the distribution of ice and vegetation.

Human (Anthropogenic) Causes:

1. **Fossil fuel combustion:** Burning coal, oil, and natural gas for electricity, heat, and transport is the largest source of man-made CO_2 — currently ∼36 billion tonnes per year.
2. **Deforestation:** Clearing forests for agriculture and urban expansion releases stored carbon and reduces the biosphere's capacity to absorb CO_2. Deforestation accounts for ∼10% of global GHG emissions.
3. **Agriculture:** Livestock (especially cattle) produce significant quantities of CH_4 through enteric fermentation; rice paddies produce CH_4 under waterlogged conditions; synthetic nitrogen fertilisers release N_2O.
4. **Cement production:** Manufacturing cement requires heating limestone ($CaCO_3$) to release CO_2: $CaCO_3 \rightarrow CaO + CO_2$. The cement industry accounts for ∼8% of global CO_2 emissions.
5. **Industrial processes:** Steelmaking, chemical production, and refrigerant manufacture release CO_2, CH_4, N_2O, and fluorinated gases.
6. **Urbanisation and land use change:** Replacing natural land with roads and buildings reduces carbon absorption and increases surface albedo changes.

PYQ: Write a short note on Global Warming. Explain greenhouse effect and climate change management. (W'22, W'23, Su'22)

Global Warming: Global warming refers to the observed, ongoing rise in Earth's average surface temperature primarily caused by the increasing concentration of greenhouse gases in the atmosphere as a result of human activities. Key facts:

- Earth's average surface temperature has risen by approximately 1.1°C since pre-industrial times (1850–1900).
- The rate of warming has accelerated in recent decades; the period 2011–2020 was the warmest decade on record.
- If current emission trajectories continue, warming could reach 2.5–4°C above pre-industrial levels by 2100 with catastrophic consequences.

Greenhouse Effect and Climate Change Management: The greenhouse effect (natural atmospheric warming) becomes a problem when human emissions amplify it. Managing climate change requires simultaneous action across three fronts:

1. **Emission Reduction (Mitigation):**

- Accelerate the transition from fossil fuels to renewable energy (solar, wind, hydropower).
- Electrify transport and heating; phase out internal combustion engines.
- Improve energy efficiency across all sectors.
- Halt deforestation; scale afforestation and forest restoration.
- Reduce industrial process emissions (cement, steel) through technology innovation and CCS.

2. Carbon Removal (Negative Emissions):

- Natural solutions: afforestation, soil carbon sequestration, restoration of wetlands and mangroves.
- Technological solutions: Direct Air Capture (DAC) machines that chemically strip CO_2 from ambient air; Bioenergy with CCS (BECCS).

3. Adaptation:

- Build climate-resilient infrastructure (flood defences, drought-resistant crops, early warning systems).
- Reform agricultural systems to maintain food security under changed conditions.
- Develop policy frameworks for climate migration and protect vulnerable communities.
- Urban heat island mitigation through urban greening, cool roofs, and reflective pavements.

4.5 Feedback Mechanisms and Tipping Points

Climate change is a complex, non-linear system with feedback loops that can either amplify or dampen warming. Engineers and planners must understand that the system does not respond proportionally to human actions.

4.5.1 Positive (Amplifying) Feedback Loops

- **Ice-albedo feedback:** As white ice and snow melt (high albedo = highly reflective), they expose dark ocean water or soil (low albedo = absorbs more heat), which absorbs more solar radiation, accelerating further warming and melting.

- **Water vapour feedback:** As temperature rises, more water evaporates from ocean surfaces. Water vapour is itself a potent greenhouse gas, so the increased atmospheric water vapour causes further warming — amplifying the initial temperature rise by a factor of ∼2–3.

- **Permafrost thaw:** Arctic permafrost stores enormous quantities of organic carbon (estimated ∼1,700 Gt C — approximately twice the current atmospheric carbon content). As the Arctic warms (at 2–4 times the global average rate), thawing permafrost releases CO_2 and CH_4, further accelerating warming.

- **Forest dieback:** As temperatures rise and droughts intensify, forests (especially the Amazon) may transition from carbon sinks to carbon sources through widespread tree death, releasing stored carbon.

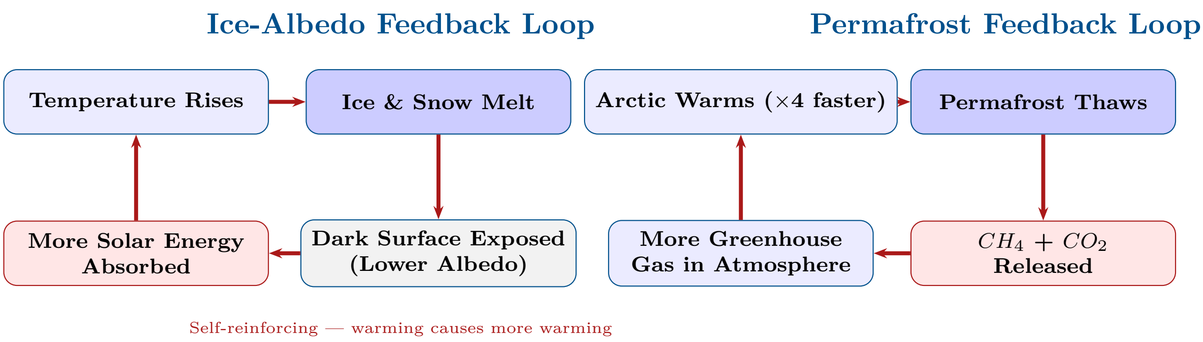


Figure 4.5: Positive (Amplifying) Climate Feedback Loops — Ice-albedo feedback (left) and Permafrost methane feedback (right) accelerate warming beyond the initial trigger

4.5.2 Climate Tipping Points

Tipping points are thresholds in the climate system beyond which change becomes self-sustaining and irreversible — even if emissions are subsequently reduced. Scientists have identified several potential tipping points, the most concerning of which include:

Tipping Element	Critical Threshold	Consequence
West Antarctic Ice Sheet Collapse	∼1.5°C	Gradual sea level rise of up to 3.3 m over centuries.
Greenland Ice Sheet Melt	∼1–3°C	Sea level rise of up to 7 m over millennia.
Amazon Dieback	∼3–4°C	Mass forest death; release of massive stored carbon; drastic changes in South American rainfall.
Arctic Sea Ice Loss (summer)	∼1.5–2°C	Near-complete summer sea ice loss; accelerated Arctic warming through ice-albedo feedback.
Permafrost Collapse	∼1.5–2°C	Massive release of CH_4 and CO_2, creating a self-sustaining warming feedback.

Table 4.7: Key Climate Tipping Points and Their Consequences

Understanding tipping points underscores the urgency of limiting warming: the probability of triggering multiple, cascading tipping points increases sharply above 1.5°C and even more so above 2°C — which is the scientific basis for the Paris Agreement targets.

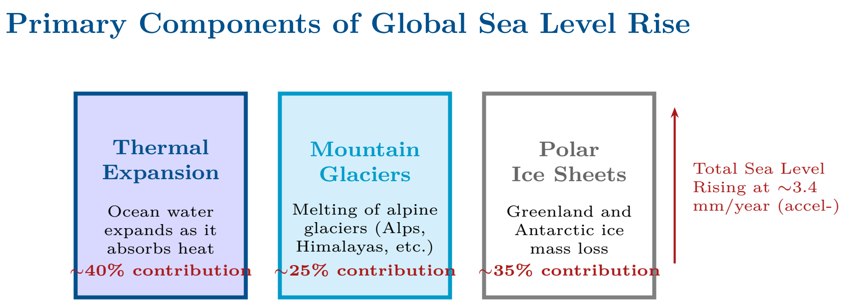


Figure 4.6: Drivers of Sea Level Rise — Thermal expansion of oceans and melting of land-based ice (glaciers and ice sheets) are the primary causes. Melting sea ice (Arctic) does NOT significantly raise sea levels.

Sector	**Direct Impact of Climate Change**	**Secondary Consequence**
Agriculture	Changing rainfall, extreme heat	Crop failure, food insecurity, malnutrition
Health	Expanded range of disease vectors	Increase in malaria, dengue, heatstroke
Economy	Infrastructure damage from storms	Reduced GDP, high insurance costs
Biodiversity	Habitat loss, temperature shifts	Species extinction, coral bleaching
Coastal Cities	Sea level rise, storm surges	Flooding, forced migration (climate refugees)
Water Resources	Glacial retreat, droughts	Water scarcity, inter-regional conflicts

Table 4.8: Cascading Impacts of Global Climate Change Across Key Sectors

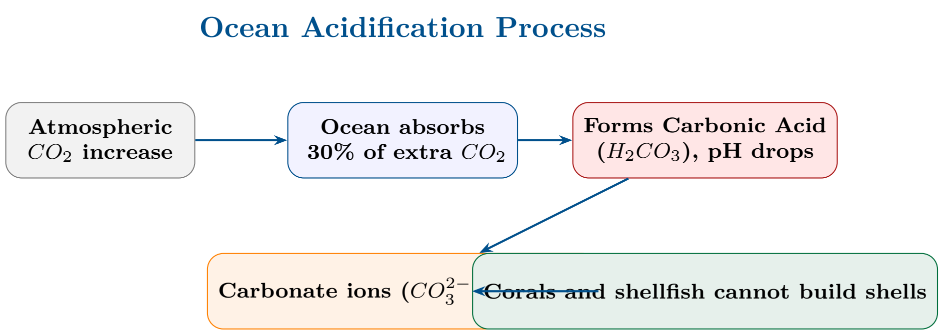


Figure 4.7: Ocean Acidification — "The Other CO_2 Problem": High atmospheric CO_2 dissolves into the ocean, reducing pH and depleting carbonate needed by marine calcifiers

Phenomenon	**El Niño Mode**	**La Niña Mode**
Pacific Ocean Surface	Unusual warming in central/eastern Pacific	Unusual cooling in central/eastern Pacific
Trade Winds	Weaken or reverse	Strengthen
South American Coast	Increased rain, flooding; suppressed fishing	Drier conditions; strong upwelling (good fishing)
Indian Monsoon	Often associated with deficit rain (drought)	Often associated with good or excess rain
Global Temperature	Temporarily boosts global average temp	Temporarily cools global average temp

Table 4.9: El Niño vs. La Niña (ENSO Cycle) — Climate impacts and characteristics

The Anthropogenic Carbon Cycle Perturbation

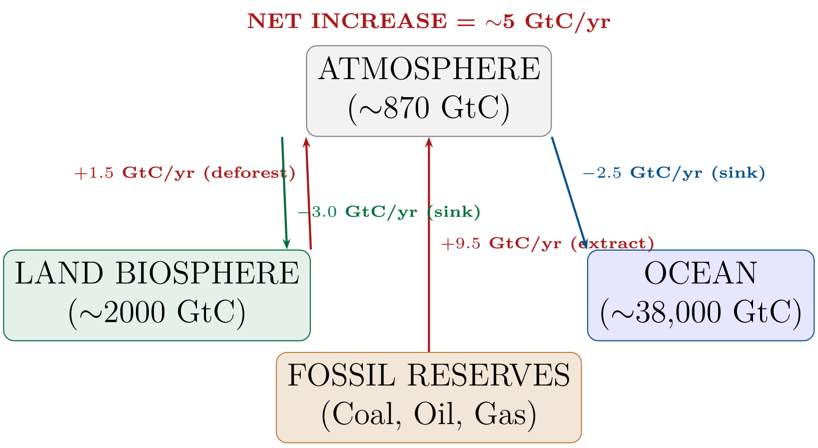


Figure 4.8: Human Perturbation to the Carbon Cycle — Fossil fuel burning and deforestation add ∼11 GtC/yr; land and oceans absorb ∼5.5 GtC/yr; the remaining ∼5 GtC/yr accumulates in the atmosphere

Region	**Vulnerability**	**Expected Climate Change Impact**
Small Island States (e.g. Maldives)	Very High	Existential threat from sea-level rise; loss of freshwater lenses.
Sub-Saharan Africa	High	Severe drought, desertification, food and water insecurity, conflict.
Indian Subcontinent	High	Monsoon variability, Himalayan glacier melt altering river flows, severe heatwaves.
Arctic Region	High	Loss of permafrost and sea ice; dramatic ecosystem changes; infrastructure damage.
Western Europe / North America	Moderate	Increased heatwaves, wildfires, extreme storms; economic damage.

