الجمهورية الجزائرية الديمقراطية الشعبية

وزارة التعليم العالي والبحث العلمي

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COURSE HANDBOOK

Intended for 3rd year Bachelor students in Ecology and Environment Specialty: Ecology and Environment

Title

Environmental Pollution

Coefficient: 3

This course, tailored for L3 in Ecology and Environmental Sciences, offers an in-depth and multidisciplinary exploration of environmental pollution. Emphasis is placed on the physicochemical and biological mechanisms underlying pollution processes, the socio-economic and ecological consequences, and current methodologies and policies for sustainable environmental management.

Academic Year : 2025/2026

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Table des matières

Chaptre I: General Notions

Chapitre II: Atmospheric Pollution

Chapire III: water pollution.

Chaptre V: Nuclear Pollution

Chaptre VI: Bioindicators as Effective Tools for Environmental Pollution Assessment

Liste des figures

Liste des tableaux

Introduction

Introduction

Over the past century, human activities have profoundly altered the Earth's environment, leading to multiple global changes such as climate change, biodiversity loss, land degradation, resource depletion, and environmental pollution (Steffen et al., 2015). These transformations are driven by rapid industrialization, population growth, urban expansion, intensive agriculture, and unsustainable resource exploitation (IPCC, 2023).

Among these global changes, pollution has emerged as one of the most pervasive and immediate threats to ecosystem functioning and human health. Unlike some environmental changes that may occur over decades or centuries, pollution can have rapid and sometimes irreversible effects on natural systems (Rockström et al., 2009).

Pollution manifests in various environmental compartments:

- **In the atmosphere**, emissions of greenhouse gases and air pollutants disrupt atmospheric composition, contributing to global warming, acidification, and respiratory illnesses (WHO, 2023).
- **In aquatic ecosystems**, the discharge of chemical contaminants, nutrients, microplastics, and pathogens degrades water quality, threatens aquatic biodiversity, and compromises freshwater availability (UNEP, 2024).
- **In terrestrial environments**, the accumulation of heavy metals, persistent organic pollutants, and agrochemicals in soils affects fertility, plant growth, and food safety, while also altering soil microbial communities (FAO, 2023).

Problematic of the course

In light of the growing pressures on the environment, **pollution in its different forms air, water, and soil represents a major scientific and societal challenge**. Each compartment is affected by specific pollutants and mechanisms of contamination, yet all are interconnected through complex environmental processe. This raises the central question of the course:

How can we analyze, understand, and manage the various forms of pollution (atmospheric, aquatic, and terrestrial), while taking into account their interactions, cumulative effects, and consequences for ecosystem stability, biodiversity preservation, and human health?

Chaptre I: General Notions

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I.I. The Concept of Environment

According to Harant (1964), the environment can be defined as "the set of biotic (living) and abiotic (physicochemical) factors of a habitat."Today, the term environment refers to "the totality, at a given moment, of physical, chemical, and biological agents, as well as social factors likely to have a direct or indirect, immediate or long-term effect on living beings and human activities." Thus, the environment encompasses a wide range of disciplines such as ecology, social sciences, geography, and public health (UNEP, 2024).

The environment can generally be divided into two interacting subsystems:

- **The human society**, characterized by sensitive flows (opinions, needs, power relations, individual aspirations, etc.).
- **The physical environment**, characterized by material and energy flows (food chains, carbon and water cycles, etc.).

These two systems partially overlap and interact continuously. The need to study and define the environment emerged from the rise of environmental nuisances and pollution related to human activities, and from the growing desire to preserve nature.

I 2. Definition of Pollution

I.2.1. Definition, sources of Pollution and Forms,

a) Definition

1) Pollution

Pollution is broadly defined as “the degradation of the environment caused by the introduction into the air, water, or soil of substances not naturally present in the environment, leading to ecosystem disturbances that may result in the migration or extinction of species unable to adapt” (Bouchibti, 2016). Beyond this ecological perspective, modern definitions also encompass pollution as any alteration of the natural composition of environmental media to levels harmful to human health, biodiversity, or ecosystem functioning (WHO, 2023).

2) Pollutant

A pollutant is defined as any natural or anthropogenic substance that, when present in excessive concentrations within the environment, exerts detrimental effects on living organisms and disrupts ecosystem balance (World Health Organization [WHO], 2020).

I.3. Sources of Pollution

Pollution originates from a variety of natural and anthropogenic (human-made) sources, each contributing differently to environmental degradation:

I.3.1 Natural Sources

Although less frequent, natural processes can introduce significant amounts of pollutants into ecosystems:

- **Volcanic eruptions** release large quantities of gases (e.g., sulfur dioxide, carbon dioxide) and particulates (ash, aerosols) that can alter air quality and contribute to acid rain (Seinfeld & Pandis, 2016).
- **Erosion of mineral-rich rocks** contributes to natural metal pollution, such as arsenic or selenium, in soils and groundwater (WHO, 2017).
- **Forest fires** emit carbon monoxide, nitrogen oxides, and particulate matter, affecting both local and global air quality (Johnston et al., 2012).
- **Natural oil seeps** release hydrocarbons into marine and coastal environments, sometimes at levels comparable to anthropogenic oil spills (Kvenvolden & Cooper, 2003).

I.3.2. Urban Sources

Rapid urbanization has intensified several pollution pathways:

- **Domestic wastewater** contains organic matter, detergents, pharmaceuticals, and pathogens that can pollute rivers and groundwater when untreated. This leads to eutrophication, antimicrobial resistance, and waterborne diseases (UNEP, 2016).
- **Solid waste mismanagement** generates leachate rich in organic and inorganic contaminants, methane emissions that contribute to greenhouse gases, and plastic debris that fragments into microplastics, affecting aquatic ecosystems and food chains (Hoornweg & Bhada-Tata, 2012).
- **Vehicle emissions** are a major source of nitrogen oxides (NO_x), volatile organic compounds (VOCs), and fine particulate matter ($PM_{2.5}$). These pollutants contribute to photochemical smog, acid rain, and have well-documented links to respiratory and cardiovascular diseases (WHO, 2021).
- **Runoff from urban surfaces** (roads, rooftops, parking lots) carries heavy metals such as lead (Pb), zinc (Zn), and copper (Cu), as well as hydrocarbons, oils, and other contaminants into rivers and lakes, degrading water quality and aquatic biodiversity (Gobel et al., 2007).

- **Industrial effluents in urban areas** release untreated or partially treated wastewater containing dyes, solvents, pesticides, and toxic heavy metals (Cd, Cr, Hg). These discharges can bioaccumulate in aquatic organisms, threatening food safety and ecosystem integrity (Zhang et al., 2015).
- **Construction and demolition activities** are significant sources of dust (suspended particulate matter), debris, and noise. Dust particles often contain silica and cement residues that contribute to air pollution, while construction runoff introduces sediments and chemicals into waterways (Singh et al., 2019).
- **Urban heat islands (UHIs)** result from the replacement of vegetation with asphalt and concrete, which absorb and re-emit heat. UHIs intensify ground-level ozone formation, exacerbate energy consumption (air conditioning), and increase mortality risks during heatwaves (Santamouris, 2015).
- **Energy production and domestic heating** through coal, biomass, kerosene, and diesel combustion is a major contributor to sulfur dioxide (SO_2), nitrogen oxides, carbon monoxide (CO), black carbon, and particulate matter emissions, worsening both indoor and outdoor air pollution (IEA, 2020).
- **Plastic pollution from urban lifestyles**, particularly single-use packaging, bottles, and bags, leads to macro- and microplastic contamination of soils and aquatic ecosystems. Microplastics can be ingested by fish, shellfish, and even humans, raising concerns about long-term health impacts (Jambeck et al., 2015).
- **Noise and light pollution**, often underestimated, are increasing in urban centers due to transport, industries, and public infrastructure. Noise exposure above recommended thresholds contributes to hypertension, sleep disorders, and cognitive impairment, while excessive artificial light disrupts circadian rhythms and affects nocturnal species (WHO, 2018).

1.3.3. Agricultural Sources

Modern agricultural practices contribute to widespread pollution:

- **Excessive use of fertilizers** (nitrogen- and phosphorus-based) leads to nutrient runoff into rivers, lakes, and coastal zones. This process accelerates **eutrophication**, resulting in harmful algal blooms, hypoxia (oxygen depletion), and fish mortality, with major impacts on aquatic biodiversity and drinking water quality (Smith & Schindler, 2009).

- **Pesticides and herbicides** used in crop protection persist in soils and may leach into groundwater or run off into surface waters. These chemicals accumulate in food chains, affect non-target organisms such as pollinators, and contribute to biodiversity decline and human health risks through chronic exposure (Aktar et al., 2009).
- **Livestock farming waste** produces large amounts of manure rich in organic matter, nitrates, and pathogens. Improper management results in contamination of groundwater and rivers, while emissions of methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3) contribute to global warming, acidification, and air quality deterioration (FAO, 2006).
- **Irrigation practices** often lead to soil salinization and waterlogging, reducing crop productivity and degrading arable land. In addition, irrigation runoff transports agrochemicals (fertilizers, pesticides) into aquatic systems, amplifying their ecological impact (Pimentel et al., 1997).
- **Antibiotic use in livestock production** contributes to the emergence of antibiotic-resistant bacteria, which can spread to humans through food, water, and the environment, representing a major global health threat (Kumar et al., 2020).
- **Agricultural burning of crop residues** releases greenhouse gases (CO_2, CH_4, N_2O), fine particulate matter, and polycyclic aromatic hydrocarbons (PAHs), degrading air quality and impacting both climate change and respiratory health (Gupta et al., 2004).

1.3.4. Industrial Sources

Industrial activities represent one of the most significant sources of environmental pollution:

- **Factory emissions** contribute to air pollution (SO_2, NO_x, CO_2) and acid deposition (Fowler et al., 2007).
- **Chemical plants** discharge hazardous substances (e.g., persistent organic pollutants, heavy metals) into air, water, and soil (UNEP, 2019).
- **Mining operations** generate acid mine drainage, releasing toxic metals such as mercury, cadmium, and lead into ecosystems (Lottermoser, 2010).
- **Heavy industry** (steel, cement, petrochemicals) produces large amounts of greenhouse gases and particulate emissions (IEA, 2020).

I.4. Types and Sources of Pollution

I.4.1. Primary Pollutants

Primary pollutants are substances directly emitted into the atmosphere from natural or anthropogenic sources. Unlike secondary pollutants, they are released in their original chemical form and frequently serve as precursors for further reactions in the atmosphere. The major primary pollutants include:

- **Carbon oxides (CO, CO_2)**
    - **Sources:** Incomplete combustion of fossil fuels in vehicles, industrial processes, biomass burning, and indoor stoves.
    - **Impacts:** Carbon monoxide (CO) binds with hemoglobin, reducing oxygen transport in the blood and causing cardiovascular and neurological disorders (WHO, 2023). Carbon dioxide (CO_2), although less toxic, is a major greenhouse gas responsible for global warming and climate change.
- **Sulfur oxides (SO_2, SO_3)**
    - **Sources:** Combustion of coal and heavy oils, metal smelting, and certain volcanic emissions.
    - **Impacts:** Sulfur oxides are precursors of acid rain (through sulfuric acid formation), which damages vegetation and aquatic ecosystems, corrodes infrastructure, and irritates the human respiratory system (Seinfeld & Pandis, 2016).
- **Nitrogen oxides (NO, NO_2, collectively NO_x)**
    - **Sources:** High-temperature combustion processes such as those occurring in motor vehicles, power plants, and industrial boilers.
    - **Impacts:** Nitrogen oxides contribute to tropospheric ozone formation and photochemical smog, aggravate asthma, and cause foliar damage to plants (Atkinson, 2000).
- **Light hydrocarbons (e.g., methane, ethane, propane)**
    - **Sources:** Fuel evaporation, natural gas leaks, industrial activities, and agricultural practices (livestock and rice paddies).
    - **Impacts:** Methane (CH_4) is a potent greenhouse gas with a high global warming potential, while non-methane hydrocarbons serve as precursors for ozone and smog formation (IPCC, 2021).

- **Volatile Organic Compounds (VOCs)**
    - **Sources:** Emitted from solvents, paints, adhesives, petrochemical industries, and various household products.
    - **Impacts:** Many VOCs such as benzene, toluene, and formaldehyde are toxic or carcinogenic. They also react with nitrogen oxides to generate ozone and secondary organic aerosols, contributing to urban air pollution (Finlayson-Pitts & Pitts, 2000).
- **Particulate matter (PM_{10} and $PM_{2.5}$)**
    - **Sources:** Emitted from the combustion of coal, oil, and biomass; vehicle exhaust; industrial emissions; and natural sources such as desert dust and volcanic ash.
    - **Impacts:** Fine particles penetrate deep into the lungs and bloodstream, leading to cardiovascular and respiratory diseases. Additionally, they reduce visibility and influence radiative forcing, thereby affecting climate (Pope & Dockery, 2006).

I.4.2. Secondary Pollutants

Secondary pollutants are not directly emitted into the atmosphere; rather, they are generated through complex photochemical and thermochemical transformations of primary pollutants. These reactions are often driven by sunlight, temperature variations, and atmospheric oxidants such as ozone and hydroxyl radicals. The resulting compounds are frequently more toxic, persistent, and capable of long-range atmospheric transport.

The main secondary pollutants include tropospheric ozone, peroxyacetyl nitrate (PAN), acid rain, and secondary particulate matter. They collectively contribute to major environmental issues such as photochemical smog, acid deposition, and climate change, posing significant risks to both ecosystems and human health.

1.4.2.1. Major Types of Secondary Pollutants

1). Ozone (O_3)

- **Formation**: Ground-level ozone is not directly emitted but produced through **photochemical reactions** between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under ultraviolet (UV) sunlight. This process is particularly intense in sunny, warm climates with high traffic or industrial emissions (Jacob, 1999).
- **Impacts**: Ozone is a key component of **photochemical smog**. It causes respiratory irritation, decreased lung function, aggravates asthma, and increases hospital admissions

for cardiopulmonary diseases. Environmentally, it reduces crop yields (e.g., wheat, soybean) and damages forests through oxidative stress (WHO, 2021).

2). Peroxyacetyl Nitrates (PANs)

- **Formation**: PANs are secondary **photochemical oxidants** formed from the reaction of aldehydes (produced by VOC oxidation) with nitrogen dioxide (NO_2) in the presence of sunlight.
- **Impacts**: PANs are strong **eye irritants**, cause breathing discomfort, and are **toxic to vegetation**, reducing photosynthesis. Their stability at lower temperatures allows them to transport NO_x over long distances, thereby contributing to **regional ozone formation** far from urban centers (Finlayson-Pitts & Pitts, 2000; Atkinson, 2000).

3). Aldehydes and Ketones

- **Formation**: These carbonyl compounds are generated both from **incomplete combustion** of fossil fuels and biomass, and from **oxidation of hydrocarbons** in the atmosphere. Formaldehyde and acetaldehyde are among the most abundant.
- **Impacts**: Many aldehydes are **toxic, carcinogenic**, and contribute to **secondary organic aerosol (SOA)** formation. Formaldehyde, for example, is classified as a human carcinogen (IARC, 2012). Beyond health effects, aldehydes play an important role as precursors in smog formation (Carlier et al., 1986).

4). Secondary Aerosols (SOAs and Sulfate/Nitrate Particulates)

- **Formation**: These aerosols form via **gas-to-particle conversion** during the oxidation of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). This produces **sulfates, nitrates, and organic aerosols** that are major components of fine particulate matter ($PM_{2.5}$) (Seinfeld & Pandis, 2016).
- **Impacts**: Secondary aerosols:
  - Reduce **atmospheric visibility** (haze events).
  - Influence **cloud formation and climate** through radiative forcing.
  - Are strongly associated with **cardiovascular and respiratory diseases**, premature mortality, and systemic inflammation (Pope & Dockery, 2006).

I.5. Transport, Transboundary, and Regional Effects

Secondary pollutants differ fundamentally from primary pollutants because they often form far from their emission sources. Their gaseous precursors—such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and ammonia (NH_3)—can remain in the atmosphere for several days and travel hundreds to thousands of kilometers before undergoing photochemical or oxidative transformations. This capacity for long-range transport leads to transboundary pollution episodes, complicating air quality management, as emission sources and impact zones may occur in different countries or even continents (UNECE, 2021; Crippa et al., 2023; Hu et al., 2025).

I.5.1. Tropospheric Ozone

a. Regional Smog Episodes

Elevated ozone concentrations frequently occur in rural and suburban regions downwind of urban or industrial centers. For instance, ozone peaks in southern Europe are often linked to precursor transport from the more industrialized regions of northern and central Europe (EEA, 2023; Velásquez-García et al., 2024).

b. Global Transport

Tropospheric ozone can persist for days to weeks, allowing intercontinental transport. Recent satellite and modeling studies confirm that pollution plumes from East Asia significantly enhance ozone levels across the Pacific Ocean, influencing surface ozone concentrations in North America (Zhan et al., 2023; Lin et al., 2021; Hu et al., 2025).

I.4.2. Secondary Inorganic Aerosols (Sulfates, Nitrates, Ammonium)

a. Acid Deposition

These aerosols dissolve in cloud droplets and rainwater, forming acidic precipitation (acid rain). Acid deposition leads to soil nutrient depletion, freshwater acidification, and biodiversity loss, particularly in sensitive ecosystems such as alpine forests and northern lakes (Fowler et al., 2020; Xu et al., 2022).

b. Long-Range Transport

Historically, sulfate pollution from coal combustion in Western Europe and North America caused acid rain in Scandinavia and Canada. Although emission controls have reduced these impacts, similar transboundary issues are now observed in East and South Asia, where industrial activities and intensive agriculture contribute to regional haze and acid deposition (Tan et al., 2021; Wang et al., 2022; Zhang et al., 2024).

I.5.3. Particulate Matter ($PM_{2.5}$)

a. Cross-Continental Transport

Fine particles ($PM_{2.5}$), including desert dust, sea salt, and biomass-burning aerosols, can be transported across oceans. For example, Saharan dust plumes regularly reach southern and western Europe and occasionally the Americas. Similarly, wildfire smoke from Canada and Siberia has been detected across Europe, the Arctic, and even North Africa (Ansmann et al., 2021; Zhai et al., 2023; Velásquez-García et al., 2024).

b. Health and Climate Effects

$PM_{2.5}$ contributes to respiratory and cardiovascular diseases and plays a crucial role in climate forcing by scattering and absorbing solar radiation. These aerosols also act as cloud condensation nuclei, altering cloud albedo and precipitation patterns (IPCC, 2021; WHO, 2023; Crippa et al., 2023).

I.6. Global Significance

Secondary pollutants contribute not only to regional air quality degradation but also to global environmental change. Their effects extend beyond local ecosystems, influencing atmospheric chemistry, climate regulation, and human health worldwide (Crippa et al., 2023; Hu et al., 2025).

I.6.1. Tropospheric Ozone as a Greenhouse Gas

Tropospheric ozone (O_3) is a unique pollutant because it acts as both a short-lived climate forcer and a toxic air contaminant. According to the **Intergovernmental Panel on Climate Change (IPCC, 2021)**, ozone ranks third among greenhouse gases in terms of radiative forcing, after carbon dioxide (CO_2) and methane (CH_4). It contributes approximately **$0.4\ W/m^2$** to global radiative forcing and plays a significant role in warming the lower atmosphere (Velásquez-García et al., 2024). In addition to its climatic role, elevated ozone levels reduce crop yields, impair photosynthesis, and weaken vegetation resistance to stress, thereby threatening global food security and carbon sequestration capacity (Emberson et al., 2020; Ainsworth et al., 2022).

I.6.2. Secondary Aerosols and Climate Forcing

Secondary inorganic and organic aerosols influence climate in complex ways. On one hand, they **scatter incoming solar radiation**, leading to a **cooling effect** on the Earth's surface (negative radiative forcing of approximately $-0.5\ W/m^2$). On the other hand, these aerosols cause **acid deposition** and **nutrient imbalances** in terrestrial and aquatic ecosystems, affecting biodiversity and soil fertility (Fowler et al., 2020; Zhang et al., 2024). Furthermore, black carbon and certain organic aerosols absorb sunlight, warming the atmosphere and accelerating glacier melting, particularly in polar and high-altitude regions (Bond et al., 2021; Zhai et al., 2023).

I.6.3. Long-Range and Cross-Border Impacts

The global circulation of secondary pollutants underscores the interconnected nature of atmospheric systems. Pollutants emitted in one region can travel across continents, altering air quality and radiative balance in distant areas. For example, studies have shown that **Asian emissions contribute to elevated ozone and particulate concentrations** over the Pacific and North America, while **Saharan dust and biomass-burning aerosols** reach Europe and the Americas (Tan et al., 2021; Hu et al., 2025). Such cross-continental transport complicates the attribution of pollution sources and necessitates coordinated international monitoring and regulation.

I.6.4. International Policy and Cooperation

The global and transboundary impacts of secondary pollutants highlight the importance of **international environmental governance**. Frameworks such as the **Convention on Long-range Transboundary Air Pollution (CLRTAP)** and its **Gothenburg Protocol** under the **United Nations Economic Commission for Europe (UNECE)** have been instrumental in reducing emissions of sulfur oxides, nitrogen oxides, and volatile organic compounds across Europe and North America (UNECE, 2021). Recent initiatives, including the **Task Force on Hemispheric Transport of Air Pollution (HTAP)** and the **Global Methane Pledge (2022)**, aim to strengthen global cooperation by promoting data sharing, emission inventories, and region-specific mitigation strategies (Crippa et al., 2023; Velásquez-García et al., 2024).

I.7. Pollution by the Nature of the Pollutant

Pollution can also be classified according to the **type of contaminant** introduced into the environment. This approach highlights the diversity of pollutants and their distinct effects on ecosystems and human health.

I.7.1. Physical Pollution

Physical pollution refers to disturbances in the physical characteristics of an ecosystem, which can alter habitat quality and species survival.

- **Suspended solids and particulates**: Dust in the air, sediment in rivers, or micro-particles in soil can reduce light penetration, clog fish gills, and carry adsorbed toxins.
- **Thermal pollution**: Typically from power plants and industries discharging heated water into rivers or seas, leading to oxygen depletion and shifts in aquatic biodiversity (e.g., fish kills due to sudden temperature rise).
- **Radioactive pollution**: Caused by nuclear accidents (Chernobyl 1986, Fukushima 2011), uranium mining, or improper waste disposal. It leads to long-term soil, water, and food contamination with isotopes like Cs-137 or Sr-90.
- **Noise pollution**: Urban traffic, airports, and industrial machinery increase stress levels, cause hearing loss in humans, and disturb communication in wildlife (e.g., whales, birds).
- **Light pollution**: Excessive or poorly directed artificial lighting disrupts circadian rhythms, affects nocturnal animals (e.g., sea turtle hatchlings misoriented by coastal lights), and wastes energy resources.

I.7.2. Chemical Pollution

Chemical pollution arises from the release of **toxic substances** into air, water, and soil, often due to industrial, agricultural, or domestic activities.

- **Heavy metals (Pb, Hg, Cd, As)**: Accumulate in food chains, causing neurological, renal, and developmental disorders in humans (e.g., Minamata disease from mercury).
- **Nitrates and phosphates**: Runoff from fertilizers leads to eutrophication, excessive algal blooms, and hypoxic “dead zones” (e.g., Gulf of Mexico).
- **Pesticides and herbicides**: Persistent organic pollutants (POPs) such as DDT and atrazine harm non-target species, reduce biodiversity, and pose risks to human health.
- **Hydrocarbons**: Oil spills (e.g., Deepwater Horizon, 2010) coat aquatic surfaces, reducing oxygen exchange and killing marine life.
- **Detergents and surfactants**: Alter water chemistry, reduce surface tension, and can be toxic to aquatic organisms.
- **Plasticizers (phthalates, bisphenol A)**: Leach from plastics into food and water, disrupting endocrine systems in humans and animals.
- **Pharmaceuticals and personal care products (PPCPs)**: Antibiotics, hormones, and cosmetics detected in wastewater interfere with aquatic organisms’ reproduction and microbial resistance.

- **Eutrophying substances**: Nutrient enrichment causes oxygen depletion, affecting fish populations and aquatic ecosystem balance

I.7.3. Biological Pollution

Biological pollution refers to the introduction and proliferation of living organisms—either pathogens or invasive species—that destabilize ecosystems and threaten health.

- **Pathogenic microorganisms**: Contamination of water bodies by bacteria (e.g., *Escherichia coli*), viruses (e.g., hepatitis A), and parasites causes outbreaks of waterborne diseases (cholera, dysentery).
- **Harmful algal blooms (HABs)**: Cyanobacteria (blue-green algae) release toxins that kill fish, contaminate drinking water, and cause liver and neurological diseases in humans.
- **Invasive alien species**: Species introduced by trade, travel, or aquaculture (e.g., zebra mussel in Europe, water hyacinth in Africa) outcompete native species, disrupt food webs, and alter habitat conditions.

Biological pollution is especially concerning in regions lacking **sanitation infrastructure** and **wastewater treatment**, where pathogen transmission is widespread (Schwarzenbach et al., 2010; WHO, 2023).

I.8. Physical Properties of Pollution

Pollution can manifest in different phases of matter—liquid, gaseous, and solid—each corresponding to specific environmental compartments. This classification highlights the pathways through which contaminants are transported, transformed, and persist in ecosystems.

I.8.1. Liquid Phase

- **Compartments**: Rivers, lakes, wetlands, estuaries, oceans, and groundwater.
- **Pollutants**: Nutrients (nitrates, phosphates), heavy metals (Hg, Pb, Cd, As), pesticides, hydrocarbons (oil spills, PAHs), microplastics, pharmaceuticals, and endocrine-disrupting compounds (EDCs).
- **Consequences**:
    - **Eutrophication** → excessive algal blooms, oxygen depletion, fish mortality, and biodiversity loss (Smith & Schindler, 2009).
    - **Toxicity** → accumulation and biomagnification of heavy metals and persistent organic pollutants (POPs) in aquatic food webs (Boudou & Ribeyre, 1997).

  - **Public health risks** → outbreaks of waterborne diseases such as cholera, hepatitis, and diarrhea caused by microbial contamination (WHO, 2023).
  - **Groundwater vulnerability** → nitrates and pesticides can persist for decades in aquifers, threatening drinking water quality (UNESCO, 2022).

I.8.2. Gaseous Phase

- **Compartments**: Atmosphere (troposphere, stratosphere) and indoor air.
- **Pollutants**:
  - **Primary pollutants**: Carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter (PM_{10}, $PM_{2.5}$).
  - **Secondary pollutants**: Ozone (O_3), peroxyacetyl nitrates (PANs), sulfates, nitrates, and secondary organic aerosols.
- **Consequences**:
  - **Human health** → respiratory diseases (asthma, COPD), cardiovascular disorders, cancer, and premature mortality (WHO, 2021).
  - **Environmental impacts** → acid rain damages forests and freshwater ecosystems; smog reduces visibility and affects urban life (Seinfeld & Pandis, 2016).
  - **Climate change** → greenhouse gases (CO_2, CH_4, N_2O) and black carbon drive global warming, while CFCs deplete the ozone layer (IPCC, 2021).
  - **Agriculture** → ozone stress reduces crop yields (e.g., wheat, soybean, rice) (Ainsworth et al., 2012).

I 8.3. Solid Phase

- **Compartments**: Agricultural lands, urban soils, sediments, industrial zones, and mining areas.
- **Pollutants**: Heavy metals (Cd, Pb, Hg, Cr), pesticides, hydrocarbons, plastics/microplastics, radionuclides, industrial residues, and electronic waste.
- **Consequences**:
  - **Soil degradation** → loss of fertility, nutrient imbalance, acidification, and disruption of microbial communities essential for soil productivity (Alloway, 2013).
  - **Food chain contamination** → toxic metals (e.g., Cd in rice, Pb in vegetables) and pesticide residues accumulate in crops and livestock products, threatening food safety (Nagajyoti et al., 2010).

- **Ecosystem impacts** → decline in soil biodiversity (earthworms, fungi, microbes) and impairment of ecosystem services such as carbon sequestration and nutrient cycling (FAO, 2018).
- **Persistence of contaminants** → unlike air or water, many pollutants (metals, plastics, radionuclides) remain in soils and sediments for centuries, acting as long-term reservoirs (Förstner & Wittmann, 2012).

I.8.4Comparative Overview

Pollutants do not remain confined to a single medium but circulate between **water, air, and soil**, creating a complex web of contamination. Their persistence and impacts vary depending on the environmental compartment in which they accumulate. For example, nutrients in aquatic systems may trigger eutrophication within weeks, while heavy metals deposited in soils or sediments can persist for centuries, threatening ecosystems and human health through **bioaccumulation and trophic transfer**. The following table summarizes the main characteristics of pollution across the three major environmental phases.**Table1.**

Table 1. Comparative Overview of Pollution in Environmental Compartments

Phase	Main Compartments	Key Pollutants	Persistence	Main Impacts
Liquid	Rivers, lakes, oceans, groundwater	Nutrients, heavy metals, pesticides, plastics	Weeks → decades (esp. groundwater)	Eutrophication, toxicity, diseases
Gaseous	Atmosphere, indoor air	CO, SO_2, NO_x, VOCs, PM, O_3	Hours → decades (GHGs)	Smog, respiratory diseases, climate change
Solid	Soil, sediments	Heavy metals, pesticides, plastics	Decades → centuries	Soil infertility, food chain contamination

I.9. Mechanisms of Dispersion and Circulation of Pollutants in the Biosphere

The biosphere functions as an interconnected system where pollutants, once released into one compartment (air, water, soil), can disperse and circulate across multiple pathways. These mechanisms explain the widespread presence of contaminants far from their original emission sources.

I.9.1. Atmospheric Dispersion

Pollutants emitted into the atmosphere undergo both **horizontal transport** (winds, jet streams) and **vertical mixing** (convection, turbulence). Meteorological factors such as temperature inversions, humidity, and precipitation strongly influence their fate. For example, sulfur dioxide (SO_2) and nitrogen oxides (NO_x) can travel hundreds of kilometers before reacting to form acid rain. Volcanic eruptions or nuclear accidents demonstrate the rapid global circulation of aerosols and radioactive isotopes (Holton et al., 1995).

I.9.2. Hydrospheric Transport

In aquatic systems, pollutants are dispersed by currents, tides, and river flows. Water acts as a powerful vector, redistributing nutrients, heavy metals, pesticides, and microplastics over long distances. Oil spills illustrate how hydrodynamic processes can spread contaminants across vast marine areas, while persistent organic pollutants (POPs) accumulate in ocean gyres, forming “plastic soups” (GESAMP, 2015).

I.9.3. Pedospheric Retention and Transfer

Soils act as both sinks and sources of pollutants. Trace elements and organic contaminants may be immobilized by adsorption onto clay minerals and organic matter, or mobilized through erosion, leaching, and volatilization. Erosion by wind and water redistributes contaminated particles to new ecosystems, while soil solution leaching can transfer soluble pollutants into aquifers (Alloway, 2013).

I.9.4. Biological Transport

Living organisms contribute to the redistribution of pollutants through uptake, accumulation, and trophic transfers. Plants absorb metals and organics from soils, while animals bioaccumulate contaminants from food and water. Migratory species (birds, fish, marine mammals) act as biological vectors, transporting pollutants across ecosystems and even continents. For example, seabirds can carry mercury and POPs from marine food webs to terrestrial ecosystems via guano deposition (Blais et al., 2007).

I.9.5. Factors Influencing Dispersion and Circulation

- **Chemical properties**: solubility, volatility, persistence, and lipophilicity determine pollutant mobility.
- **Environmental conditions**: climate, hydrology, pH, redox potential, and soil composition regulate pollutant behavior.

- **Anthropogenic activities**: agriculture, industry, urbanization, and waste disposal increase pollutant fluxes and alter natural cycles.

I.9.6. Examples of Global Circulation

Pollutants released into the environment do not remain confined to their point of emission. Instead, they undergo atmospheric and oceanic transport, chemical transformations, and deposition processes that allow them to travel across continents and oceans. This global circulation explains why contaminants are often detected in remote ecosystems, far from human activities, and why pollution is considered a transboundary issue requiring international cooperation. The following examples illustrate some well-documented cases of long-range transport and redistribution of pollutants in the biosphere.

• The "Grasshopper Effect"

Semi-volatile organic pollutants (SVOCs) such as polychlorinated biphenyls (PCBs), organochlorine pesticides (DDT, lindane), and some polycyclic aromatic hydrocarbons (PAHs) exhibit a phenomenon known as the "grasshopper effect" or "global distillation." In warm regions, these compounds evaporate into the atmosphere, then condense when reaching cooler climates. This process repeats multiple times, enabling their progressive movement toward Polar Regions. As a result, persistent organic pollutants (POPs) are detected in Arctic snow, ice, water, and even in the tissues of indigenous fauna (polar bears, seals, whales), despite the absence of local emission sources (Wania & Mackay, 1996; UNEP, 2002).

• Mercury Global Cycle

Mercury (Hg) is emitted mainly from coal combustion, mining, and waste incineration. In the atmosphere, it exists as elemental mercury (Hg^0) which can travel thousands of kilometers before being oxidized and deposited. Once in aquatic systems, mercury is converted by anaerobic microorganisms into methylmercury (CH_3Hg^+), a highly toxic and bioavailable form. Through bioaccumulation and biomagnification, methylmercury concentrates in fish and marine mammals, ultimately reaching humans via seafood consumption. This explains why populations far from emission zones (e.g., Arctic Inuit communities) exhibit high mercury exposure (Selin, 2009; AMAP, 2011).

• Carbon Cycle Perturbation

Human activities—especially fossil fuel combustion, deforestation, and industrial processes—release large amounts of carbon dioxide (CO_2) into the atmosphere. This anthropogenic

CO_2 is well-mixed globally due to atmospheric circulation and has a long residence time (~50–200 years). Excess CO_2 increases the greenhouse effect, drives global warming, and alters carbon sinks such as forests and oceans. Ocean uptake of CO_2 also leads to acidification, with consequences for coral reefs, shellfish, and marine food webs (IPCC, 2021).

• **Nitrogen and Sulfur Atmospheric Transport**

Reactive nitrogen compounds (NO_x, NH_3) and sulfur dioxide (SO_2), mainly from agriculture and fossil fuel burning, undergo long-range transport before deposition as acid rain. These pollutants acidify soils and aquatic systems, deplete nutrients, and damage forests even in remote regions. Transboundary air pollution in Europe and North America has shown that emissions from one country significantly affect ecosystems in neighboring regions (Galloway et al., 2008; UNECE, 2016).

• **Microplastics and Atmospheric Transport**

Recent studies highlight that microplastics are transported across continents via atmospheric circulation. Fibers and fragments originating from urban dust, synthetic textiles, or degraded plastics can be lifted into the atmosphere, deposited by rain, or carried by wind over long distances. Microplastics have been detected in remote environments, including the Alps, the Arctic, and even Antarctic snow (Bergmann et al., 2019). This demonstrates that global circulation processes also concern emerging pollutants.

I.10. Transfer and Concentration of Pollutants in Biomass

Pollutants introduced into the environment may be absorbed, retained, and accumulated by living organisms, a process that links abiotic compartments (air, water, soil) to the biosphere. This transfer depends on the chemical nature of the pollutant, its bioavailability, and the physiology of organisms (Newman, 2015).

I.10.1. Bioaccumulation in Primary Producers

Plants and photosynthetic organisms (algae, phytoplankton) act as entry points for many pollutants into the food web.

- **Heavy metals** such as cadmium (Cd), lead (Pb), and mercury (Hg) are taken up through root absorption from soils or directly from water. While some micronutrients (e.g., Zn, Cu) are essential, excessive accumulation leads to toxicity.

- **Persistent organic pollutants (POPs)** like polychlorinated biphenyls (PCBs) or pesticides (DDT) are absorbed passively due to their lipophilic nature. They are stored in plant tissues without metabolic degradation.
- **Microplastics** can also be retained in roots or translocated to aerial parts of plants, representing a new emerging pathway of contamination.

I.10.2. Transfer to Herbivores and Consumers

When primary producers are consumed, pollutants are transferred to herbivores and higher trophic levels:

- Metals and POPs, resistant to biodegradation, accumulate in tissues such as liver, kidneys, and fatty deposits.
- Lipid-soluble compounds concentrate in adipose tissues and biomembranes. For example, DDT residues accumulated in herbivorous insects and subsequently in birds.

I.10.3. Biomagnification in Food Chains

Unlike bioaccumulation (within a single organism), **biomagnification** refers to the progressive increase in pollutant concentration along trophic levels (from producers to top predators).

- In aquatic ecosystems, mercury is transformed into methylmercury by microorganisms, a highly toxic form that accumulates in fish (e.g., tuna, swordfish) and reaches high levels in marine mammals and humans (WHO, 2017).
- PCBs and dioxins bioaccumulate in fish and marine mammals, leading to reproductive and neurological disorders.
- In terrestrial systems, carnivorous birds such as peregrine falcons showed eggshell thinning due to DDT, a classic case of biomagnification (Carson, 1962).

I.10.4. Factors Influencing Transfer and Accumulation

- **Chemical properties**: solubility, volatility, lipophilicity, and persistence strongly affect bioavailability.
- **Environmental conditions**: soil pH, redox potential, and organic matter determine the mobility of metals and organics.
- **Biological traits**: feeding habits, lifespan, metabolic capacity, and trophic level regulate accumulation intensity. Long-lived predators (e.g., eagles, seals) show higher concentrations than short-lived prey.

I.10.5. Ecotoxicological and Human Health Impacts

- **Ecosystem effects**: Reduced reproduction, growth inhibition, behavioral alterations, and mortality in exposed fauna and flora.
- **Human health**: Pollutants transferred through the food chain pose risks of neurotoxicity (Hg, Pb), carcinogenicity (dioxins, PAHs), and endocrine disruption (PCBs, pesticides). Traditional diets relying on fish or marine mammals may result in high exposure levels for certain populations.

I.10.6.Half-Life of Pollutants in the Environment

The **residence time** or half-life of pollutants in the atmosphere varies according to their chemical composition, reactivity, and removal processes (deposition, photolysis, microbial degradation). This parameter determines their **spatial distribution**, long-range transport potential, and global impact (IPCC, 2023; WHO, 2023).**Table 2**

Table 2. Atmospheric Lifetimes and Key Characteristics of Major Air Pollutants

Pollutant	Atmospheric Lifetime	Notes
Carbon dioxide (CO_2)	**50–200 years**	**Major greenhouse gas, accumulates in the global carbon cycle.**
Methane (CH_4)	**~10 years**	**Potent greenhouse gas, precursor to tropospheric ozone.**
Nitrous oxide (N_2O)	**~150 years**	**Strong greenhouse gas and ozone-depleting substance.**
Chlorofluorocarbons (CFCs)	**65–130 years**	**Highly persistent, key driver of stratospheric ozone depletion.**
Ozone (O_3, tropospheric)	**Several days**	**Short-lived climate forcer, harmful at ground level.**
Volatile Organic Compounds (VOCs)	**Hours to days**	**Rapidly oxidized, precursors of ozone and secondary organic aerosols.**
Fine Particulate Matter (PM ≤ 1 µm)	**Days to weeks**	**Long-range transport possible, strong health impacts.**
Coarse Particulate Matter (PM 1–10 µm)	**Minutes to days**	**Rapidly deposited near emission sources.**

Groundwater (Smedley & Kinniburgh, 2002).

I.11. Elimination, Degradation, and Persistence of Pollutants

The fate of pollutants in the environment is determined by their degradability, persistence, and ability to resist elimination. While some compounds are efficiently degraded by abiotic and biotic processes, others exhibit extreme recalcitrance, enabling long-term persistence and accumulation.

I.11.1. Persistent Organic Pollutants (POPs)

- **Polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs):**

  Three main degradation pathways have been identified (Hutzinger et al., 1983):

  1. **Hydroxylation** – enzymatic or oxidative introduction of hydroxyl groups.
  2. **Oxidation with chlorine migration** – substitution or rearrangement of chlorine atoms.
  3. **Benzene ring cleavage** – leading to dihydroxydiphenyl ethers, which may undergo hydrolysis to **catechol**, a more degradable intermediate. However, due to their high hydrophobicity and halogenation degree, PCDD/Fs degrade **very slowly**, resulting in **half-lives of several years to decades** in soils and sediments.

- **Polycyclic aromatic hydrocarbons (PAHs):**

  Their persistence depends strongly on **aqueous solubility and lipophilicity**.

  - In the **atmosphere**, PAHs undergo rapid transformation via **photooxidation and chemical oxidation** reactions with hydroxyl radicals, ozone, or nitrogen oxides (Atkinson & Arey, 1994).
  - In **soils and sediments**, **microbial degradation** predominates. Several bacteria and fungi (e.g., *Pseudomonas*, *Mycobacterium*, white-rot fungi) possess **dioxygenases and peroxidases** capable of opening aromatic rings, eventually mineralizing PAHs into CO_2 and H_2O (Cerniglia, 1992).
  - In **mammals**, PAHs are metabolized through **cytochrome P450-mediated hydroxylation**, followed by **conjugation** (glucuronidation, sulfation), increasing solubility for excretion. However, some intermediates (e.g., epoxides) are **mutagenic and carcinogenic**

I.11.2. Metals and Metalloids

In contrast to organic pollutants, **trace elements cannot be degraded**, as they are elemental substances. Their environmental fate is determined by **immobilization, transformation, or redistribution**:

- **Immobilization processes:** sorption onto clays, organic matter, or oxides; precipitation as insoluble salts (carbonates, sulfides).
- **Mobilization processes:** acidification, redox changes, or complexation with dissolved organic ligands may **remobilize metals**, increasing their bioavailability.
- **Persistence:** unlike organics, metals are **permanent pollutants**; remediation relies on dilution, stabilization, or extraction (e.g., phytoremediation)

I.11.3. Key Insights

- **Organic pollutants** (PCDD/Fs, PCBs, PAHs) may be degraded through **photolysis, oxidation, or microbial activity**, but degradation rates vary widely, with halogenated compounds being extremely persistent.
- **Metals** are not degradable; their environmental risk depends on **speciation, mobility, and bioavailability** rather than chemical breakdown.
- Overall, **persistence** is a major criterion defining pollutant risk: while some PAHs degrade within weeks, dioxins and heavy metals may persist for **decades to centuries** in ecosystems.