Table 4.10: Regional Vulnerability to Climate Change Summarised

4.6 Climate Change Mitigation Strategies

Mitigation vs. Adaptation

Mitigation refers to actions that reduce the sources of greenhouse gases or enhance sinks (forests, oceans) to slow or limit climate change. Examples: deploying renewable energy, increasing energy efficiency, afforestation.
Adaptation refers to adjusting systems, behaviours, and infrastructure to reduce vulnerability to existing or expected climate change impacts. Examples: building sea walls, developing drought-resistant crops, creating early warning systems for extreme weather.
Both are essential — mitigation limits the long-term magnitude of climate change; adaptation manages its unavoidable impacts.

Feature	**Mitigation**	**Adaptation**
Goal	Reduce GHG emissions / enhance sinks	Reduce vulnerability to climate impacts
Timescale	Long-term (prevents future harm)	Near-term (deals with present impacts)
Examples	Solar farms, EVs, reforestation	Seawalls, drought-resistant crops, early warning systems
Who does it	All countries must reduce emissions	Especially critical for vulnerable developing nations
Limits	Cannot prevent all climate change	Cannot prevent the cause; expensive

Table 4.11: Mitigation vs. Adaptation to Climate Change — Key Differences

4.6.1 Energy System Transformation

The transition from a fossil-fuel-based to a low-carbon energy system is the single most important climate mitigation strategy:

- **Scaling renewable energy:** Rapidly deploying solar PV, wind, geothermal, and hydropower to decarbonise electricity generation. The cost of solar PV has fallen by over 90% since 2010, making renewables the cheapest source of new electricity generation in most of the world.

- **Electrification:** Transitioning from fossil-fuelled devices to electric equivalents — electric vehicles (EVs), electric heat pumps (instead of gas boilers), electric industrial furnaces.

- **Energy efficiency:** Improving the energy efficiency of buildings (insulation, glazing, ventilation), transport (more fuel-efficient vehicles, public transport), and industry (heat recovery, process optimisation) reduces total energy demand.

- **Grid modernisation:** Building smart electricity grids with energy storage (batteries, pumped hydro) to integrate variable renewable energy.
- **Green hydrogen:** Producing hydrogen from water electrolysis using renewable energy for use in hard-to-electrify sectors (steel, shipping, aviation).

4.6.2 Land Use and Carbon Sinks

- **Stopping deforestation:** Tropical deforestation accounts for ∼10% of global CO_2 emissions. Protecting existing forests through policies like REDD+ (Reducing Emissions from Deforestation and forest Degradation) is cost-effective mitigation.
- **Afforestation and reforestation:** Planting trees on degraded or cleared land creates new carbon sinks. India has ambitious afforestation targets (1 million hectares per year).
- **Soil carbon sequestration:** Regenerative agricultural practices (cover crops, reduced tillage, compost application) increase organic carbon stored in agricultural soils.
- **Blue carbon:** Protecting and restoring mangroves, seagrasses, and salt marshes — which store carbon in their biomass and sediments at very high rates.
- **Dietary change:** Globally reducing consumption of ruminant meat (cattle, sheep) significantly reduces agricultural methane (CH_4) emissions.

4.6.3 Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS)

CCS is a set of technologies that capture carbon dioxide emissions from large point sources (power plants, cement factories, steel mills, chemical plants), compress them, transport the CO_2 to a geological storage site, and inject it deep underground where it is expected to remain permanently isolated from the atmosphere.

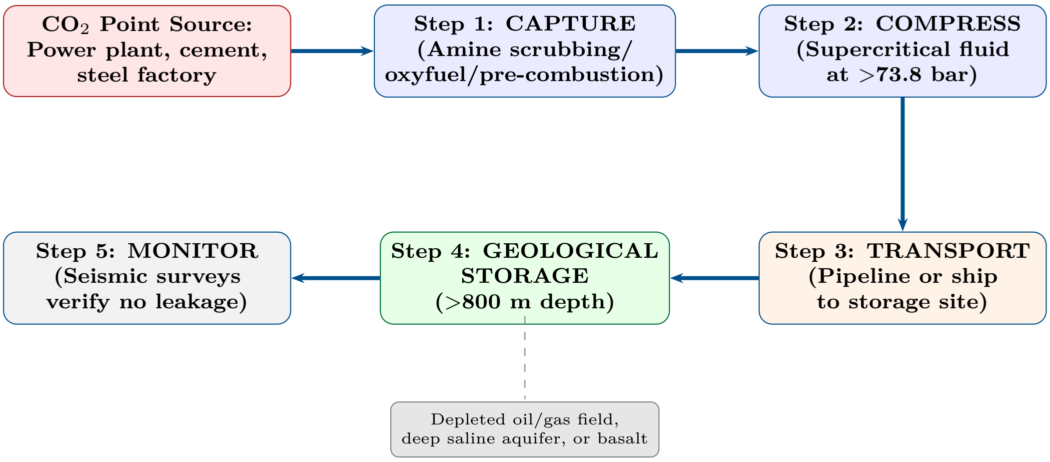


Figure 4.9: Carbon Capture and Storage (CCS) Process — five-step pathway from CO_2 capture at industrial source to permanent geological storage

CCS Process Steps

1. **Capture:** CO_2 is separated from the flue gas (exhaust gas) produced by combustion or industrial processes. Three main approaches:
   - *Post-combustion capture:* The flue gas (after burning) is passed over a liquid amine solvent that selectively absorbs CO_2. The CO_2-rich solvent is then heated, releasing pure CO_2 for compression.
   - *Pre-combustion capture:* Fossil fuel is converted to hydrogen and CO_2 before combustion (via steam methane reforming + water-gas shift reaction); CO_2 is captured before the hydrogen is burned.
   - *Oxyfuel combustion:* Fuel is burned in pure oxygen instead of air, producing a flue gas of concentrated CO_2 and water vapour, easily separated by condensation.
2. **Compression and Transport:** Captured CO_2 is compressed to a supercritical fluid (dense, liquid-like state) at pressures above 73.8 bar. It is transported via pipelines or ships to the storage site.
3. **Geological Storage:** CO_2 is injected via wells into porous rock formations deep underground (>800 m depth) such as:
   - Depleted oil and gas fields (well-characterised, sealed geological traps).
   - Deep saline aquifers (very large global capacity — tens of thousands of Gt CO_2).
   - Basalt formations (where CO_2 mineralises to calcium carbonate within years — very stable).
4. **Monitoring and Verification:** Injection sites are continuously monitored using seismic surveys and geochemical sampling to detect any leakage and verify permanent storage.

PYQ: Describe strategies for climate change mitigation. Explain CCS. (N-W'25, Su'22)

Climate Change Mitigation Strategies:

1. **Transition to Renewable Energy:** Replace coal power plants with solar, wind, and hydropower. Renewable energy is now the cheapest electricity source globally.
2. **Energy Efficiency:** Improve efficiency of buildings (insulation), vehicles (electric cars), and industry (heat recovery) to reduce total energy demand.
3. **Electrification:** Replace fossil-fuel devices with electric alternatives (EVs, heat pumps).
4. **Afforestation and Forest Protection:** Plant trees and stop deforestation to expand natural carbon sinks.
5. **Sustainable Agriculture:** Reduce ruminant livestock numbers, adopt sustainable farming practices, reduce food waste to lower agricultural methane and nitrous oxide emissions.
6. **Carbon Capture and Storage (CCS):** Capture CO_2 from industrial point sources and inject it underground for permanent storage.
7. **Carbon Pricing:** Carbon taxes or cap-and-trade systems create economic incentives to reduce emissions.

Carbon Capture and Storage (CCS): CCS captures CO_2 from large industrial sources (cement, steel, coal power plants) before it enters the atmosphere, compresses it into a supercritical fluid, transports it by pipeline, and injects it deep into porous geological formations (>800 m depth) where it is expected to remain permanently stored. Types of capture: post-combustion (amine scrubbing), pre-combustion (hydrogen production), and oxyfuel combustion. CCS is considered essential for decarbonising hard-to-electrify industries (cement, steel, chemicals) that cannot easily switch to renewable energy.

4.7 International Climate Agreements

Human-caused climate change is a global problem requiring coordinated international action. Several landmark agreements have shaped the policy landscape:

Agreement	Year / COP	Key Commitments
UN Framework Convention on Climate Change (UNFCCC)	1992 (Rio)	Established the global framework for climate negotiations; recognised the "common but differentiated responsibilities" principle.
Kyoto Protocol	1997 (COP3, Kyoto)	First legally binding treaty; set emission reduction targets for 37 industrialised nations for 2008–2012. Introduced emissions trading, CDM, Joint Implementation. Excluded USA (not ratified).
Copenhagen Accord	2009 (COP15)	Non-binding; set aspirational 2°C limit. Established the Green Climate Fund (GCF) to help developing nations.
Paris Agreement	2015 (COP21, Paris)	Landmark legally binding framework; targets to limit warming to **well below 2°C, aiming for 1.5°C**; all 196 parties submit Nationally Determined Contributions (NDCs); reviews every 5 years (ratchet mechanism).
Glasgow Climate Pact	2021 (COP26)	Accelerated phase-down of coal; strengthened NDCs; ∼$100 bn/year climate finance for developing countries.

Table 4.12: Major International Climate Agreements

Climate Action: Mitigation vs. Adaptation

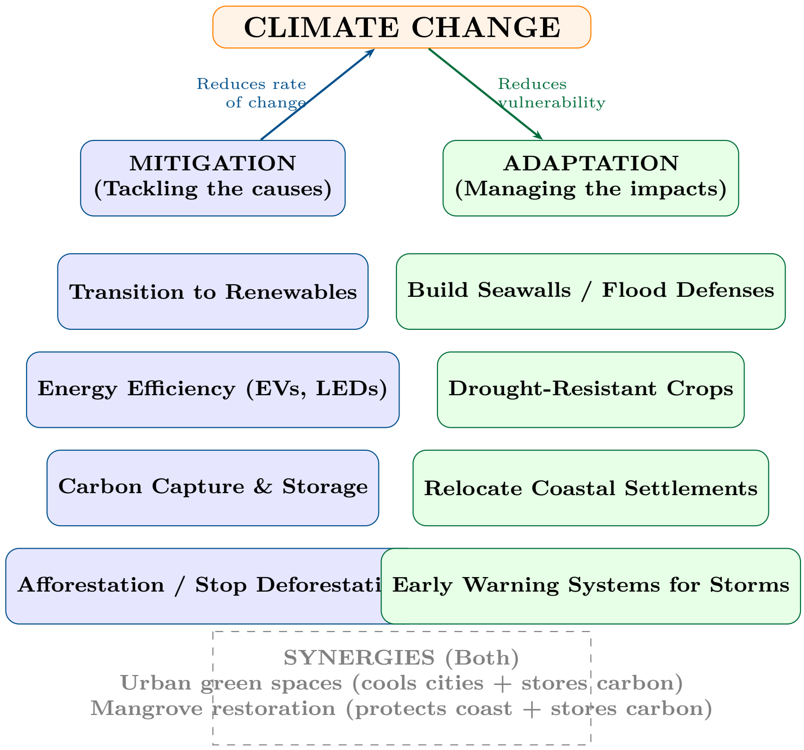


Figure 4.10: Mitigation vs. Adaptation — Mitigation addresses the root cause (emissions), while adaptation manages the unavoidable consequences; some strategies offer synergies