Chaptre II: Atmospheric Pollution

Chapitre II: Atmospheric Pollution

II. Atmospheric Pollution:

II.1.Definition

Atmospheric pollution is defined as the presence of substances in the air, introduced by natural processes or anthropogenic activities, at concentrations sufficient to produce adverse effects on human health, ecosystems, climate, and materials (Seinfeld & Pandis, 2016; WHO, 2021). While some pollutants occur naturally (e.g., volcanic emissions, dust storms, wildfires), industrialization, urbanization, and intensive energy use have dramatically increased their concentrations beyond natural background levels.

II.2. Atmospheric Stratification

The atmosphere is vertically structured into layers with distinct thermal, chemical, and dynamic characteristics (Seinfeld & Pandis, 2016; Finlayson-Pitts & Pitts, 2000):

- **Troposphere (0–12 km):**
    - Contains ~80% of the atmospheric mass.
    - Site of **weather phenomena**, human activities, and most air pollution processes.
    - Temperature decreases with altitude (~6.5°C/km).
    - Pollutants are well-mixed due to turbulence and convection.
- **Stratosphere (12–50 km):**
    - Characterized by a **temperature inversion** due to absorption of ultraviolet radiation by ozone (O_3).
    - Contains the **ozone layer**, crucial for shielding life from harmful UV-B radiation.
    - Plays a role in **long-range pollutant transport**, especially for chlorofluorocarbons (CFCs) that deplete stratospheric ozone (Solomon, 1999).
- **Mesosphere (50–85 km):**
    - Temperature decreases with altitude.
    - Important for meteoric dust deposition and certain photochemical processes, though minor in anthropogenic pollution.
- **Thermosphere (85–500 km):**
    - High temperatures due to solar radiation absorption by molecular oxygen (O_2) and nitrogen (N_2).
    - Contains the **ionosphere**, essential for radio communication.

- **Exosphere (>500 km):**
    - Outermost layer where atmospheric particles gradually escape into space.
    - Very limited role in pollution processes but important for atmospheric escape dynamics. Figue 1.

Figure 1. Vertical Stratification of the Earth's Atmosphere

II.3.The Atmosphere and Air Pollution

II.3.1 Major Atmospheric Pollutants and Their Characteristics

Air pollutants are classified as primary (directly emitted into the atmosphere) or secondary (formed through chemical or photochemical reactions from precursors). Their properties, lifetimes, and health/ecological impacts vary widely (Seinfeld & Pandis, 2016; Jacobson, 2002).

1). Sulfur Dioxide (SO_2):

a). Definition

Sulfur dioxide (SO_2) is a **toxic, colorless gas** with a sharp, suffocating odor. It belongs to the family of sulfur oxides and is one of the most significant atmospheric pollutants, both for its **direct health effects** and its role as a **precursor of acid rain and secondary particulate matter** (Seinfeld & Pandis, 2016; WHO, 2021)

b). Sources

SO_2 originates from both **natural** and **anthropogenic** processes:

- **Anthropogenic sources**:
    - Combustion of sulfur-containing fossil fuels (coal, oil, petroleum products) in **power plants, refineries, and industrial boilers**.
    - **Smelting of metal ores** (Cu, Zn, Pb) that contain sulfide minerals.
    - Oil refineries and industrial chemical processes.

Natural sources:

- **Volcanic eruptions**, which release large amounts of SO_2 directly into the troposphere and sometimes the stratosphere.
- Oxidation of **dimethyl sulfide (DMS)** emitted by oceans.

2). Nitrogen Oxides ($NO_x = NO + NO_2$)

a). Definition

Nitrogen oxides (NO_x) refer mainly to **nitric oxide (NO)** and **nitrogen dioxide (NO_2)**, two reactive gases that play a crucial role in atmospheric chemistry. They act as **precursors of tropospheric ozone, acid rain, and secondary particulate matter**. NO_x are considered key indicators of air pollution, particularly in urban and industrial areas (Seinfeld & Pandis, 2016; WHO, 2021).

b). Sources

- **Anthropogenic sources**:
    - High-temperature combustion in vehicles, thermal power plants, and industrial furnaces.
    - Biomass burning (forest fires, agricultural residue burning).
    - Use of fossil fuels in residential heating and cooking.
- **Natural sources**:
    - Lightning discharges, producing NO from atmospheric N_2 and O_2.
    - Soil microbial processes (nitrification and denitrification).
    - Wildfires and volcanic emissions.

3). Carbon Monoxide (CO)

a)Definition

Carbon monoxide (CO) is a **colorless, odorless, and tasteless gas**, produced mainly by incomplete combustion of carbon-containing fuels. Although not a greenhouse gas itself, CO plays an **indirect role in climate change** by altering the oxidative capacity of the atmosphere, thereby extending the lifetime of methane (CH_4). It is also a **major toxic air pollutant** due to its strong affinity for hemoglobin (WHO, 2021; Seinfeld & Pandis, 2016).

b). Sources

- **Anthropogenic sources**:
  - Incomplete combustion of fossil fuels (gas**oline, coal, natural gas) in vehicles, industrial processes, and household heating.**
  - Traffic emissions **are the dominant source in urban areas.**
  - **Biomass burning (agricultural residues, domestic wood stoves).**
    - Natural sources**:**
  - Wildfires and volcanic activity**.**
  - **Oxidation of** methane (CH_4) **and other hydrocarbons in the atmosphere.**

4). Ground-Level Ozone (O_3):

a). Definition

Ozone (O_3) is a secondary air pollutant formed in the troposphere through photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight (UV radiation). Unlike stratospheric ozone (beneficial shield against UV rays), tropospheric ozone is harmful to human health, ecosystems, and climate (WHO, 2021; Seinfeld & Pandis, 2016).

b). Sources

- **Anthropogenic precursors**:
  - Vehicle exhaust, industrial emissions, biomass burning (release NO_x and VOCs).
- **Natural precursors**:
  - VOCs emitted from vegetation, wildfires, and lightning (NO_x production).
- **Formation mechanism**:
  - $NO_2 + UV \rightarrow NO + O\bullet$
  - $O\bullet + O_2 \rightarrow O$

5). Particulate Matter (PM):

a). Definition

Particulate matter (PM) refers to a complex mixture of solid and liquid particles suspended in the air, with varying size, composition, and origin. Classified by aerodynamic diameter:

- **PM_{10}**: particles $\leq 10\ \mu m$ (thoracic fraction).

- **$PM_{2.5}$**: particles ≤ 2.5 µm (respirable fraction, penetrates alveoli).
- **Ultrafine particles**: < 0.1 µm, can enter bloodstream (WHO, 2021).

b). Sources

- **Anthropogenic**:
  - Combustion of fossil fuels (vehicles, power plants, industry).
  - Road dust, construction activities.
  - Biomass burning (domestic wood, agricultural residues).
- **Natural**:
  - Dust storms, sea spray, volcanic ash, wildfires.

6). Volatile Organic Compounds (VOCs):

a). Definition

Volatile Organic Compounds (VOCs) are a large group of carbon-based chemicals (excluding CO_2, CO, and carbonates) that easily evaporate at room temperature due to their high vapor pressure. They include hydrocarbons, aldehydes, ketones, alcohols, and aromatics (Atkinson, 2000). VOCs are crucial precursors in the formation of ground-level ozone (O_3) and secondary organic aerosols (SOAs) through photochemical reactions.

b). Sources

- **Anthropogenic**:
  - Fuel combustion (gasoline, diesel).
  - Industrial emissions (petrochemical plants, refineries).
  - Solvents, paints, cleaning products.
  - Cigarette smoke.
- **Biogenic**:
  - Vegetation (isoprene, monoterpenes like α-pinene and limonene).
  - Soil microbes

7). Greenhouse Gases (GHGs)

a). Definition

Greenhouse gases (GHGs) are atmospheric gases that trap infrared radiation emitted by Earth's surface, leading to the greenhouse effect. This process maintains Earth's temperature but, in excess, causes global warming and climate change (IPCC, 2021).

GHGs and Sources

- **Carbon dioxide (CO_2):**
  - Fossil fuel combustion, deforestation, cement production.

- **Methane (CH_4):**
    - Agriculture (rice paddies, ruminants), landfills, fossil fuel extraction.
- **Nitrous oxide (N_2O):**
    - Fertilizers, industrial processes, biomass burning.
- **Halocarbons (CFCs, HCFCs, HFCs):**
    - Refrigerants, propellants, industrial solvents.

In order to provide a comprehensive overview of atmospheric contamination, Table 4 summarizes the major primary and secondary air pollutants. It outlines their main anthropogenic and natural sources, physico-chemical properties, and associated impacts on human health, ecosystems, and climate. This synthesis facilitates a clearer understanding of pollutant dynamics and their role in atmospheric chemistry **table3**

Table 3. Summary of Major Atmospheric Pollutants

Pollutant	Main Sources	Lifetime	Environmental/Health Impacts
SO_2	Fossil fuel burning, volcanoes	Days	Acid rain, PM formation, respiratory problems
NO_x	Vehicles, industry, lightning	Hours–days	O_3 formation, acid rain, eutrophication
CO	Incomplete combustion (traffic, biomass)	Weeks–months	Toxic to humans, affects CH_4 lifetime
O_3 (tropospheric)	Secondary (NO_x + VOCs + UV)	Days	Respiratory irritant, crop damage, climate forcer
PM ($PM_{2.5}$, PM_{10})	Combustion, dust, industry	Days–weeks	Respiratory/cardiovascular diseases, climate forcing
VOCs	Fuels, solvents, biomass, plants	Hours–days	O_3 and SOA formation, carcinogenic
GHGs (CO_2, CH_4, N_2O, CFCs)	Fossil fuels, agriculture, industry	Years–centuries	Global warming, climate change

1). Water Vapor Content

Water vapor is the most abundant and variable constituent of the atmosphere, representing between **0% and 6% of air composition** depending on geographical and climatic conditions (Wallace & Hobbs, 2006). Its concentration is lowest in cold and arid Polar Regions, while it reaches maximum values in warm and humid tropical environments. Unlike other greenhouse gases, water vapor is not directly controlled by anthropogenic emissions but by **temperature-dependent processes** (Held & Soden, 2000).

- **Weather and climate regulation:** Water vapor acts as the most effective natural **greenhouse gas**, absorbing and re-emitting terrestrial infrared radiation. It also enhances **global warming through positive feedback loops**, since warming increases evaporation, leading to higher water vapor concentrations, which in turn intensify warming.
- **Hydrological cycle:** It is a key driver of the **global hydrological cycle**, with evaporation, condensation, and precipitation ensuring the redistribution of water between the atmosphere, land, and oceans (Trenberth et al., 2011).
- **Cloud formation and precipitation:** Once the atmosphere reaches saturation, water vapor condenses into cloud droplets or ice crystals, leading to cloud development and precipitation. These processes are fundamental to **energy exchange** within the climate system and **pollutant scavenging**.
- **Pollutant removal:** Water vapor contributes significantly to the **wet deposition of pollutants** (e.g., acid rain, heavy metals, particulates) through rainfall and snowfall, thus playing a dual role in both cleansing and redistributing contaminants in ecosystems (Seinfeld & Pandis, 2016).

II.4. Mechanisms of Atmospheric Pollution

Atmospheric pollution is governed by a series of interconnected processes that determine the fate of pollutants after their emission into the atmosphere. These mechanisms include emission, transport, transformation, and removal, which together control pollutant distribution, persistence, and impacts on human health, ecosystems, and climate.

II.4.1. Emissions and Sources

- **Primary pollutants:** Directly emitted into the atmosphere (e.g., CO, NO_x, SO_2, VOCs, particulate matter) from combustion processes, industrial activities, and transportation (Jacobson, 2002).
  - **Secondary pollutants:** Formed in the atmosphere through chemical and photochemical reactions (e.g., ozone, peroxyacetyl nitrate (PAN), secondary organic aerosols) (Finlayson-Pitts & Pitts, 2000).

II.4.2. Transport and Dispersion

- Pollutants are transported horizontally and vertically by wind and atmospheric circulation.
- Meteorological parameters (temperature inversions, atmospheric stability, wind speed) control pollutant accumulation or dilution (Wallace & Hobbs, 2006).

II.4.3. Transformation

- **Photochemical reactions:** Sunlight-driven processes (e.g., ozone formation in photochemical smog).
- **Chemical oxidation:** Conversion of SO_2 to H_2SO_4, NO_2 to HNO_3, or VOCs to secondary organic aerosols.
- **Heterogeneous reactions:** Pollutant transformation on particle surfaces or in cloud droplets.

II.4.4. Deposition and Removal

II.4.5. Dry deposition:

Direct absorption of gases and particulates by soil, water, and vegetation.

- **Wet deposition:** Pollutants scavenged by rain, snow, or fog, contributing to **acid rain** and nutrient leaching (Likens & Bormann, 1974).

II.5. Pathways of human exposure include

Humans are exposed to environmental pollutants through several routes:

- **Inhalation**: The primary pathway, involving the direct uptake of gaseous pollutants (e.g., CO, O_3, SO_2, NO_x) and particulate matter ($PM_{2.5}$, PM_{10}) via the respiratory tract.
- **Ingestion**: Consumption of contaminated food and water, a major route for heavy metals (Pb, Hg, Cd, As), pesticides, and persistent organic pollutants (POPs).
- **Dermal absorption**: Direct contact with polluted air, soil, water, or consumer products, leading to the penetration of certain organic compounds and metals through the skin (WHO, 2021; ATSDR, 2022).

II.6. Classification of Pollutants

Atmospheric pollutants are broadly classified into primary and secondary categories, depending on whether they are directly emitted into the atmosphere or formed through subsequent reactions. This distinction is crucial for understanding pollution mechanisms, health impacts, and mitigation strategies.

II.6.1. Primary Pollutants

These are substances directly emitted from both natural and anthropogenic sources in a harmful form. Their atmospheric concentration and subsequent effects depend largely on emission rates, atmospheric dispersion, chemical reactivity, and meteorological conditions (Jacobson, 2002; Seinfeld & Pandis, 2016).

Examples and sources:

- **Sulfur dioxide (SO_2):**

  Released during fossil fuel combustion (coal, oil) and ore smelting, as well as natural sources such as volcanic eruptions. SO_2 is highly soluble in water and rapidly oxidizes in the atmosphere to form **sulfuric acid (H_2SO_4)**, a major component of **acid rain** (Finlayson-Pitts & Pitts, 2000).

- **Nitrogen oxides ($NO_x = NO + NO_2$):**

  Mainly emitted by vehicle exhausts, power plants, and biomass burning. NO is relatively inert, but once oxidized to NO_2, it contributes to **tropospheric ozone (O_3)** and **photochemical smog formation**. NO_2 is also a precursor of **nitric acid (HNO_3)**, contributing to acid rain and eutrophication (WHO, 2021).

- **Carbon monoxide (CO):**

  Produced by incomplete combustion of fossil fuels and biomass (traffic, domestic heating). CO is colorless and odorless but binds to **hemoglobin** with ~250 times greater affinity than oxygen, causing **hypoxia** and cardiovascular stress in humans (EPA, 2020).

- **Volatile Organic Compounds (VOCs):**

  Emitted from solvents, paints, fuel evaporation, and vegetation (biogenic VOCs such as isoprene and terpenes). VOCs are highly reactive and play a crucial role in **ozone formation** and **secondary organic aerosol (SOA) production**. Some VOCs, such as **benzene and formaldehyde**, are known **carcinogens** (Atkinson & Arey, 2003).

- **Particulate Matter (PM):**

  Generated by industrial processes, road traffic, construction, biomass burning, volcanic eruptions, and desert dust storms. PM is classified by size: **PM_{10} (coarse), $PM_{2.5}$ (fine), and ultrafine particles (<0.1 µm)**. Fine and ultrafine particles penetrate deeply into the lungs, enter the bloodstream, and are associated with **respiratory and cardiovascular diseases, cancer, and premature mortality** (Pope & Dockery, 2006). PM also affects the climate by modifying **radiative forcing and cloud microphysics**.

II.6.2. Secondary Pollutants

Secondary pollutants are not directly emitted; instead, they are formed in the atmosphere through physical, chemical, or photochemical transformations involving primary pollutants. Their formation is highly dependent on sunlight intensity, temperature, humidity, and atmospheric chemistry (Seinfeld & Pandis, 2016; Finlayson-Pitts & Pitts, 2000).

Examples and processes:

- **Ozone (O_3):**
  Produced in the troposphere when **nitrogen oxides (NO_x)** and **volatile organic compounds (VOCs)** react under **ultraviolet (UV) radiation**. This makes O_3 a major component of **photochemical smog**. At ground level, it is a **strong oxidant** that irritates the respiratory tract, reduces lung function, and damages vegetation, crops, and natural ecosystems (WHO, 2021).
- **Peroxyacyl nitrates (PANs):**
  Formed by the photochemical reaction of **VOCs with NO_x** in the presence of sunlight. PANs are **highly toxic to plants**, causing leaf necrosis and reduced growth, and also act as **eye and respiratory irritants** in humans (Jacobson, 2002).
- **Acids (H_2SO_4 and HNO_3):**
  Produced through oxidation processes:
- **$SO_2 \rightarrow H_2SO_4$ (sulfuric acid)**
- **$NO_2 \rightarrow HNO_3$ (nitric acid)** These acids dissolve in water droplets, producing **acid rain**, which leads to **soil acidification, freshwater ecosystem damage, leaching of nutrients, and corrosion of buildings and monuments** (Likens & Bormann, 1974).
- **Secondary Organic Aerosols (SOAs):**
  Formed when VOCs (both anthropogenic and biogenic) undergo **oxidation reactions** (by OH radicals, ozone, or NO_3 radicals), producing low-volatility compounds that condense into fine particles ($PM_{2.5}$). SOAs reduce **air quality, visibility**, and contribute to **radiative forcing and climate change** (Hallquist et al., 2009).

II.7. Types of Atmospheric Pollutants

II.7.1. Gaseous Pollutants

Gaseous pollutants encompass a wide range of chemically active and inert compounds, originating from both natural and anthropogenic sources. Their environmental and health impacts depend on their chemical reactivity, atmospheric lifetime, and capacity to undergo secondary transformations (Seinfeld & Pandis, 2016; Finlayson-Pitts & Pitts, 2000).**Table 4**

Table 4. Major Air Pollutayions: Sources and Envirommental-Health Impacts.

Pollutant	Major Sources	Key Environmental and Health Impacts
Sulfur dioxide (SO_2), Sulfur trioxide (SO_3)	Fossil fuel combustion (coal, oil), smelting of sulfide ores, volcanic emissions	Precursor of sulfuric acid → **acid rain**, soil and water acidification, visibility reduction; respiratory irritation, bronchoconstriction in asthmatics (EPA, 2020).
Carbon monoxide (CO)	Incomplete combustion of fossil fuels (vehicle exhaust, residential heating, industry), biomass burning	High affinity for hemoglobin → **carboxyhemoglobin formation**, impaired oxygen transport, hypoxia, cardiovascular stress, neurotoxicity (Raub et al., 2000).
Nitrogen oxides (NO, NO_2)	High-temperature combustion (vehicles, power plants, industry), lightning, biomass burning	Formation of **photochemical smog** and tropospheric ozone, precursor of nitric acid → **acid deposition**; respiratory inflammation, reduced lung function (WHO, 2021).
Ammonia (NH_3)	Agricultural activities (fertilizer application, livestock waste), industrial processes	Neutralizes acidic gases → **secondary $PM_{2.5}$ formation** (ammonium salts); contributes to eutrophication and biodiversity loss; mucous membrane irritation (Erisman et al., 2007).
Volatile Organic Compounds (VOCs) (e.g., benzene, toluene, formaldehyde)	Industrial emissions, fuel evaporation, solvents, biomass burning	Precursor of tropospheric ozone and **secondary organic aerosols**; several VOCs are **toxic or carcinogenic** (e.g., benzene → leukemia risk; formaldehyde → respiratory toxicity, cancer) (IARC, 2012).
Hydrogen sulfide (H_2S), Carbon disulfide (CS_2), Mercaptans	Natural sources (anaerobic decomposition of organic matter), pulp and paper industry,	Strong odor nuisance at low concentrations; at higher levels → **neurotoxicity, eye and respiratory**

	petroleum refining, wastewater treatment	**irritation**, occupational health risks (Guidotti, 2010).

III.7.2.Mechanistic Considerations

Atmospheric pollutants undergo complex **chemical and photochemical transformations** that determine their persistence, secondary formation, and impacts on air quality and climate. Key mechanisms include:

- **Oxidation of SO_2 and NO_x**:

  • **Sulfur dioxide (SO_2)** is oxidized by hydroxyl radicals (OH), ozone (O_3), or hydrogen peroxide (H_2O_2) to form **sulfuric acid (H_2SO_4)**, which readily condenses into fine sulfate aerosols.

  • **Nitrogen oxides (NO_x)** undergo gas-phase and aqueous reactions to produce **nitric acid (HNO_3)**, which contributes to the formation of nitrate aerosols. Together, sulfates and nitrates are major constituents of **fine particulate matter ($PM_{2.5}$)**, linked to adverse health and climatic effects (Seinfeld & Pandis, 2016).
- **Photochemistry of VOCs and NO_x**:

  In the presence of **sunlight**, volatile organic compounds (VOCs) react with **NO_x** to generate reactive radicals and oxygenated species. These reactions lead to the production of **tropospheric ozone (O_3)** and **secondary organic aerosols (SOAs)**, which are central to **urban photochemical smog** episodes (Atkinson, 2000). Such processes are highly sensitive to **meteorological conditions** (temperature, solar radiation, humidity).
- **Role of Ammonia (NH_3)**:

  Ammonia, primarily emitted from agriculture, acts as a **neutralizing agent** by reacting with acidic species (H_2SO_4 and HNO_3), forming **ammonium sulfate ($(NH_4)_2SO_4$)** and **ammonium nitrate (NH_4NO_3)**. These compounds enhance the atmospheric **particle burden**, reduce visibility, and alter **aerosol hygroscopicity**, thereby influencing cloud formation and radiative forcing (Erisman et al., 2007).
- **Carbon Monoxide (CO) Chemistry**:

  Although relatively inert, CO has a **long atmospheric lifetime (~1–2 months)**, allowing it to influence global atmospheric chemistry. It reacts with hydroxyl radicals (OH), thereby reducing the oxidizing capacity of the atmosphere and indirectly **extending the lifetime of methane (CH_4)**. This mechanism contributes to **tropospheric ozone production** and **global warming** (Logan et al., 1981).

II.7.3. Persistent Organic Pollutants (POPs)

Persistent Organic Pollutants (POPs) are a class of synthetic organic chemicals that pose severe risks to ecosystems and human health due to their **resistance to degradation**, **tendency to bioaccumulate**, and **potential for long-range atmospheric transport**. Their persistence allows them to circulate globally, even reaching pristine environments such as the Arctic and Antarctic, far from their sources of emission (UNEP, 2019; Wania & Mackay, 1996).

Key Properties of POPs

- **Persistence**: POPs resist degradation by sunlight (photolysis), chemical processes (oxidation, hydrolysis), and biological metabolism. Their **half-lives in soil, water, and sediment** range from years to several decades (Jones & de Voogt, 1999).
- **Lipophilicity**: They have high **octanol–water partition coefficients (Kow)**, favoring storage in fatty tissues of organisms. This makes them especially dangerous for species with high fat content.
- **Bioaccumulation and Biomagnification**: POPs accumulate in organisms and increase in concentration along the food chain, particularly affecting **top predators** such as large fish, marine mammals, birds of prey, and humans. This process leads to chronic exposure even at low environmental concentrations (EPA, 2023).
- **Long-range Transport**: Through the "**grasshopper effect**," POPs volatilize in warm regions, travel through the atmosphere, and condense in colder climates, explaining their detection in the **Arctic and Antarctic** where they were never used (Wania & Mackay, 1996).

Major Classes of POPs and Sources

- **Polychlorinated dibenzo-p-dioxins (PCDDs) and furans (PCDFs)**: Unintentionally produced as by-products of **waste incineration, forest fires, and metal smelting**. Highly toxic, with **2, 3, 7, 8-TCDD** being the most dangerous dioxin.
- **Polychlorinated biphenyls (PCBs)**: Formerly used in **transformers, capacitors, lubricants, and paints**. Although banned under the **Stockholm Convention (2001)**, they remain in soils, sediments, and building materials.
- **Polycyclic aromatic hydrocarbons (PAHs)**: Formed during **incomplete combustion** of fossil fuels, wood, and biomass. Some PAHs (e.g., benzo[a]pyrene) are recognized as **carcinogenic** (IARC, 2012).
- **Organochlorine pesticides** (e.g., **DDT, aldrin, dieldrin, chlordane, hexachlorobenzene**): Once widely used in agriculture and vector control (e.g., malaria). Many are banned or restricted but persist in soils and aquatic sediments.

- **Chlorinated solvents** (e.g., **trichloroethylene, tetrachloroethylene**): Extensively applied in **metal degreasing, dry cleaning, and chemical industries**, known for groundwater contamination.

II.7.4. Heavy Metals

Heavy metals are inorganic elements with high atomic weight and density, generally above 5 g/cm³. They are environmentally persistent, non-biodegradable, and tend to bioaccumulate and biomagnify through food chains (Jaishankar et al., 2014; Tchounwou et al., 2012). Their toxicity largely depends on **speciation, solubility, and bioavailability** rather than total concentration.**Table 5**

Table 5: Major heavy metals: sources, toxic mechanisms, and associated health effects

Metal	**Main Sources**	**Toxic Mechanisms**	**Health Effects**
Mercury (Hg)	Coal burning, artisanal gold mining, chlor-alkali industry	Binds to sulfhydryl groups (-SH), disrupts enzyme activity, crosses blood-brain barrier (methylmercury)	Severe neurotoxicity, developmental defects, teratogenicity (WHO, 2016)
Lead (Pb)	Leaded fuels, batteries, paints, plumbing	Mimics calcium, interferes with neurotransmission, inhibits heme synthesis	Cognitive deficits, anemia, kidney damage, hypertension (ATSDR, 2020)
Cadmium (Cd)	Metal smelting, phosphate fertilizers, batteries	Binds metallothioneins in liver and kidney, induces oxidative stress	Renal dysfunction, osteoporosis, lung cancer (IARC, 2012)
Arsenic (As)	Mining, pesticides, contaminated groundwater	Interferes with ATP synthesis, generates ROS, alters gene expression	Skin lesions, cardiovascular diseases, cancers (skin, lung, bladder) (Naujokas et al., 2013)
Chromium (Cr, especially Cr VI)	Electroplating, leather tanning, pigments	Strong oxidant, penetrates cells as Cr(VI), reduces to Cr(III) causing DNA damage	Lung cancer, dermatitis, respiratory diseases (Dayan & Paine, 2001)

Nickel (Ni)	Metallurgy, stainless steel, batteries	Binds proteins/DNA, induces oxidative stress, allergenic	Contact dermatitis, lung fibrosis, carcinogenicity (IARC, 2012)
Copper (Cu)	Metallurgy, plumbing, pesticides	Essential element; toxicity arises from free Cu^{2+} generating ROS	Hepatotoxicity, Wilson's disease (ATSDR, 2022)
Zinc (Zn)	Galvanization, fertilizers, industry	Essential trace element; excessive Zn interferes with Cu metabolism	Nausea, immune dysfunction, anemia (Alloway, 2013)
Selenium (Se)	Glass industry, electronics, fertilizers	Narrow range between deficiency and toxicity; excess induces selenosis	Hair/nail brittleness, neurological disorders (Rayman, 2012)

II.7.5. Particulate Matter (PM)

Particulate matter (PM) refers to a heterogeneous mixture of solid and liquid particles suspended in the atmosphere, with variable chemical composition depending on emission sources and atmospheric transformations (Pope & Dockery, 2006; Seinfeld & Pandis, 2016).

a). Classification by aerodynamic diameter:

- **PM_{10} (≤10 µm):** Can penetrate into the upper respiratory tract and bronchi.
- **$PM_{2.5}$ (≤2.5 µm):** Reach the alveolar region, where gas exchange occurs.
- **PM_{1} (≤1 µm, ultrafine particles):** Can cross the alveolo-capillary barrier and enter the bloodstream, reaching systemic circulation (HEI, 2019).

b). Chemical composition:

PM is a carrier of numerous toxic compounds:

- **Metals:** Pb, Cd, Hg, As, Ni, Zn.
- **Organic pollutants:** polycyclic aromatic hydrocarbons (PAHs), dioxins, polychlorinated biphenyls (PCBs).
- **Inorganic salts:** sulfates (SO_4^{2-}), nitrates (NO_3^{-}), ammonium (NH_4^{+}).
- **Black carbon:** from incomplete combustion processes.

c). Health impacts and mechanisms:

- **Inflammation and oxidative stress:** Ultrafine PM generates reactive oxygen species (ROS), leading to DNA damage and altered signaling pathways (Kelly & Fussell, 2012).
- **Cardiovascular effects:** Systemic circulation of $PM_{2.5}$ is linked to atherosclerosis, arrhythmias, and myocardial infarction (Brook et al., 2010).

- **Respiratory diseases:** Exacerbation of asthma, chronic obstructive pulmonary disease (COPD), reduced lung function (WHO, 2021).
- **Carcinogenicity:** PM, especially $PM_{2.5}$, is classified as a **Group 1 carcinogen** by the International Agency for Research on Cancer (IARC, 2013).**Table 6**

Table 6. Particulate matterclassification, penetration, and health impacts

Fraction	**Size**	**Penetration site**	**Health impacts**
PM_{10}	≤10 µm	Upper respiratory tract, bronchi	Respiratory irritation, bronchitis
$PM_{2.5}$	≤2.5 µm	Alveoli	Asthma, COPD, lung cancer, cardiovascular diseases
PM_1	≤1 µm	Bloodstream, systemic circulation	Atherosclerosis, neurotoxicity, systemic inflammation

II.8. Natural Sources of Air Pollution (Extended)

Natural processes contribute significantly to the atmospheric burden of gases and aerosols. Although they occur independently of human activities, their intensity and impacts are increasingly modulated by climate variability and land-use change, often enhancing interactions with anthropogenic pollutants (Andreae & Merlet, 2001; Fowler et al., 2009).

a). Volcanic Eruptions

- Emissions: **SO_2 (20–30 Tg/year)**, **CO_2**, PM (ash, sulfates), halogens (HCl, HF, Br, I).
- Mechanisms:
  - SO_2 oxidized to H_2SO_4 → **sulfate aerosols** that scatter solar radiation.
  - Formation of volcanic smog (*vog*) with local respiratory impacts.
- Impacts: Large eruptions (e.g., Pinatubo 1991) caused **0.5 °C global cooling** due to stratospheric sulfate aerosol loading (Robock, 2000).

b). Wildfires and Biomass Burning

- Emissions: **$PM_{2.5}$ (2–3 g/kg biomass burned)**, black carbon, CO, CH_4, VOCs, NO_x.
- Mechanisms:
  - High-intensity fires release aerosols that influence **cloud condensation nuclei (CCN)** formation.
  - Secondary formation of tropospheric ozone through VOC–NO_x photochemistry.
- Impacts: Regional air quality crises (e.g., 2019 Amazon, 2020 Australia) with acute health effects (Johnston et al., 2012).

c). Biogenic Emissions (Vegetation and Soils)

- Vegetation releases **~1150 TgC/year VOCs**, mainly **isoprene (C_5H_8)**, monoterpenes, sesquiterpenes (Guenther et al., 2012).
- Mechanisms:
  - VOCs oxidized by OH, O_3, NO_3 → formation of **secondary organic aerosols (SOA)**.
  - Interaction with anthropogenic NO_x enhances ozone production.
- Impacts: Major contributor to **regional haze** and **oxidative capacity** of the troposphere.

d). Sea Spray Aerosols

- Composition: NaCl, Mg^{2+}, Ca^{2+}, SO_4^{2-}, organic matter.
- Mechanisms: Bubble bursting at the ocean surface injects coarse and ultrafine aerosols.
- Impacts: Influence radiative balance, cloud albedo, and act as carriers of pollutants over long distances (O'Dowd & de Leeuw, 2007).

e). Dust Storms and Aeolian Processes

- Global flux: **1000–3000 Tg/year mineral dust** injected into the atmosphere (Prospero et al., 2002).
- Composition: Silicates, Al/Fe oxides, $CaCO_3$, clays.
- Impacts:
  - Deterioration of visibility and respiratory health.
  - Long-range transport delivers nutrients (Fe, P) to oceans but also spreads **toxic metals and pathogens**.
  - Enhances heterogeneous chemistry (e.g., uptake of SO_2, NO_x).

II.9. Anthropogenic Sources of Air Pollution

Human activities are the dominant drivers of atmospheric pollution, releasing a wide spectrum of **gaseous and particulate contaminants**. These emissions disrupt air quality, human health, ecosystems, and climate stability (EEA, 2019; Seinfeld & Pandis, 2016).

a). Energy Production

- **Sources** : Coal, oil, and natural gas combustion in power plants, refineries, and furnaces.
- **Pollutants** : SO_2, NO_x, CO_2, PM, trace metals (Hg, As), VOCs.
- **Impacts** : Acid deposition, greenhouse effect, particulate smog, mercury contamination.

b). Transportation

- **Sources**: Road traffic (light/heavy-duty vehicles), aviation, shipping, diesel engines.
- **Pollutants** : CO, NO_x, VOCs, $PM_{2.5}$, ultrafine particles, black carbon.

- **Impacts**: Tropospheric ozone formation, respiratory diseases, climate forcing via black carbon.

c). Industrial Processes

- **Sources**: Metallurgy, cement, glass, pulp and paper, chemical and petrochemical industries.
- **Pollutants**: SO_2, NO_x, CO, HF, HCl, VOCs, PM, dioxins/furans, heavy metals (Pb, Cd, Cr).
- **Impacts**: Local smog, soil/water contamination, occupational health risks, persistent organic pollutants.

d). Agriculture

- **Sources**: Fertilizer application, livestock manure, open burning of residues, pesticides.
- **Pollutants**: NH_3, CH_4, N_2O, VOCs, PM.
- **Impacts**: Secondary PM (ammonium salts), eutrophication, greenhouse forcing, pesticide drift.

e). Waste Management

- **Sources**: Landfills, solid waste incineration, wastewater treatment plants.
- **Pollutants** : CH_4, CO_2, dioxins/furans, VOCs, H_2S, PM.
- **Impacts**: Greenhouse effect, odor nuisance, carcinogenic risk (POPs), bioaerosol release.

f). Residential Sources

- **Sources**: Heating with coal/wood, biomass burning, cooking (especially biomass in developing regions).
- **Pollutants**: CO, $PM_{2.5}$, PAHs, VOCs, black carbon.
- **Impacts**: Indoor air pollution, respiratory infections, household contribution to global black carbon burden.**Table 7**

Table 7. Main Anthropogenic Sources of Air Pollutants (adapted from CORINAIR/EEA, 2019; Seinfeld & Pandis, 2016)

Sector	Main Pollutants	Key Impacts (Health/Environment)
Energy production	SO_2, NO_x, CO_2, PM, Hg	Acid rain, climate change, cardiopulmonary diseases
Transportation	CO, NO_x, VOCs, $PM_{2.5}$, black carbon	Ozone formation, smog, respiratory illness, global warming

Industry	SO_2, NO_x, VOCs, PM, heavy metals	Occupational risks, soil/water contamination, carcinogens
Agriculture	NH_3, CH_4, N_2O, VOCs	PM formation, eutrophication, greenhouse gas emissions
Waste management	CH_4, CO_2, VOCs, dioxins, PM	Greenhouse effect, toxic exposure, odors
Residential sector	CO, $PM_{2.5}$, PAHs, VOCs, black carbon	Indoor air pollution, infections, climate forcing

II.10. Scales of Atmospheric Pollution

Atmospheric pollution manifests at multiple spatial scales, ranging from highly localized urban centers to global circulation patterns. Each scale has distinct pollutant sources, dispersion mechanisms, and health or ecological impacts (Seinfeld & Pandis, 2016; Jacobson, 2002).

II.10.1 Local Pollution

Local air pollution occurs at the **urban and peri-urban scale**, particularly in densely populated areas and industrial zones, where emissions accumulate under limited dispersion conditions.

a). Sources:

- Road traffic (CO, NO_2, PM, VOCs).
- Industrial processes (SO_2, heavy metals, PAHs).
- Residential heating and cooking (CO, $PM_{2.5}$, PAHs).
- Waste burning and local biomass use.

b). Pollutants:

- **Particulate Matter ($PM_{2.5}$, PM_{10}):** penetration into lungs and bloodstream, triggering inflammation.
- **Nitrogen dioxide (NO_2):** irritant gas, precursor of ozone and secondary particles.
- **Sulfur dioxide (SO_2) :** respiratory irritant, acid precursor.
- **Carbon monoxide (CO):** reduces oxygen delivery by binding hemoglobin.
- **Volatile Organic Compounds (VOCs):** contribute to photochemical smog and may be carcinogenic.

c). Health Impacts:

- **Acute effects:** eye/throat irritation, coughing, asthma exacerbation.
- **Chronic effects:** cardiovascular diseases, lung cancer, impaired child development, increased mortality (Pope & Dockery, 2006; WHO, 2021).

d). Environmental Impacts:

- Urban smog formation.
- Material corrosion (metals, buildings).
- Local ecosystem stress (vegetation damage by O_3 and SO_2).

e). Case Example:

- The **London Smog of 1952** caused ~12,000 premature deaths due to high SO_2 and PM concentrations (Bell & Davis, 2001).
- Today, megacities like Delhi, Beijing, and Cairo experience severe local pollution episodes, often exceeding WHO air quality guidelines (Gurjar et al., 2010).

II.10.2. Regional Pollution

Regional pollution refers to **atmospheric contamination that extends beyond local emission areas**, affecting **entire regions or multiple countries** through long-range transport and secondary chemical reactions. It represents a major environmental and health concern due to its **transboundary nature** and ability to alter ecosystems far from emission sources (EEA, 2019; Seinfeld & Pandis, 2016).

Main Processes and Phenomena:

- **Transboundary pollution**

  Pollutants such as SO_2, NO_x, ozone precursors, and fine particles are transported hundreds to thousands of kilometers via prevailing winds. This explains how industrial emissions in one country can affect air quality and ecosystems in neighboring regions (Stohl et al., 2006).

- **Acid rain**

  Sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emitted by fossil fuel combustion react with atmospheric water to form **sulfuric (H_2SO_4)** and **nitric acids (HNO_3)**:

  SO_2 + H_2O + [O]→H_2SO_4;2 NO_2 + H_2O→HNO_3 + HNO_2\text{SO_2 + H_2O + [O]} → \text{H_2SO_4} \quad ; \quad \text{2 NO_2 + H_2O} → \text{HNO_3 + HNO_2}SO_2 + H_2O + [O]→H_2SO_4;2 NO_2 + H_2O→HNO_3 + HNO_2

  Acid rain lowers soil and water pH, leaches nutrients (Ca, Mg), mobilizes toxic metals (Al, Pb), damages forests, aquatic ecosystems, and corrodes infrastructure (Likens & Bormann, 1974; Fowler et al., 2007).

- **Photochemical smog**

  Formed under strong solar radiation in the presence of nitrogen oxides (NO_x) and volatile organic compounds (VOCs):

VOCs + NO_x + UV→O_3 + Peroxyacyl Nitrates (PANs) + aldehydes\text{VOCs + NO_x + UV} → \text{O_3 + Peroxyacyl Nitrates (PANs) + aldehydes}VOCs + NO_x + UV→O_3 + Peroxyacyl Nitrates (PANs) + aldehydes

This mixture of oxidants, primarily ozone (O_3), causes eye irritation, respiratory diseases, crop yield losses, and ecosystem damage (Finlayson-Pitts & Pitts, 2000; Monks et al., 2015).

Examples of Regional Pollution Events:

- The **Acid Rain Crisis in Europe (1970–1990s)** severely impacted Scandinavian forests and lakes, leading to international treaties like the 1979 **Convention on Long-Range Transboundary Air Pollution (CLRTAP)** (Grennfelt et al., 2020).
- Severe **ozone episodes in Los Angeles, Mexico City, and Athens** have demonstrated the widespread impacts of photochemical smog.

II.10.3. Global Pollution

Global pollution refers to **atmospheric disturbances with worldwide consequences**, driven by persistent pollutants that remain in the environment long enough to undergo long-range transport and alter Earth's climate and atmospheric chemistry (Seinfeld & Pandis, 2016).

a). Stratospheric Ozone Depletion

- **Mechanisms:**

  Chlorofluorocarbons (CFCs), halons, and other ozone-depleting substances (ODS) release **chlorine (Cl·) and bromine (Br·) radicals** in the stratosphere upon exposure to ultraviolet (UV) radiation. These radicals catalyze the destruction of ozone (O_3) through chain reactions:

  Cl\cdotp + O_3 → ClO\cdotp + O_2;ClO\cdotp + O → Cl\cdotp + O_2\text{Cl· + O_3 → ClO· + O_2} \quad ; \quad \text{ClO· + O → Cl· + O_2}Cl\cdotp + O_3 → ClO\cdotp + O_2;ClO\cdotp + O → Cl\cdotp + O_2

  One Cl atom can destroy thousands of ozone molecules (Molina & Rowland, 1974).