Aspect	Climate Mitigation	Climate Adaptation
Primary Goal	Reduce greenhouse gas emissions or enhance carbon sinks	Protect people, infrastructure, and ecosystems from climate impacts
Scale of Action	Global benefit (applies to atmospheric commons)	Local/Regional benefit (site-specific)
Timeframe	Long-term (decades to see effect)	Short-term (immediate protection)
Examples	Solar/Wind energy, Electric Vehicles, Afforestation, CCS	Sea walls, raising roads, drought-resistant crops, early warning systems
Financial Need	Massive capital investment in energy transition	Investment in resilient infrastructure

Table 4.13: Key Differences between Climate Mitigation and Adaptation

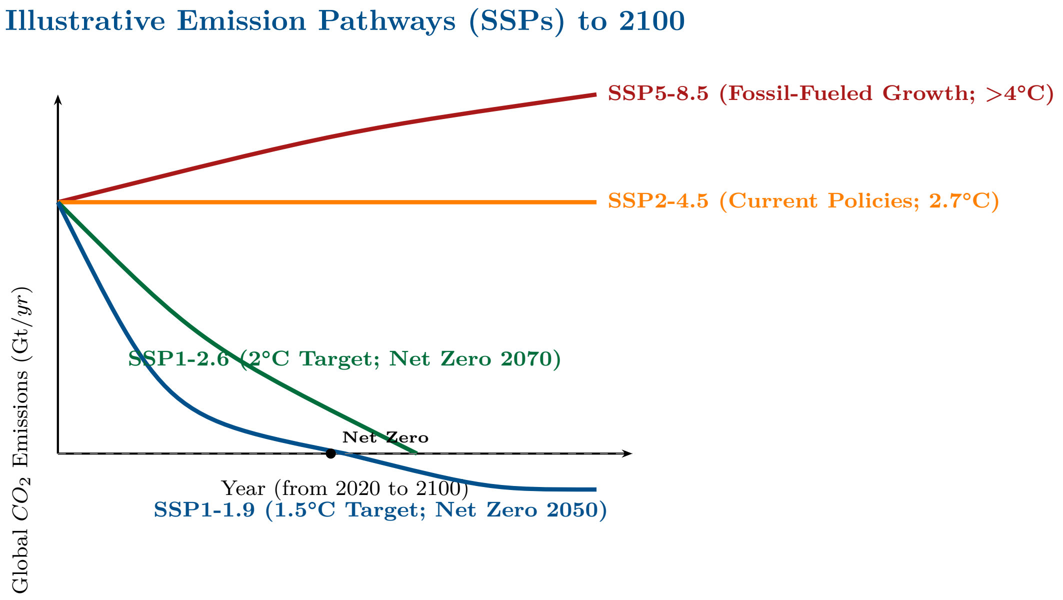


Figure 4.11: Shared Socioeconomic Pathways (SSPs) — Reaching the 1.5°C target requires global emissions to halve by 2030 and reach Net Zero around 2050

Scope	**Definition**	**Examples for a Manufacturing Company**
Scope 1	Direct emissions from owned/controlled sources	Fuel burned in company vehicles; gas burned in factory boilers
Scope 2	Indirect emissions from purchased energy	Electricity purchased from the grid to run the factory
Scope 3	All other indirect emissions in the value chain	Supply chain emissions (materials); business travel; waste disposal; customer use of product

Table 4.14: Corporate Carbon Footprinting (GHG Protocol Scope 1, 2, and 3)

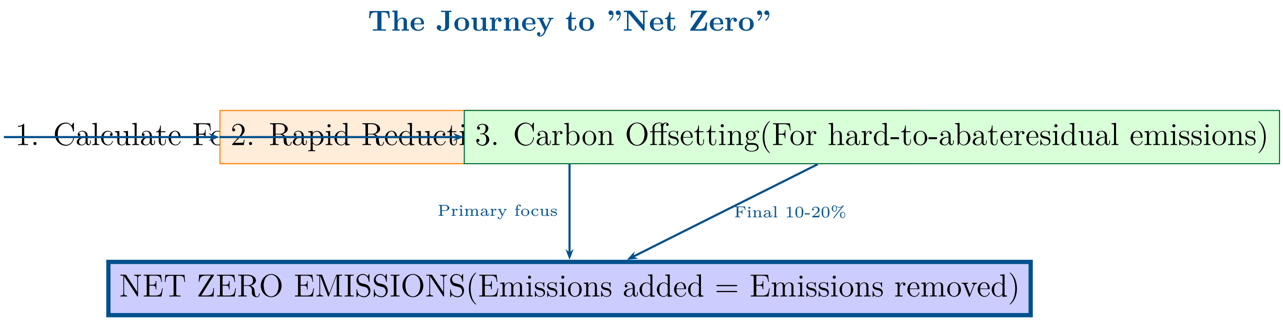


Figure 4.12: Corporate Journey to Net Zero — Prioritising rapid emission reductions before relying on carbon offsets for residual emissions

Sector	Key Mitigation Strategies
Power Generation	Phase out coal; deploy solar PV, onshore/offshore wind, hydro, nuclear; expand battery storage and smart grids.
Transport	Shift to Electric Vehicles (EVs); heavy transport (trucks/ships) shift to hydrogen fuel cells; expand public transit; active transport (cycling/walking).
Industry	Electrify industrial heating; Carbon Capture and Storage (CCS) for cement and steel; green hydrogen for chemical feedstocks; circular economy.
Buildings	Improve insulation/retrofitting; heat pumps for heating/cooling; smart energy management; passive solar design.
Agriculture & Land Use	Reduce meat consumption; precision agriculture (less fertiliser); halt deforestation; afforestation and soil carbon sequestration.

Table 4.15: Sector-by-Sector Climate Change Mitigation Strategies

Carbon Capture and Storage (CCS) Value Chain

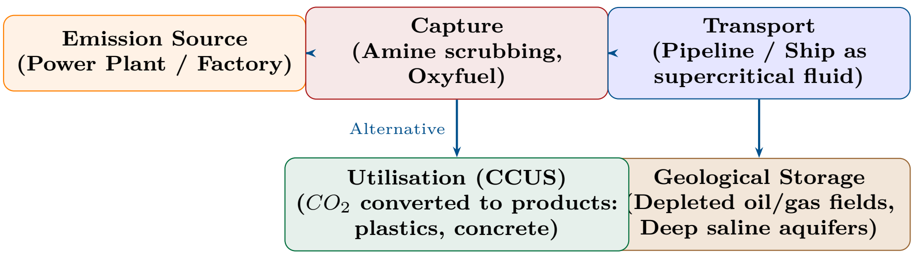


Figure 4.13: CCS vs. CCUS Value Chain — Carbon Capture and permanent Storage (CCS) vs. Carbon Capture, Utilisation, and Storage (CCUS) where CO_2 is turned into commercial products

PYQ: Write about important global agreements for mitigating climate change. (W'22, Su'22, W'23)

Key International Climate Agreements:
1. Kyoto Protocol (1997): The first legally binding international treaty setting specific greenhouse gas emission reduction targets (averaging 5.2% below 1990 levels) for 37 industrialised nations for the period 2008–2012. It introduced market mechanisms: Emissions Trading, Clean Development Mechanism (CDM, allowing rich countries to fund clean projects in developing nations), and Joint Implementation. The USA did not ratify it, undermining its effectiveness.
2. Paris Agreement (2015): The successor to Kyoto; adopted at COP21 with near-universal participation (196 parties). Key elements:

- Long-term goal: limit global warming to **well below 2°C** above pre-industrial levels, pursuing efforts to limit to **1.5°C**.
- Each country submits its own Nationally Determined Contribution (NDC) — a plan to reduce emissions and adapt to climate impacts.
- NDCs are reviewed and strengthened every five years (the "ratchet mechanism").
- Developed countries commit to mobilising at least USD 100 billion per year for developing nations for climate finance.

The Paris Agreement represents a paradigm shift from top-down (Kyoto) to bottom-up (each country sets its own NDC) governance, but critics note NDCs as submitted are insufficient to meet the 1.5°C target.

Chapter 5

Environmental Legislation and Sustainable Practices

5.1 Environmental Laws of India

India has a comprehensive body of environmental legislation, developed especially after the country's economic liberalisation in the late twentieth century. Most major Indian environmental laws were enacted between 1972 and 1986, largely in response to international environmental conferences and domestic environmental disasters.

Figure 5.1: Chronological Timeline of Major Indian Environmental Laws (1972–2002)

Act	Year	Key Purpose
Wildlife (Protection) Act	1972	Protect wild animals, birds, plants; establish protected areas
Water Pollution Act	1974	Establish CPCB/SPCB; prevention and control of water pollution
Air Pollution Act	1981	Extend pollution control to air quality; industrial emission standards
Environment (Protection) Act	1986	Umbrella law; EIA; overall environmental quality standards
Biological Diversity Act	2002	Regulate access to biological resources; protect traditional knowledge

Table 5.1: India's Major Environmental Acts — Summary

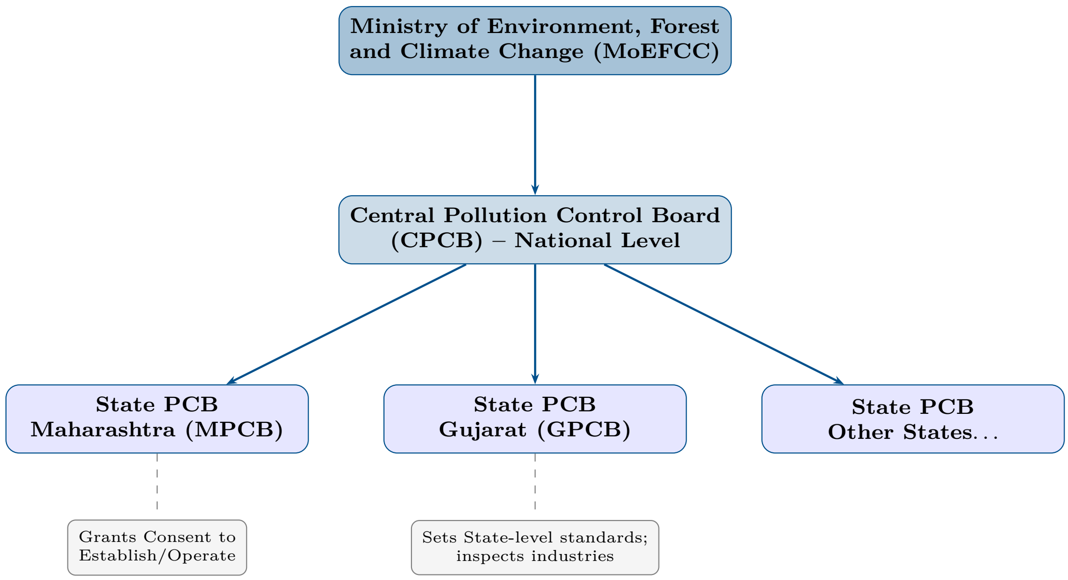


Figure 5.2: Hierarchical Structure of India's Pollution Control Bodies — MoEFCC sets policy; CPCB sets national standards; SPCBs implement at state level

5.1.1 The Wildlife (Protection) Act, 1972

Enacted in the wake of the Stockholm Conference on the Human Environment (1972), this Act provides a framework for the protection of wild animals, birds, and plants and for matters related to them.

Key provisions:

- Provides schedules (I–VI) listing protected species. Schedule I species (e.g., Bengal tiger, greater one-horned rhinoceros, Asiatic lion) receive the maximum legal protection; hunting them is a cognisable offence punishable by up to 7 years imprisonment.

- Establishment and regulation of wildlife sanctuaries, national parks, conservation reserves, and community reserves.
- Prohibition on trade in wild animal products, trophies, and derivatives.
- Regulation of zoos and recognises the Central Zoo Authority.
- Project Tiger (launched 1973) and Project Elephant are administered under its umbrella.

PYQ: Salient features of the Wildlife Protection Act 1972. (W'22)

The Wildlife (Protection) Act, 1972 is India's primary legislation for the conservation of wildlife:

- **Protected Species Schedules:** All wild animals are listed in six schedules based on protection level. Schedule I (tiger, elephant, rhino) animals are absolutely protected — any killing or trade is a grave criminal offence with severe penalties.
- **Protected Areas:** The Act empowers the government to declare National Parks (strictest protection; no human habitation or exploitation allowed) and Wildlife Sanctuaries (animals protected; limited human activity permitted).
- **Ban on Trade:** Strictly prohibits trade, possession, or transport of any wildlife product (skins, bones, ivory, feathers) without special authorisation.
- **Hunting Ban:** Hunting of any wild animal is prohibited unless declared a nuisance. Penalties include up to 7 years imprisonment and fines.
- **Regulation of Zoos:** Zoos require recognition from the Central Zoo Authority; strict standards for animal welfare and captive breeding.

5.1.2 The Water (Prevention and Control of Pollution) Act, 1974

India's first major pollution control legislation, enacted in response to rapidly worsening water quality in the nation's rivers.

Key provisions:

- Establishes the **Central Pollution Control Board (CPCB)** at the national level and **State Pollution Control Boards (SPCBs)** in each state.
- Prohibits the discharge of polluting matter (sewage, industrial effluent) into any stream, well, sewer, or on land without obtaining a "Consent to Operate" from the SPCB.
- The SPCB sets standards for the quality of water in streams and wells and monitors compliance.
- Violation in penalty: up to 6 years imprisonment and/or fine for unlawfully discharging pollutants.

5.1.3 The Air (Prevention and Control of Pollution) Act, 1981

Key provisions:

- Extends the powers of CPCB and SPCBs to cover air pollution.
- Industries in designated "air pollution control areas" must obtain consent before operating.
- The SPCB sets ambient air quality standards and emission standards for industrial units.
- Powers to inspect premises, take samples, and issue closure orders to polluting industries.

5.1.4 The Environment (Protection) Act, 1986 (EPA)

Enacted in the wake of the catastrophic **Bhopal Gas Tragedy** (2–3 December 1984, when methyl isocyanate gas leaked from the Union Carbide plant, killing over 3,000 people immediately and causing lasting health damage to over 500,000 people), the EPA is India's most comprehensive environmental legislation.

Key provisions:

- An "umbrella" act that gives the Central Government overarching power to take all measures necessary to protect and improve environmental quality.
- Empowers the government to prohibit or restrict industries, operations, or processes in sensitive areas.
- Sets environmental quality standards (ambient air, water, soil, noise).
- Environmental Impact Assessment (EIA) notifications under this Act require large development projects to obtain environmental clearance.
- Strict liability provisions — those who cause environmental damage must pay for remediation regardless of negligence.

5.1.5 The Biological Diversity Act, 2002

Enacted to fulfil India's obligations under the UN Convention on Biological Diversity (CBD, 1992).

Key provisions:

- Regulates access to biological resources (plants, animals, microorganisms) and associated traditional knowledge.
- Establishes three-tier regulatory system: National Biodiversity Authority (NBA), State Biodiversity Boards (SBBs), Biodiversity Management Committees (BMCs) at local level.

- Ensures fair and equitable sharing of benefits arising from use of biological resources with local communities.
- Gives local communities authority over their biodiversity heritage through "People's Biodiversity Registers."

PYQ: Enlist environmental Acts in India; explain any two. (W'21, W'23, Su'25)

Major Environmental Acts in India:

1. The Wildlife (Protection) Act, 1972.

2. The Water (Prevention and Control of Pollution) Act, 1974.

3. The Air (Prevention and Control of Pollution) Act, 1981.

4. The Environment (Protection) Act, 1986.

5. The Biological Diversity Act, 2002.

1. The Environment (Protection) Act, 1986: This is the most comprehensive environmental law in India, enacted after the Bhopal Gas Tragedy. It gives the Central Government power to:

- Take all necessary measures to protect and improve environmental quality.
- Issue notifications restricting industrial activity in sensitive areas.
- Set national standards for ambient air, water, and soil quality.
- Mandate Environmental Impact Assessments (EIA) for large projects.

2. The Water (Prevention and Control of Pollution) Act, 1974: India's first pollution control law. It:

- Established the Central and State Pollution Control Boards (CPCB/SPCB).
- Made it mandatory for industries to obtain "Consent to Operate" from the SPCB before discharging wastewater.
- Set water quality standards for rivers and prescribed penalties for violations.

5.1.6 Environmental Policy in India

- **National Environment Policy (NEP), 2006:** A comprehensive policy framework providing guiding principles for environmental governance across all sectors.
- **National Action Plan on Climate Change (NAPCC), 2008:** India's primary climate policy, consisting of eight national missions covering solar energy, energy efficiency, water, forests, agriculture, and sustainable urban development.
- **India's Nationally Determined Contribution (NDC):** Under the Paris Agreement, India committed to achieving 50% of cumulative electric power from non-fossil sources by 2030 and reducing emissions intensity of GDP by 45% below 2005 levels.

PYQ: Explain environmental policies of India. (W'22)

India's key environmental policies are:

1. **National Environment Policy (2006):** Provides guiding principles: integration of environmental concerns into economic decisions, precautionary principle, polluter pays principle, multi-stakeholder approach.
2. **NAPCC (2008):** Eight missions (Jawaharlal Nehru National Solar Mission, National Mission for Enhanced Energy Efficiency, National Water Mission, etc.) targeting both mitigation and adaptation.
3. **PM-KUSUM Scheme:** Kisan Urja Suraksha evam Utthan Mahabhiyan — solar pumps for farmers, reducing diesel use.
4. **FAME India:** Faster Adoption and Manufacturing of Electric Vehicles — subsidies for EVs and EV infrastructure.
5. **Swachh Bharat Mission:** National sanitation and waste management programme.
6. **Compensatory Afforestation Fund Act (2016):** Funds compensatory afforestation when forest land is diverted for development projects.

Constitutional Mandate for Environmental Protection (India)

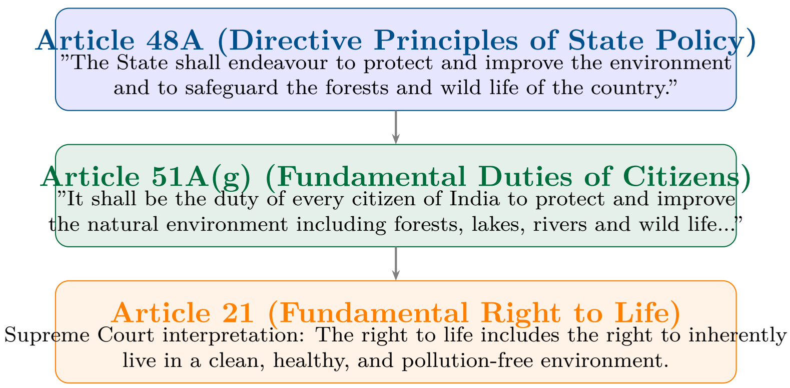


Figure 5.3: Constitutional provisions for Environmental Protection in India — Added by the 42nd Amendment Act in 1976

Act	Year	Key Focus Area
Wildlife (Protection) Act	1972	Protection of wild animals, birds, and plants; creation of protected areas.
Water Act	1974 (Amended 1988)	Prevention/control of water pollution; created CPCB and SPCBs.
Forest (Conservation) Act	1980	Prohibition of diversion of forest land for non-forestry uses without approval.
Air Act	1981 (Amended 1987)	Prevention/control of air pollution; setting ambient air standards.
Environment (Protection) Act	1986	Umbrella act giving Central Govt powers to protect entire environment.
Biological Diversity Act	2002	Conservation of biological diversity and fair sharing of genetic resources.
NGT Act	2010	Established National Green Tribunal for rapid disposal of environmental cases.

Table 5.2: Evolution of Environmental Legislation in India — Timeline of Major Acts

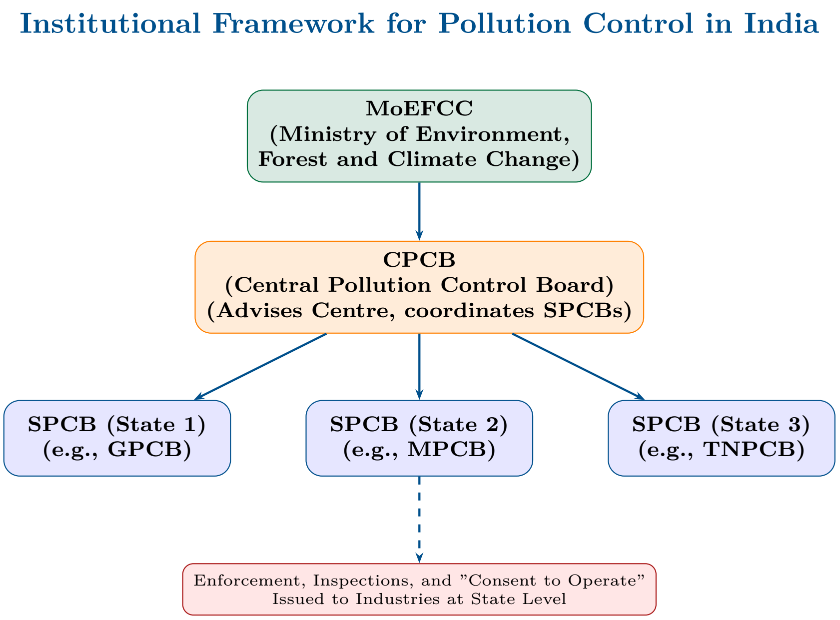


Figure 5.4: Institutional Framework — Ministry to Central Pollution Control Board (CPCB) down to State Pollution Control Boards (SPCBs) which enforce regulations locally

Schedule Level	**Protection Level**	**Animal Examples**
Schedule I	Absolute protection. Hunting/trade completely banned. Highest penalties.	Bengal Tiger, Snow Leopard, Asian Elephant, Hornbill, Whale Shark
Schedule II	High protection. Trade banned. High penalties.	Macaque, King Cobra, Flying Squirrel
Schedule III	Protected, but penalties are slightly lower.	Chital (Spotted Deer), Blue Bull, Hyena
Schedule IV	Protected, but penalties are slightly lower.	Indian Porcupine, Many bird species
Schedule V	Vermin. Can be hunted/culled with permission.	Common Crow, Fruit Bats, Mice, Rats
Schedule VI	Cultivation/trade of specified plants prohibited.	Pitcher plant, Blue Vanda, Red Vanda

Table 5.3: Schedules of the Wildlife (Protection) Act, 1972 — Classification based on threat perception and protection needed

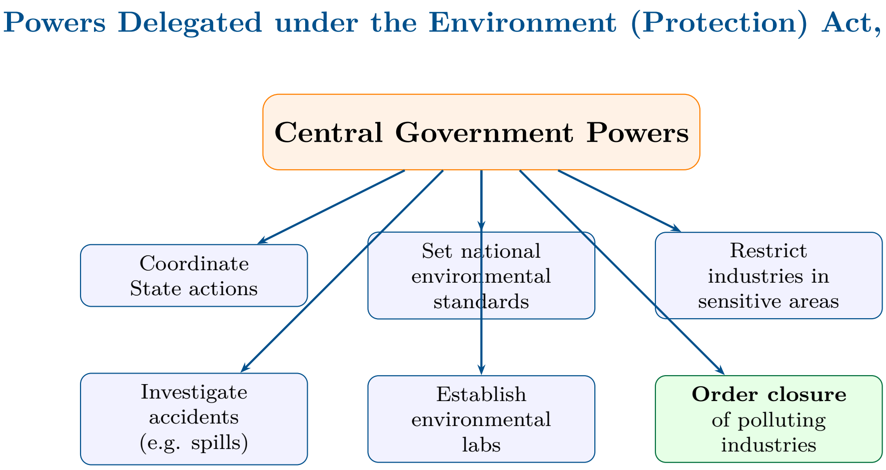


Figure 5.5: Powers of the Central Government under the Environment (Protection) Act, 1986

Mission under NAPCC	Core Objective
National Solar Mission	Become a global leader in solar energy; original target 20 GW, later revised to 100 GW.
National Mission for Enhanced Energy Efficiency	Mandate energy efficiency in energy-intensive industries (Perform, Achieve and Trade scheme).
National Mission on Sustainable Habitat	Energy efficiency in buildings, solid waste management, and public transport shift.
National Water Mission	Improve water use efficiency by 20%; basin-level integrated water management.
National Mission for Sustaining the Himalayan Ecosystem	Protect biodiversity, forest cover, and glaciers of the Himalayan region.
Green India Mission	Increase forest/tree cover on 5 million hectares and improve quality on another 5 million.
National Mission for Sustainable Agriculture	Climate-resilient agriculture, micro-irrigation, integrated farming systems.
National Mission on Strategic Knowledge for Climate Change	Support R&D, climate modeling, and data sharing networks.