- **Consequences:**
  - Formation of the **Antarctic ozone hole** due to polar stratospheric clouds and enhanced catalytic cycles (Solomon, 1999).
  - Increased penetration of harmful UV-B radiation, leading to higher risks of skin cancer, cataracts, and reduced phytoplankton productivity (UNEP, 2018).

- **Response:**

  The **Montreal Protocol (1987)** is widely regarded as the most successful international environmental treaty, phasing out CFCs and other ODS (World Meteorological Organization, 2019).

b). Global Warming and Climate Change

- **Mechanisms:**

  Greenhouse gases (GHGs) trap outgoing infrared radiation, enhancing the natural greenhouse effect. Key GHGs include:

  - **Carbon dioxide (CO_2):** fossil fuel combustion, deforestation.
  - **Methane (CH_4):** agriculture (ruminants, rice paddies), fossil fuel extraction.
  - **Nitrous oxide (N_2O):** fertilizers, industrial processes.
  - **Fluorinated gases (CFCs, HFCs, SF_6):** industrial and refrigerant use.
- **Consequences:**
  - **Rising global temperatures:** +1.1 °C since pre-industrial times (IPCC, 2021).
  - **Sea level rise:** thermal expansion and melting ice sheets (Greenland, Antarctica).
  - **Extreme weather events:** heatwaves, storms, floods, and droughts.
  - **Ecosystem impacts:** biodiversity loss, coral bleaching, changes in species distributions.
- **Response:**

  International agreements such as the **Kyoto Protocol (1997)** and the **Paris Agreement (2015)** aim to reduce global GHG emissions and limit warming to well below 2 °C above pre-industrial levels (UNFCCC, 2015).

II.11.Systemic and Multiorgan Effects of Air Pollutants

Prolonged exposure to air pollutants, including **gases (SO_2, NO_x, CO), PM, VOCs, PAHs, and heavy metals**, triggers **chronic systemic health effects**:

- **Inflammation and oxidative stress:** Generation of **reactive oxygen species (ROS)** damages lipids, proteins, and DNA (Brook et al., 2010; Pope & Dockery, 2006).
- **Cardiovascular effects:** Progression of **atherosclerosis**, coagulation disorders, **increased risks of myocardial infarction and stroke**.
- **Respiratory effects:** Chronic bronchitis, COPD exacerbation, decreased lung function.
- **Neurological disorders:** Cognitive decline, **Parkinson's and Alzheimer's disease** associations.
- **Reproductive and endocrine effects:** Altered hormone regulation, reduced fertility, and developmental toxicity.

- **Cancer risk:** Carcinogenic pollutants (PAHs, PCBs, arsenic) increase incidence of lung, bladder, skin, and liver cancers.

Mechanisms:

- Oxidative stress, inflammatory signaling, genotoxicity, epigenetic modifications, and direct tissue damage (WHO, 2013; Brook et al., 2010).

II.12. Epidemiological Evidence

Numerous epidemiological studies have demonstrated a strong association between chronic exposure to air pollution and increased morbidity and mortality from cardiovascular, respiratory, and oncological diseases. Fine particulate matter (PM2.5 and PM10) is considered one of the most harmful components due to its ability to penetrate deep into the respiratory tract and enter the bloodstream, triggering systemic inflammation, oxidative stress, and endothelial dysfunction (Pope & Dockery, 2006; Brook et al., 2010).

Long-term cohort studies, such as the **Harvard Six Cities Study** and the **American Cancer Society (ACS) Study**, have shown consistent evidence that exposure to PM2.5 is associated with premature mortality, particularly from ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (Dockery et al., 1993; Pope et al., 2002). A 16-year follow-up of the ACS cohort indicated that each 10 µg/m³ increase in PM2.5 was associated with an **8–14% increase in cardiopulmonary mortality** (Pope et al., 2002).

Meta-analyses confirm these findings on a global scale. Hoek et al. (2013) reported that long-term exposure to PM2.5 is linked to all-cause mortality, with stronger associations observed for cardiovascular outcomes. The **Global Burden of Disease (GBD) Study** estimated that ambient air pollution accounted for more than **4.2 million premature deaths worldwide in 2015**, mainly due to cardiovascular diseases and respiratory infections (Cohen et al., 2017; WHO, 2016).

More recently, large-scale European studies such as **ESCAPE (European Study of Cohorts for Air Pollution Effects)** have provided additional evidence, showing positive associations between long-term PM2.5 exposure and mortality across several countries, even at concentrations below current WHO guideline levels (Beelen et al., 2014).

Evidence also extends to **cancer epidemiology**. The **International Agency for Research on Cancer (IARC)** has classified outdoor air pollution, particularly PM2.5, as a **Group 1 carcinogen** (IARC, 2013). Associations with lung cancer incidence and mortality have been consistently documented (Raaschou-Nielsen et al., 2013).

II.13. Ecotoxicological Consequences of Air Pollution

a). Effects of Sulfur Dioxide (SO_2)

Sulfur dioxide (SO_2) is one of the earliest recognized phytotoxic air pollutants. Continuous exposure leads to characteristic foliar injuries, typically appearing as **interveinal necrotic lesions** due to differential uptake and accumulation in leaf tissues. The most sensitive species include forage crops such as **alfalfa (Medicago sativa)**, leafy vegetables such as **lettuce (Lactuca sativa)**, and members of the **Cruciferae family**. Cereals (wheat, barley, rye) show moderate sensitivity, whereas **maize, grapevine, apple, plum, and pear trees** are relatively tolerant (Keller, 1984; Wellburn, 1990).

The **mechanism of toxicity** involves rapid dissolution of SO_2 in the moist leaf surface, forming **sulfite (H_2SO_3)** and subsequently **sulfate (H_2SO_4)** ions within the apoplast and mesophyll. Excess sulfite is toxic because it disrupts chloroplast metabolism, inhibits photosynthesis, and causes oxidative stress through the generation of reactive oxygen species (ROS). This results in **chlorosis, necrosis, and reduced crop productivity** (Shrivastava et al., 2019).

SO_2 pollution is also linked to **forest decline** in industrial regions, particularly affecting conifers such as **Norway spruce (Picea abies)** and **Scots pine (Pinus sylvestris)**, due to chronic exposure and synergistic effects with acid rain (Schulze, 1989)

b). Effects of Ozone (O_3)

Ozone (O_3), a secondary pollutant formed by photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs), is among the most phytotoxic air contaminants. Harmful effects are observed at concentrations as low as **20 ppb**, with severe damage above **100 ppb**, leading to visible injury and long-term declines in vegetation productivity (Fuhrer, 2009).

Visible symptoms vary by species:

- **Deciduous trees** (maple, poplar, birch): small grayish stipples and necrotic patches.
- **Cultivated plants** (e.g., beans, tobacco, cotton, lettuce): interveinal necrosis, chlorosis, and accelerated senescence.
- **Cotton and peach trees** are particularly sensitive, while crops such as **beets, clover, and sorghum** show greater resistance (Emberson et al., 2009).

At the **cellular level**, ozone penetrates through stomata and decomposes to form **ROS** (e.g., singlet oxygen, hydroxyl radicals, superoxide anions). These molecules induce **lipid**

peroxidation, protein oxidation, and DNA damage, which trigger programmed cell death (apoptosis-like pathways) in leaf tissues (Ainsworth et al., 2012).

Chronic O_3 exposure reduces **photosynthetic efficiency, biomass accumulation, and crop yield**, posing a major risk to global food security. The **UNEP/WMO Global Assessment (2011)** estimated that ozone reduces global crop yields of wheat, rice, soybean, and maize by **7–12% annually**, representing significant economic losses.

c). Effects of Nitrogen Oxides (NO_x)

Among nitrogen oxides, nitrogen dioxide (NO_2) is the only one with significant phytotoxicity, though it is less ecotoxic than ozone. Studies have shown that the combined effects of phyto-oxidants (ozone, PAN, and NO_x) can severely reduce forest primary productivity. For example, 30-year-old trees in polluted areas have been observed to produce biomass at only one-fifth the rate of similar trees in cleaner environments.

d). Effects of Fluorine

Fluorine (F) and its derivatives (e.g., hydrogen fluoride, HF; silicon tetrafluoride, SiF_4) have **no physiological role in plants** but become toxic when present at elevated concentrations in the atmosphere.

Pathways of contamination:

- **Stomatal absorption:** gaseous fluorine compounds penetrate leaves through stomata, where they dissolve in cellular fluids.
- **Root absorption:** fluorine deposited on soil via dry fallout or rainfall dissolves and is absorbed by plant roots.

Plant toxicity:

- Fluoride accumulates in the **apical foliar parenchyma**, initially producing **chlorotic lesions** that appear **gray or greenish-gray**, eventually turning **necrotic brown**.
- Sensitive plants include **grapevine, apricot, peach, and gladiolus**, whereas **maize and barley** are more tolerant (Miller, 1993).
- Chronic fluoride exposure reduces photosynthesis and biomass accumulation, leading to growth inhibition.

Animal and insect toxicity:

- In livestock, bioaccumulation of fluorine in forage leads to **fluorosis**, characterized by **dental mottling, skeletal deformities, cachexia, and reduced milk production** (Gupta et al., 2009).
- In apiculture, fluorine derivatives act as **potent insecticides**, causing colony collapse and threatening pollination services (Sharma et al., 2006).

e). Effects of Acid Rain

Acid rain results from atmospheric transformation of **SO_2** and **NO_x**, which react with water vapor to form **sulfuric acid (H_2SO_4)** and **nitric acid (HNO_3)**. This lowers precipitation pH below natural levels ($pH < 5.6$), with multiple ecological impacts.

II.14.Ecological and Environmental Impacts of Air Pollution

II.14.1. Effects on forests and soils

- **Tree weakening**: Air pollutants such as ozone (O_3), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) directly damage leaf tissues, impairing photosynthesis and reducing carbohydrate production. Visible symptoms include **chlorosis** (loss of leaf pigmentation), **necrotic spots**, **premature defoliation**, and **reduced growth rates**.

  These physiological impairments lower the energy reserves of trees, making them more susceptible to **secondary stressors**, including insect infestations, fungal pathogens, and prolonged drought periods. Over time, this contributes to forest decline and reduced productivity (Cape, 2008).

- **Soil acidification and nutrient leaching**: Acidic deposition (“acid rain”), primarily caused by SO_2 and NO_x emissions, leads to a **progressive decline in soil pH**. This process accelerates the **leaching of essential cations** such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), which are vital for tree nutrition. As base cations are lost, soils become impoverished, reducing their buffering capacity. Moreover, the release of toxic ions like aluminum (Al^{3+}) can damage root systems. In parallel, **nitrifying microorganisms** (responsible for converting ammonium into nitrate) decline in abundance and activity, leading to a **reduction in soil nitrate availability** and altered nutrient cycling. These changes impair forest productivity and increase vulnerability to environmental stresses (Driscoll et al., 2001).

- **Decline of mycorrhizal fungi**: Mycorrhizal fungi form mutualistic associations with tree roots, enhancing the uptake of phosphorus, nitrogen, and water. Air pollution disrupts this symbiosis in several ways. Soil acidification decreases fungal diversity and favors acid-tolerant species, reducing overall functional diversity. Additionally, acidified soils mobilize heavy metals (Al^{3+}, Cd^{2+}, Pb^{2+}) that are toxic to fungal hyphae, thereby reducing root colonization. Pollutants such as ozone and NO_x also cause **oxidative stress**, disturbing carbon allocation between trees and fungi. As a result, weakened trees provide fewer carbohydrates to the mycelium, reducing fungal growth and activity. The ecological consequences are profound:

  - **Reduced nutrient acquisition** (phosphorus, nitrogen, potassium), leading to physiological deficiencies in trees.
  - **Lower drought tolerance**, since mycorrhizal networks normally extend the effective root system and improve water uptake.
  - **Loss of forest resilience**, making ecosystems more vulnerable to climate change, pests, and diseases (Smith & Read, 2008; Parrent et al., 2007).

II.14.2. Effects on aquatic ecosystems

- **Acidification of lakes and streams** disrupts **fish reproduction**, impairs **litter decomposition** (Dangles et al., 2004), and increases **amphibian egg and larval mortality** (Walker et al., 2010; Luquet et al., 2012).
- Species with permeable skin, such as amphibians, are particularly at risk. Mortality rates rise sharply at $pH < 5$, reducing biodiversity in acidified habitats (Nourris, 2007).

II.14.3. Mobilization of toxic metals

- Acidification solubilizes toxic metals such as **aluminum (Al^{3+})**, which interferes with plant root growth and damages fish gills, impairing respiration (Baker et al., 1996).

II.14.4. Geographical distribution

- Due to strict **air pollution controls**, acid rain damage has decreased significantly in **Europe and North America** since the 1980s.
- However, it remains a **major concern in rapidly industrializing countries**, particularly **China and India**, where reliance on coal continues to drive **acid deposition** (Larssen et al., 2006).

II 15. Global issues of Air Pollution

- **Climate change:** greenhouse gases (CO_2, CH_4, N_2O, tropospheric O_3) alter Earth’s radiative balance, leading to global warming, sea-level rise, and extreme weather events. Black carbon aerosols also contribute by absorbing solar radiation and accelerating glacier melting (IPCC, 2021).
- **Stratospheric ozone depletion:** chlorofluorocarbons (CFCs), halons, and related compounds release chlorine and bromine radicals that destroy ozone molecules, thinning the ozone layer. This increases ultraviolet-B (UV-B) radiation reaching Earth’s surface, with consequences for human health (skin cancers, cataracts) and ecosystems (UNEP, 2019).

Thus, the **environmental issues related to air pollutants are multidimensional**, ranging from localized toxicity to far-reaching global crises. Effective management requires integrated policies that simultaneously address urban air quality, regional ecosystem protection, and mitigation of global climate risks.

II.15.1.The Greenhouse Effect (Global Scale)

The **greenhouse effect** is a natural atmospheric process that maintains the Earth's surface temperature within a habitable range. It occurs when **greenhouse gases (GHGs)** absorb and re-emit part of the infrared radiation emitted by the Earth's surface, trapping heat in the lower atmosphere (IPCC, 2021). Without this natural effect, the average global temperature would be approximately **–18 °C**, instead of the current **+15 °C**, making life on Earth impossible (Lacis et al., 2010).

a). Key natural greenhouse gases include:

- **Water vapor (H_2O):** the most abundant GHG, responsible for ~50% of the natural greenhouse effect, though its concentration is controlled by temperature-dependent evaporation and condensation cycles.
- **Carbon dioxide (CO_2):** contributes ~25% of the natural effect. Since the Industrial Revolution, atmospheric CO_2 levels have increased from ~280 ppm to over **420 ppm in 2022**, mainly due to fossil fuel combustion, cement production, and deforestation (Friedlingstein et al., 2022).
- **Methane (CH_4):** with a shorter atmospheric lifetime (~12 years) but a **global warming potential (GWP) ~28–34 times higher** than CO_2 over 100 years, largely emitted by ruminant livestock, rice cultivation, fossil fuel extraction, and landfills.
- **Nitrous oxide (N_2O):** with a lifetime of ~120 years and a GWP ~265 times that of CO_2, primarily originating from agricultural soils, fertilizers, and industrial activities.

b). Synthetic greenhouse gases also play a major role:

- **Chlorofluorocarbons (CFCs):** potent GHGs that also deplete stratospheric ozone, now largely phased out under the Montreal Protocol.
- **Hydrofluorocarbons (HFCs):** replacements for CFCs in refrigeration and air conditioning; although ozone-friendly, they remain highly effective GHGs with GWPs ranging from hundreds to thousands (Montzka et al., 2018).

c). Amplifying feedbacks further intensify anthropogenic warming:

- **Ice–albedo feedback:** melting of polar ice reduces Earth's reflectivity, increasing absorption of solar radiation.
- **Water vapor feedback:** warming enhances evaporation, increasing atmospheric H_2O concentration, which strengthens the greenhouse effect.
- **Permafrost thawing:** releases stored CH_4 and CO_2, adding to atmospheric GHGs.

As a result, the **enhanced greenhouse effect** is the primary driver of **climate change**, manifested by rising global temperatures, shifts in precipitation patterns, increased frequency of extreme weather events, glacier retreat, and sea level rise.

d). Principal greenhouse gases and their sources:

- **Carbon dioxide (CO_2):** Fossil fuel combustion, deforestation, and cement production.
- **Methane (CH_4):** Agriculture (livestock, rice cultivation), landfills, and fossil fuel extraction.
- **Nitrous oxide (N_2O):** Fertilizer application, agriculture, and industrial processes.
- **CFCs and HFCs:** Refrigeration, air conditioning, and aerosol sprays.

II.15.2.The Role of Climate Change in the Evolution of Air Pollution

Climate change and air pollution are intimately linked through complex feedback mechanisms. Rising global temperatures, changes in atmospheric circulation, and altered precipitation patterns directly affect the formation, dispersion, and persistence of air pollutants. Among the most critical are **tropospheric ozone (O_3)** and **fine particulate matter ($PM_{2.5}$)**, both of which represent major contributors to global disease burden and environmental degradation (Fiore et al., 2015).

a). Tropospheric ozone (O_3):

- Ozone is a secondary pollutant formed by photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight.
- **Rising temperatures** accelerate these reactions, especially during summer heatwaves, leading to higher ozone concentrations (Jacob & Winner, 2009).
- Extreme events illustrate this link: during heatwaves, ozone levels often exceed **75 parts per billion (ppb)** under conditions of **>32 °C**, significantly exacerbating respiratory morbidity (e.g., asthma, chronic obstructive pulmonary disease) and cardiovascular mortality.
- Climate change also prolongs the ozone season, extending exposure risks beyond summer months (Coates et al., 2016).

b). Fine particulate matter ($PM_{2.5}$):

- $PM_{2.5}$ concentrations are influenced by both meteorology and emissions. Climate change affects their levels via:
    - **Stagnant air masses** and reduced ventilation, leading to pollutant accumulation.
    - **Changes in precipitation patterns**, reducing wet deposition and enhancing particle persistence in the atmosphere.

  - **Wildfires**, which are becoming more frequent and intense under warming climates, constitute a growing source of $PM_{2.5}$, black carbon, and other hazardous aerosols (Spracklen et al., 2009).
- Elevated $PM_{2.5}$ has been strongly associated with premature mortality, particularly from cardiovascular and respiratory diseases (WHO, 2016).

c). Climate–pollution interactions:

- Climate change modifies **pollutant transport** through altered wind patterns, enhancing transboundary pollution episodes.
- **Feedback loops** amplify risks: for example, black carbon deposited on snow and ice accelerates melting, which in turn reinforces warming and promotes further pollutant release from permafrost and biomass burning.
- Thus, climate change not only exacerbates air pollution episodes but also undermines mitigation efforts aimed at protecting public health.

II.15.4. Positive Feedback Loops between Climate Change and Air Pollution

Climate change and air pollution are tightly interconnected through **reinforcing feedback mechanisms**, creating a vicious cycle that amplifies both warming and pollution impacts.

a). Energy Use and Fossil Fuel Emissions

- **Heatwaves** increase the use of air conditioning and refrigeration.
- In regions dependent on **coal, oil, or gas**, this leads to greater emissions of **CO_2, CH_4, SO_2, NO_x, and $PM_{2.5}$**.
- These emissions intensify the **greenhouse effect** while deteriorating air quality, aggravating cardiovascular and respiratory diseases (Koplitz et al., 2017).

b). Extreme Weather Events and Pollution Peaks

- **Wildfires**: More frequent under hot and dry climates, they release massive quantities of $PM_{2.5}$, black carbon, and ozone precursors. Smoke can travel thousands of kilometers, affecting distant populations (Jaffe & Wigder, 2012).
- **Storms and floods**: Mobilize industrial pollutants, pesticides, and sewage, creating secondary contamination sources.
- **Droughts**: Increase dust storms, worsening particulate pollution in arid regions (Middle East, North Africa, Central Asia).

c). Sea Level Rise and Coastal Pollution

- With projected sea level rise of **0.15–1 m by 2100** (IPCC, 2021), coastal cities face **saltwater intrusion** into freshwater aquifers.

- Adaptation strategies such as **desalination plants** and **pumping systems** require massive energy inputs. If powered by fossil fuels, these systems amplify GHG emissions.

d). Cryosphere Feedbacks

The **cryosphere**—comprising glaciers, snow, permafrost, and sea ice—plays a critical role in regulating the Earth's energy balance and carbon cycle. Climate change and air pollution interact strongly within this system, creating **powerful positive feedback loops** that accelerate global warming.

• Permafrost thawing and greenhouse gas release

- Permafrost soils store nearly **1,500 gigatons of organic carbon**, almost twice the amount currently in the atmosphere.
- With rising temperatures, permafrost thaws and organic matter decomposes, releasing **methane (CH_4)** and **carbon dioxide (CO_2)** into the atmosphere (Schuur et al., 2015).
- Methane is particularly potent, with a **global warming potential ~28 times greater than CO_2 over 100 years**, amplifying climate forcing.
- This phenomenon is often described as a **"tipping point"**, since permafrost carbon emissions could continue even if anthropogenic emissions are reduced.

• Glacier and snow melt, albedo effect, and black carbon deposition

- Ice and snow surfaces have a high **albedo** (reflectivity), bouncing much of the Sun's radiation back into space.
- Melting reduces surface albedo, exposing darker ground or ocean surfaces that absorb more heat, thereby accelerating warming (Hall & Qu, 2006).
- Additionally, **black carbon (soot)** from incomplete combustion of fossil fuels, wildfires, and biomass burning is deposited on snow and ice surfaces.
- This reduces albedo even further and accelerates melting, especially in sensitive regions like the **Arctic** and **Himalayas** (Flanner et al., 2007).

• Sea ice decline and climate feedbacks

- The reduction of **Arctic sea ice** not only accelerates warming through albedo loss but also alters **atmospheric circulation patterns**, potentially intensifying extreme weather events at mid-latitudes (Screen & Simmonds, 2010).
- The opening of Arctic sea routes may increase **shipping traffic**, further contributing to black carbon deposition and compounding feedbacks.

II.15.5. Public Health Burden and Social Impacts

Air pollution and climate change jointly amplify health risks and deepen social inequalities, creating a cycle of vulnerability and instability.

- **Rising global health burden**
  In addition to respiratory and cardiovascular diseases, fine particulates ($PM_{2.5}$) are linked to diabetes, cognitive decline, and adverse birth outcomes. Climate-amplified exposure, especially during heatwaves, exacerbates these impacts, with urban populations facing the highest risks due to the "urban heat island" effect (Landrigan et al., 2018).
- **Unequal exposure and vulnerability**
  Marginalized communities, including low-income groups and populations in developing countries, are disproportionately exposed to both air pollution hotspots and climate-related hazards. This inequity widens global health disparities, raising ethical and governance challenges.
- **Economic and labor market impacts**
  Loss of working hours due to extreme heat is projected to reach 2.2% of total global working hours by 2030, equivalent to 80 million full-time jobs, with substantial economic losses (ILO, 2019). When combined with healthcare costs from air pollution-related diseases, the economic toll becomes severe.
- **Migration, security, and governance pressures**
  Climate-induced migration—triggered by crop failure, water scarcity, or extreme weather—intensifies urban overcrowding and social tensions. Governments face mounting challenges to balance energy demands, economic stability, and environmental protection, creating potential risks for political instability.

II.15.6. Stratospheric Ozone Depletion ("Ozone Hole")

The stratospheric ozone layer is often described as the Earth's "protective shield" because it filters out much of the Sun's harmful ultraviolet (UV) radiation. Without this natural barrier, life on land and in aquatic systems would be severely threatened by increased risks of skin cancer, eye damage, reduced agricultural productivity, and disruptions in ecosystems. However, since the mid-20th century, human-made chemicals have damaged this layer, especially over Polar Regions, leading to the phenomenon widely known as the "ozone hole."

a). Formation and Importance of Stratospheric Ozone

The stratospheric ozone layer, found between 15 and 35 km altitude, is created by photochemical reactions:

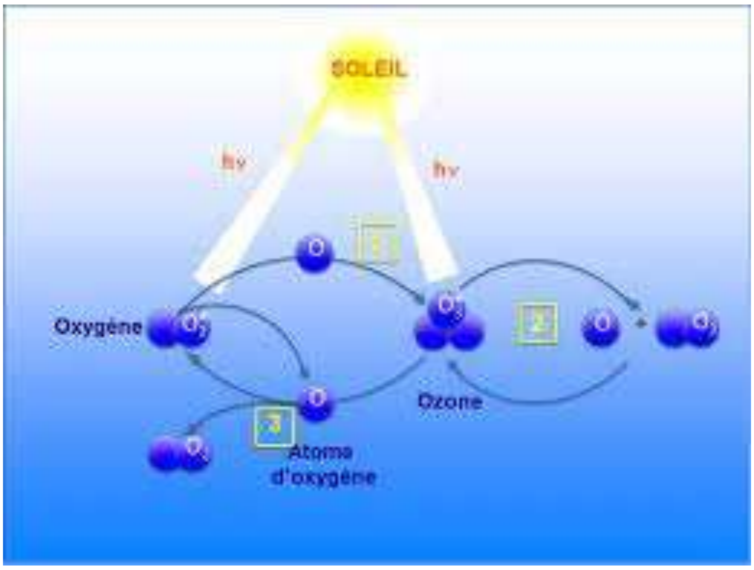
- **Oxygen photolysis:**

  $(O_2 + h\nu \; (\lambda < 240 \, nm) \rightarrow 2O)$

- **Ozone formation:**

  $(O + O_2 \rightarrow O_3)$

About 90% of atmospheric ozone resides in this layer. It absorbs harmful UV-B (280–315 nm) and part of UV-C radiation, shielding organisms from DNA damage, skin cancer, cataracts, and ecological disturbances (WMO, 2018).**Figue 2**



Figue 2. The Ozone Cycle in the Stratosphere"

b). Human Causes of Ozone Depletion

Ozone loss mainly results from persistent halogenated compounds produced by human activities:

- **Chlorofluorocarbons (CFCs):** refrigeration, aerosols, solvents.
- **Halons:** fire suppression systems.
- **Hydrochlorofluorocarbons (HCFCs):** temporary CFC substitutes.
- **Methyl bromide (CH_3Br):** former agricultural fumigant.

These compounds, due to their stability, reach the stratosphere where UV radiation breaks them down, releasing chlorine (Cl•) and bromine (Br•) radicals. For example:

- $(CFCl_3 + h\nu \rightarrow CFCl_2 + Cl\bullet)$
- $(Cl\bullet + O_3 \rightarrow ClO\bullet + O_2)$

One chlorine atom can destroy up to 100,000 ozone molecules (Molina & Rowland, 1974). Bromine, though less abundant, is ~60 times more destructive (Solomon, 1999).

Polar Stratospheric Clouds (PSCs) and Seasonal Ozone Hole

- In polar winters, stratospheric temperatures drop below –80 °C, forming PSCs.

- These clouds enable reactions that convert inactive chlorine ($ClONO_2$, HCl) into reactive forms (Cl_2, HOCl).
- With spring sunlight, photolysis liberates Cl•, triggering massive ozone loss.

The Antarctic ozone hole appears annually from September to November, with ozone dropping below 220 Dobson Units (DU). The Arctic is less affected due to generally higher stratospheric temperatures.

c). Consequences of Ozone Depletion

- **Human health:** higher rates of skin cancers (melanoma, non-melanoma), cataracts, and immune suppression (WHO, 2003).
- **Ecosystems:** reduced phytoplankton productivity, marine food web disruption, crop yield losses, altered terrestrial biodiversity, and UV-B sensitivity in amphibian eggs and larvae (Bais et al., 2015).
- **Materials and economy:** faster degradation of plastics, paints, and building materials; increased healthcare and agricultural costs.

d). The Montreal Protocol and Global Progress

The **Montreal Protocol (1987)** is considered the most successful environmental treaty:

- CFCs and halons phased out in developed countries in the mid-1990s, later in developing countries.
- HCFCs and HFCs (also potent greenhouse gases) regulated under the **Kigali Amendment (2016)**.
- Without the protocol, ozone depletion would have been catastrophic, with UV radiation up to 200% higher by 2065 (Newman et al., 2009).

e). Signs of Recovery:

- Since the early 2000s, satellite data show gradual ozone recovery.
- The Antarctic ozone hole is shrinking in size and depth, despite yearly variations (WMO, 2018; NASA, 2021).
- Full recovery is projected globally by 2040–2060, and over Antarctica by ~2060.

f). Climate Co-Benefits:

As many ozone-depleting substances are also greenhouse gases, the Montreal Protocol is estimated to have prevented 0.5–1 °C of additional global warming by 2100 (Velders et al., 2007).

II.15.7. Urban Smog Phenomena

The term *smog*—a blend of *smoke* and *fog*—refers to air pollution episodes in urban areas where pollutants accumulate under unfavorable meteorological conditions. Two major types are generally distinguished: industrial smog (sulfurous) and photochemical smog.

a). Industrial Smog (Sulfurous Smog)

Industrial smog is mainly associated with the massive burning of coal and occurs under three conditions:

- **Temperature inversion**: A warm air layer traps cooler, denser air at the surface, preventing pollutant dispersion.
- **High emissions of SO_2 and particulate matter**: From coal combustion, power plants, and heavy industry.
- **High humidity**: Promotes conversion of SO_2 into H_2SO_4 aerosols, enhancing smog density.

Historical case:

The **London Great Smog of December 1952** caused ~4,000 immediate deaths and an estimated **12,000 excess fatalities** over subsequent weeks due to respiratory and cardiovascular complications (Bell & Davis, 2001).

Current relevance:

While sulfurous smog has largely declined in Europe and North America due to pollution controls and energy transitions, it remains a **major issue in rapidly industrializing countries** (e.g., northern China, India, Mongolia), particularly during winter heating seasons (Chen et al., 2017).

b). Photochemical Smog

Photochemical smog, often called **"Los Angeles-type smog"**, arises from the interaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under intense solar radiation.

Key mechanisms (Seinfeld & Pandis, 2016):

- Emission of NO and NO_2 from vehicles and industrial combustion.
- Under sunlight, NO_2 photolyzes to produce atomic oxygen:
  NO2+hν→NO+ONO_{2} + h\nu \rightarrow NO + ONO2+hν→NO+O
- The free oxygen reacts with O_2 to form ozone (O_3).
- O_3, NO_x, and VOCs react further, producing secondary pollutants such as **peroxyacetyl nitrates (PANs)**, aldehydes, and other oxidants.

Characteristics:

- More prevalent in **summer**, during high solar radiation and temperatures.
- Irritating to the eyes, nose, and throat; reduces lung function and exacerbates asthma.
- Ground-level ozone, a major component, is a **criteria pollutant** regulated worldwide.

Case examples:

- Los Angeles (USA): Chronic smog episodes since the 1940s.
- Mexico City and Santiago (Chile): High-altitude cities prone to photochemical smog due to geographical basin effects.
- Beijing and New Delhi: Frequent severe smog episodes combining photochemical and industrial smog dynamics (Guttikunda & Gurjar, 2012).

c). Comparative Synthesis

To provide a clearer understanding of the distinctive features of the two major types of urban smog, **industrial (sulfurous) smog** and **photochemical smog**, a comparative overview is presented in the following table. This synthesis emphasizes differences in precursor emissions, meteorological drivers, pollutant composition, health outcomes, and control strategies. It further underlines that effective mitigation requires context-specific approaches adapted to both the dominant sources and the prevailing environmental conditions.**Table 8**

Table 8. Comparative synthesis of industrial smog and photochemical smog in terms of sources, impacts, and mitigation strategies.

Aspect	Industrial Smog (Sulfurous)	Photochemical Smog
Primary precursors	SO_2, PM from coal combustion	NO_x, VOCs from vehicles & solvents
Meteorological conditions	Cold, humid air with temperature inversion	Warm, sunny conditions with stagnant air
Main pollutants	SO_2, H_2SO_4 aerosols, soot	O_3, PANs, aldehydes, secondary oxidants
Health impacts	Respiratory illnesses, cardiovascular stress, acid aerosols	Eye irritation, asthma, reduced lung function, oxidative stress
Control focus	Stationary sources (power plants, industries)	Mobile sources (vehicles, transport sector)
Technological measures	Flue-gas desulfurization, particulate filters, fuel switching	Catalytic converters, clean fuels, EV adoption

Regulatory framework	Clean Air Acts (e.g., UK, 1956); SO_2 emission caps	Ozone reduction programs, vehicle emission standards
Case study	London Great Smog (1952) → Clean Air Act	Los Angeles smog (1970s) → vehicle emission reforms

II.15.8. Acidification and Photochemistry: Regional/Continental Scale (Mesoclimates)

Acidification and photochemical processes represent major regional and continental environmental challenges. These phenomena are not confined to urban or industrial centers but extend over vast areas, altering the chemical balance of soils, surface waters, and ecosystems. Understanding their mechanisms is essential for assessing their ecological consequences and guiding pollution control policies (Seinfeld & Pandis, 2016).

II.15.8.1Acid Rain

Acid rain is one of the most striking manifestations of atmospheric pollution. It is characterized by the presence of strong acids in rainwater, leading to abnormally low pH values. While natural rainwater typically has a slightly acidic pH (around 5.6 due to dissolved CO_2), in unpolluted continental environments it remains above 6, as confirmed by ice core records (Likens & Bormann, 1974). In extreme cases of severe pollution, rainwater pH may drop below 3, with profound impacts on ecosystems and human-made structures.

a) Mechanism of Acid Rain Formation

The formation of acid rain results primarily from the emission of sulfur and nitrogen oxides during fossil fuel combustion (coal, fuel oil, diesel). These compounds undergo chemical transformations in the atmosphere, leading to the production of strong acids such as sulfuric and nitric acids. Additional pollutants, such as hydrochloric acid released during the incineration of plastics or ammonia from agricultural activities, can also contribute to acid deposition. The main reactions responsible for generating acidity are as follows:

$SO_2 + \frac{1}{2} O_2 + H_2O \rightarrow H_2SO_4$

$2NO_2 + \frac{1}{2} O_2 + H_2O \rightarrow 2HNO_3$

$NO_2 + SO_2 + H_2O \rightarrow H_2SO_4 + NO$

In remote areas far from urban centers, approximately 70% of the acidity of precipitation originates from sulfuric acid, while about 30% comes from nitric acid (Galloway et al., 1994). This highlights the long-range transport of atmospheric pollutants and the global nature of acidification problems. **Figure 3**

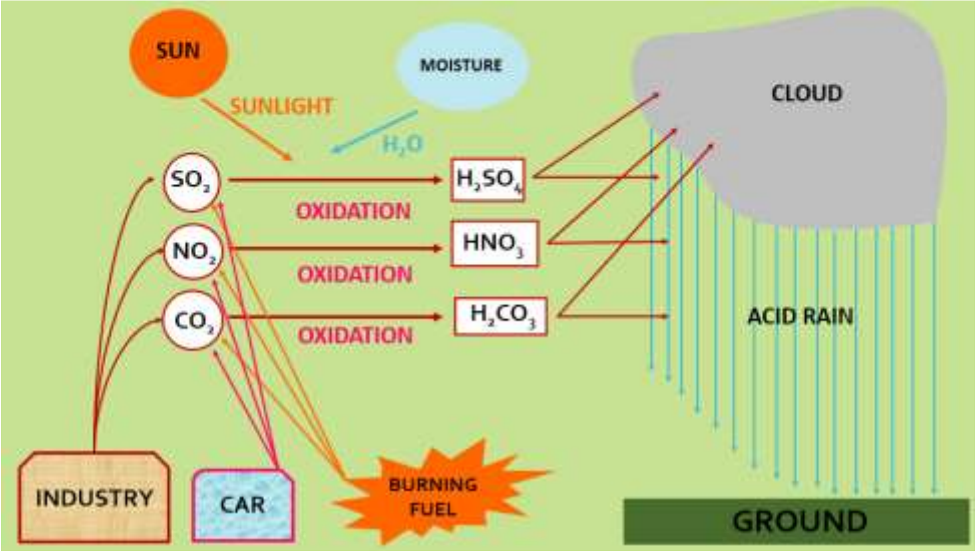


Figure 3. Mechanism of Acid Rain Formation

II.15.9.The Urban Pollution Dome and Its Climatic Effects

The **urban pollution dome** is a mass of warm and polluted air that forms above large cities, especially during calm weather with little or no wind. Even in the absence of temperature inversion, this phenomenon occurs regularly in densely urbanized areas. From a distance, it is visible as a **yellow-orange haze**, mainly due to high concentrations of **nitrogen dioxide (NO_2)** released from industrial and vehicular combustion (Seinfeld & Pandis, 2016).

a). Formation of the Dome: The Role of the Urban Heat Island

The main driver of this dome is the **Urban Heat Island (UHI)** effect. Cities are consistently warmer than surrounding rural areas due to several factors (Oke, 1982; Santamouris, 2015):

- **Anthropogenic heat sources**: residential heating, industrial boilers, vehicles, and machinery constantly release heat.
- **Urban materials**: asphalt, concrete, and glass absorb solar energy during the day and release it at night.
- **Lack of vegetation**: reduced evapotranspiration limits natural cooling processes.

b). Structure and Dynamics of the Dome

As a result, a **spherical cap of polluted air** develops above the city. This warm air mass rises through **convective upward currents** produced by urban heat. The rising motion transports gases (NOx, SO_2, CO, VOCs) and fine particles (dust, soot, metals) into the **upper troposphere**. The dome may extend several kilometers in height and usually dissipates only when **winds** disperse pollutants or when **precipitation** washes them out (Jacobson, 2002).

c). Local and Regional Climatic Effects

The pollution dome affects not only air quality but also local climate:

- **Enhanced urban rainfall**: Upward convection leads to cooling of moist air at higher altitudes, causing condensation and increased precipitation. Urban areas often record higher rainfall than surrounding rural zones (Shepherd, 2005).
- **Role of aerosols**: Fine particles and metallic aerosols act as **condensation nuclei**, facilitating cloud droplet formation and precipitation (Andreae & Rosenfeld, 2008).
- **Amplification of UHI**: By trapping heat and pollutants, the dome further strengthens the Urban Heat Island effect, sometimes altering local and regional atmospheric circulation.

d). Environmental and Health Implications

The urban pollution dome poses serious challenges:

- **Air quality**: accumulation of tropospheric ozone, NO_2, and fine particles leads to respiratory and cardiovascular health risks.
- **Urban climate**: intensification of local warming and modification of hydrological cycles.
- **Pollutant transport**: pollutants lifted to higher altitudes can travel long distances, contributing to **transboundary pollution**.

II.16. Disruption of Biogeochemical Cycles by Pollution

a) General

The scale and persistence of atmospheric pollution have, over recent decades, reached such a magnitude that they profoundly disrupt the biogeochemical cycles of major gaseous elements (carbon, nitrogen, sulfur). Human activities, through fossil fuel combustion, industrialization, agricultural intensification, and land-use changes, have amplified the natural fluxes of these elements to unprecedented levels. This imbalance modifies not only atmospheric chemistry but also climate regulation, biodiversity, and ecosystem services (Vitousek et al., 1997; Rockström et al., 2009; Steffen et al., 2015)

b) Disruption of the Carbon Cycle

Carbon is the backbone of life and climate regulation. However, anthropogenic activities have dramatically altered the balance between carbon sources and sinks:

- **Major Anthropogenic Sources of CO_2**
  - Combustion of fossil fuels (coal, oil, natural gas) → ~36.6 $GtCO_2$/year (2022) (Friedlingstein et al., 2022).
  - Cement production → ~2.9 $GtCO_2$/year.

  - Land-use change and deforestation → ~3.3 $GtCO_2$/year (Houghton & Nassikas, 2017).
- **Natural Sinks Under Pressure**
  - Oceans absorb ~25% of annual anthropogenic emissions, but increasing **ocean acidification** reduces their buffering capacity (Le Quéré et al., 2018).
  - Terrestrial ecosystems (forests, soils) absorb ~30%, yet **deforestation, degradation, and climate-driven stress** (droughts, wildfires, pests) are weakening these sinks (Canadell et al., 2007; Friedlingstein et al., 2020).

c) Carbon Cycle Imbalance – Current Estimates

The global carbon cycle, once in relative equilibrium before industrialization, is now profoundly disrupted by human activities. Anthropogenic emissions, primarily from fossil fuel combustion, cement production, and deforestation, have significantly altered the natural carbon fluxes between the atmosphere, oceans, and terrestrial biosphere. According to the Global Carbon Budget (2022) and analyses by Friedlingstein et al. (2022) and Le Quéré et al. (2023), fossil fuel combustion currently contributes about 10.2 gigatonnes of carbon (GtC) per year, while cement production adds nearly 0.8 GtC per year, both showing an upward trend.

Land-use change and deforestation release an additional 1.0–1.5 GtC per year, exerting strong impacts on ecosystem carbon storage capacity. In contrast, natural sinks—such as the oceans and terrestrial biosphere—absorb part of this excess carbon, with oceans taking up approximately 2.5–3.0 GtC per year, leading to ocean acidification, and terrestrial ecosystems capturing around 3.0–3.5 GtC per year, though their efficiency is decreasing due to climate feedbacks.

Overall, this imbalance results in a net atmospheric carbon accumulation of about 5.1 ± 0.2 GtC per year (2022), which is directly linked to the accelerating greenhouse effect and global temperature rise. **Table 9**

Table 9. Current estimates of global carbon fluxes and their anthropogenic perturbations (2022–2023)

Component	Natural Flux (GtC/year)	Anthropogenic Flux (GtC/year)	Trend/Impact
Fossil fuel combustion	–	~10.2	Rising
Cement production	–	~0.8	Rising
Deforestation & land-use change	–	~1.0–1.5	High impact
Ocean uptake	~90	~2.5–3.0 extra	Acidification

Terrestrial biosphere uptake	~120	~3.0–3.5 extra	Decreasing efficiency
Net atmospheric accumulation	~0 (balanced preindustrial)	~5.1 ± 0.2 (2022)	Accelerating greenhouse effect

(Source: Global Carbon Budget, 2022; Friedlingstein et al. 2022; Le Quéré et al., 2023).

d) Consequences of the Perturbation

- **Climate change** → intensification of the greenhouse effect, leading to global warming, sea-level rise, and altered precipitation regimes.
- **Ecosystem impacts** → biodiversity loss, species migration, coral bleaching, forest dieback.
- **Feedback loops** → thawing permafrost releases methane and CO_2, amplifying climate forcing.
- **Societal impacts** → increased risks to food security, water availability, and human health.

e) Interlinkages with Other Biogeochemical Cycles

- **Nitrogen cycle**: Increased use of fertilizers enhances soil respiration and N_2O emissions, a potent greenhouse gas.
- **Phosphorus cycle**: Altered by eutrophication, which interacts with carbon storage in aquatic ecosystems.
- **Sulfur cycle**: Fossil fuel combustion increases SO_2 emissions, influencing cloud formation and radiative forcing..

II.17. Solutions for Air Pollution

Air pollution is a major challenge for public health, biodiversity, and climate stability. Effective strategies require a multidimensional approach, combining technological innovation, strict regulation, ecological restoration, and lifestyle changes.

II.17.1. Source Reduction

- **Energy transition**: replacing fossil fuels with renewable sources (solar, wind, hydropower, sustainable biomass) to reduce greenhouse gases and secondary pollutants (IEA, 2021).
- **Energy efficiency and conservation**: development of low-energy buildings, energy-efficient appliances, and optimized industrial processes (Sharma et al., 2020).
- **Sustainable mobility**: expansion of public transport, promotion of active transport (walking, cycling), electric and hybrid vehicles, and the use of biofuels (WHO, 2018).

- **Sustainable agriculture**: reduction of nitrogen fertilizer use and improved livestock waste management to lower ammonia (NH_3) emissions, a precursor of fine secondary particles (FAO, 2020).

II.17.2. Pollution Control Technologies

- **Industrial filters and scrubbers**: electrostatic precipitators, bag filters, and wet scrubbers effectively reduce particulates and toxic gas emissions (Wang et al., 2019).
- **Automobile catalytic converters**: three-way catalysts reduce carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (Zhao et al., 2020).
- **Carbon capture and storage (CCS)**: an innovative solution to capture CO_2 from power plants and heavy industries, then store it in saline aquifers or depleted oil fields (IEA, 2021).
- **Smart monitoring systems**: integration of IoT sensors and artificial intelligence algorithms to track pollution levels in real time and adapt control strategies (Kumar et al., 2021).

II.17.3. Natural and Ecological Approaches

- **Urban greening** : Tree planting, green roofs and vertical gardens reduce concentrations of NO_2 and $PM_{2.5}$ while mitigating urban heat islands (Nowak et al., 2018).
- **Vegetation barriers and green belts** : hedgerows and peri-urban forests act as natural filters for particles and gaseous pollutants (Abhijith et al., 2017).
- **Nature-based solutions (NbS)**: restoring wetlands, forests, and grasslands improves air quality and contributes to climate change mitigation (UNEP, 2019).

II.17.4. Policies and Societal Changes

- **Standards and regulations**: strict implementation of frameworks such as the EU Air Quality Directive (2008/50/EC) and the WHO Air Quality Guidelines revised in 2021, which lower acceptable thresholds for $PM_{2.5}$ and ground-level ozone.
- **Green taxation and incentives**: subsidies for clean energy, carbon taxes, and incentives for electric vehicle adoption (OECD, 2020).
- **Education and awareness**: school programs and public campaigns to encourage responsible behaviors (e.g., reduced domestic burning, carpooling, recycling).
- **Sustainable urban planning**: development of smart cities with pedestrian zones, low-emission districts, and optimized transportation networks (Zhou et al., 2020).

II.17.5. International Cooperation

- **Global agreements**: enforcement of international treaties such as the Paris Agreement (2015) and the Geneva Convention on Long-Range Transboundary Air Pollution (1979).
- **Technology transfer**: international aid programs that provide developing countries with advanced pollution control technologies (UNEP, 2021).

In summary, combating air pollution requires an integrated approach that combines emission reduction, pollutant control, ecosystem restoration, and socio-economic reforms, all supported by strong international governance.

Chapire III: water pollution.

Chapire III: water pollution.

III.1. Water Resources

Water, a fundamental component of ecosystems and human societies, exists in three physical states—liquid, solid, and gas—and covers about **70% of the Earth's surface**. Its distribution, however, is highly uneven: approximately **97.4%** of global reserves are saline waters (oceans and seas), around **2.1%** are locked in glaciers and polar ice caps, and only **0.5%** are accessible freshwater stored in rivers, lakes, and aquifers (Shiklomanov & Rodda, 2003; UNESCO, 2019).

III.1.1.Types of water resources

- **Natural water bodies:**

  Rivers, lakes, aquifers, wetlands, lagoons, seas, and oceans, each with distinct physical and chemical characteristics depending on their origin and environmental transformations (Maidment, 1993). These water bodies serve as the primary reservoirs of water on Earth, supporting ecosystems, human consumption, agriculture, and industry. Their quality and availability are influenced by climate, geology, and human activities.

- **Raw water sources for drinking water production** are generally classified into three main groups:

a). Groundwater sources (aquifers):

These are underground reservoirs that store water in permeable rocks and sediments. Groundwater is often of high chemical quality, naturally filtered through soil and rock layers. However, it is vulnerable to overexploitation, which can lower water levels, and contamination from agricultural runoff, industrial waste, or leaking sewage systems. Groundwater is essential in arid regions or where surface water is scarce.

b). Flowing surface waters (rivers and streams):

These waters are dynamic and vary in flow and quality depending on seasonal rainfall and snowmelt. They are directly influenced by land use, pollution, and climatic variations. Rivers and streams are crucial for supplying water to urban centers, irrigation, and hydropower production but are more susceptible to contamination than groundwater.

c). Stored surface waters (reservoirs and dams):

These are artificial or natural lakes used to regulate water supply for domestic, agricultural, and industrial purposes (Gleick, 1993). They help manage seasonal variability in river flows, provide flood control, and support water availability during dry periods. However, reservoirs can also impact ecosystems, cause sedimentation, and change water temperature and chemistry.

III.1.2.The hydrological cycle

The total amount of water on Earth is estimated at about **1,350 million km³**, of which more than **97%** is stored in the oceans. All water originates from the oceans and eventually returns there through a continuous hydrological cycle (Oki & Entekhabi, 2004).

The **hydrological cycle** is the sequence of processes that allow water to change its state (solid, liquid, gas) and move between the different components of the Earth system: the atmosphere, oceans, land surfaces, and the biosphere (Wang et al., 2021). This cycle is in perpetual motion and constitutes a fundamental regulator of the global climate system.

Water, in its three physical states, circulates continuously through interconnected pathways (NOAA, 2025).

a). Evapotranspiration

This term combines *evaporation* from oceans, lakes, and rivers with *transpiration* from plants. Under the influence of solar radiation, surface waters evaporate and plants release water vapor through their stomata (NOAA, 2025). Evapotranspiration is essential for regulating terrestrial water balance and local to regional climates (Wang et al., 2021).

b). Precipitation

Atmospheric water vapor condenses into clouds, which generate precipitation in the form of rain, snow, or hail. Precipitation represents the primary source of almost all freshwater reserves. Its distribution is highly variable and depends on regional climate and relief (Britannica, 2025).

c). Runoff

Once precipitation reaches the ground, part of it flows over the surface toward rivers, lakes, or directly to the oceans. This is known as surface runoff, a key mechanism that replenishes surface waters but can also cause flooding and erosion when excessive (ScienceDirect Topics, 2025).

d). Infiltration and Percolation

Another portion of precipitation infiltrates into soils and subsurface layers. Infiltration rehydrates soils, sustains vegetation, and ensures groundwater recharge. It also maintains underground rivers and aquifers, which are vital sources of drinking water (ScienceDirect Topics, 2025).**Figure 4**

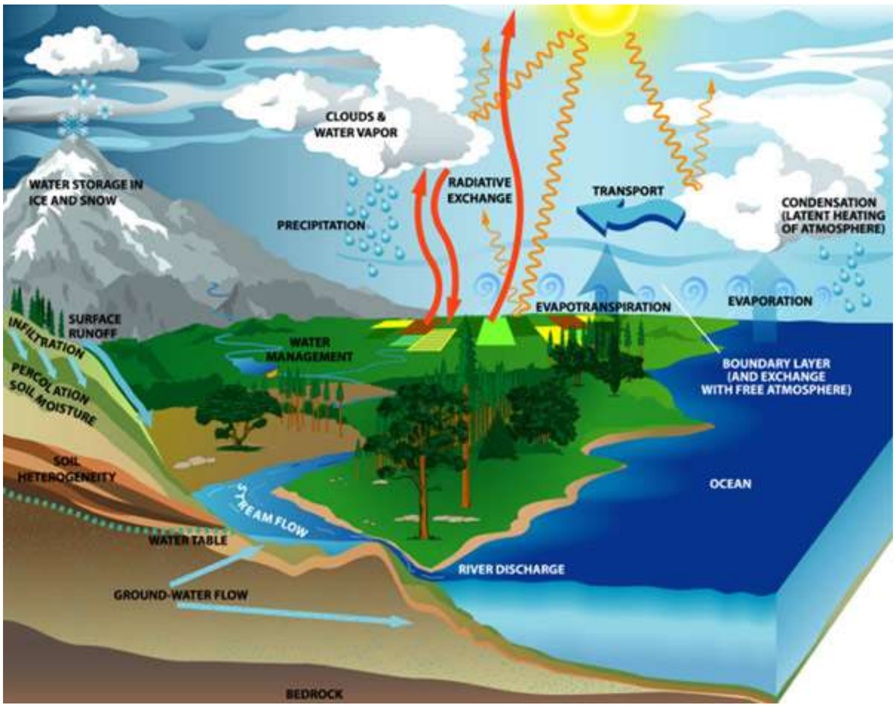


Figure 4. hydrological cycle

II.2. Types of Water

According to Degrémont (2005), natural water reserves can be categorized into three main groups: **groundwater** (infiltration and aquifers), **stagnant surface water** (lakes and reservoirs), and **flowing surface water** (rivers). Each type is characterized by distinct origins, physico-chemical properties, and degrees of vulnerability to pollution.

III.2.1. Rainwater

Rainwater represents a form of **atmospheric water**. In its natural state, it is generally of high quality for human consumption, being saturated with **oxygen** and **nitrogen** while containing negligible amounts of dissolved salts. However, its purity is strongly influenced by the level of atmospheric contamination. In industrialized or urbanized regions, rainwater often becomes enriched with **aerosols, atmospheric dust, and gaseous emissions** (e.g., SO_2, NO_x), leading to acidification and secondary pollutants (Rejsek, 2002). Consequently, while pristine rainwater is a potential freshwater source, its use as drinking water requires careful monitoring and treatment.

III.2.2. Surface Water

Surface water encompasses all **water masses flowing or accumulating on the Earth's surface**, including rivers, lakes, and artificial reservoirs. It derives primarily from **precipitation, surface runoff, and groundwater discharge from aquifers** (Valiron, 1994).

The **chemical composition** of surface waters depends largely on the **geological formations** encountered along their flow paths within drainage basins. For this reason, mineral content, hardness, and alkalinity vary widely between catchments. At the same time, surface waters are highly vulnerable to contamination by both **mineral pollutants** (e.g., heavy metals, nutrients) and **organic contaminants** (e.g., agricultural runoff, wastewater discharges) (MDDEP, 2012).

According to Echenfelder (1982), surface water—whether flowing or stagnant—is rarely of sufficient quality to be directly drinkable without treatment, due to its susceptibility to microbial and chemical pollution.

III.2.2.1. Surface Water Quality

Natural surface waters contain a wide range of dissolved or particulate mineral and organic substances. Because of its molecular properties, water is an excellent solvent and therefore rarely exists in a chemically pure state (Lacroix, 1991). The quality of surface water is evaluated through a set of **physico-chemical parameters** that determine its purity and its suitability for drinking, domestic, agricultural, or industrial purposes.

Surface waters are generally characterized by:

- The presence of dissolved gases, particularly oxygen.
- A high load of suspended solids, especially in flowing waters.
- The presence of naturally occurring organic materials.
- The presence of plankton (both phytoplankton and zooplankton).
- Daily fluctuations linked to temperature and precipitation (Ramade, 2000).

Water quality can vary considerably over short timeframes, even within the same day, as biological processes such as photosynthesis directly influence dissolved oxygen concentrations. Furthermore, changes in river flow and hydrological conditions contribute to this variability (Chaguer, 2013).

III.2.3. Physico-Chemical Characteristics of Surface Water

Water is a universal solvent that dissolves soluble substances, transports suspended matter, and carries sediments, thereby acting as a natural vector of pollutants. Surface waters can be either **flowing** (rivers, streams) or **stagnant** (lakes, reservoirs), and these two types are often interconnected. Rivers may be supplied by groundwater springs, while lakes can be replenished through precipitation or subsurface inflows.

The **chemical composition** of surface water is influenced primarily by the geological formations encountered along its course within drainage basins. As it circulates, water dissolves various minerals and elements from soils and rocks. Furthermore, through interactions at the

water–atmosphere interface, it absorbs dissolved gases such as oxygen, nitrogen, and carbon dioxide (Monod, 1989).

III.2.4. Groundwater

Groundwater accounts for approximately **22% of global freshwater reserves**. It originates from the infiltration of precipitation into the soil, a process influenced by topography, permeability, and geological structure. Generally, groundwater is naturally protected from many sources of pollution, which explains its **superior physico-chemical and microbiological quality** compared to surface waters (Mebarki, 1982).

In many cases, groundwater can be consumed without prior treatment, although its **mineral composition** depends on the nature of underlying geological formations and the depth of the aquifer (Echenfelder, 1982). Because of its relative stability and low vulnerability, groundwater remains one of the **most reliable sources of potable water** (Margat, 1992).

III.2.5. Wastewater

Wastewater refers to water that has been used or contaminated during domestic, agricultural, or industrial activities. It contains physical, chemical, and biological pollutants that require treatment or purification before being released into the environment or reused for human consumption (Rodier et al., 2009; WHO, 2022).

a). Physical States of Water

Water naturally exists on Earth in three physical states—liquid, solid, and gaseous—and its ability to shift between these states makes it fundamental to the hydrological cycle and to sustaining life (USGS, 2021).

1. Liquid State (H_2O, liquid)

Liquid water represents the largest share of the hydrosphere, covering about 70% of the planet’s surface (oceans, seas, lakes, rivers, and groundwater). In this state, water molecules are loosely bonded by hydrogen bonds, allowing them to move freely, which gives water its fluidity and incompressibility. As the universal solvent, liquid water facilitates chemical reactions, nutrient transport, and biological activity (Gleick, 2019).

2. Solid State (ice, snow, glaciers)

When frozen, water molecules arrange into a rigid hexagonal crystalline structure stabilized by hydrogen bonds. This makes ice less dense than liquid water, allowing it to float. Solid water is mainly stored in polar ice caps, glaciers, and mountain snow, representing about 2.1% of Earth’s water reserves. Ice and snow also regulate the global climate through their high albedo effect, reflecting solar radiation back into space (Trenberth et al., 2007; IPCC, 2021).

3. Gaseous State (water vapor)

In the gaseous state, water molecules are widely spaced and highly mobile, without a fixed structure. Water vapor forms through evaporation from oceans, rivers, soils, and plant transpiration. Although invisible, it is a critical greenhouse gas that regulates atmospheric temperature and energy fluxes. Water vapor condensation drives cloud formation, precipitation, and weather patterns (Held & Soden, 2000; NOAA, 2025).

b) Phase Transitions of Water

Water's unique molecular structure and hydrogen bonding enable it to undergo **phase transitions** between solid, liquid, and gaseous states. These processes are governed by variations in **temperature** and **pressure**, and they form the foundation of the **hydrological cycle** by driving exchanges of water and energy between Earth's compartments.

- **Melting (fusion): ice → liquid water (Kobayashi et al., 2019)**

  Melting occurs when ice absorbs heat and reaches 0 °C under standard atmospheric pressure. At this point, hydrogen bonds in the crystalline lattice are partially broken, allowing molecules to move more freely. This endothermic process requires the absorption of latent heat (approximately 334 kJ/kg), which is stored in the liquid water and plays a crucial role in regulating seasonal snowmelt, glacier retreat, and river flow.

- **Freezing (solidification): liquid water → ice (USGS, 2021)**

  Freezing takes place when liquid water loses heat until it reaches 0 °C, leading to the reorganization of molecules into a hexagonal crystalline structure. This process releases latent heat into the environment, which helps stabilize local temperatures. Freezing governs the formation of sea ice, permafrost, and snow cover, with direct implications for climate feedbacks and ecosystems.

- **Evaporation: liquid water → water vapor (Wallace & Hobbs, 2006)**

  Evaporation is a surface phenomenon in which high-energy molecules escape from the liquid phase into the atmosphere. It requires the absorption of latent heat (about 2,260 kJ/kg at 100 °C), making it a major mechanism for transferring both water and energy from Earth's surface into the atmosphere. Evaporation drives cloud formation and powers atmospheric circulation.

- **Condensation: water vapor → liquid water (Wallace & Hobbs, 2006)**

  Condensation is the reverse of evaporation, where water vapor loses energy and returns to the liquid state, forming droplets. This exothermic process releases latent heat into the atmosphere, fueling storm systems and influencing weather dynamics. Condensation is the key mechanism behind cloud formation, fog, and precipitation.

- **Sublimation: ice → water vapor (Gleick, 2019)**

  Sublimation is the direct transformation of solid water (ice or snow) into vapor without passing through the liquid phase. It typically occurs under low humidity and low pressure conditions, such as in Polar Regions and high-altitude mountains. Sublimation contributes to glacier mass loss and snowpack reduction, especially under warming climates.

- **Deposition (desublimation): water vapor → ice (USGS, 2021)**

  Deposition is the opposite of sublimation, where water vapor directly forms ice crystals without becoming liquid first. This occurs when air is saturated and temperatures are below freezing. Deposition is responsible for phenomena such as frost formation on surfaces, snowflake crystallization in clouds, and hoarfrost on vegetation during winter.

III.2.6. Main Types of Water Pollutants

Water pollution results from the introduction of substances or energy into aquatic systems that alter their physical, chemical, or biological properties, leading to harmful consequences for ecosystems and human health. These pollutants are highly diverse in origin and composition, but they can be broadly categorized into organic, inorganic, and synthetic compounds. Below is a detailed overview of the main types of water pollutants, their mechanisms of action, and ecological and sanitary impacts.

III.2.6.1. Fermentable Organic Matter

Fermentable organic matter originates primarily from domestic sewage, food industry effluents, agricultural runoff, and decaying biomass. When these materials enter water bodies, microorganisms such as bacteria and fungi utilize them as energy sources. Their decomposition consumes dissolved oxygen, leading to hypoxic or anoxic conditions (Dodds & Smith, 2016).

This oxygen depletion severely disrupts aquatic ecosystems. Primary producers (algae and aquatic plants) are unable to perform photosynthesis efficiently due to reduced light penetration, while fish and invertebrates experience respiratory stress or mortality (Allan & Castillo, 2007). Elevated turbidity also interferes with predator-prey interactions and reduces habitat quality. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are widely used indicators to quantify this type of pollution.

III.2.6.2. Mineral Nutrients (Nitrates and Phosphates)

Nitrogen and phosphorus are essential nutrients for primary productivity. However, excessive enrichment from agricultural fertilizers, livestock farming, wastewater discharges, and urban runoff induces eutrophication (Smith & Schindler, 2009).

Eutrophication is characterized by the rapid proliferation of algae and macrophytes. Harmful algal blooms (HABs), often dominated by cyanobacteria, not only block sunlight and reduce oxygen levels during decomposition but also release cyanotoxins, which are harmful to aquatic fauna and human health (Paerl et al., 2016). In lakes and reservoirs, eutrophication reduces water clarity, alters trophic dynamics, and can render water unfit for drinking or recreational use. On a global scale, nutrient enrichment has been identified as one of the leading drivers of freshwater ecosystem degradation (Grizzetti et al., 2021).

III.2.6.3. Trace Metals

Trace metals, including mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr), enter aquatic environments mainly through industrial effluents, mining activities, battery disposal, and urban runoff. Unlike organic matter, metals are non-biodegradable and persist in the environment for long periods (Tchounwou et al., 2012).

Their toxicity is linked to their ability to bind with proteins, enzymes, and nucleic acids, disrupting vital biochemical processes. For instance, mercury interferes with the nervous system, cadmium damages kidneys, and arsenic is carcinogenic (Jaishankar et al., 2014). In aquatic systems, metals accumulate in sediments and biomagnify along the food chain, reaching high concentrations in top predators such as fish and birds. This biomagnification poses severe health risks to humans through the consumption of contaminated seafood (Ali et al., 2019).

III.2.6.4. Synthetic Organic Compounds

Synthetic organic pollutants encompass a broad range of chemicals, including solvents, detergents, pesticides, herbicides, pharmaceuticals, and endocrine-disrupting compounds. Their persistence and toxicity make them among the most concerning pollutants of the 21st century (Richardson & Ternes, 2018).Many of these compounds interfere with hormonal systems, leading to reproductive disorders in fish and amphibians. For example, exposure to estrogenic compounds causes feminization of male fish (Sharma & Chatterjee, 2017). Pesticides disrupt nervous systems, while solvents and detergents alter cell membranes and oxygen transfer. In addition, degradation of these compounds consumes oxygen, further exacerbating hypoxia.

Emerging contaminants, such as microplastics and per- and polyfluoroalkyl substances (PFAS), have raised increasing concerns. Microplastics serve as vectors for hydrophobic organic pollutants and heavy metals, while PFAS are extremely persistent, bioaccumulative, and toxic (Eerkes-Medrano et al., 2015).

III.2.6.5. Hydrocarbons

Hydrocarbons mainly originate from oil spills, petroleum extraction, transportation, and industrial discharges. Once released, hydrocarbons may float as surface films, preventing gas exchange, or adhere to sediments, where they degrade slowly under anaerobic conditions (Kingston, 2002).Polycyclic aromatic hydrocarbons (PAHs), a subgroup of hydrocarbons, are particularly concerning due to their carcinogenic and mutagenic properties. Hydrocarbons impair fish respiration, smother benthic organisms, and reduce biodiversity. In marine ecosystems, large oil spills have long-term consequences, persisting for decades in sediments and food webs (Beyer et al., 2016).

III.2.6.6. Domestic and Urban Pollution

Urban wastewater contains a complex mixture of pollutants derived from households, hospitals, and industries. These include pharmaceuticals, hormones, cleaning agents, plasticizers, and heavy metals (Luo et al., 2014). When inadequately treated, urban effluents contribute to long-term contamination of rivers, lakes, and groundwater.

Stormwater runoff in cities also transports hydrocarbons, microplastics, fertilizers, and pathogens into receiving waters, especially during heavy rainfall events (Eerkes-Medrano et al., 2015). The combined effect of multiple stressors from urban environments makes this type of pollution particularly difficult to control.

III.2.6.7. Agricultural Pollution

Agricultural activities are among the leading global contributors to water pollution (Mateo-Sagasta et al., 2017). Excessive use of fertilizers releases nitrates and phosphates, while pesticides and herbicides contaminate both surface and groundwater. During rainfall, runoff enhances leaching processes, increasing nitrate concentrations in aquifers and pesticide residues in streams (Carpenter, 2005).

Long-term agricultural pollution causes eutrophication, groundwater nitrate contamination, and pesticide bioaccumulation. For instance, atrazine, a widely used herbicide, is linked to endocrine disruption in amphibians and fish (Schwarzenbach et al., 2010). Climate change further exacerbates these impacts by intensifying rainfall events, leading to more frequent and severe runoff episodes (Paerl et al., 2016).

III.2.6.8. Atmospheric Pollution

Atmospheric deposition represents a significant pathway by which airborne contaminants enter aquatic ecosystems. Pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), emitted mainly from fossil fuel combustion, undergo complex atmospheric transformations, forming acidic compounds like sulfuric acid (H_2SO_4) and nitric acid (HNO_3).

These are subsequently incorporated into precipitation, leading to **acid rain**, which lowers the pH of surface waters, disrupts buffering capacities, and mobilizes toxic metals (e.g., aluminum) from soils into rivers and lakes. Acidification impairs fish reproduction, reduces biodiversity, and alters aquatic community structures (Driscoll et al., 2001; Likens et al., 2022).

Dry deposition of particulate matter, heavy metals (e.g., lead, mercury), and persistent organic pollutants (POPs) can also occur, particularly near industrialized and urban regions. During storm events, these pollutants are rapidly transported into drainage networks, amplifying contamination loads (Grantz et al., 2003). Long-range transport of airborne pollutants has global implications, with Arctic lakes and remote ecosystems increasingly showing contamination from industrialized regions (Schindler, 2009). Thus, atmospheric inputs act as diffuse, transboundary sources of water pollution, complicating management strategies.

III.2.6.9. Microbiological Pollution

Microbiological contamination of water remains a critical public health concern. Wastewater and sewage effluents often carry a wide diversity of **pathogenic microorganisms**, including:

- **Bacteria**: *Vibrio cholerae*, *Escherichia coli* O157:H7, *Salmonella* spp.
- **Viruses**: enteroviruses, rotaviruses, hepatitis A and E viruses
- **Protozoa**: *Giardia lamblia, Cryptosporidium parvum*
- **Helminths**: eggs and larvae of intestinal worms (e.g., *Ascaris lumbricoides*).

These pathogens are typically transmitted through the **fecal–oral route**, often when contaminated water is consumed or used in food preparation. They cause widespread waterborne diseases such as **cholera, dysentery, typhoid fever, and hepatitis**, which remain leading causes of morbidity and mortality in low-resource regions (WHO, 2017).

The persistence and infectivity of pathogens in aquatic environments depend on several factors: temperature, UV radiation, nutrient availability, and interactions with suspended particles or biofilms. Protozoan cysts and helminth eggs are particularly resistant to conventional water treatment processes, posing major challenges for disinfection (LeChevallier & Au, 2004). Climate change and extreme rainfall events are expected to exacerbate microbial contamination by overwhelming wastewater infrastructure and increasing runoff (Hunter et al., 2010).

In addition to direct health risks, microbiological pollution also affects **ecosystem integrity** by altering microbial communities, nutrient cycling, and oxygen dynamics. Effective mitigation requires integrated wastewater management, improved sanitation infrastructure, and continuous monitoring using advanced molecular techniques for pathogen detection (Hrudey et al., 2006).

III.3. Natural Pollution of water

Water quality is not only influenced by anthropogenic activities but can also be significantly affected by natural processes. These natural sources of contamination play a crucial role in the biogeochemical dynamics of aquatic ecosystems (Birech, 2006).

1. **Physical agents**

   Suspended particulate matter, including clay, silt, and sand, is mobilized through soil erosion driven by precipitation, runoff, or wind (Fondriest, 2024). The influx of these particles increases turbidity, reduces light penetration, and consequently inhibits primary production in aquatic systems. Additionally, benthic habitats are disrupted, impairing the ecological integrity of riverbeds (Fondriest, 2024).

2. **Organic chemical agents**

   The decomposition of terrestrial vegetation releases humic and fulvic substances into water bodies (Bolan et al., 1998; Thurman, 2010). These compounds can alter water color, taste, and odor, and contribute to local acidification. Furthermore, they complex with trace metals, modifying their bioavailability and potential toxicity. Peatland and forested wetland waters frequently exhibit high concentrations of humic substances, resulting in characteristic brownish coloration (Bolan et al., 1998).

3. **Inorganic chemical agents**

   Geochemical processes, including the dissolution of rocks and minerals such as limestone, gypsum, halite, and arsenopyrite, release cations and anions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Fe^{2+}/Fe^{3+}, As^{3+}, Pb^{2+}) into aquatic systems (Florida DEP, 2024; Smith et al., 2024). These naturally occurring ions increase water conductivity and, at elevated concentrations, can exert toxic effects on aquatic biota and accumulate in sediments. High arsenic levels in rivers traversing arsenic-rich geological formations exemplify such natural contamination (Smith et al., 2024).

4. **Biological agents**

   Litterfall and the decay of organic matter introduce nutrients (nitrogen and phosphorus) and dissolved organic carbon into aquatic systems (UCAR, 2024). These inputs stimulate microbial and algal activity, potentially altering food web dynamics and disrupting biogeochemical cycles. Wetland ecosystems are particularly affected by this natural enrichment, which may lead to localized oxygen depletion (UCAR, 2024).

5. **Other natural phenomena**

   Volcanic eruptions can release ash and acidic gases into watercourses, while floods and high-flow events mobilize sediments and organic matter from terrestrial landscapes into rivers. Coastal erosion contributes additional particulate matter and salts to estuarine and nearshore environments (Birech, 2006)

III.4.Types of Water Pollution (Geographic Classification)

1. **Point-Source Pollution**

   Point-source pollution originates from fixed and easily identifiable discharges, such as industrial effluent pipes, municipal wastewater outlets, or thermal power plant discharges. Because the source is localized, it is generally possible to monitor, regulate, and mitigate through targeted treatment technologies (Bouziane, 2000). Examples include untreated sewage discharged directly into rivers, chemical effluents from factories, and oil leaks from pipelines.

2. **Non-Point-Source (Diffuse) Pollution**

   Non-point-source pollution results from multiple dispersed sources, making it difficult to measure, regulate, and control. It often occurs over large areas and is carried into water bodies by surface runoff, leaching, or atmospheric deposition (Birech, 2006). Common contributors include agricultural runoff rich in fertilizers and pesticides, urban stormwater carrying hydrocarbons and heavy metals, and airborne pollutants such as nitrogen oxides and sulfur compounds that settle into aquatic systems. Unlike point-source pollution, its diffuse nature poses greater challenges for environmental management.

3. **Transboundary Pollution**

   Transboundary pollution refers to contamination that crosses political or geographical borders, often carried by rivers, groundwater flow, or atmospheric circulation. A pollutant released in one country can affect water quality in neighboring regions, complicating regulation and requiring international cooperation.

- In the **Mediterranean Basin**, untreated municipal and industrial waste discharged by coastal cities in North Africa, Southern Europe, and the Middle East has cumulative impacts, as water circulation spreads pollutants across national boundaries. For instance, the discharge of urban wastewater along the Algerian and Tunisian coasts contributes to regional eutrophication and degradation of marine biodiversity.

- **The Nile River** is a major example of transboundary pollution in Africa. Agricultural runoff, pesticides, and untreated sewage discharged upstream in countries like Sudan or Ethiopia are transported downstream to Egypt, affecting water quality and public health.
- **The Medjerda River** (Tunisia–Algeria) also illustrates this phenomenon, as industrial discharges and agricultural runoff cross borders, necessitating bilateral management to ensure safe water use.

These examples demonstrate that transboundary pollution is not only a global issue but also a pressing regional challenge for the Maghreb and Mediterranean countries, requiring coordinated strategies, joint monitoring, and international agreements for effective water governance.

III.5. Major Types of Water Pollution

III.5.1. Chemical Pollution

Chemical pollution is defined as the contamination of water by toxic inorganic and organic substances. These pollutants may enter aquatic systems through industrial effluents, agricultural runoff, urban wastewater, or natural geochemical processes (WHO, 2017; Birech, 2006). Their presence modifies the physicochemical balance of water, affects aquatic organisms, and represents a major threat to human health.

a) Main Chemical Pollutants and Effects

Chemical pollution represents one of the most critical threats to water quality, as it involves the introduction of toxic inorganic and organic substances that can persist in aquatic ecosystems and accumulate in the food chain. These pollutants originate from agricultural practices, industrial activities, domestic discharges, and accidental spills. Their presence not only alters the physicochemical balance of water bodies but also poses significant risks to aquatic life and human health. The major chemical pollutants, their primary sources, and associated environmental and health impacts are summarized in **Table 10**

Table 10. Major Chemical Pollutants in Water, Their Sources, and Associated Environmental and Health Effects

Pollutant	Primary Sources	Main Environmental and Health Effects
Nitrates (NO_3^-)	Agricultural runoff, untreated sewage	Eutrophication; methemoglobinemia ("blue baby syndrome")
Phosphates (PO_4^{3-})	Detergents, fertilizers	Algal blooms → oxygen depletion

Heavy metals (Pb, Hg, Cd, As)	Industry, mining, batteries	Bioaccumulation; neurotoxicity; organ damage
Pesticides (DDT, glyphosate, etc.)	Agriculture	Carcinogenic effects; endocrine disruption; aquatic toxicity
Hydrocarbons	Oil spills, stormwater	Surface films, suffocation of aquatic life

Case Study – Minamata Disease (Japan): Industrial discharge of methylmercury in the 1950s contaminated seafood, causing neurological disorders in local populations (Harada, 1995).

III.5.2. Physical Pollution

Physical pollution refers to the alteration of the physical properties of water bodies, which negatively impacts aquatic ecosystems and reduces water quality. Unlike chemical or biological pollution, physical pollution primarily affects parameters such as temperature, turbidity, and sediment load, but its ecological consequences can be equally severe.

II.5.2. 1.Thermal Pollution

- **Causes:** Thermal pollution arises from the discharge of heated effluents by power plants, steel industries, refineries, and other industrial facilities. Additional sources include urban runoff from paved surfaces and the reduction of riparian vegetation that normally provides shading and cooling of streams (Kaushal et al., 2010). Climate change is also exacerbating natural thermal stress in aquatic ecosystems.
- **Effects:** Elevated water temperature lowers the solubility of dissolved oxygen, accelerates microbial activity, and alters the metabolic and reproductive physiology of aquatic organisms. Fish and invertebrates adapted to narrow thermal ranges may suffer increased mortality or be forced to migrate to cooler habitats (Parmesan & Yohe, 2003). In extreme cases, thermal shocks from sudden releases of hot water can cause mass die-offs of sensitive species.
- **Case Studies:**
    - Thermal discharges along the Indian coastline have been linked to shifts in plankton communities and decreased fish abundance (Rabalais, 2002).
    - In the Great Lakes region (USA–Canada), elevated temperatures near power plant outlets have altered seasonal spawning cycles of several fish species (Magnuson et al., 1997).

III.5.2.2. Mechanical Pollution

- **Causes:** Mechanical pollution results from excessive sedimentation due to deforestation, overgrazing, agriculture, and construction; plastic waste from urban areas; and mining tailings released into rivers (Syakti et al., 2017). Hydroelectric dams also contribute by modifying sediment transport and accumulating large amounts of suspended particles downstream.

- **Effects:**
    - **Turbidity:** Increased suspended solids reduce light penetration, suppressing photosynthesis and decreasing oxygen production.
    - **Sedimentation:** Fine particles settle on benthic substrates, smothering fish eggs, invertebrate habitats, and coral reefs.
    - **Plastics:** Macroplastics cause entanglement and ingestion risks, while microplastics and nanoplastics enter food webs, with potential toxicological effects (Jambeck et al., 2015).
    - **Mining residues:** Heavy sediment loads combined with toxic elements such as mercury and arsenic from tailings severely degrade aquatic ecosystems.
- **Examples:**
    - The **Citarum River (Indonesia)**, often labeled the “world’s dirtiest river,” receives thousands of tons of plastic waste and industrial effluents daily, threatening biodiversity and human populations (Lebreton & Andrady, 2019).
    - In the **Amazon Basin**, gold mining activities discharge sediments and mercury, leading to widespread turbidity and contamination of aquatic food chains (Lacerda, 1997).
    - Coral reef systems in the **Caribbean and Southeast Asia** are highly vulnerable to sediment runoff, which causes coral smothering and reef degradation (Fabricius, 2005).

III.5.4. Biological Pollution

Biological pollution refers to the introduction and proliferation of living organisms or their by-products that disrupt aquatic ecosystems and threaten human health. It encompasses microbiological contamination, excess organic matter, and the spread of invasive species.

III.5.4.1. Microbiological Pollution

Wastewater frequently carries pathogenic microorganisms that contaminate water supplies and pose severe health risks.**Table 11**

Table 11. Examples of waterborne pathogens, associated diseases, and transmission routes.

Pathogen	Associated Disease	Transmission
Vibrio cholerae	Cholera	Contaminated water
Giardia lamblia	Giardiasis	Fecal–oral route
Hepatitis A virus	Hepatitis A	Polluted water

Risk factors include poor sanitation (affecting approximately 1.7 billion people worldwide, WHO, 2022) and the impacts of climate change, which accelerate pathogen survival, transport, and spread. Waterborne outbreaks are particularly acute in flood-prone and densely populated regions.

III.5.4.2. Organic Matter Pollution

- **Sources:** Domestic sewage (80% of which remains untreated in developing countries, UNEP), effluents from dairy industries (rich in biodegradable organic load, high BOD), and paper mill discharges (lignins and cellulose residues).
- **Effects:** Excess organic matter promotes microbial decomposition, leading to oxygen depletion (hypoxia). Under anaerobic conditions, hydrogen sulfide is released, further degrading water quality. Severe hypoxia has resulted in the formation of “dead zones,” notably in the Gulf of Mexico, where marine biodiversity collapses due to lack of oxygen.

III.5.4.3. Invasive Species

- **Example:** *Caulerpa taxifolia* (“killer algae”) introduced in the Mediterranean Sea.
- **Impact:** This invasive alga produces toxins, outcompetes native seagrass (*Posidonia oceanica*), and reduces benthic biodiversity by up to 90% (Meinesz, 2001). Its rapid expansion has altered habitats, diminished fish populations, and caused significant ecological and economic damage to coastal ecosystems.

III.5.4.4.Comparative Table: Pollution Types

Water pollution can be classified into three main categories—chemical, physical, and biological—depending on the nature of the contaminants and their impacts on aquatic ecosystems and human health. Each type of pollution is associated with specific pollutants, environmental effects, and tailored mitigation strategies. While chemical pollutants such as heavy metals and nutrients contribute to toxicity and eutrophication, physical pollution alters habitat conditions, and biological pollution spreads pathogens or invasive species. A synthesis of these pollution types is presented in **Table 12.**

Table 12. Comparative Synthesis of Water Pollution Types, Key Pollutants, Effects, and Mitigation Strategies

Type	Key Pollutants	Primary Effects	Mitigation Strategies
Chemical	Heavy metals, nitrates, phosphates	Toxicity, eutrophication	Advanced oxidation, phytoremediation
Physical	Plastics, heated effluents	Habitat disruption, hypoxia	Cooling towers, sediment barriers
Biological	Pathogens, organic matter, invasives	Disease outbreaks, biodiversity loss	UV disinfection, ballast water treatment

III.6. Impacts of Water Pollution

Water pollution exerts profound consequences on ecosystems, human health, and socio-economic activities. These impacts are often cumulative and interconnected, amplifying ecological degradation and social vulnerability.

a) Environmental Impacts

- **Oxygen depletion:** Excessive organic matter decomposition reduces dissolved oxygen, increasing fish vulnerability to toxins and leading to mortality (Pesson et al., 1976).
- **Eutrophication:** Nutrient enrichment causes uncontrolled algal blooms, which upon decomposition further decrease oxygen levels, reduce biodiversity, and alter ecosystem functioning (Menouer & Taibi, 2014).
- **Physical alterations:** Pollution changes water temperature, turbidity, and flow regimes, affecting photosynthesis, sedimentation patterns, and aquatic habitats (Ouikene, 2011).
- **Bioaccumulation and biomagnification:** Pollutants such as pesticides and heavy metals accumulate in organisms, moving up the food chain and affecting top predators and biodiversity (UNEP, 2016).
- **Greenhouse gas emissions:** Decomposition of organic pollutants in anaerobic waters generates methane (CH_4) and nitrous oxide (N_2O), potent greenhouse gases that contribute to climate change (Rabalais et al., 2014).

b) Human Health Impacts

- **Infectious diseases:** Contaminated water transmits cholera, hepatitis A, dysentery, malaria, and filariasis, representing a major global public health burden (WHO, 2022).

- **Toxic effects:** Heavy metals (e.g., mercury, lead, cadmium) bioaccumulate in the human body, causing neurological impairments, renal dysfunction, hepatic damage, and developmental disorders (Moletta, 2014).
- **Chronic exposure risks:** Long-term ingestion of contaminated water is associated with increased cancer risks and endocrine disruption due to synthetic organic pollutants (Birech, 2006).
- **Antibiotic resistance:** Discharge of untreated hospital effluents and pharmaceutical residues fosters the spread of antimicrobial-resistant bacteria, posing new challenges to healthcare systems (WHO, 2019).

c) Economic Impacts

- **High treatment costs:** Purifying polluted water for drinking or industrial use requires advanced and costly technologies, burdening municipalities and developing economies (Moletta, 2014).
- **Loss of ecosystem services:** Eutrophication and contamination reduce fisheries productivity, undermine agricultural irrigation, and degrade wetland functions.
- **Tourism and recreation losses:** Algal blooms, foul odors, and poor coastal water quality discourage recreational use and reduce tourism revenue, particularly in Mediterranean and tropical regions.
- **Equity issues:** A disparity often exists between polluters (industrialized sectors, upstream regions) and the affected populations (rural, downstream communities), raising environmental justice concerns.
- **Food insecurity:** Pollution of irrigation water contaminates crops, while fish kills diminish protein sources for vulnerable populations (FAO, 2017).

d) Sociopolitical Impacts

- **Water scarcity conflicts:** Transboundary pollution and unequal access to clean water may exacerbate tensions between neighboring regions or countries.
- **Migration pressures:** Long-term water degradation can force populations to relocate, intensifying rural-to-urban migration and regional instability (UNEP, 2016).