Table 5.4: The Eight Missions under India's National Action Plan on Climate Change (NAPCC, 2008)

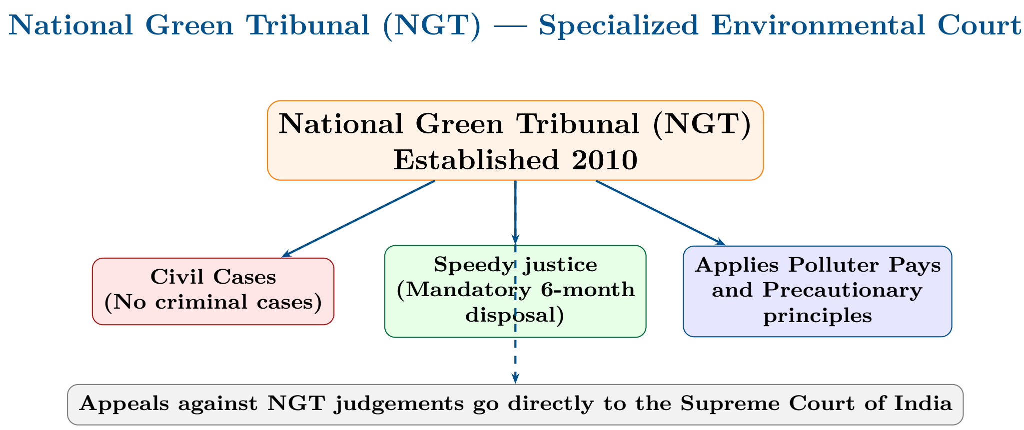


Figure 5.6: National Green Tribunal (NGT) — Key features of India's fast-track environmental court

5.2 Sustainable Development

Sustainable Development (Brundtland Definition)

"**Sustainable development** is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
— Brundtland Commission, *Our Common Future*, 1987.

Dimension	**Unsustainable (current trend)**	**Sustainable (goal)**
Economic	GDP growth at any environmental cost	Inclusive growth with resource efficiency
Environmental	Ecosystem degradation; biodiversity loss	Restored ecosystems; zero net deforestation
Social	Inequality; poverty; poor health	Universal access to clean water, food, healthcare
Cultural	Destruction of indigenous knowledge	Respect for and integration of traditional ecology

Table 5.5: Three (and more) Dimensions of Sustainable Development

5.3 The Circular Economy

Circular Economy

A **circular economy** is an economic system that aims to eliminate waste and the continual use of resources by keeping products, materials, and resources in use at their highest value for as long as possible. It is based on three principles: **Design out waste and pollution**, **Keep products and materials in use**, and **Regenerate natural systems**.

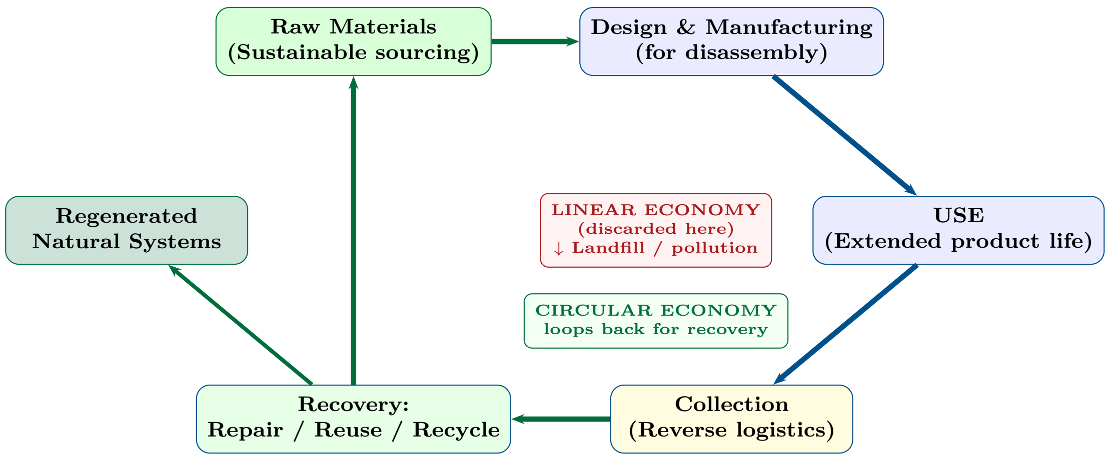


Figure 5.7: Circular Economy Model — products and materials cycle continuously; waste is designed out; contrasted with the linear take-make-dispose economy

5.4 ISO 14000 Environmental Management System (EMS)

ISO 14000 Series

The **ISO 14000** series is a family of internationally recognised standards developed by the International Organisation for Standardisation (ISO) to help organisations (companies, government bodies, NGOs) manage their environmental responsibilities in a systematic way. The core standard is **ISO 14001**, which specifies the requirements for an Environmental Management System (EMS).

5.4.1 What is an EMS?

An Environmental Management System is a set of processes and practices that enables an organisation to:

- Identify, monitor, and control its environmental aspects and impacts.
- Set environmental targets and objectives.
- Demonstrate legal compliance.
- Continuously improve its environmental performance.

5.4.2 The ISO 14001 PDCA Cycle

ISO 14001 is based on the **Plan-Do-Check-Act (PDCA)** continuous improvement cycle:

1. **Plan:** The organisation identifies environmental aspects (activities/products/services that interact with the environment), evaluates their significance, determines legal obligations, and sets measurable environmental objectives and targets.

2. **Do:** Implements the plans — provides resources (financial, human, technological), training, communication, and documented procedures. Establishes operational controls for significant environmental aspects.

3. **Check:** Monitors and measures key environmental performance indicators (KPIs), evaluates compliance with legal requirements, conducts internal audits, and investigates nonconformities.

4. **Act:** Reviews results at management level (Management Review), takes corrective and preventive actions, and updates objectives for continuous improvement.

5.4.3 Benefits of ISO 14001 Certification

- **Legal compliance:** Systematic monitoring ensures all environmental regulations are met, reducing risk of fines and prosecution.
- **Cost savings:** Identifying waste and inefficiency in energy and material use reduces operational costs.
- **Market advantage:** Certification signals environmental responsibility to customers, investors, and regulators, enhancing brand reputation and market access (especially for export to environmentally stringent markets like the EU).
- **Risk reduction:** Proactive identification of environmental risks prevents costly incidents (spills, pollution, regulatory violations).
- **Employee engagement:** Systematic training and involvement of staff in environmental programs improves morale and environmental awareness.
- **Stakeholder trust:** Demonstrates corporate responsibility to communities and NGOs, reducing reputational risk.

PYQ: Explain the concept and benefits of ISO 14000. (W'21, N-W'25)

ISO 14000: An internationally recognised family of standards for Environmental Management Systems (EMS), developed by ISO. The core standard ISO 14001 provides a systematic framework for organisations to manage their environmental impacts.

Key Elements (PDCA):

1. **Plan:** Identify significant environmental aspects (e.g., CO_2 emissions, wastewater discharge), set objectives and targets.
2. **Do:** Implement controls, training, and procedures; allocate resources.
3. **Check:** Monitor performance indicators; conduct internal audits.
4. **Act:** Top management reviews results; take corrective actions; continuously improve.

Benefits:

- Ensures compliance with environmental laws, reducing legal liability.

- Reduces resource consumption (energy, water, materials) through systematic identification of waste.
- Improves corporate environmental image and provides competitive advantage in green markets.
- Reduces risk of environmental incidents (spills, emissions violations).
- Provides a globally recognised credential that builds customer and investor confidence.

5.5 Life Cycle Analysis (LCA)

Life Cycle Analysis (LCA)

Life Cycle Analysis (LCA), also called Life Cycle Assessment or Cradle-to-Grave Analysis, is a systematic method for compiling and evaluating the inputs (materials, energy), outputs (products, emissions, waste), and potential environmental impacts associated with a product system throughout its entire life cycle — from raw material extraction through production, distribution, use, and end-of-life (disposal or recycling). LCA is governed by international standards ISO 14040 (principles and framework) and ISO 14044 (requirements and guidelines).

5.5.1 Four Stages of LCA

1. **Goal and Scope Definition:** Define the purpose of the LCA, the product system to be studied, the reference unit ("functional unit" — e.g., 1 tonne of cement; 1 km driven by a car), and the system boundary (which life cycle stages to include).

2. **Life Cycle Inventory (LCI):** Collect quantitative data on all inputs (raw materials, energy, water) and outputs (products, co-products, emissions to air/water/soil, solid waste) for each process in the system boundary. This is the most data-intensive stage.

3. **Life Cycle Impact Assessment (LCIA):** Classify and characterise the inventory data into environmental impact categories. Common categories include:
   - Climate change (Global Warming Potential, GWP, in kg CO_2-equivalent).
   - Ozone depletion potential.
   - Human toxicity potential.
   - Freshwater eutrophication potential.
   - Land use.
   - Water scarcity.

4. **Interpretation:** Identify the most significant life cycle stages and processes contributing to the total environmental burden; identify opportunities for improvement;

communicate results to decision-makers.

5.5.2 Cradle-to-Cradle Design

Traditional LCA covers "cradle to grave" — from extraction to disposal. A more progressive concept is **Cradle to Cradle (C2C)**, developed by architect William McDonough and chemist Michael Braungart, which aims to design products and systems such that at the end of their use phase, all materials are either:

- **Biological nutrients:** Safe to return to the natural environment through composting or biodegradation (e.g., biodegradable packaging).
- **Technical nutrients:** Safe to return indefinitely to industrial systems through recycling and remanufacturing (e.g., aluminium cans, glass bottles).

PYQ: What is Life Cycle Analysis (LCA)? Explain its stages. (Su'22, Su'25, N-Su'25, N-W'25)

Life Cycle Analysis (LCA): A systematic methodology for evaluating the total environmental impacts of a product or service throughout its entire life — from raw material extraction to final disposal.

Four Stages:

1. **Goal and Scope:** Define what is being studied and to what depth, including the functional unit (e.g., "1 tonne of packaging material") and system boundary (cradle-to-gate? cradle-to-grave?).
2. **Life Cycle Inventory (LCI):** Collect data on all material and energy inputs and all emissions and waste outputs for each process in the system.
3. **Life Cycle Impact Assessment (LCIA):** Convert inventory data into scores for environmental impact categories (global warming potential, water use, eutrophication, toxicity, etc.).
4. **Interpretation:** Identify hotspots — which stages cause the most environmental impact — and recommend improvements.