III.7. Drinking Water Quality Standards

The quality of drinking water is evaluated based on a series of organoleptic **and** physico-chemical parameters **that ensure both safety and acceptability for human consumption. These parameters are defined by international guidelines such as those of**

the World Health Organization (WHO)**, the** European Commission**, and other regulatory agencies.**

III.7.1. Organoleptic Parameters

a). Colour

Water colour is classified as true colour, caused solely by dissolved substances, and apparent colour, which includes the effects of suspended particles. According to the World Health Organization (WHO, 2022), the acceptable colour intensity for drinking water should not exceed 15 platinum–cobalt units (PCU or TCU) on the platinum–cobalt scale. Colour in water commonly arises from the presence of dissolved organic matter such as humic and fulvic acids, as well as metals like iron and manganese (WHO, 2022; Eawag, 2022). Changes in water colour can indicate contamination events, corrosion in distribution systems, or inefficient treatment processes (World Bank, 2021). Elevated colour levels are not only aesthetically unpleasant but may also interfere with disinfection efficiency by shielding microorganisms, thus posing potential health risks (WHO, 2022; European Commission, 2020).).

b). Turbidity

Turbidity results from fine suspended particles, including colloids, that scatter light and give water a cloudy appearance. It is measured in Nephelometric Turbidity Units (NTU). According to the World Health Organization (WHO, 2022) and the European Commission (2020), turbidity in drinking water should remain below 1 NTU at the distribution point and below 2 NTU at the consumer’s tap to ensure effective disinfection and acceptable aesthetic quality. In natural aquatic systems, turbidity may increase significantly — sometimes reaching 10,000 NTU — during events such as heavy rainfall, soil erosion, or sediment resuspension (EPA, 2021). Elevated turbidity often indicates a higher risk of microbiological contamination, as pathogens can attach to suspended particles and evade disinfection (WHO, 2022; Sensorex, 2023). Furthermore, high turbidity can reduce light penetration, limiting photosynthesis in aquatic ecosystems, and clog fish gills, thereby affecting aquatic biodiversity (UNEP, 2020).

d). Odour

Potable water must be completely free from any unpleasant or objectionable odours, as odour is a key indicator of water quality and acceptability to consumers. The presence of odour often reflects microbial activity, organic matter decomposition, or chemical contamination from industrial discharges, pesticides, or chlorination by-products (WHO, 2022; EPA, 2021). According to the World Health Organization (WHO, 2022), odorous compounds such as hydrogen sulfide (H_2S), phenols, and geosmin can be detected even at very low concentrations and may cause consumer complaints despite posing limited health risks. However, persistent odours can signal serious contamination by volatile organic compounds (VOCs), petroleum hydrocarbons, or algal metabolites (European Commission, 2020; UNEP, 2023). Maintaining odour-free drinking water requires regular monitoring, proper disinfection, and control of pollution sources to ensure both public health protection and consumer confidence.

III.7.2. Physico-Chemical Parameters

a).Temperature

Water temperature is a key physical parameter influencing chemical, biological, and aesthetic characteristics of drinking water.

- **Optimal range:** The recommended temperature for drinking water is **9–12 °C**, and it should not exceed **15 °C** for consumer acceptability (WHO, 2017).
- **Chemical effects:**
    - Higher temperatures accelerate **reaction kinetics**, enhancing corrosion, scaling, and chlorine decay.
    - Temperature also controls the **solubility of gases** such as oxygen and carbon dioxide, influencing redox processes.
- **Biological effects:**
    - Warm water promotes **microbial regrowth** in distribution systems, increasing risks of biofilm formation and pathogen proliferation.
    - Cold water (< 5 °C) may limit microbial activity but is often associated with reduced consumer palatability.
- **Ecological relevance:** In surface waters, elevated temperatures reduce dissolved oxygen concentrations, increase fish metabolism, and can lead to thermal stress and biodiversity loss (Bouziane, 2000).
- **Consumer perception:** Water above 15 °C is often rejected due to unpleasant taste and reduced refreshment quality.

b). Ph

pH is a critical parameter in water quality assessment, as it governs chemical reactions, biological activity, and the solubility of metals. It also plays a central role in controlling corrosion and scaling in water supply systems.

- **Acceptable range:** Drinking water pH values are recommended to fall between **6.5 and 8.5** (WHO, 2007; Council of the European Communities, 1998).
- **Low pH (acidic, < 6.5):** Corrosive to pipes and metallic fixtures, leading to the release of toxic metals (e.g., lead, copper, zinc) into drinking water. Acidic water also imparts a sour taste and may cause gastrointestinal irritation.

- **High pH (alkaline, > 8.5):** Can cause scaling in pipes and water heaters, reducing hydraulic efficiency and increasing maintenance costs. Alkaline water may also have a bitter taste and reduce the effectiveness of chlorination.
- **Ecological implications:** Aquatic life is highly sensitive to pH fluctuations. Most freshwater organisms thrive between pH 6.5 and 8.0. Acidification (< 5.0) can cause fish kills and biodiversity loss, while alkaline conditions (> 9.0) may impair reproduction and growth in aquatic species (Camargo & Alonso, 2006).
- **Buffering capacity:** Natural waters with adequate alkalinity (bicarbonates, carbonates) can resist pH changes, reducing vulnerability to acid rain and industrial discharges.

c). Hardness

Water hardness is mainly determined by the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, though other multivalent cations (e.g., Fe^{2+}, Mn^{2+}) can also contribute. Hardness is usually expressed in French degrees (°F), where 1 °F = 10 mg/L $CaCO_3$ equivalent:

- **Very soft:** TH < 7 °F → Not potable; corrosive to pipes and metallic surfaces.
- **Soft:** 7–14 °F → Good quality for domestic use.
- **Moderately hard:** 14–22 °F → Fair; acceptable for consumption.
- **Hard:** 22–32 °F → Fair; may cause scaling.
- **Very hard:** > 32 °F → Poor; significant scaling problems (Lenntech, n.d.).

Implications of Water Hardness

- **Domestic impacts:** Hard water reduces soap efficiency, leaves deposits on dishes, and produces scaling in boilers, heaters, and distribution networks (Sawyer et al., 2003).
- **Health effects:** Moderate hardness is not harmful and may even provide beneficial calcium and magnesium intake; however, very high hardness is associated with gastrointestinal discomfort and may correlate with cardiovascular issues (WHO, 2011).
- **Industrial impacts:** Scaling decreases energy efficiency in heat exchangers and increases maintenance costs. Industries requiring soft water (textile, paper, electronics) must invest in treatment systems.
- **Environmental relevance:** Hardness influences aquatic life by buffering against acidification and controlling metal bioavailability. Soft water enhances the toxicity of heavy metals such as cadmium and lead (Camargo & Alonso, 2006).

d). Redox Potential (Eh)

The oxidation-reduction potential (Eh) is a key indicator of the redox state of aquatic environments, reflecting their tendency to promote oxidation or reduction reactions. It is governed by the balance between oxidized and reduced chemical species, such as Fe^{2+}/Fe^{3+},

Mn^{2+}/Mn^{4+}, or NO_3^-/NH_4^+ couples (Sawyer et al., 2020; Chapra, 2021). Oxidation corresponds to the loss of electrons, whereas reduction involves their gain.

Example:

$$\mathbf{Fe^{2+} \rightleftharpoons Fe^{3+} + e^-}$$

Eh values are measured in millivolts (mV) using a platinum electrode referenced to a standard electrode. Positive Eh values indicate oxidizing conditions, typically associated with oxygenated waters, while negative values signify reducing conditions, common in anoxic or organic-rich environments (Wetzel, 2020).

The redox potential plays a crucial role in controlling the chemical speciation, solubility, and mobility of elements such as iron, manganese, sulfur, and heavy metals. It also affects nutrient cycling, particularly nitrogen and phosphorus transformations, and influences microbial processes like denitrification and sulfate reduction (Zhang et al., 2020). Consequently, Eh is an essential parameter in assessing water quality, ecological health, and the self-purification capacity of aquatic systems.

Implications of Water Eh

The oxidation-reduction potential (Eh) of water has profound implications for its chemical stability, biological activity, and environmental quality. It determines whether the aquatic environment favors oxidation or reduction reactions, which directly influences the speciation, solubility, and mobility of many chemical elements (Sawyer et al., 2020).

In **oxidizing conditions** (Eh > +300 mV), dissolved oxygen is abundant, and metals such as iron and manganese exist predominantly in their oxidized, less soluble forms (Fe^{3+}, Mn^{4+}). These conditions enhance the precipitation of oxides and hydroxides, contributing to the natural purification of water (Wetzel, 2020). Oxidative environments also support aerobic microbial communities and promote the degradation of organic pollutants.

Conversely, **reducing conditions** (Eh < 0 mV) occur in oxygen-depleted waters or sediments rich in organic matter. Under such conditions, bacteria utilize alternative electron acceptors such as nitrate, sulfate, or carbon dioxide, leading to processes like denitrification, sulfate reduction, and methanogenesis (Zhang et al., 2020). These reactions can release reduced compounds (NH_4^+, H_2S, CH_4), increase nutrient availability, and remobilize toxic metals such as Fe^{2+}, Mn^{2+}, or As^{3+} into the water column, potentially degrading water quality (Chapra, 2021).

e). Dissolved Oxygen (DO)

Dissolved oxygen (DO) is one of the most essential parameters in evaluating water quality and the ecological status of aquatic systems (WHO, 2020). It represents the amount of gaseous oxygen (O_2) present in water, which is vital for the survival of fish, invertebrates, and aerobic microorganisms. Oxygen enters water primarily through **atmospheric diffusion**, **photosynthesis by aquatic plants and algae**, and **aeration caused by turbulence** (Wetzel, 2020). The equilibrium concentration of DO depends on **temperature**, **salinity**, **altitude**, and **biological activity**—it decreases with increasing temperature and salinity, which lowers oxygen solubility (Chapra, 2021).

The concentration of DO in natural waters typically ranges between **8–14 mg/L** under normal conditions, but levels below **5 mg/L** can stress aquatic life, and concentrations under **2 mg/L** may lead to **hypoxic conditions** (EPA, 2023). Low DO levels are often caused by **organic pollution**, **excess nutrient inputs** (eutrophication), or **thermal discharges** that enhance microbial oxygen consumption. These conditions can lead to **fish kills**, **loss of biodiversity**, and **anaerobic decomposition**, producing harmful substances such as methane (CH_4), ammonia (NH_3), and hydrogen sulfide (H_2S) (Zhang et al., 2022).

In contrast, **supersaturation of DO** (>100%) may occur during intense photosynthesis, especially in nutrient-rich or algal-bloom-prone waters. Although high DO may appear beneficial, it can cause **gas bubble disease** in fish and signal excessive nutrient enrichment or unstable ecosystem dynamics (Li et al., 2021).

Dissolved oxygen also plays a central role in **biogeochemical cycles**, particularly in the oxidation of **nitrogen, sulfur, and iron compounds**, influencing nutrient availability and contaminant behavior. For instance, in oxic waters, ammonia (NH_4^+) is converted to nitrate (NO_3^-) through nitrification, whereas in anoxic conditions, denitrification and sulfate reduction dominate (Zhao et al., 2020).

Monitoring DO levels is therefore essential for **detecting pollution**, **evaluating self-purification processes**, and **guiding water treatment and ecosystem management**. It serves as an early warning indicator for eutrophication, organic loading, and ecosystem imbalance, helping ensure the sustainability of aquatic environments (UNEP, 2023).

f). Total Suspended Solids (TSS)

Total Suspended Solids (TSS) represent the particulate fraction of pollution, consisting of **mineral or organic biodegradable and non-biodegradable materials** that remain dispersed in water due to turbulence or flow dynamics (Sawyer et al., 2020). These particles include silt, clay, detritus, plankton, and industrial or domestic waste residues. TSS concentration is expressed in **milligrams per liter (mg/L)** and reflects the total amount of solid matter transported by wastewater or surface water.

The TSS content is determined by **filtering a known volume of water** through a **0.45 µm pore-size filter**, followed by **drying the filter at 105°C** for two hours. The concentration is then calculated using the formula:

TSS=(P2−P1)×1000VTSS = \frac{(P_2 - P_1) \times 1000}{V}TSS=V(P2−P1)×1000

where:

- **P_1** = weight of the filter before filtration (mg),
- **P_2** = weight of the filter after drying at 105°C (mg),
- **V** = filtered water volume (mL).

High TSS levels significantly affect **water quality, light penetration, and aquatic productivity**. Suspended solids reduce transparency and **limit photosynthesis**, decreasing oxygen production and altering aquatic food webs (Wetzel, 2020). Excess TSS can clog fish gills, smother benthic habitats, and transport adsorbed pollutants such as heavy metals, nutrients, and pathogens (Zhang et al., 2022). Moreover, high turbidity increases **water treatment costs** and reduces the **aesthetic and recreational value** of aquatic ecosystems (EPA, 2023).

In sedimentation zones, the deposition of suspended particles alters **hydrological regimes**, promotes **eutrophication**, and can release **toxic substances** during anaerobic decomposition (Li et al., 2021). Therefore, monitoring TSS is essential for assessing **sediment transport**, **pollution loads**, and the **ecological integrity** of aquatic systems.

III.7.3. Organic Matter

Organic matter in water comes from **natural sources** (soil humic substances, plant debris, microbial biomass) and **anthropogenic inputs** (domestic sewage, industrial effluents, agricultural runoff). It strongly influences **drinking water quality**, as it affects colour, odour, taste, oxygen balance, and may lead to the formation of **toxic disinfection by-products (DBPs)** during chlorination. Its characterization involves several key parameters:

a). Oxidizability (using $KMnO_4$)

This test estimates the amount of oxidizable organic and some inorganic substances (iron, manganese, nitrites). Under controlled conditions, potassium permanganate is consumed proportionally to the oxidizable load. Although less specific than TOC or COD, it provides a **simple and rapid indication** of overall organic matter content, particularly useful for routine monitoring of drinking water treatment (WHO, 2017).

b). Total Organic Carbon (TOC)

TOC measures the total amount of carbon bound in organic molecules, whether dissolved or particulate, biodegradable or refractory. High TOC values often reflect **organic pollution**

from sewage, fertilizers, or surface runoff rich in humic and fulvic acids. In drinking water, TOC is closely monitored because it directly correlates with the potential formation of **DBPs such as trihalomethanes (THMs) and haloacetic acids (HAAs)** during disinfection (Tribocare, n.d.).

c). Chemical Oxygen Demand (COD)

COD represents the oxygen equivalent of the total oxidizable matter (both biodegradable and non-biodegradable). The method, based on potassium dichromate oxidation in acidic medium, provides a **global picture of organic contamination**, especially from industrial effluents (textiles, tanneries, food-processing industries). High COD values indicate severe organic load and correlate with environmental risks such as **oxygen depletion and toxic releases** in aquatic systems (European Commission, 2020).

d). Biochemical Oxygen Demand (BOD_5)

BOD_5 specifically reflects the oxygen consumed by microorganisms during biodegradation of organic matter over five days at 20 °C. It is a **key ecological indicator**, as it reflects the potential of a water body to sustain life. Excessive BOD_5 values indicate high levels of biodegradable waste, leading to **hypoxia, fish mortality, and ecosystem imbalance**. The **BOD_5/COD ratio** is widely used to assess biodegradability:

- Ratio > 0.4 → high biodegradability (domestic wastewater)
- Ratio < 0.2 → low biodegradability (toxic or industrial wastewater).

e). Alkalinity

Alkalinity expresses the buffering capacity of water, i.e., its ability to resist sudden pH changes when acids are added. It depends mainly on bicarbonates (HCO_3^-), carbonates (CO_3^{2-}), and hydroxides (OH^-). Adequate alkalinity ensures **stability of water treatment processes** such as coagulation, neutralization, and disinfection. Low alkalinity makes water corrosive, whereas high alkalinity may cause scaling in pipes and interfere with chlorination efficiency (APHA, 2017).

III.7.4. Microbiological Parameters

The microbiological quality of drinking water is one of the most critical determinants of public health safety. Contamination by **pathogenic microorganisms** remains the leading cause of waterborne diseases worldwide, including **cholera, dysentery, typhoid fever, and gastroenteritis**.

The main microbial indicators are:

- ***Escherichia coli* (E. coli)**: Its presence indicates recent fecal contamination and the possible presence of enteric pathogens such as viruses (rotavirus, hepatitis A virus), protozoa (*Giardia*, *Cryptosporidium*), or bacteria (*Vibrio cholerae*).
- **Coliform bacteria (total and fecal coliforms)**: Used as general indicators of hygienic quality. Their detection suggests possible contamination by other pathogens.
- **Streptococcus (Enterococci)**: Considered more resistant than coliforms and useful for indicating contamination in saline waters or groundwater.
- **Salmonella**: A strict pathogen that should be completely absent from potable water, as it causes salmonellosis and typhoid fever.

According to the **WHO (2017)** and the **EU Drinking Water Directive (2020)**:

- **E. coli and Enterococci must be absent in any 100 mL sample** of drinking water.
- Other pathogens such as *Salmonella*, *Clostridium perfringens*, and *Pseudomonas aeruginosa* are also monitored, particularly in vulnerable populations (hospitals, infants, immunocompromised individuals).

Microbiological monitoring is performed using standardized methods such as **membrane filtration**, **multiple-tube fermentation tests**, and **molecular techniques (qPCR)** for rapid detection.

III.7.5. Criteria for Potable Water

Potable water is defined as water that is **safe, acceptable, and suitable for human consumption** without risk to health over a lifetime of use. To achieve this, it must comply with **multiple categories of standards**:

1. **Organoleptic Standards**
    - Ensure **acceptability** to consumers by regulating parameters such as **colour, turbidity, odour, and taste**. Even if water is chemically safe, unpleasant sensory characteristics may reduce consumption compliance or indicate contamination.
2. **Chemical Standards**
    - Include **physico-chemical parameters** (pH, hardness, temperature, dissolved oxygen) and **toxic chemical contaminants** (heavy metals, pesticides, nitrates, hydrocarbons).
    - Thresholds are established to prevent **acute toxicity** (e.g., nitrate-linked methemoglobinemia in infants) and **chronic toxicity** (e.g., lead-induced neurological damage, arsenic carcinogenic effects).

3. **Microbiological Standards**
    - Require complete absence of pathogenic bacteria, viruses, and protozoa. This is considered the **most essential criterion** since microbial contamination can cause immediate and large-scale health impacts.
4. **Radiological Standards**
    - Defined for radionuclides (e.g., radon, uranium, cesium) to avoid **chronic exposure risks**. These are particularly relevant in groundwater-rich regions with natural radioactivity.

International and regional frameworks guiding these criteria include:

- **WHO Guidelines for Drinking Water Quality** (2017): Provide global benchmarks based on health risk assessments.

III.8.5. Elemental Composition

Aquatic environments contain essential elements that play key roles in biogeochemical cycles and ecosystem functioning. The most important among them are carbon, nitrogen, and phosphorus.

a) Carbo

Carbon exists in aquatic systems in multiple forms: particulate organic carbon (POC), particulate inorganic carbon (PIC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC).Inorganic carbon originates from several sources, including the erosion of sedimentary rocks, dissolution of atmospheric CO_2, dissolution of carbonate minerals, and degradation of organic matter by microbial activity.

Organic carbon is derived from three main sources:

- **Allochthonous natural carbon**: Humic substances derived from soil leaching within the watershed.
- **Autochthonous carbon**: Produced within the aquatic system itself, mainly by primary producers such as macrophytes, benthic algae, and phytoplankton.
- **Allochthonous anthropogenic carbon**: Introduced through domestic, industrial, and agricultural discharges, whether treated or untreated (Wetzel, 2001).

b) Nitrogen

Nitrogen occurs naturally in air, water, and soils, and plays a fundamental role in biological processes through its cycle, which ensures assimilation by primary producers and regeneration via heterotrophic bacteria. In aquatic environments, nitrogen is found in three main forms: gaseous, organic, and mineral.

- **Atmospheric nitrogen (N_2):** Constitutes ~78% of the Earth's atmosphere. Most organisms cannot use it directly, except for specific bacteria and cyanobacteria capable of nitrogen fixation, which converts N_2 into ammonium (NH_4^+) or ammonia (NH_3).
- **Organic nitrogen:** Originates from proteins, urea, and humic substances. Its mineralization releases ammonium (NH_4^+), which undergoes nitrification to nitrites (NO_2^-) and subsequently to nitrates (NO_3^-).
- **Mineral nitrogen:**
  - *Ammonium (NH_4^+):* A reliable tracer of domestic pollution from human waste (Chapman, 1996).
  - *Nitrites (NO_2^-):* An intermediate product of nitrification; its accumulation reflects oxygen imbalance or reduced bacterial activity at low temperatures.
  - *Nitrates (NO_3^-):* The final oxidized form of nitrogen, mainly originating from agricultural runoff (fertilizers), as well as urban and industrial discharges (WHO, 2017).

c) Phosphorus

Phosphorus is essential for all living organisms, especially plants, as it is a structural component of phospholipids and nucleotides. Unlike nitrogen, phosphorus has no gaseous form. It is abundant in volcanic and sedimentary rocks, particularly in calcium phosphate minerals, from which weathering and erosion transfer it into aquatic systems.

In aquatic environments, phosphorus occurs in two main forms:

- **Particulate phosphorus:** Associated with organic matter and soil minerals, due to the strong affinity of phosphate (PO_4^{3-}) for clay minerals and iron/aluminum oxyhydroxides.
- **Dissolved phosphorus:** Primarily in the form of orthophosphate (PO_4^{3-}), which is directly bioavailable to aquatic plants.

Eutrophication

The enrichment of aquatic systems with nitrogen, phosphorus, and organic matter can lead to *eutrophication*, a process characterized by excessive algal and plant growth. This results in oxygen depletion, reduced biodiversity, and disruption of aquatic ecosystems (Smith et al., 1999).

- **EU Drinking Water Directive** (European Commission, 2020): Establish legally binding standards for all EU member states, focusing on **health protection and consumer acceptability**.

- **National legislations**: Adapted to local hydrological, economic, and health contexts, often using WHO and EU guidelines as reference models.

Thus, **safe drinking water** must be:

- **Free from pathogens** (biological safety),
- **Low in toxic chemicals** (chemical safety),
- **Acceptable in sensory qualities** (organoleptic compliance),
- **Non-radioactive above thresholds** (radiological safety).

Only when these combined requirements are met can water be classified as **potable and safe for human consumption**.

III.9. Solutions for Wastewater Treatment

Water pollution represents a major challenge for human health and ecosystem balance. Different treatment approaches, ranging from conventional processes to innovative technologies, are implemented to improve water quality.

III.9.1. Physico-chemical treatments

Physico-chemical processes include coagulation-flocculation, sedimentation, filtration, and adsorption.

- **Coagulation-flocculation**: removes suspended solids and heavy metals using coagulants such as aluminum or iron salts (Zhao et al., 2020).
- **Adsorption**: adsorbent materials such as activated carbon and biochar derived from biomass have proven effective for removing dyes, heavy metals, and pesticides (Zhang et al., 2019).
- **Ozonation and advanced oxidation processes (AOPs)**: ozone application and Fenton or photo-Fenton processes degrade persistent organic pollutants, including pharmaceutical micropollutants (Martins et al., 2021).

III.9.2. Biological treatments

Biological processes rely on microorganisms to degrade organic matter and nutrients.

- **Activated sludge**: widely applied in wastewater treatment plants to reduce biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Li et al., 2020).
- **Natural lagoons and constructed wetlands**: exploit the purifying capacity of aquatic plants (macrophytes) and microbial biofilms to remove nitrogen, phosphorus, and pathogens (Vymazal, 2018).

- **Bioremediation**: certain bacteria and fungi can degrade hydrocarbons, pesticides, and heavy metals. Species such as *Pseudomonas* and *Bacillus* have shown strong potential for detoxifying aquatic environments (Singh et al., 2020).

III.9.3. Membrane technologies

Membrane-based methods represent an effective solution for advanced wastewater treatment.

- **Ultrafiltration and nanofiltration**: effective for eliminating microorganisms, colloids, and salts (Goh et al., 2020).
- **Reverse osmosis**: widely used for desalination and removal of organic and pharmaceutical micropollutants (Shannon et al., 2018).
- **Hybrid membranes**: membranes functionalized with nanoparticles (TiO_2, ZnO, Ag) provide improved antibacterial efficiency and enhanced resistance to fouling (Wang et al., 2021).

III.9.4. Phytoremediation and ecological approaches

Phytoremediation uses aquatic plants to absorb, accumulate, and degrade pollutants.

- Species such as *Eichhornia crassipes* (water hyacinth) and *Typha latifolia* (cattail) show remarkable capacity to absorb heavy metals (Rahman et al., 2020).
- This technique is considered a sustainable, low-cost alternative for wastewater treatment, especially in developing countries, and can be integrated into nature-based solutions (Ansari et al., 2021).

Chaptre IV : Soil Pollution

Chaptre IV: Soil Pollution

IV.1. General Characteristics of Soil Phases

IV.1. 1.Definition of Soil

Soil is a natural, superficial, and often loose unit resulting from the transformation, decomposition, and weathering of the parent rock through contact with the atmosphere and living organisms, under the influence of water and air. It generally originates from the underlying rock, shaped by physical, chemical, and biological processes. Soil is a biologically active medium, differentiated into horizons of varying thickness, where plants, animals, and bacteria thrive and interact, contributing to its balance and sustainability (Deprince, 2003).

In pedology, soil is defined as the part of the Earth's crust where geology and biology intersect. It is a living medium composed of organic and mineral matter. It is also a vital natural resource used in various sectors such as industry, agriculture, and urban development. For geologists, soil is the surface layer of the parent rock altered by climatic, biological, and human factors. For farmers, soil is simply a rich medium that supports the growth and harvest of numerous plant products (Benyahia & Mahdaoui, 2011).

More recent perspectives define soil as an interactive system, a non-renewable bioreactor, spatially variable with undefined boundaries. As such, soil is considered a **“structured bio-organo-mineral complex”** (Gaviglio, 2013).

Soils are open and dynamic systems that exchange matter and energy with the atmosphere, biosphere, and hydrosphere. They perform five essential basic functions:

- Provide physical, chemical, and biological habitat for living organisms;
- Support biological activity and diversity necessary for plant growth and animal productivity;
- Offer mechanical support for living organisms and their structures;
- Regulate water flow, store and recycle nutrients and other essential elements;
- Filter, buffer, transform, immobilize, and detoxify organic and inorganic substances (Sahnoune, 2014).

IV.1.2. Soil Components

Soil life relies on the continuous and dynamic interactions between its mineral and organic elements, which together create a complex and living system essential for terrestrial ecosystems. Soil is a porous medium composed of five primary components: solid minerals, organic matter, living organisms, a gaseous phase, and a liquid phase (Calvet, 2003; Brady & Weil, 2021). The mineral fraction—derived from the weathering of parent rock—forms the structural matrix that determines soil texture and stability. Organic matter, originating from decomposed plant and animal residues, improves nutrient availability, water retention, and soil aggregation, while also serving as an energy source for microorganisms (Lal, 2020; FAO, 2022). The biological component, consisting of bacteria, fungi, and soil fauna, plays a critical role in decomposition, nutrient cycling, and soil respiration, thus maintaining soil fertility and productivity (UNEP, 2023).

The liquid phase (soil solution) contains dissolved ions and nutrients accessible to plants, whereas the gaseous phase allows oxygen diffusion and carbon dioxide exchange essential for root and microbial respiration (IPBES, 2022; FAO, 2024). The equilibrium among these five components ensures soil health, resilience, and ecosystem sustainability, making soil one of the most vital resources for environmental balance and food security worldwide.

IV.2.1.The Solid Phase of Soil

The solid phase constitutes the structural backbone of the soil, representing approximately 50–70% of its total volume. It comprises mineral particles and organic matter, which together determine the soil's texture, structure, and fertility. Mineral components are divided into primary minerals, derived from parent rock (e.g., quartz, feldspar, mica), and secondary minerals, formed through weathering processes (e.g., clays, oxides, hydroxides) (Calvet, 2003; Brady & Weil, 2021). The organic fraction includes decomposed plant and animal residues, humus, and microbial biomass, all of which contribute to nutrient cycling, cation exchange capacity, and water retention (Lal, 2020).

Additionally, soil organisms, such as bacteria, fungi, and microfauna, interact continuously with these solid components, transforming organic matter and releasing essential nutrients. These biotic and abiotic interactions are fundamental for maintaining soil structure, aeration, and fertility (FAO, 2022). The balance between the mineral matrix and organic content determines the soil's capacity to support vegetation and regulate water and nutrient dynamics, making the solid phase a critical factor in ecosystem productivity and environmental sustainability

IV.2.1.1The Mineral Fraction

The mineral fraction of soil originates from the physical and chemical weathering of the parent rock and forms the structural and functional foundation of the soil system. It represents the inorganic matrix responsible for many of the soil's physical, chemical, and biological properties (Quenea, 2004; Brady & Weil, 2021). This fraction can be described through three complementary parameters:

- Elemental composition – reflecting the concentration of essential elements such as silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), and magnesium (Mg), which determine the soil's chemical fertility and buffering capacity;
- Mineralogy – describing the types and proportions of minerals present, including primary minerals (e.g., quartz, feldspar, mica) derived from unaltered parent rock and secondary minerals (e.g., clay minerals, oxides, hydroxides) formed through weathering and pedogenic processes;
- Particle size distribution (granulometry) – referring to the relative proportions and sizes of mineral particles that govern water retention, aeration, and root penetration (FAO, 2022; Lal, 2020).

Based on particle size, soil minerals are generally classified into three main categories (USDA, 2020):

- Sand: 2000–50 µm — contributes to soil drainage and aeration;
- Silt: 50–2 µm — improves water and nutrient retention;
- Clay: <2 µm — provides a large surface area for ion exchange and adsorptive reactions.

The soil texture represents the relative proportions of these three fractions and strongly influences soil behavior, fertility, and erosion susceptibility. It determines key agronomic properties such as water-holding capacity, permeability, nutrient availability, and ease of tillage (Brady & Weil, 2021; FAO, 2024). Recent studies emphasize that the mineral composition also affects carbon sequestration potential and microbial activity, linking soil mineralogy directly to climate regulation and ecosystem services (IPBES, 2022; UNEP, 2023). Thus, understanding the mineral fraction is fundamental for evaluating soil quality, fertility, and environmental sustainability.

IV.2.1.2. Organic Fraction

The organic fraction of the soil encompasses all carbon-based compounds, ranging from simple molecules to complex polymers, which may exist in living organisms or in decomposed, non-living structures. This fraction plays a vital role in soil fertility, nutrient cycling, and ecosystem functioning, as it forms the physical and biological foundation for terrestrial life (Stevenson, 1994; Brady & Weil, 2021). Soil organic matter (SOM) is typically divided into four main categories:

- Living organisms (biomass): includes microorganisms such as bacteria, fungi, protozoa, and soil fauna that drive decomposition and nutrient transformation;
- Dead organisms in decomposition: organic residues undergoing enzymatic breakdown, releasing essential elements like nitrogen, phosphorus, and sulfur;

- Organic intermediates: transient compounds formed during mineralization and humification processes;
- Humic substances: stable, high–molecular weight organic polymers that improve soil structure, cation exchange capacity, and water retention (FAO, 2022; UNEP, 2023).

Soil provides a favorable habitat for microbial life, with densities reaching 10^6–10^9 bacterial cells per gram of soil, far exceeding those found in freshwater or marine ecosystems (Atlas & Bartha, 1992; IPBES, 2022). The diversity and abundance of these microorganisms depend on multiple factors, including soil type, vegetation cover, climate, and anthropogenic influence (Lal, 2020; FAO, 2024). Soil microbes are fundamental for the decomposition of organic residues, the release of nutrients, and the formation of humus, contributing significantly to carbon sequestration and soil resilience against degradation. Recent studies (FAO, 2022; UNEP, 2023) highlight that maintaining a healthy organic fraction is crucial not only for soil fertility but also for climate regulation, pollution mitigation, and sustainable agricultural productivity.

IV.2.2. Liquid Phase of the Soil

The liquid phase of the soil, commonly known as the soil solution, occupies part of the pore space and plays a central role in nutrient transport, ion exchange, and plant nutrition. It consists primarily of water containing dissolved organic and inorganic substances (such as ions, organic acids, and soluble humic compounds), as well as fine suspended colloidal particles (Quenea, 2004; Brady & Weil, 2021). The composition and concentration of solutes in the soil solution vary dynamically depending on climatic conditions, anthropogenic inputs (e.g., fertilizers, pesticides, and waste discharge), and biological activity (e.g., root exudates, microbial metabolism, and decomposition products) (FAO, 2022; Lal, 2020).

Chemically, the soil solution behaves as a dilute electrolyte, with total ionic strength typically ranging from 10^{-3} to 10^{-5} mol/L. It contains various macro- and micronutrients such as Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^-, SO_4^{2-}, and $H_2PO_4^-$, essential for plant growth (Atlas & Bartha, 1992; IPBES, 2022). The H^+ and OH^- ion concentrations determine the soil reaction, expressed by pH, which directly influences nutrient availability, microbial activity, and metal solubility (FAO, 2024; UNEP, 2023).

The liquid phase also mediates chemical weathering, solute transport, and redox reactions, linking the solid and gaseous phases in a dynamic equilibrium. Changes in soil moisture or contamination can alter the composition of the soil solution, affecting both plant health and groundwater quality. Thus, understanding the soil solution's chemical and biological dynamics is essential for managing soil fertility, agricultural productivity, and environmental sustainability.

IV.2.3. Gaseous Phase of the Soil

The gaseous phase of the soil consists of the same principal components as atmospheric air, mainly nitrogen, oxygen, and carbon dioxide, but their relative proportions differ considerably due to biological and physicochemical processes within the soil. The composition of this phase depends largely on soil porosity, depth, texture, moisture content, and the rate of air renewal through diffusion and convection (Quenea, 2004; Brady & Weil, 2021).

In well-aerated soils, the predominant gases are nitrogen (78–80%), oxygen (18–20%), and carbon dioxide (0.2–3%). However, in poorly drained or compacted soils, oxygen levels decrease while carbon dioxide and other trace gases accumulate due to microbial respiration and root metabolism (FAO, 2022; Lal, 2020). The oxygen concentration determines whether the soil environment is aerobic or anaerobic, directly influencing microbial community composition, enzyme activity, and nutrient cycling (IPBES, 2022).

Carbon dioxide (CO_2), produced by the respiration of soil organisms, reacts with the liquid phase to form carbonic acid (H_2CO_3) and carbonates, thereby affecting soil pH and mineral weathering (UNEP, 2023). In addition to these main gases, soil air contains minor but ecologically significant components such as nitric oxide (NO), nitrous oxide (N_2O), ammonia (NH_3), methane (CH_4), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs). These trace gases contribute to greenhouse gas emissions and soil–atmosphere exchanges (Atlas & Bartha, 1992; FAO, 2024).

Overall, the composition and dynamics of the soil gaseous phase exert strong control over plant root development, microbial survival, and biogeochemical cycles, linking soil functioning to global climate regulation and ecosystem sustainability (Lal, 2020; FAO, 2024).

Figure 5

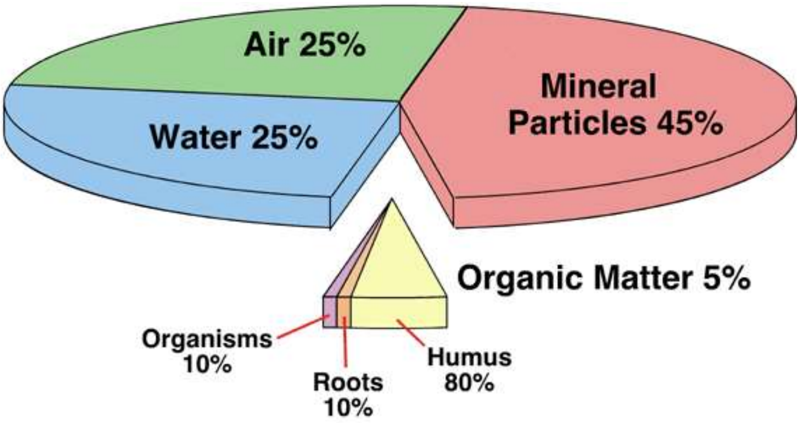


Figure 5: Composition volumique moyenne du sol

IV.3. Soil Properties

IV.3.1. Chemical Properties

IV.3.1.1. Hydrogen Potential (pH)

Soil **pH** expresses whether the medium is **acidic, neutral, or alkaline**, depending on the concentration of free hydrogen ions (H^+) in solution. It plays a key role in **nutrient availability, microbial activity, and soil structure stability**. Although the pH scale ranges from 0 to 14 (7 being neutral), most soils exhibit values between **4.5 and 8.5**, depending on their **mineral composition, organic matter content, and climatic conditions** (Prévost, 2006; FAO, 2022).

Soil pH is primarily influenced by the **nature of the parent material**, **litter composition**, and particularly by the **carbon-to-nitrogen (C/N) ratio** of organic residues (Chauda & Lecle, 1999; Brady & Weil, 2021). The hydrogen potential is mathematically expressed as:

$$\mathbf{pH = \log (1/[H^+])}$$

Recent studies emphasize that **soil acidification** is often driven by **intensive agriculture**, **acid rain**, and **nitrogen fertilizer overuse**, while **alkalinization** is linked to **arid climates and salinization processes** (Lal, 2020; Zhang et al., 2023). Managing pH balance is thus essential for maintaining **soil fertility and biological activity** (FAO, 2024).

IV.3.1.2. Organic Matter

Soil organic matter (SOM) originates from the **biodegradation and transformation** of plant and animal residues through **microbial and enzymatic activity**. The end product of this decomposition is **humus**, a complex and stable fraction that plays a central role in **soil fertility and ecosystem functioning** (Halitim, 1988; Huber et al., 2011).

Organic matter includes, in varying proportions depending on ecological conditions:

- Fresh or partially decomposed organic residues
- Materials undergoing **humification** or already **humified substances**

It is important to distinguish between **fresh organic matter**, which serves as a **rapid nutrient source**, and **humified organic matter**, which ensures **long-term fertility** through its **colloidal and buffering properties** (Brady & Weil, 2021; FAO, 2023).

Soil organic matter performs three essential functions :

- **Energy source** — providing carbon for microbial metabolism;
- **Physical role** — improving **soil aggregation**, **porosity**, and **water retention**;
- **Nutritional role** — supplying **macro- and micronutrients** to plants through mineralization (Lal, 2020; UNCCD, 2022).

The **quantity, quality, and degree of transformation** of organic matter determine the soil's **biological activity and fertility**. It enhances **soil structure**, reduces **erosion susceptibility**, stabilizes **temperature and moisture**, and supports **microbial biodiversity** (Zhang et al., 2022). Conversely, the **absence or depletion** of organic matter leads to **structural instability**, **nutrient loss**, and **decline in productivity** (FAO, 2024).

IV.3.1.3. Cation Exchange Capacity (CEC)

The **Cation Exchange Capacity (CEC)**—also referred to as *total exchange capacity*—represents the total quantity of **exchangeable cations** that soil particles can adsorb and release at a specific pH. It is a fundamental indicator of **soil fertility**, reflecting the ability of the soil to **retain essential nutrients** such as Ca^{2+}, Mg^{2+}, K^+, and Na^+, and to **buffer against chemical changes** (Calvet, 2003; FAO, 2023).

CEC depends mainly on the **amount and nature of clay minerals** and **soil organic matter**. Clays with high surface area (e.g., montmorillonite) and humic substances exhibit greater cation exchange capacities than quartz-rich or sandy soils (Kessel, 2015; Brady & Weil, 2021). Soils with **high CEC** possess a better ability to **retain and supply nutrients**, resist acidification, and stabilize metal pollutants, making them more productive and resilient (Lal, 2020; Zhang et al., 2023).

The comparison of **basic (Ca^{2+}, Mg^{2+}, K^+, Na^+)** and **acidic cations (H^+, Al^{3+})** provides an indicator of **base saturation**, which is closely linked to **soil fertility and weathering degree** (FAO, 2022; He et al., 2021). Modern studies also highlight the role of CEC in **metal mobility and pollutant adsorption**, making it a key parameter in environmental risk assessment (Zhou et al., 2022; Li et al., 2024).

IV.3.1.4. Electrical Conductivity

Electrical Conductivity (EC) expresses the soil's ability to **conduct an electrical current**, which depends directly on the **concentration of soluble salts** and **ionic strength** of the soil solution. It is a key indicator of **soil salinity**, affecting water uptake, plant growth, and microbial processes (Clément, 2003; FAO, 2024).

The higher the concentration of **dissolved ions (Na^+, Cl^-, SO_4^{2-}, NO_3^-)**, the greater the electrical conductivity. EC is thus widely used to monitor **salinization**, **fertilizer management**, and **irrigation water quality** (Brady & Weil, 2021; Li et al., 2024).

Optimal EC values generally range between **0 and 4 dS/m** for most crops. Values exceeding this threshold indicate **salinity stress**, which can hinder nutrient absorption and reduce agricultural productivity (FAO, 2022; UNCCD, 2022). Furthermore, excessive salinity may alter **soil structure** and **microbial activity**, accelerating **land degradation** (Lal, 2020; Zhang et al., 2023).

IV.3.2. Physical Properties

IV.3.2.1. Texture

Soil texture refers to the distribution of soil particles according to their size and the relative proportions of coarse sand, fine sand, silt, and clay. It represents one of the most stable physical properties of soils, providing essential information about their genesis, water retention, aeration, and fertility (Halitim, 1988; Gobat et al., 2010).

Two types of textures are commonly distinguished:

- **Mineral texture**, corresponding to the relative proportions of mineral particles (sand, silt, and clay), determined by particle-size analysis;
- **Organic texture**, associated with the presence of fibrous and micro-aggregated materials derived from organic matter (Soltner, 1988).

Particle-size analysis (mechanical analysis) is carried out by classifying soil particles based on their diameter, as presented in **Table 5**, which shows the main granulometric fractions according to international standards (AFNOR, 1998; FAO, 2021). This property directly affects soil structure, influencing porosity, permeability, water retention capacity, and root penetration (Brady & Weil, 2019).

Clay particles, because of their small size and large specific surface area, play a central role in soil aggregation and the formation of the **clay–humus complex**, which contributes to the **cation exchange capacity (CEC)** and nutrient retention (Six et al., 2020; Zhang et al., 2022). Therefore, soil texture is an essential parameter for assessing soil fertility and ecological function, as it governs hydrological behavior, microbial activity, and carbon storage capacity (Gülser et al., 2023; Peng et al., 2024). **Table 13**

Table 13. Granulometric classification of soil particles according to international standards (adapted from FAO, 2021).

Soil Fraction	Particle Diameter (µm)
Coarse sand	2000 – 200 µm
Fine sand	200 – 50 µm
Coarse silt	50 – 20 µm
Fine silt	20 – 2 µm
Clay	< 2 µm

IV.3.2.2. Structure

Soil structure refers to the spatial organization and arrangement of solid particles—minerals, organic matter, and living organisms—into aggregates or peds, and the voids between them that contain air and water. It can be analyzed at two main scales:

- **Macroscopic scale**, visible to the naked eye, which describes the general arrangement of aggregates and pores;
- **Microscopic scale**, or *microstructure*, observed under the microscope, which reveals the arrangement of particles, organic matter, and micro-aggregates (Duchaufour, 2001; Bronick & Lal, 2005).

The structure includes not only the size and shape of aggregates but also the continuity and connectivity of pore spaces. Large pores generally facilitate air circulation and drainage, whereas smaller pores retain water through capillary forces. This organization strongly influences hydrological and biological processes, such as water infiltration, retention, gas exchange, and root development (Calvet, 2003; Dexter, 2020).

The **clay–humus complex** plays a major role in maintaining and stabilizing soil structure. Clay minerals act as binding agents for organic matter, forming stable microaggregates that resist erosion. In contrast, degradation of organic matter or compaction reduces pore connectivity and weakens soil aggregation, thereby impairing water infiltration and gas diffusion (Six et al., 2020; Peng et al., 2023).

A well-structured soil provides several agronomic and ecological benefits, including :

- efficient water drainage and retention balance,
- adequate aeration for microbial and root activity,
- improved seed germination and root penetration,
- andenhanced nutrient availability for plants (Zhang et al., 2021; FAO, 2022).

Soil structure is a key indicator of soil health and resilience. Its degradation through intensive tillage, overgrazing, or pollution leads to compaction, reduced infiltration, and increased erosion risk (Reichert et al., 2024). Therefore, maintaining good soil structure through organic matter management, reduced tillage, and vegetation cover is essential for sustainable soil functioning and ecosystem productivity.

IV.3.2.3. Porosity

Soil porosity refers to the proportion of the total soil volume that is occupied by voids or pores, which may be filled with air, water, or both. It is a key physical property that governs soil aeration, water retention, and root development. Porosity directly influences several essential soil functions, including:

- water and air movement,
- solute transport and nutrient diffusion
- root penetration and microbial activity (Hillel, 2004; Lahlou et al., 2005).

Porosity (n) is expressed as the ratio between the volume of voids (Vv) and the total soil volume (Vt):

n=VvVtn = \frac{V_v}{V_t}n=VtVv

It is a dimensionless parameter, generally ranging from **0.3 to 0.7**, depending on the soil's texture, structure, and organic matter content (Dexter, 2020).

Porosity can be characterized by **pore size distribution, shape, and connectivity**, which determine the movement and storage of water and gases within the soil matrix. Pores are generally grouped into three main size categories:

- **Micropores** (<0.2 µm): retain water through capillary forces; inaccessible to roots and microorganisms.
- **Mesopores** (0.2–30 µm): store plant-available water.
- **Macropores** (>30 µm): allow rapid drainage and air exchange (Zhang et al., 2021; Peng et al., 2023).

From a functional perspective, soil porosity can also be classified according to its **origin**:

- **Structural porosity** – derived from the arrangement of soil aggregates and biological activity.

It is dynamic and can be modified by tillage, compaction, or organic matter inputs. High structural porosity enhances air circulation, water infiltration, and hydraulic conductivity (FAO, 2022).

- **Textural porosity** – determined by the particle-size distribution (texture). It is inherent to the soil and cannot be easily modified. Fine-textured soils (e.g., clay) generally have high total porosity but lower permeability, whereas sandy soils have lower porosity but higher permeability (Reichert et al., 2024).

Soil compaction and degradation significantly reduce porosity, restricting gas exchange and water flow. This leads to reduced root penetration, increased surface runoff, and ultimately lower crop productivity. Conversely, maintaining good porosity through organic amendments, cover crops, and reduced tillage supports soil health and sustainable agricultural performance (Dexter, 2020; Lal, 2022).

IV.3.2.4. Permeability

Soil permeability refers to the rate at which gravitational water infiltrates and percolates through the soil profile. It is generally expressed in centimeters per second ($cm \cdot s^{-1}$) or centimeters per hour ($cm \cdot h^{-1}$) for slower infiltration rates (Hillel, 1984). Permeability reflects the soil's ability to transmit water and air through its pore spaces and is therefore a key indicator of soil hydraulic functioning, structure, and health.

Infiltration is the process by which water enters the soil surface and moves vertically downward under the influence of gravity and capillary forces. This process plays a fundamental role in the hydrological cycle, influencing **runoff generation, groundwater recharge, and soil moisture dynamics** (Hillel, 2004; Vereecken et al., 2021). The **infiltration rate** depends on both surface conditions (e.g., crusting, compaction, residue cover) and subsurface structural characteristics such as porosity, aggregation, and organic matter content.

When rainfall intensity exceeds the infiltration capacity, surface ponding and **runoff formation** occur. In contrast, when soils are well-structured, infiltration is enhanced, reducing erosion risk and improving water availability to plants (Rawls et al., 2020). Conversely, in degraded soils, especially under intensive tillage or heavy rainfall, soil aggregates can break down, leading to surface sealing and decreased permeability (Henin et al., 1969; Assouline & Or, 2022).

Several factors govern soil permeability:

- **Texture:** Sandy soils exhibit higher permeability due to large pores, whereas clayey soils have lower permeability because of finer pores and higher water retention.
- **Structure:** Well-aggregated soils with stable macropores (from roots or fauna) enhance infiltration.
- **Organic matter:** Increases aggregate stability and pore continuity.
- **Compaction:** Reduces pore volume and connectivity, thus lowering permeability.
- **Biological activity:** Earthworms and roots create biopores that improve water flow (Dexter, 2020; Lal, 2022).

Soil permeability is therefore a critical property in evaluating soil quality and erosion risk, designing irrigation systems, and predicting contaminant transport in the vadose zone. Sustainable management practices—such as reduced tillage, organic amendments, and vegetative cover—help maintain or restore soil permeability, ensuring hydrological balance and agricultural productivity (FAO, 2022; Reichert et al., 2024).

IV.3.2.5. Water Movement in Soil

The movement of water through soil is governed by gradients of gravitational, matric, and osmotic potentials, which collectively determine the direction and rate of water flow within the soil profile (Hillel, 2004; Vereecken et al., 2021). The spatial and temporal variability of these forces results in different flow regimes, depending on the degree of soil saturation and structure.

Water Movement in Saturated Soils

Under saturated conditions, all pores are filled with water, and flow is primarily controlled by **gravitational potential gradients**. Water generally moves **vertically downward**, unless it encounters an impermeable or low-permeability horizon that redirects it laterally. This process is referred to as **percolation**, which plays a key role in groundwater recharge. When water movement serves to remove excess water from the soil surface or root zone, the term **drainage** is used (Duchaufour, 2001; Šimůnek et al., 2022). Saturated hydraulic conductivity (K_s) quantifies the rate of water flow under these conditions and depends strongly on **soil texture, structure, bulk density, and pore continuity** (Rawls et al., 2020). Sandy soils, for example, exhibit higher K_s values than clayey soils due to larger and better-connected pores.

Water Movement in Unsaturated Soils

When the soil’s water content drops below **field capacity**, the influence of gravity becomes less significant, and water movement is instead governed by **matric potential gradients**—the capillary forces that pull water from wetter to drier zones. This type of flow, known as **unsaturated or capillary flow**, is considerably slower than saturated flow but critical for maintaining plant-available water in the root zone (Duchaufour, 2001; Assouline & Or, 2022).

In this regime, the hydraulic conductivity decreases exponentially with decreasing water content, reflecting reduced pore connectivity and the dominance of small capillary pores (Vereecken et al., 2021).

Soil management practices such as **organic matter amendment**, **minimum tillage**, and **vegetative cover** can improve unsaturated water flow by enhancing pore stability and continuity (FAO, 2022; Lal, 2022).

IV.3.3. Biological Properties

The biological component of soil represents one of its most dynamic and essential aspects, encompassing plant roots, soil fauna, and microorganisms such as bacteria, fungi, actinomycetes, and protozoa. These living organisms interact continuously with the soil’s physical and chemical properties, thereby influencing its structure, nutrient availability, and organic matter dynamics (FAO, 2022; Wall et al., 2023). Soil biological activity is widely recognized as a key indicator of soil health and fertility, integrating both ecological processes and anthropogenic pressures (Zhao et al., 2023).

In the long term, biological processes play a fundamental role in soil formation and evolution through the decomposition of organic residues, the transformation of minerals, and the enrichment of humified organic matter. Plant roots and mycorrhizal fungi actively contribute to mineral weathering and the stabilization of soil organic carbon by releasing root exudates and forming microbial associations that promote aggregate stability and carbon sequestration (Cotrufo et al., 2021; Tian et al., 2023). In the short term, soil biological activity directly affects soil structure, porosity, and the movement of air and water. The production of microbial polysaccharides and fungal hyphae enhances aggregate cohesion, while soil fauna—such as earthworms, termites, and arthropods—facilitate aeration and nutrient redistribution through bioturbation (Lavelle et al., 2020; Li et al., 2022).

Soil organisms act as principal drivers of **biogeochemical cycles**, mediating several key transformations:

- **Mineralization**, the decomposition of organic matter into inorganic nutrients such as ammonium, nitrate, and phosphate, which become available to plants;
- **Immobilization and humification**, which involve the conversion of inorganic nutrients into stable organic forms, contributing to long-term carbon storage;
- **Redox transformations**, through which bacteria and archaea regulate oxidation–reduction reactions of nitrogen, sulfur, and iron, maintaining soil redox balance (Bardgett & van der Putten, 2014; Zhou et al., 2022; Sun et al., 2024).

Through assimilation, soil organisms incorporate organic substrates into their biomass, while through secretion, they release extracellular enzymes, organic acids, and polysaccharides that promote nutrient mobilization and soil aggregation. Mineralization processes release mineral ions essential for plant growth and microbial metabolism. Altogether, these biological interactions regulate the carbon and nutrient fluxes that sustain soil fertility, ecological functioning, and ecosystem productivity (FAO, 2022; Zhang et al., 2023; Wang et al., 2024).

IV.4.Soil Pollution

IV.4.1.Definition

Soil pollution refers to the abnormal and exogenous accumulation of chemical, organic, mineral, or biological substances (including pathogens) that alter the natural composition of the soil and degrade its quality, fertility, and ecological functions. It generally results from human activities such as intensive agriculture, industrial operations, urbanization, or improper waste management. These contaminants can harm biodiversity, reduce agricultural productivity, and pose health risks to humans through bioaccumulation in the food chain (Kabata-Pendias, 2011; Alloway, 2013; Rodrigues et al., 2020).

IV.4.2. Forms of Soil Pollution

The nature and distribution of soil contaminants vary according to how pollutants enter the soil system and the extent of their dispersion. Based on these criteria, two major forms of soil pollution can be identified: **diffuse pollution** and **point (or accidental) pollution**.

a) Diffuse Pollution

Diffuse soil pollution is characterized by the widespread but low-concentration presence of contaminants over large areas. It results from repeated or long-term inputs of pollutants, which gradually accumulate in the upper soil horizons. The main sources include agricultural activities (use of fertilizers, herbicides, fungicides, and insecticides), industrial atmospheric fallout, and vehicular emissions containing heavy metals such as lead (Pb), cadmium (Cd), and zinc (Zn).

Diffuse pollution is often difficult to detect and quantify because of its heterogeneous distribution and the low concentrations involved. However, its cumulative effects are significant. Over time, pollutants can alter soil physicochemical properties, affect microbial diversity, and contribute to the contamination of groundwater through leaching processes. Pesticide residues, nitrates, and heavy metals are the most common contaminants associated with diffuse pollution.

According to Carvalho et al. (2021) and Wang et al. (2022), this form of pollution poses long-term risks to ecosystems and human health due to bioaccumulation in crops and trophic transfer. It leads to what are often described as “uniformly contaminated areas” (ISO 11074:2015). Monitoring such pollution requires integrated approaches combining remote sensing, soil sampling, and risk modeling.

b) Point or Accidental Pollution

Point-source (or accidental) pollution refers to the localized contamination of soil and subsoil by hazardous substances, often in high concentrations. It typically originates from discrete events or specific sites, such as industrial accidents, chemical spills, leaky storage tanks, mining residues, and waste disposal areas.

Unlike diffuse pollution, which develops gradually, point pollution often occurs suddenly and can severely degrade soil quality in a limited area. It leads to the formation of "hot spots" with extremely high concentrations of pollutants such as hydrocarbons, heavy metals, and persistent organic pollutants (POPs).

These contaminated sites pose immediate environmental and health risks, including soil toxicity, groundwater pollution, and vegetation stress. Restoration of such sites requires targeted remediation strategies, including bioremediation, soil washing, or immobilization of heavy metals (Sharma & Nagpal, 2022; Liu et al., 2023). Such pollution creates "locally contaminated sites," as defined by ISO 11074 (2015), which are a priority for environmental assessment and management.

IV.4.3. Spatial Distribution of Pollutants in Soils

The spatial distribution of pollutants in soils is influenced by multiple interacting factors, including the nature and source of contamination, soil physico-chemical properties (texture, pH, organic matter content, cation exchange capacity), climatic conditions, and anthropogenic activities. Understanding this distribution is essential for assessing environmental risks, pollutant mobility, and remediation potential (Kabata-Pendias & Pendias, 2020; Alloway, 2013; Wu et al., 2022).

Spatial distribution can be examined along two main dimensions: **vertical distribution**, according to soil horizons, and **horizontal distribution**, depending on the location and landscape position.

IV4.3.1. Vertical Distribution (According to Soil Horizons)

Vertical distribution reflects the mobility, retention, and transformation of pollutants within soil profiles.

- **Surface horizon (A horizon)**:

  This layer receives direct inputs from atmospheric deposition, agricultural practices, and surface runoff. It typically exhibits the highest concentrations of heavy metals (Pb, Cu, Zn, Cd) and persistent organic pollutants (PAHs, pesticides, hydrocarbons). These contaminants tend to bind to soil organic matter, oxides of iron and manganese, and fine particles (Li et al., 2020).

  Studies have shown that metal accumulation is often controlled by the soil's cation exchange capacity and redox conditions (Zhao et al., 2021).

- **Subsurface horizon (B horizon)**:

  Pollutants that are relatively mobile—such as nitrates, cadmium, or zinc—can migrate downward depending on rainfall, leaching, and soil permeability. However, adsorption, complexation, and precipitation processes may limit this vertical movement.

For example, cadmium mobility decreases with increasing soil pH, whereas nitrate leaching intensifies in coarse-textured soils (Zhang et al., 2022).

- **Deep horizon (C horizon)**:

  The deepest layers generally show the lowest pollutant concentrations, unless the soil has been exposed to long-term or severe contamination. Highly soluble compounds and some organometallic complexes may reach groundwater, posing risks to aquifer quality (Liang et al., 2021; Wu et al., 2023).

Therefore, the vertical distribution pattern depends on both the soil's structure and the physicochemical properties of the contaminants themselves. Understanding these interactions is key for evaluating pollutant persistence and developing sustainable remediation strategies.

IV.4.3.2. Horizontal Distribution (According to Landscape Position)

The horizontal distribution of soil pollutants varies with **topography**, **proximity to pollution sources**, and **hydrological dynamics**.

- **Proximity to emission sources**:

  Concentrations are highest near industrial areas, mining sites, roads, and waste disposal zones. For instance, roadside soils often exhibit elevated levels of lead, copper, and zinc derived from tire wear, brake dust, and fuel combustion (Chen et al., 2022; Huang et al., 2021).

- **Topographical effects**:

  On sloping terrain, runoff redistributes surface particles and associated contaminants, leading to pollutant accumulation in lower slope positions, depressions, and floodplains (Li et al., 2021).

- **Soil texture and hydrology**:

  Clayey soils tend to retain heavy metals due to their higher adsorption capacity, whereas sandy soils favor pollutant mobility. Water flow and drainage conditions also create heterogeneous pollutant patterns across short distances (Wu et al., 2022).

- **Anthropogenic activities**:

  Agricultural practices such as fertilizer application, wastewater irrigation, and pesticide use contribute to spatial heterogeneity. Urbanization and traffic further increase contamination in surface soils (Zheng et al., 2020).

Consequently, mapping the spatial variability of pollutants using **geostatistical tools** (e.g., kriging, GIS-based modeling) allows for a better understanding of contamination dynamics and helps guide **site-specific remediation** measures (Zhang et al., 2023

IV.5. Origins of Soil Pollutants

Soil pollution results from the introduction of harmful substances into the soil system through both **anthropogenic** and **natural processes**. While natural sources contribute marginally and are often balanced by ecological cycles, human activities have drastically intensified pollutant inputs, leading to the degradation of soil structure, fertility, and ecological functions. The origins of soil pollutants can be grouped into **five major categories**: agricultural, industrial, urban and transport-related, waste-related, and natural sources.

IV.5.1.Agricultural Sources

IV.5.1.1. Agricultural Sources

Agriculture is one of the major global contributors to **diffuse soil pollution**, largely due to the intensive use of agrochemicals and unsustainable farming practices. Excessive application of **chemical fertilizers**, **pesticides**, and **plastic mulches** introduces a variety of persistent pollutants that alter soil composition, disturb microbial balance, and reduce long-term soil fertility (Carvalho et al., 2021).

a) Fertilizers and Nutrient Pollution

The repeated use of nitrogen- and phosphorus-based fertilizers results in the accumulation of **nitrates (NO_3^-)** and **phosphates (PO_4^{3-})** in soils. When these nutrients exceed plant uptake capacity, they are lost through **leaching and surface runoff**, leading to the eutrophication of aquatic ecosystems. Long-term overfertilization also causes **soil acidification**, **salinization**, and disruption of **cation exchange capacity** (Wang et al., 2022).
Additionally, some phosphate fertilizers contain trace concentrations of **cadmium (Cd)** and **lead (Pb)** derived from raw phosphate rocks, contributing to heavy-metal accumulation in agricultural soils (Chen et al., 2023).

b) . Pesticides and Persistent Organic Pollutants

Pesticides, widely used to protect crops, are among the most persistent agricultural contaminants. They include **herbicides**, **insecticides**, and **fungicides**, each introducing specific compounds with distinct toxicological and environmental profiles. Their persistence depends on soil pH, organic-matter content, and microbial activity. Many of them resist degradation and accumulate in soils, where they can move into surface and groundwater systems, posing ecological and human health risks (Zhang et al., 2023).

c) Herbicides

Herbicides are chemicals used to eliminate unwanted vegetation and control weeds. Commonly used herbicides include **glyphosate**, **atrazine**, and **paraquat**. Although effective in crop management, many herbicides persist in the soil for months or years.

- **Glyphosate**, one of the most widely applied herbicides, binds strongly to soil particles, altering microbial respiration and nitrogen cycling (Singh et al., 2021).
- **Atrazine** is known for its high mobility and potential to contaminate groundwater.
- **Paraquat**, despite being less mobile, remains toxic to soil invertebrates and can cause oxidative stress in plants and microorganisms.

Continuous herbicide exposure can reduce soil biodiversity, inhibit enzyme activity, and modify root-microbe interactions essential for plant growth.

d) Insecticides

Insecticides target harmful insects but often have non-selective effects on soil biota. Organophosphates (e.g., **chlorpyrifos**), neonicotinoids (e.g., **imidacloprid**), and pyrethroids (e.g., **cypermethrin**) are among the most common classes.

- **Chlorpyrifos** persists for long periods in soil and can inhibit acetylcholinesterase in beneficial soil organisms (Kaur & Kaur, 2022).
- **Neonicotinoids** are systemic and highly water-soluble, allowing them to leach into soil and groundwater, negatively affecting pollinators and soil invertebrates.
- **Pyrethroids** tend to adsorb strongly to soil organic matter, reducing their mobility but prolonging persistence.

Prolonged insecticide application contributes to **resistance development** in pests and disrupts soil food webs, especially earthworm and microbial populations.

e) Fungicides

Fungicides are applied to prevent fungal diseases in crops but may exert toxic effects on soil microorganisms and enzymes involved in organic-matter decomposition.

- **Copper-based fungicides** (e.g., Bordeaux mixture) accumulate in soils, leading to phytotoxicity and microbial inhibition.
- **Azoles** (e.g., tebuconazole) and **strobilurins** (e.g., azoxystrobin) persist in soil for extended periods, affecting nitrogen-cycling bacteria and actinomycetes (Gupta et al., 2022).
- Repeated fungicide use also contributes to the emergence of resistant fungal strains, increasing the frequency and dose of applications required, thus intensifying contamination.

Overall, pesticide residues can interact synergistically, amplifying their negative impact on soil biodiversity and fertility.

f) Nutrients and Animal Wastes

Excess nitrogen (N) and phosphorus (P) from fertilizers and animal manure cause nutrient imbalance and eutrophication of nearby water bodies. When applied in excess or under poor management conditions, these nutrients leach into the soil and groundwater as nitrates, leading to contamination and health risks (Zhang et al., 2023).

Animal husbandry is a major source of organic and inorganic soil pollution.

- **Sheep and goats (ovines)** produce manure rich in **ammonia (NH_3)** and **organic nitrogen**, which volatilizes and contributes to soil acidification and nitrate accumulation upon transformation through nitrification (Li et al., 2021). In arid regions, where manure is often used directly as fertilizer without proper composting, ammonia emissions increase the soil's alkalinity and can lead to salinization (Rahman et al., 2022).
- **Poultry farming** generates large quantities of litter and droppings containing **high nitrate and phosphate levels**. Poultry waste, rich in uric acid and easily mineralized nitrogen compounds, accelerates nitrate leaching and contributes to groundwater pollution when applied untreated to fields (Sharma et al., 2023).

Improper manure management also introduces **pathogenic microorganisms (e.g., E. coli, Salmonella)** and **antibiotic residues**, contributing to the emergence of antimicrobial resistance in soil environments (Chen et al., 2024)

g) Emerging Agricultural Pollutants

Beyond conventional agrochemicals, new categories of contaminants are emerging in agricultural soils:

- **Microplastics and nanoplastics** originating from plastic mulches, irrigation pipes, and greenhouse films alter soil porosity, water retention, and microbial activity (Zhang et al., 2023).
- **Pharmaceutical residues** and **antibiotic resistance genes** introduced via animal manure and wastewater irrigation disrupt microbial communities and pose public-health risks.
- **Salts and trace metals** from low-quality irrigation water contribute to soil salinization and heavy-metal accumulation, especially in arid and semi-arid regions (Li et al., 2021).

IV.5.2. Industrial Sources

Industrialization has led to the release of large quantities of inorganic and organic contaminants. Pollutants originate from **mining**, **metal smelting**, **chemical manufacturing**, **textile dyeing**, and **petrochemical industries**.

Typical contaminants include:

- **Heavy metals** (e.g., Hg, Pb, Cd, Cr, Ni, Zn, Cu), which bind strongly to soil particles and persist for decades.
- **Polycyclic aromatic hydrocarbons (PAHs)** and **persistent organic pollutants (POPs)** from fossil fuel combustion.
- **Volatile organic compounds (VOCs)** and **hydrocarbons** from refineries and fuel storage.

Industrial effluents, when improperly treated, infiltrate soil layers, contaminating both the topsoil and underlying groundwater. Mining activities, in particular, produce **tailings and acid mine drainage**, releasing sulfuric acid and toxic metals that destroy soil structure and inhibit vegetation recovery (Liu et al., 2023).

Recent studies emphasize that industrial hotspots, especially in rapidly urbanizing regions, pose the greatest ecological and human health risks due to cumulative contamination (Gupta et al., 2022).

IV.5.3. Urban and Transport-Related Sources

Urbanization, industrialization, and the expansion of transportation networks have become major contributors to soil pollution in modern societies. Cities act as complex systems where multiple sources—traffic, construction, energy production, and domestic activities—interact to deposit a wide range of contaminants into urban soils (Chen et al., 2022; Ali et al., 2023).

a) Transport-Related Pollution

Road traffic represents a dominant source of heavy metals and organic pollutants. Emissions originate from fuel combustion, tire and brake wear, and the corrosion of vehicle components. Soils adjacent to roads and highways accumulate metals such as **lead (Pb), copper (Cu), zinc (Zn), cadmium (Cd), and antimony (Sb)**, which are resistant to degradation and tend to concentrate in surface layers.

- **Tire abrasion** releases Zn and Cd.
- **Brake wear** emits Cu, Sb, and Ba.

- **Fuel combustion** produces Pb, Ni, and volatile organic compounds (VOCs). These pollutants reduce soil fertility, inhibit plant growth, and can bioaccumulate in food chains (Wang et al., 2022).

Urban soils are also contaminated with **polycyclic aromatic hydrocarbons (PAHs)**, **black carbon**, and **soot particles** generated by incomplete combustion of fuels. These compounds are persistent, hydrophobic, and carcinogenic, representing a serious concern for human health (Gao et al., 2023).

b) Construction and Demolition Activities

Urban development and infrastructure expansion release large quantities of dust, debris, and micro-particles into the environment. **Cement dust**, **asbestos fibers**, **synthetic polymers**, and **paint residues** can alter soil pH, permeability, and microbial composition. In addition, poorly managed construction waste contributes to heavy metal accumulation and microplastic pollution (Yin et al., 2023).

c) Energy Production Emissions

Energy generation—especially from fossil fuels such as coal, oil, and natural gas—emits substantial quantities of airborne and solid pollutants that eventually settle on surrounding soils.

- **Thermal power plants** release fly ash rich in heavy metals (Hg, Pb, Cr, Ni) and radionuclides.
- **Oil refining and gas flaring** produce hydrocarbons, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) that lead to acid deposition and soil acidification.
- **Coal combustion residues**, often used as landfill or construction material, contaminate soils with toxic trace elements (Zhou et al., 2021).

Renewable energy technologies, though cleaner, also present emerging challenges: for instance, **solar panel waste** and **wind turbine coatings** introduce rare earth elements and microplastics into the environment during manufacturing and disposal (Duan et al., 2023).

d) Domestic and Urban Waste

Household waste, sewage sludge, and untreated stormwater runoff add another layer of contamination. These materials often contain **pharmaceutical residues, microplastics, detergents, and organic matter** that alter soil chemistry and microbiota. Open dumping or uncontrolled landfilling in urban peripheries further exacerbates heavy metal and pathogen accumulation (Abubakar et al., 2024).

e) Human Exposure Risks

Several studies across major metropolitan areas—including Beijing, Lagos, Paris, and Algiers—have revealed that **roadside, schoolyard, and playground soils** often exceed safety thresholds for Pb, Zn, and PAHs, posing significant health risks for children exposed through hand-to-mouth behavior and dust inhalation (Ali et al., 2023; Gao et al., 2023).

Overall, the combined effects of transportation, construction, energy production, and domestic emissions have transformed urban soils into long-term sinks for persistent pollutants. Managing these complex mixtures requires integrated environmental monitoring, green infrastructure, and cleaner energy transitions.

IV.5.4. Waste Disposal and Accidental Releases

Improper **solid waste management** is a major driver of localized soil pollution. Open dumping and uncontrolled landfilling allow **leachates** rich in organic matter, heavy metals, and microplastics to infiltrate soils. **Electronic waste (e-waste)** is an emerging concern because it contains hazardous components such as mercury (Hg), cadmium (Cd), and brominated flame-retardants.

Accidental releases, including oil spills, chemical leaks, and explosions, cause **acute contamination** and long-lasting ecological damage. For instance, petroleum hydrocarbons and lubricants can form impermeable layers that block gas exchange and reduce soil fertility (Sharma & Nagpal, 2022).

Inadequate remediation after such incidents results in persistent “toxic hotspots,” which remain contaminated for decades and continuously release pollutants into surrounding ecosystems (O’Connor et al., 2021).

IV.6. Nature of Soil Pollution

Soil pollution refers to the abnormal introduction or accumulation of foreign substances into the soil matrix, leading to the alteration of its physical, chemical, and biological properties, and compromising its ecological and productive functions (Kabata-Pendias & Pendias, 2020; Wu et al., 2023).

It results from both **natural (geogenic)** processes and, more importantly, **anthropogenic** activities such as industrialization, agriculture, urbanization, and waste mismanagement.

Depending on the nature and behavior of contaminants, soil pollution can be classified into five main categories: **inorganic**, **organic**, **radioactive**, **biological**, and **physico-chemical** pollution.

IV.6.1. Inorganic Pollution (Heavy Metals and Metalloids)

Inorganic pollution represents one of the most persistent and hazardous forms of soil contamination. It primarily involves **heavy metals** such as lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), zinc (Zn), chromium (Cr), and nickel (Ni), as well as **metalloids** including arsenic (As), antimony (Sb), and selenium (Se).

Unlike organic contaminants, heavy metals are **non-biodegradable** and can remain in soils for decades, posing long-term ecological and health risks (Kabata-Pendias & Pendias, 2020; Zhang et al., 2022).

IV.6.1.1. Sources of Contamination

Heavy metal contamination arises from a variety of **anthropogenic and natural** sources. The most significant contributors include:

- **Industrial sources:** emissions from smelting, mining, electroplating, and battery manufacturing processes release large quantities of metallic particles and effluents into the surrounding environment.
- **Agricultural sources:** application of phosphate fertilizers, sewage sludge, and metal-based pesticides introduces trace metals such as Cd, Zn, and Cu into soils.
- **Urban sources:** vehicular traffic, household waste disposal, and untreated wastewater discharge contribute additional loads of Pb, Cu, and Zn through atmospheric deposition and runoff (Chen et al., 2022).

These inputs tend to accumulate in surface horizons (0–20 cm), particularly in areas adjacent to industrial zones, roadsides, and agricultural fields receiving repeated fertilizer or sludge applications (Li et al., 2021).

IV.6.1.2. Behavior and Dynamics in Soil

Heavy metals interact complexly with soil components, influencing their **mobility, bioavailability, and persistence**.

They may exist in several chemical forms, including exchangeable, carbonate-bound, oxide-bound, organic-bound, and residual fractions (Wu et al., 2023).

Their behavior is mainly controlled by several soil properties:

- **pH:** In **acidic soils**, protonation enhances metal solubility, thereby increasing leaching and bioavailability. In contrast, **alkaline soils** favor metal precipitation and adsorption onto clay minerals, iron and manganese oxides.
- **Organic matter content:** Humic and fulvic acids can form stable complexes with metals such as Cu and Zn, reducing their mobility.
- **Cation exchange capacity (CEC):** Soils with high CEC retain metals more effectively through electrostatic interactions.
- **Texture:** Fine-textured soils (rich in clay and silt) generally immobilize metals more efficiently than sandy soils due to higher surface area and adsorption sites (Zhang et al., 2022).

Overall, the distribution of heavy metals in soil is governed by both **geochemical processes** (sorption, precipitation, redox reactions) and **biological activity** (uptake by plants and microorganisms).

IV.6.1.3. Ecotoxicological and Health Impacts

Heavy metal contamination exerts multiple adverse effects on **soil ecosystems**, **plant health**, and **human well-being**.

- **Reduction of soil enzymatic activity and microbial biodiversity:** Metals such as Cd and Pb inhibit essential enzymes (dehydrogenase, urease, phosphatase), disrupting nutrient cycling and microbial growth (Alloway, 2013).
- **Phytotoxicity:** High metal concentrations cause chlorosis, reduced root elongation, and inhibited photosynthesis, particularly under Cd and Pb exposure.
- **Bioaccumulation and biomagnification:** Toxic metals enter the food chain through plant uptake and accumulate in edible tissues, eventually posing severe health risks such as kidney dysfunction, neurological disorders, and carcinogenicity (As, Hg, Cd).

Example: Li et al. (2021) reported that agricultural soils located near mining areas exhibited Cd and Pb concentrations up to **five times higher** than the maximum permissible limits established by the **World Health Organization (WHO)**. Such contamination poses a direct risk to food safety and human health through crop consumption.

IV.6.1.4. Summary of Key Characteristics

Heavy metals represent one of the most persistent and hazardous groups of soil contaminants due to their non-biodegradable nature and tendency to accumulate in the upper soil horizons. Their behavior, toxicity, and ecological risks depend on multiple factors, including chemical speciation, soil pH, redox potential, and organic matter content. Once introduced into the environment, these elements can disrupt soil microbial activity, reduce enzymatic functions, and enter food chains, posing significant risks to both ecosystem integrity and human health (Zhang et al., 2022; FAO, 2023; Wang et al., 2024) **Table 14**

Table 14. Characteristics of major heavy metals in soils(Li et al., 2021)

Parameter	Description
Main Elements	Pb, Cd, Hg, Cu, Zn, Cr, Ni, As, Sb, Se
Major Sources	Industrial emissions, mining, fertilizers, wastewater, urban runoff
Environmental Behavior	Non-degradable, persistent, accumulate in topsoil, mobility influenced by pH and organic matter
Ecological Effects	Enzyme inhibition, loss of microbial diversity, phytotoxicity

Human Health Effects	Bioaccumulation, kidney and liver damage, neurotoxicity, carcinogenicity
Example	Cd and Pb levels near mining sites exceed WHO limits by up to 5×

IV.6.2. Organic Pollution

Organic pollution refers to the accumulation of **synthetic or natural carbon-based compounds** in soil, which can significantly alter its chemical and biological properties. These pollutants include **hydrocarbons** (e.g., petroleum derivatives, polycyclic aromatic hydrocarbons — PAHs), **pesticides**, **chlorinated solvents**, **polychlorinated biphenyls (PCBs)**, and **dioxins**.

Due to their persistence, toxicity, and bioaccumulative potential, organic pollutants are considered among the most critical threats to soil and environmental quality (Huang et al., 2021; Zhang et al., 2023).

IV.6.2.1. Main Sources

Organic contaminants originate primarily from **anthropogenic activities**, including:

- **Agriculture:** the excessive use of pesticides, herbicides, and fungicides contributes to the accumulation of persistent residues such as organochlorines and organophosphates in agricultural soils.
- **Petrochemical industry:** accidental oil leaks, spills, and the release of solvents and lubricants during transport and refining processes result in local and diffuse hydrocarbon contamination.
- **Domestic and industrial waste:** the infiltration of **persistent organic pollutants (POPs)** from municipal landfills, industrial effluents, and wastewater sludge leads to long-term soil degradation.

Furthermore, **atmospheric deposition** of combustion by-products (soot, black carbon, PAHs) and **waste incineration** can also contribute to organic soil contamination in urban areas (Zheng et al., 2020).

IV.6.2.2. Physicochemical Characteristics and Behavior in Soil

Most organic pollutants are **hydrophobic**, exhibiting low solubility in water but a strong affinity for soil organic matter.

This characteristic limits their bioavailability and **slows down natural biodegradation**, allowing them to persist for years or even decades in the soil matrix (Huang et al., 2021).

For instance, **polycyclic aromatic hydrocarbons (PAHs)** and **chlorinated hydrocarbons** are known for their long-term stability under aerobic and anaerobic conditions.

These compounds tend to accumulate in the **topsoil (0–10 cm)** layer due to adsorption onto humic substances and clay particles.

However, under certain conditions — such as heavy rainfall, soil disturbance, or the presence of solvents — some pollutants may **migrate vertically** through the soil profile, posing a serious risk of **groundwater contamination** (Li et al., 2021).

IV.6.2.3. Environmental and Health Impacts

The persistence and toxicity of organic pollutants generate multiple adverse effects on soil ecosystems, plants, and human health:

- **Alteration of soil structure:** accumulation of hydrocarbons and hydrophobic residues reduces soil porosity and aeration, impairing water infiltration and root respiration.
- **Microbial inhibition:** many organic compounds (especially pesticides and PAHs) suppress beneficial microbial populations such as nitrifying and nitrogen-fixing bacteria, thereby disturbing soil biochemical cycles.
- **Groundwater contamination:** soluble or mobile organic compounds leach into aquifers, compromising drinking water quality and ecosystem integrity.
- **Toxicological risks to humans:** several organic pollutants, notably PAHs, PCBs, and dioxins, are **carcinogenic, mutagenic, or endocrine-disrupting**, posing chronic health risks through bioaccumulation in the food chain (Huang et al., 2021).

Example: Following petroleum spills, **high-molecular-weight PAHs**, such as *benzo[a]pyrene,* can remain in surface horizons for **more than ten years**, illustrating their high persistence and low degradability (Zhang et al., 2023).

IV.6.2.4. Summary of Main Characteristics

Organic pollutants constitute a diverse group of persistent contaminants that pose significant ecological and health risks due to their stability, lipophilicity, and resistance to biodegradation. These compounds—originating primarily from agricultural, industrial, and urban activities—tend to accumulate in soil organic matter, where they can persist for years or even decades. Their mobility and bioavailability are strongly influenced by soil texture, organic carbon content, and environmental conditions. Once introduced into the soil system, these pollutants can alter microbial activity, reduce soil fertility, and contaminate groundwater, ultimately affecting both terrestrial and aquatic ecosystems (FAO, 2022; Kim et al., 2023; Wang et al., 2024). **Table 15**

Table 15. Characteristics of major organic pollutants in soils

Parameter	Description
Principal Pollutants	Hydrocarbons, PAHs, pesticides, PCBs, chlorinated solvents, dioxins
Main Sources	Agriculture (pesticides), petrochemical industries, domestic and industrial waste
Behavior in Soil	Hydrophobic, strongly adsorbed to organic matter, low biodegradability
Environmental Impacts	Reduced porosity and microbial activity, groundwater contamination
Health Effects	Carcinogenic, mutagenic, and endocrine-disrupting potential
Example	Persistence of benzo[a]pyrene in topsoil >10 years after oil spills (Zhang et al., 2023)

IV.6.3. Radioactive Pollution

Radioactive pollution arises from the accumulation of **radioactive isotopes** in soils, leading to the emission of ionizing radiation that can damage living organisms and disrupt ecological processes.

Common isotopes involved include **uranium (U)**, **thorium (Th)**, **cesium-137 (Cs)**, **strontium-90 (Sr)**, and **radon (Rn)** (Wang et al., 2022).

IV.6.3.1. Sources of Radioactive Contamination

The origin of soil radioactivity is often **anthropogenic**, although natural sources also contribute. Major pathways include:

- **Atmospheric deposition** following **nuclear tests or accidents**, such as those at **Chernobyl (1986)** and **Fukushima (2011)**.
- **Mining and processing of radioactive ores**, including uranium and thorium extraction.
- **Improper disposal** of radioactive waste from **medical, industrial, and research facilities**.
- **Natural emission** of radon gas from uranium-rich bedrock and mineralized zones.

These sources lead to heterogeneous distribution patterns, with contamination typically concentrated near emission or disposal sites.

IV.6.3.2. Behavior in Soil

Radioactive isotopes interact with **clay minerals, iron oxides, and organic matter**, forming complexes that may remain fixed in soil for extended periods.

However, depending on pH, moisture, and soil texture, certain radionuclides (e.g., Cs-137, Sr-90) exhibit **partial mobility**, migrating into groundwater or being **absorbed by plant roots** (Wang et al., 2022).

Soil erosion and resuspension of contaminated dust can further redistribute these elements across broader areas.

IV.6.3.3. Biological and Ecological Effects

Exposure to ionizing radiation induces serious biological and ecological consequences:

- **Mutagenic effects** on soil microorganisms, reducing their diversity and enzymatic functions.
- **Carcinogenic and genetic risks** to exposed fauna and humans.
- **Bioaccumulation in crops**, leading to long-term contamination of the food chain and chronic internal exposure.

The persistence and invisibility of radioactive contamination make it particularly challenging to monitor and remediate.

IV.6.3.4. Summary of Main Characteristics

Radioactive pollutants constitute a critical category of soil contaminants due to their long half-lives, radiotoxicity, and potential for bioaccumulation. These elements and isotopes originate primarily from nuclear fallout, mining activities, and the disposal of medical or industrial radioactive waste. Once released into the environment, they interact strongly with soil components, especially clays and organic matter, but their mobility can vary according to soil pH, redox potential, and mineral composition. The persistence of certain radionuclides poses long-term ecological and health risks, including DNA damage, carcinogenic effects, and chronic internal exposure through the food chain (IAEA, 2021; Wang et al., 2022; Li et al., 2023). **Table 16**

Table 16. Key characteristics of radioactive pollutants in soils

Parameter	Description
Main Isotopes	U, Th, Cs-137, Sr-90, Rn
Sources	Nuclear fallout, mining, medical and industrial waste
Behavior in Soil	Fixed on clays and organic matter; partially mobile depending on pH and redox potential

Ecological Effects	Mutation and mortality of soil organisms, decreased fertility
Health Effects	Carcinogenicity, genetic damage, internal exposure via food chain
Example	Cs-137 persistence decades after Chernobyl and Fukushima accidents (Wang et al., 2022)

IV.6.4. Biological Pollution

Biological pollution refers to the contamination of soils by living organisms, including **pathogenic microorganisms** (such as *Escherichia coli*, *Salmonella spp.*, *Clostridium perfringens*, viruses, protozoa, and helminths) and **invasive species** that disrupt native ecosystems. This form of pollution often results from anthropogenic activities that introduce biological agents into the soil environment.