Applications:

- Compare the environmental footprint of different products performing the same function (e.g., paper bag vs. plastic bag vs. cotton tote bag).
- Identify which stage of a product's life cycle creates the most environmental harm.
- Inform eco-design decisions (use less material? use recycled content? design for disassembly?).
- Substantiate "green" marketing claims and environmental product declarations (EPDs).

5.6 The 5R Concept (Waste Reduction Hierarchy)

The 5R Hierarchy

The **5R concept** provides an ordered hierarchy of waste prevention and management strategies, from the most preferred (at the top) to the least preferred (at the bottom). Strategies higher in the hierarchy are generally more beneficial for the environment because they avoid waste generation entirely, rather than managing it after the fact.

The five Rs in order of priority:

1. **Refuse:** The most powerful strategy — simply say no to unnecessary items, especially single-use disposables. If you don't accept a disposable straw, plastic bag, or unwanted freebie, no waste is generated in the first place. *Example:* Carry a reusable bag to the supermarket; decline promotional plastic merchandise; choose products without packaging where possible.

2. **Reduce:** Use less of a resource in the first place. This involves conscious consumption choices and efficiency improvements. *Examples:* Use energy-efficient appliances (reduce electricity); fix dripping taps (reduce water); print double-sided (reduce paper); buy durable products (reduce frequency of replacement).

3. **Reuse:** Use items multiple times before discarding them, either for the same purpose or a different one. Reuse requires no reprocessing energy. *Examples:* Use glass bottles multiple times; use cloth napkins instead of paper; refill ink cartridges; lend and borrow tools rather than buying.

4. **Repurpose (Upcycle):** Give a discarded item a new use — transform it into something of equal or greater value. *Examples:* Turn old tyres into garden planters; use glass jars as storage containers; convert pallets into furniture; repurpose worn shirts as rags.

5. **Recycle:** Process used materials so they can be remanufactured into new products. Recycling does require energy and processing but is far preferable to landfill or incineration. *Examples:* Separate paper, glass, metal, and plastic for kerbside or drop-off recycling; take e-waste to authorised recyclers.

PYQ: Explain the 5R concept in detail. (W'21, Su'22, W'22, N-Su'25)

The 5R Concept: A sustainable waste management hierarchy of five actions, listed from most to least preferred, to reduce environmental impact:

1. **Refuse:** Decline unnecessary or single-use items. Example: say no to disposable plastic straws and bags.
2. **Reduce:** Consciously use less. Example: print only when necessary; choose concentrated cleaning products.
3. **Reuse:** Use items repeatedly. Example: use stainless steel water bottles; use

cloth shopping bags.

4. **Repurpose:** Creatively give waste items a new function. Example: old tyres as garden plant pots; glass jars as storage containers.
5. **Recycle:** Submit materials for reprocessing into new products. Example: aluminium cans, paper, glass, and plastic can be recycled.

Why follow this order?

- Refusing and reducing are better because they prevent waste at the source — no energy or resources are spent processing a product that was never made.
- Reuse is better than recycling because it requires no reprocessing energy.
- Recycling is the last resort (before disposal) because it requires energy and produces some residue.
- Landfill and incineration (disposal) are the least preferred — they represent a complete loss of material value.

5.7 Carbon Credits and Carbon Markets

Carbon Credit

A **carbon credit** is a tradeable permit or certificate representing the right to emit one metric tonne of carbon dioxide (or its equivalent in other greenhouse gases, measured in **tonnes of CO_2-equivalent, tCO_2e**). Carbon credit systems are market-based mechanisms to incentivise GHG emission reductions by putting a financial price on carbon pollution.

5.7.1 How Carbon Markets Work

Two main types of carbon markets exist:

1. **Compliance (Regulatory) Markets:** Created by government regulation. Emitters covered by the scheme are allocated a fixed number of emission permits (a "cap"). If a company emits less than its cap, it can sell surplus permits; if it emits more, it must buy permits from the market. The cap is progressively tightened over time to achieve emission reductions. Example: EU Emissions Trading System (EU ETS) — the world's largest carbon market.

2. **Voluntary Markets:** Companies, organisations, or individuals voluntarily purchase carbon credits (verified by standards like Gold Standard or Verra's VCS) to offset their emissions — typically by funding projects that reduce or remove CO_2 elsewhere (reforestation, renewable energy, improved cookstoves). Voluntary markets lack the regulatory teeth of compliance markets.

5.7.2 The Clean Development Mechanism (CDM)

Under the Kyoto Protocol's CDM, companies in rich countries could earn Certified Emission Reduction (CER) credits by investing in emission reduction projects in developing countries, and count those credits against their own Kyoto targets. This transferred clean technology and climate finance to developing nations while reducing the cost of compliance for developed countries.

PYQ: Explain the concept of Carbon Credit. (W'23)

Carbon Credit: A tradeable permit representing the right to emit one tonne of CO_2-equivalent of greenhouse gases.

How it works:

- A government or regulatory body sets a **cap** on total allowable GHG emissions from covered sectors (e.g., power generation, heavy industry).
- Companies are allocated or auction for emission permits equal to their share of the cap.
- Companies that reduce their emissions below their allocation can **sell** their surplus credits on the carbon market — this is their financial reward for being clean.
- Companies that emit **above** their allocation must **buy** additional credits from the market — this makes exceeding the cap financially costly.
- Over time, the **cap is reduced**, shrinking the total permits available and driving further emission reductions.

Benefits of Carbon Markets:

- Creates a financial incentive for companies to reduce emissions.
- Allows emission reductions to happen where they are cheapest, reducing the overall cost of meeting environmental targets.
- Generates revenue (through permit auctions) for government investment in clean energy and climate adaptation.

Eco-Tourism (also from W'23 PYQ): A form of responsible travel to natural areas that conserves the environment, sustains the well-being of local communities, and involves education and interpretation of the natural environment. India's eco-tourism sites include Kaziranga (Assam), Periyar Wildlife Sanctuary (Kerala), and Coorg (Karnataka). It promotes conservation funding through tourism revenue.

The 5R Waste Hierarchy (Most to Least Preferred)

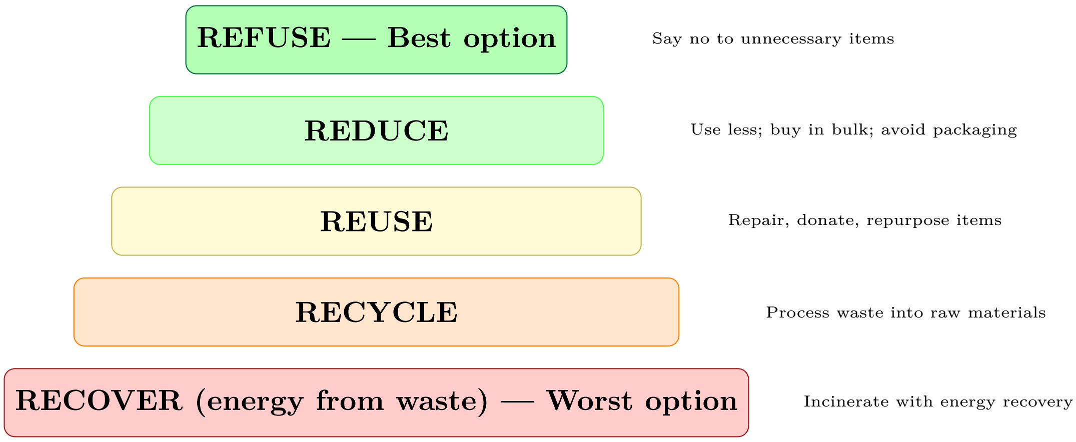


Figure 5.8: 5R Waste Hierarchy Pyramid — from most preferred (Refuse) to least preferred (Recover); each level reduces the volume of waste reaching the next

"R"	**Meaning**	**Example**	**Impact**
Refuse	Decline unnecessary items	Refuse plastic bags, single-use cutlery	Prevents waste at source
Reduce	Minimise consumption	Buy concentrated detergent; less packaging	Reduces resource use
Reuse	Use items multiple times	Cloth bags, reusable water bottles, repair	Extends product life
Recycle	Convert waste to new material	Paper $\rightarrow$ cardboard; glass $\rightarrow$ bottles	Recovers material value
Recover	Extract energy from waste	Waste-to-energy incineration, biogas	Last resort; some energy recovered

Table 5.6: The 5R Framework — Refuse, Reduce, Reuse, Recycle, Recover with Examples and Impact

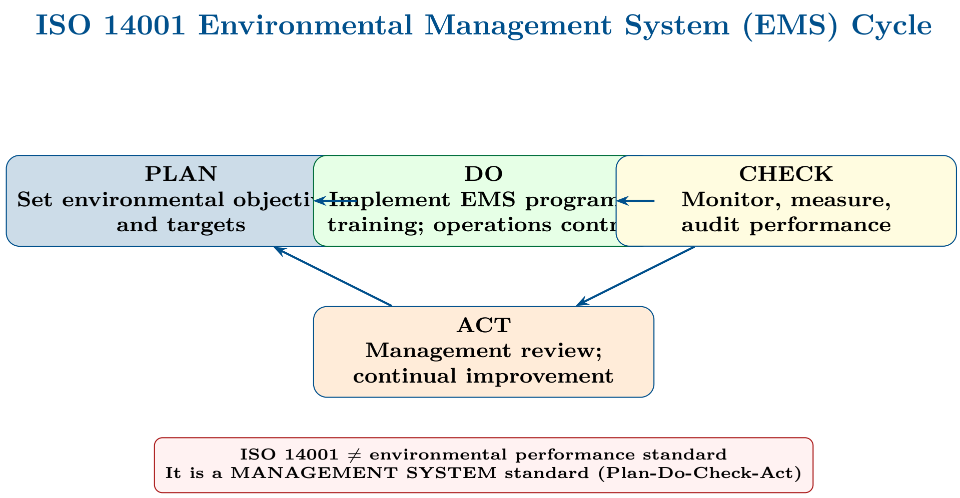


Figure 5.9: ISO 14001 Environmental Management System — Plan-Do-Check-Act (PDCA) cycle for continual improvement of environmental performance

ISO 14000 Standard	**Scope / Purpose**
ISO 14001	Environmental Management Systems (EMS) — Requirements and guidance
ISO 14004	EMS — General guidelines on implementation
ISO 14006	Eco-design guidelines for products
ISO 14020–14025	Environmental labels and declarations (Types I, II, III ecolabels)
ISO 14040–14044	Life Cycle Assessment (LCA) — principles, requirements, procedures
ISO 14064	Greenhouse gas accounting and verification
ISO 14090	Adaptation to climate change — principles and requirements

Table 5.7: ISO 14000 Family of Environmental Management Standards

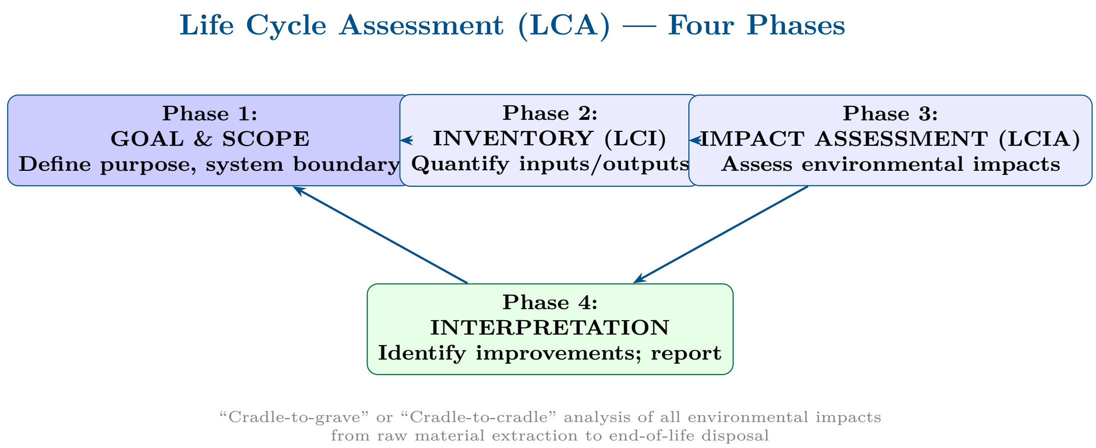


Figure 5.10: Life Cycle Assessment (LCA) — Four-phase iterative process for quantifying the environmental impact of products from cradle to grave