IV.6.4.1.Main Sources

- **Agricultural practices:** Application of **untreated sewage sludge**, **animal manure**, or **organic compost** that has not undergone adequate stabilization or pathogen reduction.
- **Irrigation practices:** Use of **untreated or insufficiently treated wastewater**, which often contains pathogenic bacteria and viruses.
- **Waste management: Leachates from landfills** and waste disposal sites that carry microbial contaminants into the soil profile (Rahman et al., 2020; Zhang et al., 2022).

IV.6.4.2. Environmental and Health Impacts

- **Crop contamination:** Pathogenic microorganisms can colonize the rhizosphere or adhere to edible plant surfaces, leading to contamination of vegetables and cereals.
- **Transmission of diseases:** Biological pollutants contribute to outbreaks of **foodborne and waterborne diseases**, including gastrointestinal infections and parasitic diseases.
- **Soil microbiome disturbance:** The introduction of foreign microbial species disrupts the natural **ecological balance** of soil microorganisms, affecting nutrient cycling and soil fertility (Singh et al., 2023).

Example

Studies have shown that the reuse of untreated wastewater for irrigation in peri-urban areas leads to the persistence of *Salmonella* and *E. coli* in topsoil layers, posing a significant health risk to farmers and consumers (Rahman et al., 2020).

IV.6.5. Physico-Chemical Pollution

Physico-chemical pollution refers to **alterations in the soil’s physical structure and chemical balance**, often resulting from human-induced processes rather than direct contamination by toxic substances. These changes affect the soil’s ability to sustain plant and microbial life.

IV.6.5.1. Major Forms

1. **Salinization**
    - **Causes:** Excessive irrigation, poor drainage, or high evaporation rates, particularly in arid and semi-arid regions.
    - **Effects:** Accumulation of soluble salts such as **$NaCl$** and **$MgSO_4$** in the root zone leads to **osmotic stress**, inhibiting water uptake and reducing plant productivity (Abdullah et al., 2021).
2. **Acidification**
    - **Causes:** Deposition of **acid rain**, excessive use of **ammonium-based fertilizers**, and **industrial emissions** of sulfur and nitrogen oxides (SO_2, NO_x).
    - **Effects:** Acidic conditions **increase metal solubility** (e.g., Al^{3+}, Cd^{2+}, Pb^{2+}), resulting in **toxicity to plants and microorganisms** and a decline in soil fertility (Liu et al., 2020).
3. **Alkalinization**
    - **Causes:** Accumulation of **sodium ions (Na^+)** due to irrigation with sodic water or evaporation in dry climates.
    - **Effects:** Sodium displaces essential cations (Ca^{2+}, Mg^{2+}), leading to **soil dispersion**, **reduced permeability**, and **root suffocation** (Huang et al., 2022).

IV.6.5.2. Environmental Consequences

- Degradation of **soil structure** and loss of aggregate stability.
- Imbalance in **nutrient availability** and **cation exchange capacity (CEC)**.
- Decline in **crop yields** and **agricultural productivity**.
- Alteration of **soil-water-air interactions**, affecting both flora and soil fauna.

Example

According to Zhang et al. (2023), long-term irrigation with saline-sodic water in semi-arid agricultural zones of northern China led to a 40% reduction in soil permeability and a significant decrease in organic carbon content. **Table 17**

Table 17. Summary of Main Soil Pollution Types and Their Effects

Type of Pollution	Main Sources	Major Effects	References
Inorganic (Heavy metals)	Mining, fertilizers, industrial waste	Bioaccumulation, toxicity to plants and humans	Zhang et al., 2022
Organic (PAHs, Pesticides)	Petrochemical, agriculture	Carcinogenicity, microbial inhibition	Huang et al., 2021
Radioactive	Nuclear fallout, mining	Genetic mutations, carcinogenesis	Wang et al., 2022
Biological	Wastewater, manure	Pathogenic contamination, ecosystem imbalance	Rahman et al., 2020
Physico-chemical	Irrigation, acid rain	Soil degradation, nutrient imbalance	Liu et al., 2020

IV.6.6. Summary

Soil pollution is a multifactorial process that results from the accumulation of various contaminants of inorganic, organic, radioactive, biological, or physico-chemical origin. Each category exhibits specific behavior in the soil matrix, depending on factors such as pH, organic matter content, redox potential, and microbial activity. Inorganic pollutants (especially heavy metals) are persistent and non-degradable, while organic pollutants often exhibit high toxicity and long-term persistence. Radioactive and biological contaminations, though less widespread, pose significant health and ecological risks. Physico-chemical alterations such as salinization and acidification further compromise soil fertility and structure. A global understanding of these pollution types is essential for designing efficient remediation and sustainable management strategies.**Table 18**

Table 18. Main Categories of Soil Pollution: Sources, Pollutants, and Environmental Effects

Type of Pollution	Main Pollutants	Dominant Source	Major Effects
Inorganic	Heavy metals, metalloids	Industry, agriculture	Toxicity, bioaccumulation
Organic	Hydrocarbons, pesticides, PCBs	Agriculture, petrochemical industries	Carcinogenicity, endocrine disruption
Radioactive	U, Th, Cs, Sr	Nuclear waste, mining	Mutagenicity, carcinogenicity

Biological	Bacteria, viruses, parasites	Wastewater, sludge	Disease transmission, crop contamination
Physico-chemical	Salts, H^+, Na^+	Irrigation, acid rain	Soil degradation, loss of fertility

IV.6.7. References

- Alloway, B. J. (2013). *Heavy Metals in Soils: Trace Metals*

IV.7. Organic Pollutants

Organic pollutants represent a diverse group of carbon-based compounds that originate from both **natural processes** and **anthropogenic activities** such as agriculture, industry, and urbanization. Once introduced into the soil, these substances interact with soil components through **adsorption, volatilization, degradation, and leaching**. Their environmental fate depends largely on soil characteristics and the compound's own physicochemical properties, which determine whether the pollutant remains immobilized, undergoes biodegradation, or migrates toward groundwater.

IV.7.1. Soil Organic Matter Content

Soil organic matter (SOM) plays a crucial role in both the **retention and degradation** of organic pollutants. Hydrophobic compounds such as **polycyclic aromatic hydrocarbons (PAHs)**, **pesticides**, and **industrial solvents** strongly adsorb onto organic matter, reducing their mobility but increasing their **persistence and potential for long-term accumulation**. Moreover, SOM supports a rich microbial community, which enhances **biodegradation processes**, particularly for biodegradable compounds (Wu et al., 2020).

IV.7.2. Soil Type and Texture

The **texture and mineral composition** of soils influence the **adsorption capacity** and **transport behavior** of organic contaminants. **Clayey and loamy soils**, rich in fine particles and colloids, exhibit a high sorption capacity that limits pollutant mobility, whereas **sandy soils**, characterized by low cation-exchange capacity and high permeability, promote **leaching and groundwater contamination** (Kabata-Pendias, 2011).

IV.7.3. pH, Moisture, and Temperature

The **soil pH** affects both the chemical stability and microbial degradation of organic compounds. Near-neutral to slightly alkaline conditions generally enhance microbial activity, while strongly acidic environments can inhibit biodegradation. **Soil moisture** regulates the diffusion of nutrients and oxygen, essential for microbial metabolism, and **temperature** influences both **chemical reaction rates** and **biological activity**. Optimal degradation typically occurs under moderate temperatures (20–35 °C) (Zhang et al., 2021).

IV.7.4. Solubility and Chemical Structure

The **aqueous solubility** of an organic compound is a key factor controlling its **mobility and bioavailability**. Low-solubility (hydrophobic) substances tend to bind to soil particles, whereas highly soluble compounds can **migrate rapidly** through the soil profile, posing a risk to **groundwater quality**. Additionally, molecular structure and functional groups influence the compound's **persistence and susceptibility to microbial attack**.

IV.8.Characteristics of Organic Pollutants

Organic pollutants are **complex carbon-based compounds** that differ from inorganic contaminants because they are not classified solely by their chemical structure but rather by a set of **four key environmental properties** determining their persistence and ecological impact (Matei et al., 2023; Duan et al., 2024):

- **Toxicity:** Organic pollutants exhibit one or several proven adverse effects on human health and ecosystems. Many compounds such as **pesticides**, **polycyclic aromatic hydrocarbons (PAHs)**, and **polychlorinated biphenyls (PCBs)** are **carcinogenic, mutagenic, teratogenic**, or act as **endocrine disruptors**, affecting metabolic and reproductive functions even at trace concentrations (Assey et al., 2023).
- **Environmental persistence:** These molecules are highly resistant to **biological, chemical, and photolytic degradation** due to their stable aromatic or halogenated structures. As a result, they remain in soils, sediments, and organisms for long periods, often exceeding several decades. This persistence contributes to their **bioavailability and long-term ecological risk** (Li et al., 2023).
- **Long-range atmospheric transport:** Many persistent organic pollutants (POPs) are **semi-volatile**, enabling them to **evaporate, travel through the atmosphere**, and condense in colder regions, far from their emission sources. This property explains the widespread detection of POPs in **polar environments** and remote ecosystems (Wania & Mackay, 1998; Monteiro-Alves et al., 2024).
- **Bioaccumulation and biomagnification:** Due to their **lipophilic nature**, organic pollutants tend to accumulate in **fatty tissues of living organisms**. Over time, their concentrations increase along the **trophic chain**, leading to **biomagnification** in top predators and humans. Chronic exposure may cause immune, neurological, and reproductive disorders (Wang & Gao, 2016; Jacobs & Jacob, 2024). A crucial parameter for evaluating the behavior of organic pollutants is the **octanol–water partition coefficient (Kow)**, expressed as:

- Kow=CoctanolCwaterK_{ow} = \frac{C_{octanol}}{C_{water}}Kow=Cwater Coctanol
- This coefficient reflects the **hydrophobic (lipophilic) character** of a compound and its tendency to accumulate in organic matter and living organisms. **High Kow values** indicate low water solubility and high potential for **bioaccumulation and persistence**, whereas **low Kow values** correspond to more hydrophilic compounds with greater **mobility in aqueous environments** and higher risk of **groundwater contamination** (Mackay et al., 2006; Fenner et al., 2004).
- Other physicochemical parameters—such as **vapor pressure**, **Henry's law constant**, and **half-life (t½)**—further describe the pollutant's **volatility, degradation rate, and environmental mobility**. Together, these properties define the **fate, transport mechanisms, and ecological hazard** of organic pollutants in terrestrial ecosystems (Mateescu et al., 2024).

IV.9. Parameters Influencing the Fate of Pollutants in Soil

The behavior and fate of pollutants in soils are determined by a combination of **physicochemical, biological, and environmental parameters**. These factors influence the **adsorption, mobility, degradation, and bioavailability** of both organic and inorganic contaminants.

IV.9.1 Organic Pollutants

IV.9.1.1. Organic Matter Content

Soil organic matter (SOM) plays a critical role in the retention of organic pollutants. Hydrophobic organic contaminants such as PAHs and PCBs have a strong affinity for humic substances and other carbon-rich materials. Soils rich in organic matter generally show **greater adsorption capacity**, reducing pollutant mobility but enhancing **long-term persistence** (Gao et al., 2022). However, excessive SOM can also shield pollutants from microbial degradation.

IV.9.1.2. Soil Type and Texture

The mineral composition and particle size distribution determine **surface area and cation exchange capacity (CEC)**, which control the sorption of organic compounds. **Clay-rich soils** retain more pollutants than sandy soils due to higher surface reactivity and porosity (Zhao et al., 2021).

IV.9.1.3. Soil pH

The acidity or alkalinity of the soil affects the **ionization state** of organic molecules. Under acidic conditions, many organic pollutants become less soluble and more strongly adsorbed, while basic conditions often increase their mobility and potential for leaching (Xu et al., 2023).

IV.9.1.4. Soil Moisture

Moisture content regulates the **diffusion of pollutants** and **microbial activity**. Moderate humidity enhances biodegradation by providing optimal conditions for microbial metabolism. Conversely, excessive water saturation limits oxygen diffusion and promotes **anaerobic conditions**, slowing down degradation (Chen et al., 2022).

IV.9.1.5. Temperature

Temperature influences both **chemical reaction rates** and **microbial enzymatic activity**. Higher temperatures generally accelerate volatilization and degradation processes, whereas low temperatures enhance pollutant persistence, especially in cold climates (Duan et al., 2024).

IV.9.1.6. Solubility

Water solubility governs the **mobility and transport potential** of organic pollutants. Highly soluble compounds (e.g., certain pesticides) move easily through soil layers, reaching groundwater, while poorly soluble compounds tend to **sorb to organic matter and sediments** (Wang et al., 2023).

IV.9.2. Inorganic Pollutants

IV.9.2.1. Soil Ph

The pH strongly controls the **speciation and solubility of metals**. Under acidic conditions, metals such as Cd^{2+}, Pb^{2+}, and Zn^{2+} become more soluble and mobile, increasing their bioavailability and toxicity. Conversely, neutral or slightly alkaline pH promotes metal precipitation or adsorption onto clay and organic matter (Li et al., 2023).

IV.9.2.2. Temperature and Moistur

These parameters affect the **redox state** and **mobility** of inorganic elements. Increased temperature enhances diffusion rates and microbial transformations, while soil moisture regulates oxygen availability and therefore the **oxidation–reduction balance** (Zhang et al., 2022).

IV.9.2.3. Microbial Biomass

Soil microorganisms influence the **biotransformation and immobilization** of metals. Certain bacterial and fungal species can **reduce, oxidize, or chelate** metals, transforming them into less bioavailable forms. This **microbial remediation potential** is crucial in natural attenuation processes (Huang et al., 2023).

IV.9.2.4. Redox Potential (Eh)

The redox state of the soil determines the **chemical form** and therefore the **mobility and toxicity** of inorganic pollutants. In reducing (anaerobic) environments, some metals (e.g., Fe, Mn) become soluble, whereas in oxidizing conditions they tend to precipitate or adsorb to soil particles (Zhao & Li, 2024).

IV. 10. Effects of Soil Pollution on the Ecosystem: Biotope and Biocenosis

Soil pollution exerts profound impacts on ecosystems by disrupting both **abiotic components (biotope)** and **biotic communities (biocenosis)**. These alterations affect not only soil chemistry and structure but also the functioning of plants, microorganisms, and animals that depend on soil resources.

IV.10.1. Effects on the Biotope

The **biotope**, representing the physical and chemical environment of an ecosystem, undergoes significant modifications under the influence of pollutants.

- **Alteration of Soil Structure and Fertility:**

  Heavy metals, hydrocarbons, and persistent organic pollutants (POPs) can disrupt soil aggregation and porosity, reducing water infiltration and aeration. This degradation leads to **soil compaction**, **loss of fertility**, and a decline in **nutrient cycling efficiency** (Zhang et al., 2023).

- **Changes in Physicochemical Properties:**

  Soil pollution alters **pH, redox potential, and cation exchange capacity (CEC)**. Acidification caused by acidic deposition or industrial emissions increases the solubility and mobility of toxic metals such as Cd, Pb, and Zn, enhancing their bioavailability and risk to biota (Li et al., 2021).

- **Disruption of Soil Microbial Balance:**

  Toxic compounds reduce microbial biomass and enzymatic activities involved in nitrogen and carbon cycles. This disruption slows down **organic matter decomposition** and **nutrient mineralization**, leading to a less productive environment (Huang et al., 2023).

- **Hydrological and Geochemical Changes:**

  Polluted soils often experience **reduced water retention** and **altered ion exchange processes**, which affect groundwater quality and contribute to **secondary contamination** of adjacent ecosystems (Chen et al., 2022).

IV.10.2. Effects on the Biocenosis

The biocenosis, or living community within the ecosystem, also suffers multiple stress responses due to soil contamination.

- **Impact on Vegetation:**

  Plants absorb contaminants through their roots, leading to **phytotoxicity**, **growth inhibition**, **chlorosis**, and reduced photosynthetic activity. The accumulation of metals such as Cd, Pb, and As in plant tissues can cause cellular damage and alter metabolic pathways (Wang et al., 2024). Furthermore, **pollutant bioaccumulation** in edible plants poses direct risks to herbivores and humans through food chain transfer.

- **Impact on Soil Fauna:**

  Soil invertebrates, including earthworms, nematodes, and arthropods, are sensitive indicators of contamination. Exposure to pesticides and metals reduces their population density, reproductive capacity, and enzymatic functions. This loss of biodiversity weakens soil bioturbation processes and nutrient redistribution (Duan et al., 2024).

- **Impact on Microorganisms:**

  Microbial diversity decreases in polluted soils as sensitive species are replaced by resistant strains, leading to **loss of functional redundancy** and **imbalanced biogeochemical cycles**. Certain xenobiotic-degrading bacteria may proliferate, but at the expense of general microbial health (Gao et al., 2023).

- **Ecosystem-Level Consequences:**

  The cumulative effects of soil pollution on both biotope and biocenosis result in **ecosystem destabilization**, reduced **primary productivity**, and impaired **self-regulation mechanisms**. Long-term contamination can lead to **loss of biodiversity**, **disruption of trophic networks**, and even **ecosystem collapse** in severely degraded environments (Xu et al., 2022).

IV. 11. Soil Decontamination Techniques

The remediation of contaminated soils involves several approaches that aim to reduce the concentration, mobility, or toxicity of pollutants. These methods can be grouped into **physico-chemical**, **biological**, and **phytoremediation** techniques, depending on the nature of the contaminants and the site conditions. In recent years, **integrated and nanotechnology-based methods** have also gained prominence.

IV.11.1. Physico-Chemical Methods

IV.11.1.1. Soil Washing

This technique uses water or chemical solutions (surfactants, chelating agents, or acids) to extract pollutants such as heavy metals, hydrocarbons, or pesticides from the soil matrix. It is effective for **sandy or low-clay soils** but may require post-treatment of wash effluents (Zhou et al., 2021).

IV.11.1.2. Soil Flushing

Similar to soil washing, but applied **in situ**, this method involves injecting flushing solutions (e.g., EDTA, citric acid) into the contaminated zone to mobilize pollutants, which are then recovered through extraction wells (Kim et al., 2022).

IV.11.1.3. Thermal Desorption

Contaminated soils are heated (100–600 °C) to volatilize organic compounds such as petroleum hydrocarbons and PAHs. The vapors are then captured and treated, making this an efficient technique for **hydrocarbon-polluted soils** (Mansour et al., 2023).

IV.11.1.4. Stabilization/Solidification (S/S)

Pollutants are immobilized by mixing the soil with binding agents (cement, lime, fly ash). This process reduces the **leaching potential and bioavailability** of metals and radionuclides (Li et al., 2023).

IV.11.1.5. Electrokinetic Remediation

This method applies a **low-intensity electric field** to drive charged contaminants (e.g., heavy metals) toward collection electrodes. It is particularly useful for **fine-grained soils (clay, silt)** (Huang et al., 2024).

IV.11.2. Biological Methods: Bioremediation

IV.11.2.1. Natural Attenuation

This passive process relies on **natural microbial, chemical, and physical mechanisms** (biodegradation, volatilization, sorption) to gradually reduce contaminant levels without human intervention (Rizzo et al., 2022).

IV.11.2.2. Biostimulation

Nutrients (nitrogen, phosphorus) and electron acceptors (oxygen, nitrate) are added to the contaminated site to **enhance the activity of indigenous microorganisms**, accelerating the biodegradation of hydrocarbons and organic pollutants (Singh et al., 2023).

IV.11.2.3. Bioaugmentation

Involves the **inoculation of specialized microbial strains** capable of degrading specific contaminants. It is often combined with biostimulation to improve effectiveness, especially for **recalcitrant compounds** such as PAHs or chlorinated solvents (Duan et al., 2024).

IV.11.2.4. Composting and Landfarming

These ex situ techniques enhance microbial degradation by mixing contaminated soil with organic amendments (e.g., manure, straw). They are effective for **petroleum hydrocarbons and pesticides** (Zhang et al., 2022).

IV.11.3. Phytoremediation

Phytoremediation uses plants to extract, degrade, or stabilize pollutants. It is cost-effective, eco-friendly, and applicable to large areas with low-to-moderate contamination.

- **Phytoextraction:** Uptake of heavy metals by roots and their accumulation in plant tissues (e.g., *Brassica juncea*, *Helianthus annuus*).
- **Phytostabilization:** Plants immobilize contaminants in the rhizosphere, reducing leaching.
- **Phytodegradation:** Enzymatic degradation of organic pollutants within plant tissues.
- **Rhizofiltration:** Absorption or precipitation of contaminants from water by plant roots.
- **Phytovolatilization:** Transformation of pollutants into volatile forms that are released into the atmosphere (e.g., selenium, mercury).

IV.11.4. Emerging and Hybrid Techniques

IV.11.4.1. Nanoremediation

Utilizes **nanoparticles** (e.g., nano-zero-valent iron, TiO_2, carbon nanotubes) to adsorb or degrade pollutants rapidly. This approach offers **high reactivity and efficiency**, especially for heavy metals and chlorinated organics (Wang et al., 2024).

IV.11.4.2. Mycoremediation

Employs **fungi and their enzymes (laccases, peroxidases)** to degrade complex organic molecules like hydrocarbons, dyes, and pesticides (Gao et al., 2023).

IV.11.4.3. Biochar-Assisted Remediation

Biochar improves soil structure, adsorbs pollutants, and supports microbial communities, making it an efficient **synergistic amendment** for both organic and inorganic contamination (Chen et al., 2022).

IV.11.4.4. Combined and Integrated Approaches

Modern remediation projects often integrate **biological and physico-chemical methods**, such as **electro-bioremediation** or **phytobioaugmentation**, to enhance overall efficiency and reduce treatment time (Xu et al., 2023).

Chaptre v: Nuclear Pollution

Chaptre V: Nuclear Pollution

V. Nuclear Pollution

Nuclear or radioactive pollution represents one of the most hazardous forms of environmental contamination due to the persistence and high toxicity of radionuclides. Unlike organic pollutants, radioactive elements are non-biodegradable and may persist in ecosystems for hundreds or even thousands of years. During their disintegration, these elements release ionizing radiation capable of inducing DNA damage, leading to mutagenic and carcinogenic effects in humans and other living organisms (UNSCEAR, 2000; IAEA, 2019).

V.1. Nuclear Fission

Nuclear fission refers to the splitting of heavy atomic nuclei into two fragments of comparable mass, accompanied by the release of a large amount of energy and several free neutrons (Krane, 1988). This reaction typically occurs in isotopes such as uranium-235 and plutonium-239, which are *fissile materials*.

Compared to chemical reactions, nuclear fission liberates millions of times more energy, explaining its application in nuclear power generation and nuclear weapons. For instance, the fission of 1 gram of uranium-235 can release energy equivalent to the combustion of about 3 tons of coal (Shultis & Faw, 2002).

V.2. Definition of Radioactivity

Radioactivity is defined as the spontaneous transformation of an unstable atomic nucleus into a more stable configuration, accompanied by the emission of particles (α, β) or electromagnetic radiation (γ rays). This natural tendency of unstable nuclei to reach equilibrium was first discovered by Henri Becquerel in 1896 and later studied by Pierre and Marie Curie (Curie, 1898).

Over time, the quantity of unstable nuclei decreases exponentially, described by the concept of *half-life*, which is the time required for half of the radioactive atoms to disintegrate (Choppin et al., 2013).

Two main categories of radioactivity are distinguished:

- **a) Natural radioactivity**

  Certain isotopes, such as uranium-238, thorium-232, and potassium-40, have existed since the formation of the Earth. Their decay contributes significantly to background radiation. Radon-222, a radioactive noble gas resulting from the decay of uranium in soil and rocks, is the most important natural source of exposure to the general population and is considered the second leading cause of lung cancer after smoking (WHO, 2009).

- **b) Artificial radioactivity**

  Stable elements can be made radioactive by neutron capture in nuclear reactors or by bombardment with high-energy particles in accelerators. These *artificial radioisotopes* (e.g., cobalt-60, iodine-131, cesium-137) are widely used in medicine, industry, and research, but also represent potential environmental contaminants if not properly managed (IAEA, 2018).

V.3. Sources of Nuclear Pollution

Nuclear or radioactive pollution refers to the release and accumulation of radionuclides in the environment — soil, water, air — which emit ionizing radiation and thus pose risks to ecosystems and human health. These sources can be **natural (geogenic/ambient)** or **anthropogenic (industrial, accidental, medical, etc.)**.

V.3.1. Natural Sources

Natural background radiation accounts for the majority of the average human exposure to ionizing radiation, typically **75–85 %** of the annual effective dose. This exposure originates from several natural sources:

V.3.1.1. Radon gas (Rn-222)

Radon is a colorless, odorless radioactive gas produced from the decay of uranium-238 present in soils and rocks (especially granitic or volcanic geology). It is often considered the **single largest natural contributor** to radiation dose, responsible for nearly a third of the total dose in many regions (Darby et al., 2005; UNSCEAR). When inhaled, radon and its decay progeny deposit in the lungs, irradiating epithelial tissues and increasing lung cancer risk. The **World Health Organization** recognizes radon as the **second leading cause of lung cancer** after tobacco smoking.

V.3.1.2. Cosmic radiation

High-energy particles from outer space (solar and galactic origin) interact with Earth's atmosphere to generate secondary particles (neutrons, muons, protons). The cosmic dose increases with **altitude** (e.g. airline crew) and **latitude** (less geomagnetic shielding near poles). (O’Brien, 2005; ICRP 2012)

V.3.1.3. Terrestrial radionuclides (NORMs: Naturally Occurring Radioactive Materials)

Radioactive isotopes such as uranium-238, thorium-232, and potassium-40 are ubiquitous in soils, rocks, groundwater, and building materials. They contribute to **external**

gamma radiation and **internal exposure** via ingestion or inhalation of dust or particles. In regions with high natural radioactivity (e.g. certain granitic terrains), doses can exceed global averages significantly (Popoola et al., 2025)

V.3.1.4. Radionuclides in food and water

All humans ingest small amounts of radionuclides naturally present in the environment: potassium-40 (ubiquitous in biological matter), carbon-14 (incorporated in organic cycles), and trace radium-226 in groundwater in certain areas. Although individual doses are small, they represent a continuous exposure throughout life (Eisenbud & Gesell, 1997).

V.3.2. Industrial & Anthropogenic Sources

While natural sources dominate background exposure, **anthropogenic (man-made)** operations are responsible for **local contamination**, spikes of exposure, and long-lived radionuclide releases. Major categories include:

a) Nuclear Power Plants (NPPs)

Nuclear reactors generate electricity via controlled fission (e.g. of U-235). However, by-products include **spent fuel** and **effluents** that may contain radionuclides such as tritium (^3H), carbon-14, krypton-85, cesium-137, strontium-90, etc. Routine discharges (under regulatory limits) and potential leaks can contaminate nearby soil, water, and air (IAEA, 2015).

b) Reprocessing and Spent Fuel Management

Reprocessing spent fuel (to recover uranium or plutonium) produces high-level radioactive waste streams requiring long-term containment. Storage facilities and disposal sites (e.g. deep geological repositories) must guard against leakage or migration of radionuclides into soil and groundwater (NEA, 2008; Alinejad et al., 2025)

c) Industrial Applications of Radioisotopes

Radioactive isotopes are used in many industrial, medical, and research applications, including:

- Food irradiation (e.g. cobalt-60, cesium-137)
- Gamma radiography for nondestructive testing
- Sterilization of medical equipment
- Industrial tracers and gauges

When poorly handled, disposed, or lost, such sources can contaminate soil or surface water (mayeh et al., 2025) s.

d) Accidental Releases / Nuclear Accidents

Catastrophic failures in nuclear facilities can lead to massive radionuclide release.

- **Chernobyl (1986)**: Released I-131, Cs-137, Sr-90, etc., contaminating vast areas across Europe, with long-term ecological and health effects (WHO, 2006).
- **Fukushima Daiichi (2011)**: Emissions of Cs-134, Cs-137, tritium, etc., with marine and terrestrial fallout; concerns over marine contamination and food safety remain (IAEA; discharge of treated water)
- Wildfires in contaminated zones can remobilize radionuclides into the atmosphere or water systems (e.g. Chernobyl wildfires in 2020 increased solubility and transport) Also, leaks, mishandling, or accidents in non-nuclear facilities (e.g. radiography sources) contribute to local contamination.

V.3.3. Military Sources

Military nuclear activities remain among the most significant contributors to global radioactive contamination.

a) Atmospheric nuclear weapons testing

Between 1945 and 1980, over 500 atmospheric nuclear tests were carried out by the United States, Soviet Union, France, China, and the United Kingdom. These detonations released vast quantities of radionuclides—particularly strontium-90, cesium-137, iodine-131, and plutonium isotopes—into the stratosphere, which were later dispersed globally through rainfall (Simon et al., 2006; UNSCEAR, 2000). Fallout subsequently entered food chains such as milk and cereals, increasing thyroid and bone cancer risks due to the bioaccumulation of iodine and strontium (Bouville et al., 2010).

Recent studies confirm that residual radionuclide concentrations persist in many former test areas, indicating long-term soil contamination and ecological risks (*Diaz-Maurin, 2024; Journal of Environmental Chemical Engineering, 2023*).

b) Underground and underwater tests

Following the 1963 Partial Test Ban Treaty, underground and underwater tests continued, leading to localized contamination of soils, groundwater, and marine ecosystems. Sites such as Nevada (USA), Semipalatinsk (Kazakhstan), Mururoa (French Polynesia), and Novaya Zemlya (Russia) remain critical environmental monitoring zones (NRC, 2012; *Diaz-Maurin, 2024*).

c) Nuclear submarine accidents

The sinking of nuclear-powered submarines, including the Soviet *K-129* (1968), *K-219* (1986), and *Kursk* (2000), released radioactive materials into marine environments. Long-term radionuclide leakage, notably of cesium-137 and plutonium, poses enduring threats to oceanic ecosystems (IAEA, 2001).

d) Nuclear weapons disposal

During the Cold War, obsolete reactors and radioactive waste were dumped into oceans, particularly by the Soviet Union in Arctic regions. These sunken materials continue to pose contamination risks due to corrosion and radionuclide diffusion (Osvath et al., 2011; *Diaz-Maurin, 2024*).

V.3.4. Medical Sources

The medical field is one of the largest civilian users of radioisotopes, contributing significantly to public health but also to potential localized radioactive pollution. While the benefits are undeniable, improper handling, disposal, or accidental release of medical isotopes can lead to environmental contamination and occupational exposure.

a) Diagnostic applications

Nuclear medicine uses isotopes such as iodine-131, technetium-99m, and fluorine-18 for imaging and functional diagnostics (e.g., thyroid scans, PET scans). Trace amounts of these isotopes are excreted in biological waste and can enter wastewater systems, contributing to low-level contamination (UNSCEAR, 2008).

b) Therapeutic applications

Radiotherapy employs cobalt-60 and cesium-137 for cancer treatment, while brachytherapy uses sealed radioactive sources implanted in or near tumors. Improper management of these materials may result in radioactive waste concerns (Podgorsak, 2005).

c) Sterilization of medical equipment

Gamma irradiation using cobalt-60 is widely applied for sterilizing surgical tools, syringes, and implants. Despite its efficiency, incidents in handling facilities have occasionally resulted in severe occupational exposure (IAEA, 2013).

Recent analyses indicate that medical staff working in radiology and nuclear medicine still receive measurable radiation doses, sometimes close to regulatory limits (*European Radiology, 2023*).

d) Incidents and risks

Several accidents involving medical sources have led to contamination, notably the Goiânia incident in Brazil (1987), in which a disused cesium-137 source caused multiple deaths and widespread contamination (IAEA, 1988). More recent evaluations emphasize the importance of strengthening waste tracking systems to prevent similar events (*European Radiology, 2023*).

V.3.5. Accidental Sources

Nuclear accidents represent the most catastrophic form of radioactive pollution, releasing vast amounts of radionuclides into the environment and causing long-lasting transboundary contamination.

Major accidents

- **Chernobyl (Ukraine, 1986):**

  The explosion and fire in reactor No. 4 emitted approximately 5–10% of its radioactive inventory, including iodine-131, cesium-137, and strontium-90 (WHO, 2006). Over 350,000 people were displaced, and increased thyroid cancer rates were observed among children (Cardis et al., 2005). Vast exclusion zones remain uninhabitable.

- **Fukushima Daiichi (Japan, 2011):**

  Triggered by a massive earthquake and tsunami, meltdowns in three reactors released large quantities of cesium-134, cesium-137, and tritium into the air and Pacific Ocean (IAEA, 2015; Buesseler et al., 2017). Ongoing monitoring in 2023–2024 continues to detect residual contamination near the plant (*Seo, 2024*).

Other incidents

The partial meltdown at *Three Mile Island* (USA, 1979) resulted in minor radioactive gas releases, prompting stricter safety regulations (NRC, 1980). The *Mayak* accident (Russia, 1957) contaminated the Techa River basin with large amounts of radionuclides (Medvedev, 1979).

V.3. Main Types of Radiations

V.3.1. Radioisotopes

Isotopes that are unstable and emit radiation are called **radioisotopes**. A radioisotope is an isotope of a chemical element that undergoes **spontaneous nuclear decay**, releasing radiation as it transforms into a more stable form. This process continues until the isotope reaches a stable, non-radioactive state (IAEA, 2013; Choppin et al., 2013).

A key characteristic of radioisotopes is their **half-life (T½)**, which represents the time required for half of the radioactive atoms in a sample to decay. Half-lives vary widely, from fractions of a second (e.g., polonium-214) to billions of years (e.g., uranium-238), influencing both their environmental persistence and their health impacts (Shultis & Faw, 2011).

There are three principal types of radioactive decay:

V.3.1.1. Alpha decay (α-decay)

In alpha decay, the nucleus emits an **alpha particle** composed of two protons and two neutrons (equivalent to a helium-4 nucleus). This process reduces the **atomic number by two** and the **mass number by four**, producing a lighter element.

- **Common alpha emitters:** radium (Ra), radon (Rn), uranium (U), thorium (Th).
- **Penetration power:** low; alpha particles can be stopped by a sheet of paper or the outer layer of human skin.
- **Health risks:** dangerous when inhaled or ingested (e.g., radon exposure in lungs).

V.3.1.2. Beta decay (β-decay)

In beta decay, a **neutron transforms into a proton**, releasing an **electron (β^- particle)** and an **antineutrino ($\bar{\nu}_e$)**. In some cases, a proton may convert into a neutron, releasing a **positron (β^+ particle)** and a neutrino.

- **Effect:** increases (β^-) or decreases (β^+) the atomic number by one, while the mass number remains unchanged.
- **Common beta emitters:** strontium-90 (^{90}Sr), tritium (^{3}H), carbon-14 (^{14}C), sulfur-35 (^{35}S).
- **Penetration power:** medium; beta particles can pass through paper but are stopped by a few millimeters of aluminum.
- **Applications:** radiotracers in medicine (e.g., ^{14}C dating, ^{3}H labeling).

V.3.1.3. Gamma decay (γ-decay)

Gamma decay involves the release of **excess nuclear energy** in the form of **high-energy electromagnetic photons (γ-rays)**. This usually occurs **after alpha or beta decay**, or following **neutron capture in nuclear reactors**.

- **Effect:** does not change the atomic number or mass of the isotope, but reduces the nucleus's energy state.
- **Penetration power:** very high; requires several centimeters of lead or meters of concrete for shielding.
- **Health risks:** deep tissue penetration, capable of causing DNA damage and increasing cancer risk.
- **Applications:** sterilization of medical equipment, food irradiation, cancer therapy (γ-knife).

V.3.1.4. Importance of Radioisotopes

- **Natural presence:** Radioisotopes such as uranium-238, thorium-232, and potassium-40 occur naturally in the environment.

- **Medical use:** Iodine-131 for thyroid disorders, cobalt-60 for radiotherapy, technetium-99m for diagnostic imaging.
- **Environmental concerns:** Improper disposal, nuclear accidents, and weapons testing increase human and ecological exposure.

V.4. Categories and Sources of Radiation

Radiation is the **emission and propagation of energy** through space or matter, occurring in the form of **waves (electromagnetic radiation)** or **particles (corpuscular radiation)**. Depending on its energy level and ability to ionize atoms, radiation is broadly classified into **non-ionizing** and **ionizing radiation** (Hall & Giaccia, 2019; UNSCEAR, 2000).

V.4.1. Non-ionizing radiation

Non-ionizing radiation carries relatively **low energy** and lacks sufficient power to remove tightly bound electrons from atoms. Instead, it can cause **excitation of electrons**, **molecular vibrations**, or **heating effects**. Though often perceived as less harmful, certain forms of non-ionizing radiation may still induce **biological and ecological impacts**, especially after chronic exposure.

V.4.1.1. Examples and sources:

- **Visible light:** fundamental for human vision, photosynthesis in plants, and circadian rhythm regulation.
- **Infrared radiation (IR):** emitted as heat from the sun, living organisms, and electronic devices; widely used in thermal imaging and remote sensing.
- **Microwaves:** used in communication (radar, satellite transmission) and domestic food heating.
- **Radio waves:** applied in broadcasting (radio, television), telecommunications, and MRI imaging in medicine.
- **Ultraviolet (UV) radiation (low-energy range, UVA and UVB):** although mostly non-ionizing, prolonged exposure damages skin cells, accelerates photoaging, and increases risks of cataracts and melanoma (WHO, 2006; IARC, 2012).

V.4.1.2. Biological effects:

- Short-term: erythema (sunburn), eye irritation, hyperthermia.
- Long-term: premature skin aging, immunosuppression, carcinogenesis (particularly melanoma and squamous cell carcinoma).

V.4.1.3. Environmental effects:

- UV radiation influences **plant physiology** (e.g., reduced chlorophyll content, altered growth).
- Disruption of **aquatic ecosystems** by damaging phytoplankton DNA, with cascading effects on food webs (Häder et al., 2015).

V.4.2. Ionizing Radiation

Ionizing radiation possesses **sufficient energy to remove tightly bound electrons** from atoms or molecules, producing ions. This process leads to the formation of **reactive oxygen species (ROS)** and other radicals, which interact with cellular components such as lipids, proteins, and especially **DNA**, causing strand breaks and base modifications. If not properly repaired, these lesions can result in **mutations, chromosomal aberrations, cancer, or cell death** (Hall & Giaccia, 2012; UNSCEAR, 2000).

V.4.2.1. Sources of Ionizing Radiation

1. **Natural sources** (≈80% of annual dose, UNSCEAR, 2000):

- **Cosmic rays:** High-energy particles from outer space; intensity increases with altitude and latitude.
- **Terrestrial radionuclides:** Uranium (U), thorium (Th), radium (Ra), and their decay products (e.g., radon gas) in rocks and soils.
- **Food and water:** Naturally occurring radionuclides such as **potassium-40 (^{40}K)** and **carbon-14 (^{14}C)** ingested daily.

2. **Artificial sources:**

- **Nuclear power plants:** Radiation from nuclear fission (e.g., uranium-235, plutonium-239) and spent fuel.
- **Medical uses:** Diagnostic radiology (X-rays, CT scans), nuclear medicine (e.g., iodine-131, technetium-99m), and radiotherapy (e.g., cobalt-60, cesium-137).
- **Industrial applications:** Food irradiation, radiography for material testing, sterilization of products.

V.4.2.2. Types of Ionizing Radiation

- **Alpha particles (α):**

  Heavy, positively charged (two protons + two neutrons).

  - **Penetration:** Very low, stopped by a sheet of paper or skin.
  - **Hazard:** High ionization density (high LET, linear energy transfer). Extremely dangerous if inhaled or ingested (e.g., radon-222, polonium-210).

- **Beta particles (β):**
  High-energy electrons or positrons.
  - **Penetration:** Moderate; can pass through a few millimeters of tissue but stopped by plastic, glass, or thin aluminum.
  - **Hazard:** Can cause skin burns and damage to superficial tissues. Examples: strontium-90, tritium, carbon-14.
- **Gamma rays (γ) and X-rays:**
  Electromagnetic waves of very short wavelength.
  - **Penetration:** Very high; can travel meters in air and pass through the human body.
  - **Shielding:** Requires dense materials like lead or thick concrete.
  - **Hazard:** Deep penetration makes them particularly dangerous for internal organs.
- **Neutrons:**
  Electrically neutral particles produced in nuclear fission and fusion.
  - **Penetration:** Highly penetrating due to absence of charge; interact indirectly via collisions with nuclei (especially hydrogen).
  - **Shielding:** Hydrogen-rich materials such as water, polyethylene, or concrete.
  - **Hazard:** Particularly damaging in nuclear reactors and explosions due to high biological effectiveness (ICRP, 2007).

V.5. Biological Effects of Ionizing Radiation

Ionizing radiation interacts with biological matter by producing **ionization and excitation** of atoms and molecules within cells, leading to **chemical and structural damage** of vital macromolecules such as DNA, proteins, and lipids (Hall & Giaccia, 2012). The biological effects depend on the **type of radiation**, its **energy**, the **exposure route**, and the **radiosensitivity** of the affected tissues.

V.5.1. Types of Ionizing Radiation

a) Alpha radiation (α)

Alpha particles (helium nuclei) have **high linear energy transfer (LET)**, depositing large amounts of energy over a short distance. Although they cannot penetrate the skin, their **internalization** through inhalation or ingestion leads to severe localized damage. For instance, **inhaled radon-222** and its progeny (polonium-218, polonium-214) irradiate bronchial epithelium, increasing **lung cancer risk** (WHO, 2021; UNSCEAR, 2020).

b) Beta radiation (β)

Beta particles (electrons or positrons) possess **moderate LET** and can penetrate several millimeters into biological tissue. Chronic exposure may cause **skin burns**, **eye lens opacity**, or **genetic mutations** (ICRP, 2019). Beta emitters like **strontium-90** and **tritium** are major environmental pollutants from nuclear fallout and industrial discharges.

c) Photon radiation (gamma [γ] and X-rays)

Gamma rays and X-rays are **highly penetrating electromagnetic radiations** capable of traversing human tissues and ionizing atoms along their path. Their effects include **acute radiation syndrome** (ARS) at high doses and **stochastic effects** (e.g., cancer, teratogenesis) at lower chronic exposures (Hall & Giaccia, 2019). Gamma-emitting isotopes like **cesium-137** and **cobalt-60** are common in nuclear accidents and medical radiotherapy.

d) Neutron radiation (n)

Neutrons are **uncharged particles** with very high penetration capacity. They indirectly cause ionization by colliding with nuclei in tissues, producing **secondary charged particles**. Neutron exposure results in **severe biological effects**, particularly **DNA double-strand breaks**, due to their high relative biological effectiveness (RBE) (ICRP, 2021). Major sources include **nuclear reactors**, **particle accelerators**, and **cosmic rays** at high altitudes.