Feature	**Carbon Tax**	**Carbon Trading (Cap-and-Trade)**
Mechanism	Government sets price per tonne CO_2	Government sets cap; companies trade credits
Price certainty	Yes — fixed price	No — price fluctuates with market
Quantity certainty	No — emissions may vary	Yes — total emissions capped
Revenue use	Government revenue; can fund green projects	Between companies; no direct govt. revenue
Flexibility	Simple to administer	Complex; requires monitoring
Example	Sweden carbon tax ($130/t)	EU Emissions Trading Scheme (EU ETS)

Table 5.8: Carbon Tax vs. Carbon Trading (Cap-and-Trade) — Two approaches to carbon pricing

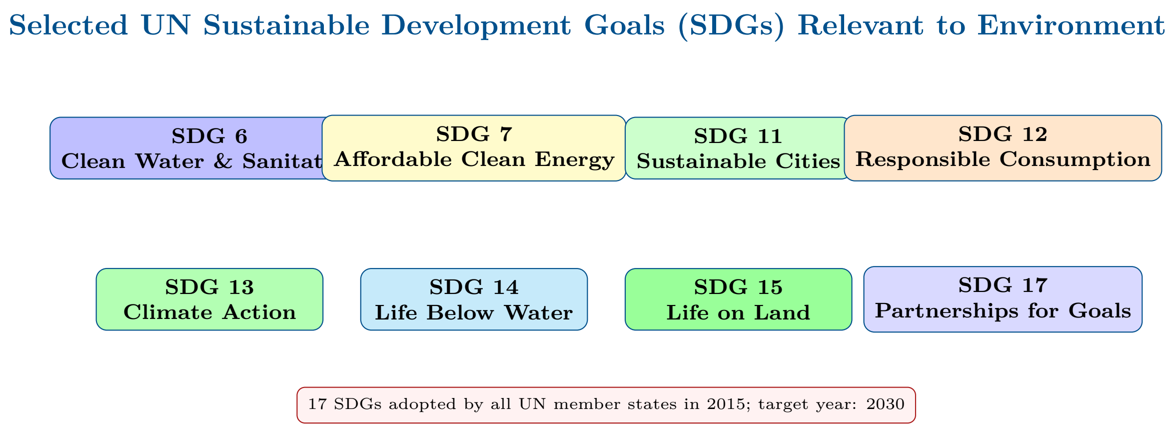


Figure 5.11: Environmentally Relevant UN Sustainable Development Goals (SDGs) — Key goals for environmental sustainability and climate action

Tool / Framework	**Purpose**	**Applied By**
ISO 14001 EMS	Manage and improve environmental performance	Industries, organisations
Life Cycle Assessment	Quantify environmental impact of products	Product designers, manufacturers
Environmental Impact Assessment	Assess impacts before project implementation	Developers, regulators
Carbon Footprint Analysis	Measure GHG emissions of activities	Companies, individuals
Ecological Footprint	Measure human demand on Earth's biocapacity	Nations, cities, individuals
Material Flow Analysis	Track inputs/outputs of materials	Industrial ecologists, planners

Table 5.9: Key Sustainability Assessment Tools and Frameworks

5.8 Green Buildings

Green Building

A **green building** (also called a sustainable, high-performance, or eco-building) is a structure that is designed, constructed, and operated to minimise its environmental impacts and maximise its efficiency in using resources — including energy, water, and materials — while also providing healthy indoor environments for occupants.

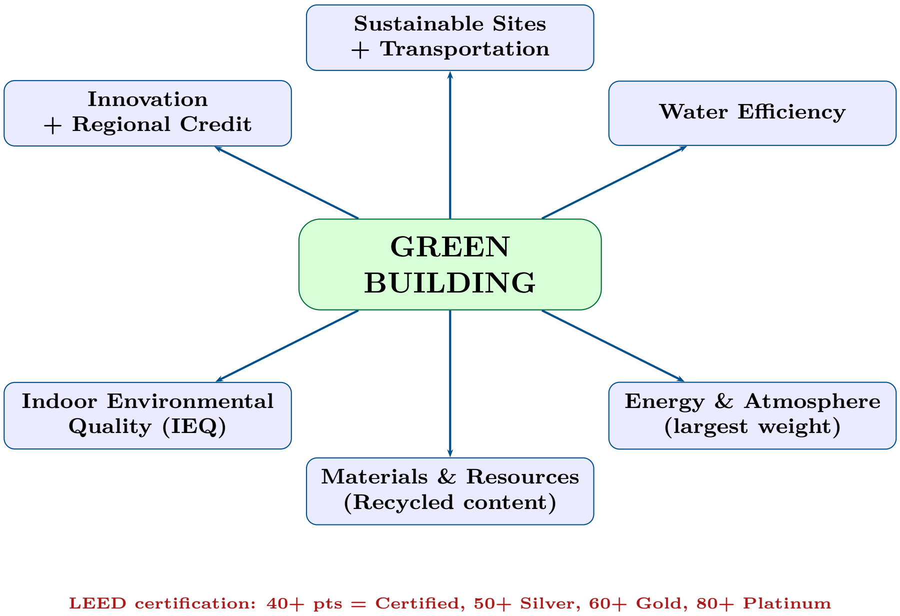


Figure 5.12: LEED Green Building Rating System — Six credit categories around the central green building concept

Feature	**Conventional Building**	**Green Building**
Energy	High consumption; fossil-fuel HVAC	Solar panels, natural ventilation, LED, BAS
Water	High use; no recycling	Low-flow fixtures, rainwater harvesting, greywater
Materials	Virgin materials, high embodied carbon	Recycled, regional, rapidly renewable materials
Indoor quality	Poor air quality, VOC materials	HEPA filtration, non-toxic paints, daylighting
Waste	Landfill of construction waste	Deconstruction; 90%+ debris recycling
Cost	Lower upfront, higher lifetime ops cost	Higher upfront; 20–30% lower lifetime cost

Table 5.10: Green Building vs. Conventional Building — Key Design Differences

5.8.1 Goals of Green Buildings

1. **Energy Efficiency:** Drastically reduce operational energy demand through passive design strategies (building orientation, shading, thermal mass) and high-performance active systems (LED lighting, high-efficiency HVAC, building energy management systems). Renewable on-site generation (rooftop solar PV) can further reduce or eliminate net energy consumption.

2. **Water Efficiency:** Minimise potable water use through water-efficient fixtures (low-flow taps, dual-flush toilets), rainwater harvesting, greywater recycling (reusing water from sinks and showers for toilet flushing), and water-efficient or native landscaping.

3. **Material Efficiency:** Use sustainable, low-emissions, and recycled materials; design buildings for adaptability, with modular components that can be replaced or reorganised; plan for eventual deconstruction so materials can be recovered rather than landfilled.

4. **Indoor Environmental Quality:** Provide healthy indoor spaces through good natural ventilation, maximised daylight access, use of low-VOC (volatile organic compound) paints, flooring and adhesives, and control of thermal comfort and acoustic quality.

5. **Site Sustainability:** Preserve existing vegetation and topography; restore damaged ecosystems; provide green roofs and walls; connect building to public transport.

6. **Waste Reduction:** Minimise construction waste; provide facilities for ongoing waste segregation and recycling by occupants.

5.8.2 Advantages of Green Buildings

Benefit Category	Specific Advantages
Environmental	Reduces carbon footprint; conserves water and materials; reduces construction waste; improves urban biodiversity through green roofs and walls.
Economic	Lower utility bills (20–40% lower energy costs typical); higher property values; improved occupant productivity; reduced maintenance costs; longer building lifespan.
Health	Better indoor air quality reduces respiratory illness and absenteeism; natural daylight improves mood and cognitive function; thermal comfort increases productivity.
Social	Demonstrates corporate sustainability commitment; improves community quality of life; reduces urban heat island effect.

5.8.3 Green Building Rating Systems in India

Rating systems provide a standardised framework for certifying the sustainability performance of buildings:

GRIHA (Green Rating for Integrated Habitat Assessment)

GRIHA is India's **national green building rating system**, developed by The Energy and Resources Institute (TERI) in collaboration with the Ministry of New and Renewable Energy (MNRE).

Key features:

- GRIHA rates large commercial and residential buildings on a scale of **1 to 5 stars** (maximum 100 points, awarded based on performance across multiple sustainability criteria).
- Rating criteria cover: site planning, energy performance, water conservation, materials, waste management, health and well-being, and innovation.
- A GRIHA-3 star rating requires achieving at least 50 points; 5-star requires 75+ points.
- India's government mandates GRIHA certification for public sector buildings.

LEED (Leadership in Energy and Environmental Design)

Originally developed in the USA by the US Green Building Council (USGBC), LEED is widely used globally including in India. It awards Certified, Silver, Gold, and Platinum ratings.

PYQ: Goals and advantages of a Green Building. Write a note on GRIHA. (W'21, Su'22, N-Su'25, N-W'25)

Green Building: A building that is designed and operated to minimise its environmental impact and maximise the health and well-being of occupants, using strategies around energy, water, materials, and site.

Goals:

1. Reduce energy consumption by 20–50% through passive design, efficient systems, and renewable energy.
2. Conserve fresh water through water-efficient fixtures and rainwater harvesting.
3. Use sustainable, low-embodied-carbon construction materials (recycled steel, fly ash bricks, bamboo).
4. Provide a healthy indoor environment: good air quality, natural lighting, thermal comfort.
5. Minimise construction and operational waste.

Advantages:

- Lower utility bills — reduced energy and water consumption directly cuts operational costs.
- Higher property value and marketability.
- Better occupant health, productivity, and satisfaction.
- Reduced carbon footprint and environmental impact over the building's life.
- Compliance with evolving environmental regulations.

GRIHA (Green Rating for Integrated Habitat Assessment): India's national rating system for sustainable buildings, developed by TERI and the Ministry of New and Renewable Energy. GRIHA assesses buildings on a 100-point scale across five categories: site planning, energy (most heavily weighted at 35 points), water, materials, and health and well-being. Star ratings range from 1 to 5 (5 being the highest). GRIHA is mandatory for central government buildings in India and encourages the use of local and traditional materials along with modern sustainability technologies suited to Indian climate conditions.

5.9 Rainwater Harvesting

Rainwater Harvesting

Rainwater harvesting (RWH) is the collection, storage, and beneficial use of rainwater that falls on rooftops, land surfaces, roads, or other catchment areas before it has the opportunity to run off into drains, rivers, or the sea. RWH is one of the most ancient and effective strategies for augmenting freshwater supply and reducing dependence on groundwater.

5.9.1 Need for Rainwater Harvesting

- Over two-thirds of India's rainfall occurs in just 4 months (June–September), while water scarcity prevails for the other 8 months.
- Rapid urbanisation has replaced permeable soil with concrete, drastically reducing groundwater recharge and increasing flood risk.
- Groundwater tables are falling in many parts of India due to over-extraction.
- Municipal water supply is inadequate in most Indian cities; RWH can supplement supply.

5.9.2 Methods of Rainwater Harvesting

A. Rooftop Rainwater Harvesting

The most common and practical form of RWH for urban areas:

1. **Catchment (Roof):** The roof of a building collects rainfall. Preferred materials: metal (galvanised iron, aluminium) or tiles — these are clean and have low contamination risk. Avoid asbestos roofs (leach harmful asbestos fibres).
2. **Gutters and Downpipes:** Channel rainfall collected from the roof into the conveyance system. Should be sloped correctly to prevent stagnation.
3. **First-Flush Diverter:** A device that diverts the first few minutes' of rainfall (which contains the highest concentration of dirt, bird droppings, and debris from the roof) away from the storage tank. After flushing the roof surface, cleaner water is directed to storage.
4. **Filter:** A screen (mesh) filter removes leaves and large debris; a gravel/charcoal/sand filter removes finer particles and some biological contaminants.
5. **Storage Tank:** An underground or above-ground tank (PVC, RCC, or Ferro-cement) stores the filtered water for later use. Properly covered to prevent mosquito breeding and evaporation.
6. **Overflow / Recharge Pit:** When the storage tank is full, excess water is directed to a recharge pit or borewell to replenish groundwater.

B. Surface Run-off Harvesting

Captures rainfall falling on land (roads, fields, open ground) rather than on rooftops:

- **Check dams:** Small barriers built across streams to slow run-off and allow water to percolate into the ground.
- **Percolation tanks:** Pits dug in the ground in open areas to collect surface run-off and allow it to percolate slowly into the ground, recharging the aquifer.

- **Contour trenches:** Horizontal trenches dug along the contour lines on slopes to capture run-off and encourage infiltration.
- **Farm ponds and tanks:** Earthen reservoirs on farms that collect monsoon run-off for dry-season irrigation.

C. Khet Talavadi (Farm Pond)

A traditional Indian water harvesting structure, particularly common in Gujarat and Rajasthan:

- A small fan-shaped or rectangular earthen pond, typically 30 m × 30 m, excavated at the lowest point of a farm field.
- Monsoon run-off from the surrounding farmland flows by gravity into the pond.
- Water stored in the Khet Talavadi is used for supplemental irrigation of the rabi (winter) crop and for livestock watering.
- The Khet Talavadi reduces soil erosion on the farm and allows water to slowly percolate into the ground to recharge nearby wells.

PYQ: Explain various methods of rainwater harvesting and their advantages. (W'21, Su'22, W'22, N-W'25, Su'25)

Rainwater Harvesting (RWH): Collection and storage of rainwater from rooftops or land surfaces for beneficial use, reducing dependence on groundwater and municipal supply.
Methods:
1. Rooftop Harvesting: Rainfall on the roof is channelled through gutters and downpipes through a first-flush diverter (discards initial dirty water) and filter (removes debris and sediment) into an underground storage tank. Tank overflow is directed to a recharge pit to replenish groundwater. Suitable for urban households and institutions.
2. Surface Run-off Harvesting: Includes check dams (across streams), percolation tanks (open pits allowing infiltration), contour trenches on slopes, and farm ponds. These collect run-off from large land areas, store it for irrigation, and recharge groundwater.
3. Khet Talavadi (Farm Pond): A traditional earthen pond dug at the lowest point of a farm. Monsoon run-off from the field drains into it by gravity. Used for supplemental irrigation of dry-season crops and livestock watering. Common in Gujarat and Rajasthan.
Advantages of RWH:

- Supplements fresh water supply, especially during dry seasons.
- Reduces dependence on groundwater, slowing aquifer depletion.
- Recharges groundwater when overflow is directed to recharge pits.
- Reduces urban flooding by capturing and storing run-off that would otherwise overwhelm drains.

- Reduces water bills for households and institutions.
- Provides water security in areas with unreliable municipal supply.

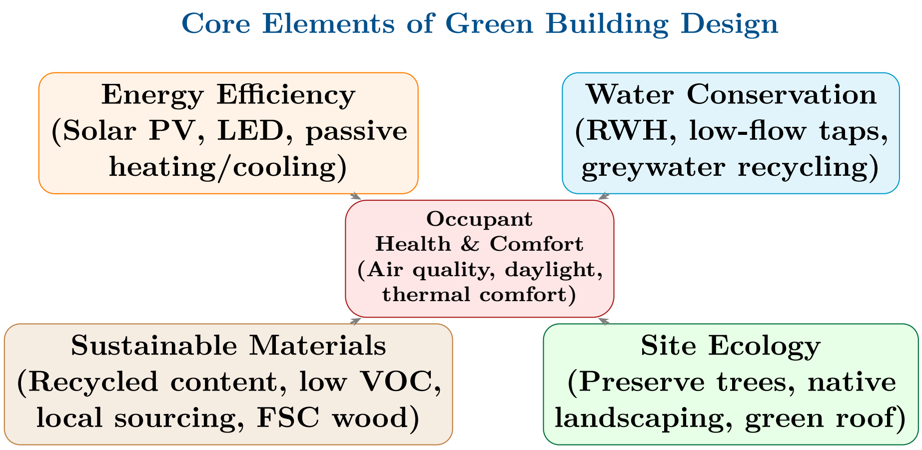


Figure 5.13: The Five Pillars of Green Building Design — Energy, Water, Materials, Site, and Indoor Environmental Quality (Occupant Health)

Green Building Rating System	**Country of Origin / Key Managing Body**
GRIHA (Green Rating for Integrated Habitat Assessment)	India (TERI and Ministry of New and Renewable Energy)
LEED (Leadership in Energy and Environmental Design)	USA (US Green Building Council - USGBC)
IGBC (Indian Green Building Council) Ratings	India (CII - Confederation of Indian Industry)
BREEAM (Building Research Establishment Environmental Assessment Method)	United Kingdom (BRE)
CASBEE	Japan
Green Star	Australia / South Africa

Table 5.11: Major Green Building Rating Systems Worldwide

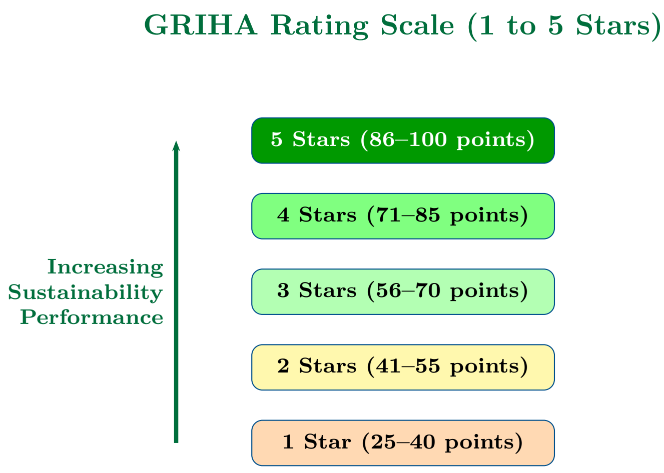


Figure 5.14: GRIHA Star Rating Scale — Buildings are evaluated out of 100 points across 30+ criteria

Parameter	Conventional Building	Green Building
Site & Landscaping	Cleared site, impermeable concrete, imported exotic plants.	Preserves topsoil/trees, porous paving, native drought-resistant plants.
Energy Use	High reliance on grid power, inefficient HVAC/lighting.	Uses passive design, solar PV, LED, smart sensors (saves 20-50%).
Water Management	Uses potable municipal water for all needs; rainwater flows to drains.	Low-flow fixtures, rainwater harvested, greywater recycled for flushing.
Materials	Energy-intensive materials (cement, new steel, glass).	Recycled steel, fly ash bricks, rapidly renewable materials (bamboo).
Indoor Air Quality	Poor ventilation, toxic VOC paints and adhesives.	Excellent ventilation, daylighting, low-VOC paints, healthy environment.

Table 5.12: Comparison: Conventional vs. Green Building

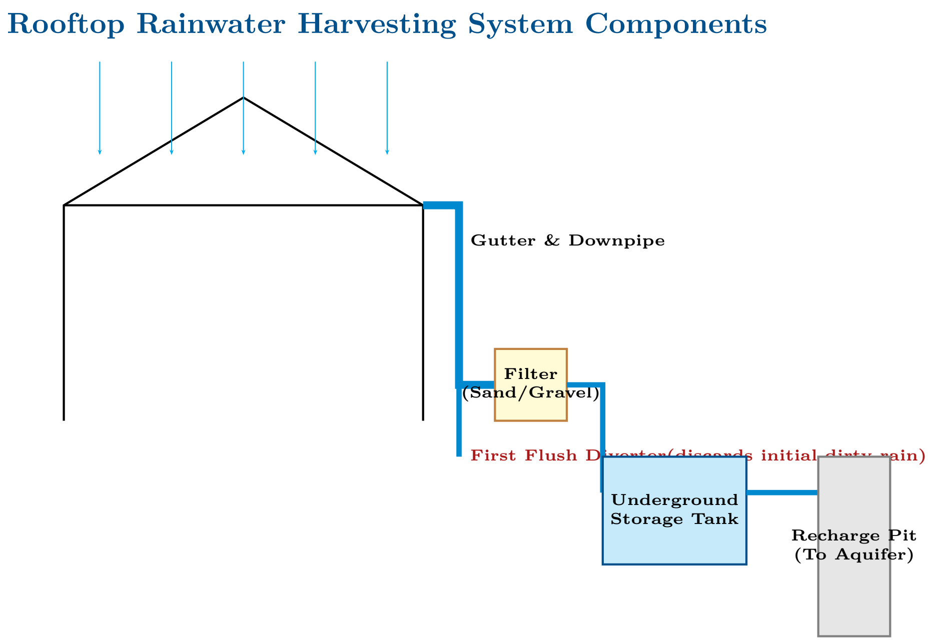


Figure 5.15: Rooftop Rainwater Harvesting (RWH) Schematic — showing the essential components: Catchment (roof), Delivery system (gutters/downpipes), First flush diverter, Filter, Storage tank, and Recharge pit for overflow

RWH Component	**Function**	**Common Materials**
Catchment Area	The surface receiving rainfall.	Rooftops (sloped or flat), paved courtyards, unpaved lawns.
Conveyance System	Transports harvested water from catchment to storage.	PVC pipes, GI gutters, downspouts.
First Flush Diverter	Diverts the first spell of rain (containing dust, bird droppings, leaves) away from the storage tank.	Simple PVC pipe arrangement with a manual or automatic valve.
Filter Unit	Removes suspended pollutants, dirt, and debris from water before it enters the tank.	Sand, gravel, charcoal, sponge, wire mesh screens.
Storage Tank	Stores the filtered water for future use.	Underground RCC/masonry tanks, surface plastic (Sintex) tanks.
Recharge Structure	Directs overflow from the storage tank directly into the ground to replenish the aquifer.	Borewells, percolation pits / trenches.

Table 5.13: Components of an Urban Rainwater Harvesting System

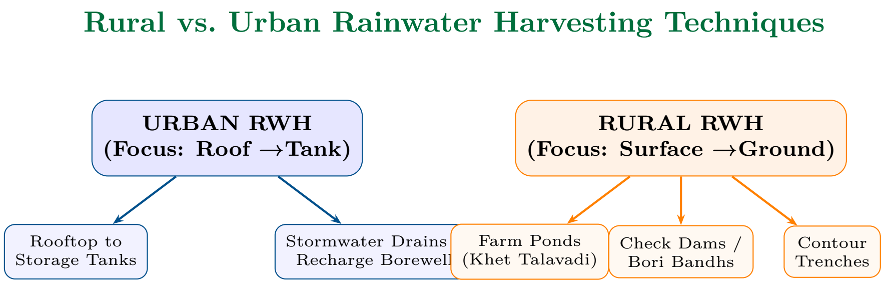


Figure 5.16: Classification of Rainwater Harvesting Techniques based on setting (Urban vs. Rural)