V.5.2. Mechanisms of Biological Damage

Ionizing radiation affects biological systems through **two main pathways**:

- **Direct action:** Radiation directly ionizes DNA molecules, causing **single- and double-strand breaks** that may lead to **mutations, chromosomal aberrations**, or **cell death**.
- **Indirect action:** Radiation interacts with water molecules to generate **reactive oxygen species (ROS)** such as hydroxyl radicals (•OH) and hydrogen peroxide (H_2O_2), which subsequently damage DNA, proteins, and cellular membranes (Azzam et al., 2020).

The body's **repair mechanisms** (e.g., base excision repair, non-homologous end joining) can often fix such damage, but misrepair may result in **carcinogenesis** or **heritable genetic effects**.

V.5.3. Biological and Health Impacts

- **Acute effects:** Occur at high doses (>1 Gy) and include nausea, bone marrow suppression, hemorrhages, and death in severe cases (ICRP, 2021).
- **Chronic effects:** Long-term exposure, even to low doses, increases risks of **cancer**, **cataracts**, **cardiovascular diseases**, and **reproductive disorders** (UNSCEAR, 2022).
- **Genetic and developmental effects:** Prenatal exposure can cause **malformations**, **growth retardation**, or **neurodevelopmental deficits** (Hall & Giaccia, 2019).

- **Ecological effects:** Radiation affects **non-human biota**, leading to **reduced fertility**, **mutations**, and **biodiversity loss** in contaminated ecosystems such as Chernobyl and Fukushima (Møller & Mousseau, 2023).

V.6. Pathways of Contamination

Ionizing radiation reaches living organisms through **external** and **internal** exposure routes, which together determine the **dose absorbed** and **biological impact**.

V.6.1. External irradiation

External irradiation **occurs when ionizing radiation originates from a source** outside the human body**. Unlike internal contamination—where radionuclides are absorbed or inhaled—external exposure affects the body through radiation that travels through air or materials before reaching tissues.**

V.6.1.1. Principal Sources

External exposure arises from both **natural** and **anthropogenic** origins:

- **Cosmic Radiation:**

  Originates from galactic and solar sources, consisting mainly of high-energy protons and heavy nuclei. The intensity of cosmic rays increases with altitude and proximity to the poles due to the thinning of Earth's atmosphere and weaker magnetic shielding. Aircrew members and astronauts are therefore subject to higher doses (ICRP, 2020; NASA, 2022).

- **Terrestrial Radiation:**

  Caused by naturally occurring radionuclides such as **uranium-238**, **thorium-232**, and **potassium-40** present in rocks, soils, and construction materials. These emit alpha, beta, and gamma radiation, contributing to background exposure in the environment. In certain granitic or volcanic regions, natural radioactivity may be significantly elevated (UNSCEAR, 2021).

- **Man-Made Sources:**

  Include **X-ray diagnostic equipment**, **radiotherapy devices**, **industrial radiography**, and **nuclear reactor emissions**. Occupational exposure in medical, research, and nuclear sectors constitutes one of the main pathways of artificial external irradiation (IAEA, 2023).

V.6.1.2. Types of Radiation Involved

External irradiation primarily involves **gamma rays** and **neutrons**, which possess **high penetration power**:

- **Gamma Rays (γ):**

  These high-energy photons can traverse several centimeters of tissue or meters of air. They require dense shielding materials such as **lead** or **concrete**. Chronic exposure leads to cumulative DNA damage, increasing the risk of cancers, cataracts, and cardiovascular diseases (Hall & Giaccia, 2021).

- **Neutrons:**

  Uncharged particles produced mainly in nuclear reactors and cosmic interactions. Because of their high energy, neutrons can deeply penetrate tissues and induce **secondary radiation** (gamma or charged particles) upon interaction with nuclei. Shielding against neutrons requires **hydrogen-rich materials** such as water, polyethylene, or paraffin wax (IAEA, 2022).

V.6.1.3. Biological Implications

The severity of biological damage depends on the **dose rate**, **radiation type**, and **duration of exposure**:

- **Acute High-Dose Exposure:**

  Causes immediate tissue damage and can result in **acute radiation syndrome (ARS)** characterized by nausea, hematopoietic suppression, and, at very high doses, death.

- **Chronic Low-Dose Exposure:**

  Leads to **accumulated cellular and DNA damage** over time, increasing the risk of **carcinogenesis**, **genetic mutations**, and **cardiovascular effects** (ICRP, 2020; Little et al., 2023).

Prolonged external exposure to penetrating radiation such as gamma rays or neutrons can result in **whole-body irradiation**, damaging critical organs like the **bone marrow**, **thyroid**, and **reproductive tissues**, thereby elevating **lifetime cancer risks** and **hereditary effects** in offspring.

V.6.1.4. Protective Measures

Radiation protection principles are based on the **ALARA concept** (“As Low As Reasonably Achievable”), involving:

- **Time:** Minimizing exposure duration.
- **Distance:** Increasing distance from radiation sources.
- **Shielding:** Using appropriate protective barriers (lead for gamma rays, hydrogenous materials for neutrons).

- **Monitoring:** Using dosimeters to measure accumulated doses and ensure occupational safety (IAEA, 2023).

V.6.2. Internal Irradiation

Internal contamination occurs when radionuclides enter the body via **inhalation, ingestion, or absorption** through wounds.

a) Inhalation

Airborne radionuclides such as **radon-222**, uranium dust, or radioactive iodine are inhaled and lodge in the respiratory system. Radon and its progeny are major contributors to **lung cancer**, particularly in mining areas and granite-rich regions (Darby et al., 2020; WHO, 2021).

b) Ingestion

Consumption of **contaminated food or water** introduces radionuclides into the digestive tract. Following the **Fukushima Daiichi accident**, elevated levels of **cesium-137 and strontium-90** were detected in fish and agricultural products, illustrating long-term bioaccumulation in food chains (Buesseler et al., 2022).

c) Absorption through Skin or Wounds

In medical or industrial accidents, direct contact with radioactive materials can lead to **localized incorporation** through open wounds or damaged skin, causing **severe tissue necrosis** and chronic radiation ulcers (IAEA, 2023).

Once internalized, radionuclides accumulate selectively in specific organs depending on their chemical affinity: **Table 19**

Table 19. Distribution of Major Radionuclides in the Human Body and Their Associated Health Effects

Radionuclide	Target Organ	Health Effect
Iodine-131	Thyroid gland	Thyroid cancer, hypothyroidism
Strontium-90	Bones, teeth	Bone cancer, leukemia
Cesium-137	Muscles	Cellular ion imbalance
Plutonium-239	Liver, bones	Lung and bone sarcomas

Because of their **long physical and biological half-lives**, these isotopes continue irradiating tissues internally for extended periods, leading to **chronic disorders** such as cancer, genetic mutations, and immune dysfunction (Hall & Giaccia, 2020; UNSCEAR, 2021).

V.6.3. Environmental Transfer and Bioaccumulation

- **Soil-to-plant transfer:** Plants absorb radionuclides through roots, particularly cesium and strontium, mimicking essential nutrients (potassium and calcium).
- **Trophic transfer:** Herbivores accumulate radionuclides, which biomagnify through food webs, ultimately exposing humans (IAEA, 2020).
- **Aquatic systems:** Radionuclides such as tritium and cesium-137 disperse in water and accumulate in sediments and aquatic organisms, threatening marine biodiversity (Buesseler et al., 2017; Møller & Mousseau, 2023).

V.7. Biological Effects of Radiation

The biological impact of radiation depends on its type, energy, dose, and exposure pathway. Living cells differ greatly in their **radiosensitivity**, and the biological consequences can range from reversible cellular damage to mutations, cancer, or death.

V.7.1. Radiosensitivity of Cells and Organisms

- **Prokaryotic cells** (e.g., bacteria) are generally more resistant to radiation due to their simpler structure, efficient DNA repair systems, and ability to survive in extreme environments. For example, *Deinococcus radiodurans* can survive doses exceeding 5,000 Gy (Cox & Battista, 2005).
- **Eukaryotic cells** are more radiosensitive, particularly those with a high mitotic index and limited capacity for DNA repair. Highly sensitive tissues include:
    - **Bone marrow** (hematopoietic stem cells).
    - **Gastrointestinal epithelium**.
    - **Germ cells** (sperm and ova).
    - **Developing embryos and fetuses**, where radiation may cause teratogenic effects (Hall & Giaccia, 2012).
- In contrast, differentiated tissues such as muscle and nervous tissue are more resistant.

V.7.2. Acute and Chronic Effects

- **Acute Radiation Syndrome (ARS):** High doses delivered over a short period cause nausea, vomiting, hematopoietic failure, gastrointestinal damage, and, at very high levels, cardiovascular and neurological collapse (Mettler & Voelz, 2002).
- **Stochastic effects:** Even at lower doses, ionizing radiation increases the risk of cancer and heritable mutations. The risk is cumulative and has no threshold (ICRP, 2007).
- **Non-stochastic (deterministic) effects:** These occur only above a certain threshold dose (e.g., skin erythema, cataracts, sterility).

V.7.3. Bioaccumulation and Biomagnification

Ionizing radionuclides (e.g., cesium-137, strontium-90, iodine-131, plutonium isotopes) may enter **aquatic and terrestrial ecosystems**, where they persist due to long half-lives. They accumulate in organisms and are **biomagnified along food chains**, posing significant risks to human health:

- **Aquatic organisms** (fish, mollusks, crustaceans) can concentrate radionuclides from water and sediments. Humans consuming contaminated seafood may be chronically exposed (IAEA, 2010).
- **Terrestrial food chains** show similar effects, with radionuclides entering plants via soil and then passing to herbivores and carnivores. For example, strontium-90 mimics calcium, depositing in bones and teeth, while cesium-137 behaves like potassium, accumulating in soft tissues (UNSCEAR, 2000).

V.7.4. Radioactive Waste Management

The management of radioactive waste is a major challenge for public health and environmental protection. These wastes come from various sources, including nuclear power plants, hospitals (nuclear medicine, radiotherapy), research laboratories, and certain industries. Their hazard level depends on their **radioactivity, half-life, physical and chemical nature**, and their potential for dispersion.

V.7.4.1. Classification of Radioactive Waste

According to the International Atomic Energy Agency (IAEA, 2018), waste is classified into:

- **Very low-level waste (VLLW)**: Slightly contaminated materials, often from facility decommissioning.
- **Low- and intermediate-level waste (LILW)**: Contain short-lived radionuclides (< 30 years). Example: medical equipment or contaminated filters.
- **High-level waste (HLW)**: Highly radioactive and heat-generating, mainly **spent nuclear fuel**. They require strict confinement and cooling.

V.7.4.2. Management Principles

Safe management relies on three fundamental pillars (ICRP, 2007; IAEA, 2018):

1. **Isolation** of waste from the biosphere to avoid dispersion.
2. **Confinement** using multiple barriers (containers, geology, storage systems).
3. **Control** through continuous regulatory and environmental monitoring.

V.7.4.3. Management and Storage Methods

- **Temporary storage**: Surface or near-surface storage allowing radioactive decay of short-lived isotopes.
- **Deep geological disposal**: The preferred method for HLW, confining them in stable geological formations (e.g., ONKALO project in Finland).
- **Immobilization**: Incorporating radionuclides into stable matrices (glass, bitumen, ceramics) to reduce mobility.
- **Transmutation** (under research): Converting long-lived radionuclides into shorter-lived isotopes through neutron irradiation.
- **Medical and research waste**: Often packaged in shielded drums and stored in specialized facilities.

V.7.4.4. Challenges and Issues

- **Extremely long hazard duration**: Some wastes (e.g., plutonium-239, half-life ~24,000 years) remain dangerous for millennia.
- **Contamination risks**: Groundwater infiltration, atmospheric dispersion in case of accidents.
- **Social acceptance**: Frequent opposition from local populations to storage site installations.
- **Security and proliferation**: Risk of diversion of radioactive materials for malicious purposes.

V.7.4.5. International Recommendations

- **ALARA principle** (*As Low As Reasonably Achievable*): Minimize exposure doses for workers and the public.
- **Post-closure monitoring** of geological disposal sites for several centuries.
- **International cooperation** to share expertise, ensure waste traceability, and maintain transparency with the public (IAEA, 2018; OECD-NEA, 2020).

V.8. Solutions to Nuclear Pollution

Nuclear pollution, primarily resulting from activities related to atomic energy production, radioactive waste management, and industrial accidents, poses a long-term threat to ecosystems and human health. Its remediation requires an integrated approach that combines preventive, curative, and regulatory strategies, grounded in recent scientific and technological advances.

V.8.1. Preventive Measures

Preventive measures aim to reduce the risk of release or spread of radioactive substances at the source.

V.8.1.1. Improving Reactor Safety

New reactor designs, particularly fourth-generation reactors and Small Modular Reactors (SMRs), integrate passive safety systems that function without human intervention, minimizing the risk of major accidents.

These technologies also improve energy efficiency and reduce the volume of waste produced (OECD/NEA, 2022; IAEA, 2023).

V.8.1.2. Safe Management and Storage of Radioactive Materials

Safe storage is based on a multi-barrier strategy, combining corrosion-resistant containers with deep geological repositories. Notable examples include Finland’s Onkalo site, the first deep geological repository for long-term spent fuel disposal (Posiva Oy, 2022). Continuous monitoring through remote sensing technologies and real-time surveillance systems helps prevent potential leaks (IAEA, 2021).

V.8.1.3. Reducing Radioactive Waste Generation

The adoption of a closed fuel cycle, which allows for the recycling of uranium and plutonium, significantly reduces the amount of high-level radioactive waste. In addition, research into nuclear transmutation seeks to convert long-lived isotopes (such as cesium-137 or strontium-90) into more stable or short-lived forms (Ahn et al., 2023).

V.8.2. Remediation and Decontamination Technologies

Nuclear decontamination technologies focus on stabilizing, recovering, or neutralizing radionuclides present in soil, water, and air.

V.8.2.1. Physical and Chemical Methods

Excavation and vitrification involve extracting contaminated soil and transforming it into an insoluble glass matrix, preventing radionuclide migration.

Ion exchange and adsorption processes using materials such as synthetic zeolites, biochar, and nanomaterials (graphene, metal oxides) are highly effective at trapping cesium (Cs^+), strontium (Sr^{2+}), and uranium (U^{6+}) (Wang et al., 2023; Chen et al., 2024).

V.8.2.2. Phytoremediation

Certain hyperaccumulator plants such as *Brassica juncea* and *Helianthus annuus* can absorb and concentrate radioactive elements from the soil.

Although slow, this ecological approach offers a sustainable solution for the gradual rehabilitation of contaminated land (Kumar et al., 2022).

V.8.2.3. Microbial Bioremediation

Radioresistant bacteria such as *Deinococcus radiodurans* and *Shewanella putrefaciens* can reduce or immobilize radionuclides like uranium (U), technetium (Tc), or neptunium (Np). Recent studies highlight the role of microbial consortia and biofilms in stabilizing radionuclides over the long term in contaminated environments (Jia et al., 2021).

V.8.2.4. Containment and Isolation

Highly contaminated zones can be encapsulated or cemented to prevent radioactive migration into groundwater. The Chernobyl sarcophagus, replaced in 2019 by the New Safe Confinement, illustrates international efforts to isolate long-term radiation sources (IAEA, 2020).

V.8.3. Monitoring, Regulation, and Public Awareness

V.8.3.1. Environmental Monitoring

The establishment of radiological surveillance networks using spectrometric sensors, mapping drones, and GIS (Geographic Information Systems) enables rapid detection of anomalies and efficient planning of remediation actions (Guo et al., 2024).

V.8.3.2. Regulatory Framework and International Cooperation

Safety and radioactive waste management standards are defined by the International Atomic Energy Agency (IAEA) and governed by international conventions such as the Joint Convention on the Safety of Spent Fuel Management (1997). The revised Safety Standards Series SSR-5 (IAEA, 2023) serves as a global reference for radiological protection.

V.8.3.3. Public Communication and Participation

Transparent communication about nuclear risks, safety measures, and emergency protocols helps strengthen public trust and awareness.Involving local communities in monitoring programs enhances social acceptance of nuclear facilities (OECD/NEA, 2022).

V.8.4. Future Perspectives

Recent research is focusing on more sustainable and intelligent technologies:

- Artificial intelligence (AI) and machine learning are used to model radionuclide dispersion and optimize waste management (Li et al., 2024).
- Advanced nanomaterials, particularly metal-organic frameworks (MOFs), show great potential for radionuclide adsorption in contaminated waters (Zhang et al., 2025).
- The emergence of a circular nuclear economy promotes the controlled reuse of isotopes for medical, agricultural, or industrial purposes.

Chapter VI: Bioindicators, Biomarkers, and Bioaccumulation Processes

Chaptre VI: Bioindicators as Effective Tools for Environmental Pollution Assessment

VI.1. Definition and Significance of Bioindicators

Bioindicators are living organisms (plants, animals, fungi, or microorganisms) that exhibit measurable responses to pollutants in their environment. Their physiological, morphological, or behavioral alterations provide insights into environmental quality and contamination levels (Niemi & McDonald, 2020). Unlike chemical analyses, which reflect conditions at a single point in time, bioindicators integrate **cumulative and long-term effects of pollutants**, making them indispensable for ecological monitoring.

VI.1.2. Criteria for Selecting Biomarkers for Field Applications

Mayer et al. (1992) highlighted essential criteria for selecting biomarkers suitable for environmental monitoring:

1. **Simplicity and Cost-Effectiveness** – Biomarkers should be measurable with standard laboratory or field techniques, allowing **large-scale monitoring at reasonable costs**.
2. **Dose-Dependent Response** – The biomarker must demonstrate a **quantifiable change correlated with pollutant concentration and exposure time**, enabling accurate risk assessment.
3. **High Sensitivity** – Capable of detecting **low pollutant levels**, providing **early warning signals** before significant ecological damage occurs.
4. **Controlled Influence of Non-Toxic Factors** – Variations due to climate, substrate, season, or organismal age should be **minimal or well-characterized**, ensuring reliable interpretation.
5. **Biological Relevance** – The biomarker should reflect **meaningful physiological, reproductive, or ecological effects**, impacting homeostasis at the individual or population level.

These criteria ensure that bioindicators deliver **reproducible, interpretable, and ecologically meaningful data**, allowing robust assessment of pollution impacts and the effectiveness of remediation strategies.

VI.1.3.Mechanisms of Bioindicator Responses

Bioindicators respond to environmental pollution through a variety of **biochemical, physiological, genetic, and ecological mechanisms** that reflect both the presence and the intensity of contamination. These responses serve as measurable biological signals that integrate the effects of multiple stressors over time, providing essential information for environmental monitoring and risk assessment (Bennett et al., 2021; Zhang et al., 2023; FAO, 2024).

The main mechanisms include:

- **Bioaccumulation** – The absorption and retention of pollutants (such as heavy metals, organic compounds, or radionuclides) within tissues. This process reflects both environmental exposure and the organism's ability to metabolize or sequester contaminants (Ali et al., 2020; Pereira et al., 2022).
- **Physiological Alteration** – Pollution often disrupts essential metabolic processes, including photosynthesis, respiration, reproduction, and enzymatic activity. Such changes may involve oxidative stress, inhibition of chlorophyll synthesis, or alterations in antioxidant defense systems (Huang et al., 2021; Singh et al., 2023).
- **Genetic Modification** – Exposure to mutagenic or genotoxic agents can induce DNA damage, mutations, or chromosomal aberrations. These molecular responses are commonly used in genotoxic bioassays and serve as early indicators of environmental stress (Qian et al., 2022; Li et al., 2023).
- **Ecological Changes** – Pollution can alter species diversity, abundance, and community structure, leading to ecological imbalances and loss of functional biodiversity. Shifts in bioindicator populations (e.g., lichens, benthic macroinvertebrates, or soil microorganisms) provide integrative signals of long-term ecosystem disturbance (Buczko et al., 2021; Suárez et al., 2024).

Through these combined responses, bioindicators enable scientists to assess the **nature, origin, and magnitude of environmental pollutants**, whether **chemical, organic, metallic, or radioactive**. Their multi-level sensitivity—from molecular to community scales—makes them indispensable tools for evaluating **ecosystem health** and **environmental sustainability** (FAO, 2024; Zhang et al., 2023).

VI.1.4. Classification of Bioindicators

VI.4.1 Accumulative Bioindicators

Species that absorb and store contaminants, providing **quantitative data** on environmental pollution.

Examples: lichens and mosses for heavy metals, aquatic plants (*Lemna minor*), fish and benthic invertebrates for metals and pesticides.

VI.4.2 Effect Bioindicators

Species that show **observable biological effects** such as malformations, mortality, or genetic damage.

Examples: *Allium cepa* root assay, *Daphnia* and trout for toxicity, microalgae for eutrophication detection.

VI.4.3 Ecological Bioindicators

Species that reflect **ecosystem health** through diversity, abundance, or community structure.

Examples: macroinvertebrate indices (BMWP, IBGN), changes in plant communities, lichen sensitivity to SO_2.

VI.1.5. Application of Bioindicators to Pollution Assessment

VI.5.1 Atmospheric Pollution

Lichens, mosses, and conifer needles detect heavy metals, ozone, and sulfur dioxide (Biazrov et al., 2021).

VI.5.2 Water Pollution

Benthic macroinvertebrates, microalgae, and aquatic plants reflect freshwater ecosystem quality.

VI.5.3 Soil Pollution

Earthworms, mycorrhizal fungi, and hyperaccumulating plants indicate contamination by heavy metals or hydrocarbons.

VI.5.4 Radioactive Pollution

Lichens, mosses, and certain fungi can accumulate radionuclides such as Cs-137 and Sr-90, used after the Chernobyl and Fukushima nuclear accidents (IAEA, 2023).

VI.6. Advantages and Limitations of Bioindicators

VI.6.1. Advantages:

- Capture **cumulative and chronic pollutant effects**.
- Reveal **bioavailability** of contaminants.
- Provide **ecological insights beyond chemical measurements**.
- Low-cost, non-destructive, and scalable.

VI.6.2. Limitations:

- Influenced by natural environmental variables.
- Require **local baseline data**.
- Linking observed effects to specific pollutants can be difficult.

- Some species may be rare or **taxonomically challenging**.

VI.6.2. Examples of Bioindicator Species

The examples presented in Table 14 illustrate the diversity of bioindicator species across different environmental compartments. Each species reflects specific types of pollutants, either through accumulation, observable biological effects, or ecological changes. Selecting appropriate bioindicators depends on the pollutant type, environmental medium, and monitoring objectives, ensuring reliable and meaningful assessment of ecosystem health. These species provide valuable insights into both the presence and biological impact of contaminants, supporting effective environmental management and pollution mitigation strategies. **Table 20**

Table 20. Examples of Bioindicator Species for Monitoring Different Types of Environmental Pollution

Environment	Bioindicator Species	Detected Pollutants	Indicator Type
Air	*Xanthoria parietina* (lichen)	SO_2, heavy metals	Accumulative
Water	*Daphnia magna*	Pesticides, metals	Effect
Soil	*Lumbricus terrestris* (earthworm)	Cd, Pb, Zn	Accumulative
Freshwater	*Lemna minor* (duckweed)	Nutrients, metals	Effect
Forest	Pine needles	Atmospheric deposits	Accumulative
Urban zones	Periphytic microalgae	Nitrates, phosphates	Ecological

Bioindicators are **powerful tools for environmental monitoring**, enabling scientists to detect the **real impacts of pollution** on organisms and ecosystems. Integrating bioindicators into monitoring programs supports **sustainable ecosystem management** and **mitigation of ecotoxicological risks**.

VI.7. Pollution Biomarkers: Concepts and Applications

VI.7.1. Definition and Importance

Pollution biomarkers are measurable biological indicators that reflect exposure to environmental pollutants or the physiological and biochemical effects of this exposure on organisms. Unlike direct chemical analyses, which provide only a snapshot of contaminant concentrations at a given time and location, biomarkers integrate cumulative and long-term biological responses, offering a dynamic assessment of environmental health (Mayer et al., 1992; El-SiKaily et al., 2024). They can detect sublethal and early-stage effects, often preceding visible symptoms or population-level declines, making them invaluable for proactive environmental monitoring.

These tools are essential for several purposes:

- **Ecological monitoring**: Biomarkers allow the evaluation of ecosystem integrity by revealing subtle changes in organism physiology, behavior, and population health that chemical analyses might miss. For instance, enzyme inhibition, oxidative stress, or DNA damage in sentinel species can signal pollution before overt ecological degradation occurs (Bai et al., 2024).
- **Environmental risk assessment**: By quantifying exposure levels and biological responses, biomarkers help identify sublethal effects of contaminants such as heavy metals, hydrocarbons, pesticides, and emerging pollutants like microplastics. This enables more precise ecological risk assessments and supports the development of regulatory thresholds (Calisi et al., 2023).
- **Environmental management and conservation**: Data from biomarkers guide decision-making for ecosystem restoration, pollution mitigation, and policy formulation. For example, the monitoring of bioaccumulated heavy metals in fish or mussels can inform safe harvesting practices and remediation strategies in contaminated water bodies (El-SiKaily et al., 2024).
- **Human health implications**: Some biomarkers also serve as early warning indicators for potential human exposure, particularly in cases of bioaccumulative pollutants in food chains, bridging the gap between ecological and public health surveillance (WHO, 2021).

Additionally, modern approaches integrating **omics technologies** (genomics, proteomics, metabolomics) with traditional biomarkers provide a comprehensive understanding of molecular and cellular responses to pollutants, enabling predictive modeling of ecosystem responses to environmental stressors (Calisi et al., 2023).

VI.7.2. Types of Biomarkers

a. Exposure Biomarkers

Exposure biomarkers serve to quantify the presence and accumulation of environmental pollutants within biological systems. They provide **direct evidence of contaminant exposure**, enabling early and precise ecological risk assessment.

Key characteristics include:

- **Quantification of contaminant concentrations:** These biomarkers allow the measurement of heavy metals (e.g., lead, cadmium, mercury) in fish tissues or soil invertebrates, as well as pesticide residues in plants and insects. They also encompass persistent organic pollutants (POPs) detected in human and wildlife tissues.
- **Assessment of bioavailability:** Exposure biomarkers inform whether pollutants are merely present in the environment or whether they are biologically accessible and capable of entering the food chain.
- **Representative examples:** Blood mercury levels in fish and humans, polychlorinated biphenyls (PCBs) in avian eggs, and microplastics quantified in marine organisms' gastrointestinal tracts.

b. Effect Biomarkers

Effect biomarkers reflect the **biological responses elicited by pollutant exposure**, offering insights into sublethal physiological, biochemical, or genetic alterations. Unlike exposure biomarkers, they do not merely indicate presence but demonstrate the biological impact of contaminants.

characteristics include:

- **Enzymatic modifications:** Inhibition of acetylcholinesterase (AChE) activity due to exposure to organophosphate or carbamate pesticides.
- **Oxidative stress indicators:** Elevation of malondialdehyde (MDA) levels, lipid peroxidation, and alterations in antioxidant enzyme activities such as superoxide dismutase, catalase, and glutathione peroxidase.
- **Genotoxic markers:** DNA strand breaks detectable via comet assay and micronucleus formation in erythrocytes or buccal cells.
- **Physiological consequences:** Disruption of endocrine function, reproductive impairments, or modulation of immune responses.

c. Susceptibility Biomarkers

Susceptibility biomarkers indicate the **intrinsic vulnerability** of individuals or populations to environmental contaminants, reflecting genetic, epigenetic, or physiological predispositions.

Characteristics include:

- **Genetic polymorphisms:** Variations in genes encoding detoxifying enzymes (e.g., glutathione S-transferases, cytochrome P450 enzymes) that modulate the organism's ability to metabolize and eliminate toxicants.

- **Physiological responses:** Differences in DNA repair efficiency, antioxidant defense mechanisms, or immune system competence.
- **Epigenetic modifications:** DNA methylation and histone modifications influencing stress responsiveness.
- **Life stage sensitivity:** Early developmental stages often exhibit heightened susceptibility relative to mature individuals.

VI.7.3. Selection Criteria for Biomarkers

The selection of appropriate biomarkers is a fundamental step in environmental and ecotoxicological studies, as it determines the validity and interpretability of the results. According to Mayer et al. (1992), an effective biomarker must satisfy several essential criteria to ensure both scientific robustness and practical applicability.

- **Sensitivity:** The biomarker should be capable of detecting low levels of pollutants, allowing early identification of contamination before adverse effects become pronounced.
- **Specificity:** It must respond clearly and exclusively to the target pollutant, minimizing interference from other environmental factors or chemical compounds.
- **Reliability:** The biomarker should provide consistent and reproducible results across different studies, populations, and environmental conditions.
- **Biological relevance:** There should be a direct and demonstrable link between the biomarker and the health or physiological status of the organism, ensuring that observed changes are meaningful in terms of ecological or toxicological impact.
- **Practicality:** The biomarker should be feasible to measure under field or laboratory conditions, considering cost, equipment requirements, and sample handling.

Extended discussion:

Applying these criteria ensures that the selected biomarkers provide both **scientific validity and operational efficiency**. In practice, the choice of a biomarker depends not only on its biochemical precision but also on its ecological context. A balance must be maintained between laboratory-controlled precision and field-based applicability. For instance, while molecular biomarkers may offer high specificity, their field application can be limited by analytical constraints. Conversely, physiological markers may be more accessible but less discriminative. Therefore, an integrative approach combining multiple biomarker types—molecular, biochemical, and physiological—is increasingly advocated to obtain a comprehensive understanding of environmental stress and organismal response (Costa et al., 2020; Olsson et al., 2020).

VI.7.4. Practical Applications

Biomarkers have become indispensable tools in environmental monitoring, ecotoxicology, and human health risk assessment. Their versatility allows for the evaluation of pollutant exposure, the detection of biological effects, and the identification of vulnerable species or populations.

- **Aquatic ecotoxicology:** Biomarkers are extensively used to evaluate the effects of pollutants on fish and aquatic invertebrates. For example, acetylcholinesterase inhibition in fish is a well-established indicator of exposure to organophosphate pesticides (El-SiKaily et al., 2024).

Contextual explanation:

By integrating biomarker responses with population- and ecosystem-level data, researchers can identify early signs of ecological disruption, evaluate contaminant bioavailability, and support the design of conservation and remediation strategies. This integration also facilitates the development of biological indices that complement chemical monitoring, allowing for a more holistic assessment of aquatic ecosystem health.

- **Air quality monitoring:** Oxidative stress biomarkers, such as elevated levels of malondialdehyde (MDA) or altered antioxidant enzyme activity, are measured in humans exposed to air pollutants to assess subclinical health effects (Bai et al., 2024).

Contextual explanation

These biomarkers provide a mechanistic link between pollutant exposure and physiological stress, offering early indicators of potential respiratory or cardiovascular diseases before clinical symptoms appear. Their use in epidemiological and occupational studies enhances our understanding of air pollution’s impact on public health and guides preventive policies and exposure limit regulations.

- **Health risk assessment:** Biomarkers are employed to identify sublethal effects of contaminants on wildlife and plants, including genetic damage, reproductive impairment, and immune system alterations.

Contextual explanation

This application enables researchers and policymakers to predict long-term ecological consequences and establish thresholds of toxicological concern. By detecting early biological responses, risk assessment frameworks can shift from reactive to proactive strategies, promoting ecosystem protection and sustainable environmental management. Moreover, in agricultural contexts, biomarkers can be applied to evaluate pesticide residues and heavy metal accumulation in crops, ensuring food safety and compliance with environmental regulations (Chen et al., 2022).

Extended discussion

Beyond these specific applications, biomarkers are increasingly being integrated into **multidisciplinary monitoring programs** that combine biochemical, molecular, and ecological indicators. Such integrative approaches improve the accuracy of environmental assessments and facilitate cross-species comparisons. The use of biomarkers as **sentinel indicators** of environmental health is particularly valuable for detecting early biological changes that precede visible ecological degradation. As analytical technologies advance—such as omics (genomics, proteomics, metabolomics)—biomarker-based assessments are becoming more sensitive, specific, and predictive, offering powerful tools for future environmental surveillance and policy development (Al-Sabahi et al., 2021; El-SiKaily et al., 2024).

VI.7.5. Limitations and Challenges

Despite their recognized importance in environmental assessment, biomarkers are subject to several **methodological and interpretative limitations** that must be carefully considered when designing studies and analyzing results. These challenges may arise from natural biological variability, species-specific responses, and the complexity of environmental contaminant mixtures.

- **Natural variability:** Environmental parameters such as temperature, salinity, pH, photoperiod, and nutrient availability can significantly influence biomarker responses, thereby complicating data interpretation.

Contextual explanation

For instance, oxidative stress markers or enzyme activities may fluctuate naturally due to seasonal metabolic changes, reproductive cycles, or food availability. Such physiological variations can obscure or mimic pollutant-induced effects if not properly accounted for. To address this, it is essential to include appropriate control populations, replicate sampling across seasons, and normalize biomarker data against relevant physiological or environmental covariates (Costa et al., 2020).

- **Species specificity:** Many biomarkers exhibit species- or taxon-specific responses, which can limit their general applicability across different ecosystems or organisms.

Contextual explanation

This specificity requires the **careful selection of sentinel species** that are both ecologically relevant and sensitive to the contaminants of interest. Sentinel organisms—such as bivalves in marine environments or fish in freshwater systems—act as bioindicators, providing valuable insights into the health of their respective ecosystems. However, extrapolating biomarker responses from one species to another must be done cautiously, as differences in metabolism, physiology, and ecological niche can alter the biomarker's response pattern (Olsson et al., 2020).

- **Complex interactions:** Environmental contamination rarely occurs as isolated single-pollutant exposure. Instead, organisms are often subjected to multiple stressors, including mixtures of heavy metals, organic pollutants, and changing environmental conditions that may interact synergistically or antagonistically.

Contextual explanation

Such **multifactorial exposures** can produce confounding or nonlinear effects on biomarker responses, making it challenging to attribute observed changes to a single contaminant. To overcome this limitation, researchers increasingly employ **integrative approaches**, such as multi-biomarker panels, multivariate statistical models, or systems biology frameworks. These approaches enhance interpretability by capturing complex biological interactions and improving the predictive power of biomarker-based assessments (Bai et al., 2024; El-SiKaily et al., 2024).

Extended discussion

In addition to these factors, issues related to **analytical standardization**, **sample preservation**, and **data comparability** across laboratories remain significant challenges. Establishing standardized protocols and reference materials is therefore crucial to ensure consistency and reliability of biomarker data. Moreover, future research should focus on integrating biomarkers with **omics technologies**—including genomics, transcriptomics, proteomics, and metabolomics—to achieve a more comprehensive understanding of organismal responses to complex environmental stressors.

Conclusion

While biomarkers represent powerful diagnostic and predictive tools in ecotoxicology and environmental health, their application requires critical evaluation of biological, methodological, and ecological contexts. Only through rigorous experimental design, standardized analytical frameworks, and interdisciplinary integration can biomarkers fully realize their potential as early-warning indicators of environmental change and ecosystem health.

VI.7.6. Future Perspectives

- **Omics technologies**: integrating transcriptomics, proteomics, and metabolomics for a holistic understanding of pollutant effects.
- **Predictive models**: developing adverse outcome pathway (AOP)-based models to predict ecotoxicological impacts (Calisi et al., 2023).
- **Real-time monitoring**: using biological and electronic sensors for continuous pollutant detection. **Table 21**

Table 21. Examples of Pollution Biomarkers

Biomarker Type	Organism	Pollutant	Target Tissue	Observed Effect
Enzyme	Fish (*Oncorhynchus mykiss*)	Organophosphate	Brain	Acetylcholinesterase inhibition
Oxidative Stress	Mussel (*Mytilus spp.*)	Heavy metals	Hepatopancreas	Increased lipid peroxidation
Genetic Damage	Fish (*Danio rerio*)	Pesticides	Blood cells	Micronucleus formation
Metabolism	Plant (*Brassica juncea*)	Hydrocarbons	Roots	Accumulation of specific metabolites

VI.8. Bioaccumulation of Environmental Pollutants – Detailed Explanation

VI.8.1. Definition and Importance

Bioaccumulation is the process by which pollutants progressively accumulate in the tissues of living organisms over time. Unlike transient exposure, bioaccumulated substances persist because the rate of intake exceeds the rate of elimination or metabolic degradation (Bargagli, 2020).

This phenomenon is critical for understanding environmental pollution because it provides insight into:

- **Ecological risks:** Higher trophic-level species, such as predators, often accumulate higher pollutant loads through biomagnification. This can disrupt food webs, reduce biodiversity, and impair reproductive success, growth, and survival in wildlife populations (Bargagli, 2020). Persistent pollutants like mercury, PCBs, and dioxins are particularly prone to biomagnification, causing sublethal or lethal effects in top predators such as birds of prey, large fish, and marine mammals.

- **Human health risks:** Consumption of contaminated organisms can introduce toxic substances into human food chains, leading to bioaccumulation in humans over time. Chronic exposure to heavy metals (e.g., mercury, cadmium, lead) or persistent organic pollutants (POPs) can result in neurological disorders, endocrine disruption, immune dysfunction, and increased cancer risk (Dar et al., 2021; Buesseler et al., 2022). Populations dependent on fish, shellfish, or locally contaminated crops are particularly vulnerable.
- **Long-term environmental monitoring:** Bioaccumulation reflects the cumulative impact of contaminants, integrating spatial and temporal variations better than snapshot chemical analyses. It allows for the detection of slow-moving or persistent pollutants that may not be apparent in short-term environmental measurements. For example, the progressive accumulation of heavy metals in sediments, plants, or benthic invertebrates can reveal historical pollution trends and identify contamination hotspots (Li et al., 2022).
- **Assessment of pollutant bioavailability:** Unlike total chemical measurements, bioaccumulation indicates the fraction of contaminants that is biologically available to organisms. This is critical for ecological risk assessments because only bioavailable pollutants can exert toxic effects (Huang et al., 2021).
- **Evaluation of remediation effectiveness:** Tracking pollutant concentrations in bioindicator organisms provides a practical tool for assessing the success of soil, water, or ecosystem remediation strategies over time, highlighting residual contamination or potential ecological recovery.

VI.8.2. Physiological Stages of Bioaccumulation

Bioaccumulation in organisms is a complex physiological process that occurs in distinct stages, reflecting both the interaction with the environment and internal handling of pollutants. Understanding these stages is essential for assessing ecological and human health risks.

VI.8.2.1 Initial Uptake (Biosorption)

- During this stage, pollutants are rapidly adsorbed at the external surfaces of organisms, including the skin, gills, mucous membranes, or the intestinal lining in the case of ingestion (Bargagli, 2020).
- The efficiency of uptake depends on several physicochemical properties of the pollutant:

  - **Solubility:** Water-soluble pollutants are readily absorbed via aqueous pathways, whereas hydrophobic compounds preferentially bind to lipid-rich surfaces.
  - **Lipophilicity:** Lipid-soluble substances (e.g., polychlorinated biphenyls [PCBs], polycyclic aromatic hydrocarbons [PAHs]) have higher affinity for biological membranes, facilitating rapid absorption.
  - **Environmental concentration:** Higher pollutant concentrations in soil, water, or food increase the rate of uptake, although saturation effects may occur at very high levels (Li et al., 2022).
- This stage represents the **interface between the organism and its environment** and is influenced by abiotic factors (temperature, pH, salinity) as well as biotic factors such as the organism's surface area, age, and metabolic activity.

VI.8.2.2 Intracellular Accumulation

- Following uptake, pollutants are transported into tissues and sequestered in specific cellular or organ compartments for storage or detoxification. Major storage sites include the **liver, kidneys, muscles, and adipose tissue** (Huang et al., 2021).
- The fate of pollutants is strongly determined by their chemical nature:
  - **Lipophilic compounds** (e.g., dioxins, PCBs) preferentially accumulate in fatty tissues, leading to prolonged retention and potential biomagnification through trophic levels.
  - **Heavy metals** (e.g., cadmium, mercury) bind to metallothioneins or other proteins, concentrating in the liver, kidneys, and sometimes bones, potentially causing organ-specific toxicity.
- Intracellular accumulation reflects the **balance between uptake, metabolic transformation, and excretion**, and determines the biological half-life of pollutants within organisms. Persistent compounds with slow excretion rates pose the highest ecological and human health risks (Bargagli, 2020; Buesseler et al., 2022).

VI.8.3. Factors Influencing Bioaccumulation

Bioaccumulation is a multifactorial process influenced by both **abiotic** and **biotic** factors that determine the extent, rate, and pattern of pollutant accumulation in organisms. Understanding these factors is essential for accurate risk assessment and ecological monitoring.

VI.8.3.1. Abiotic Factors

- **pH:** Soil or water pH affects the solubility, speciation, and mobility of metals and other pollutants. For instance, acidic conditions increase the solubility of cadmium and lead, enhancing their uptake by plants and aquatic organisms (Zhang et al., 2023).
- **Temperature:** Metabolic rates and enzymatic activities increase with temperature, often accelerating pollutant uptake and transformation. For example, mercury methylation in aquatic systems is faster in warmer waters, leading to higher bioaccumulation in fish (Li et al., 2022).
- **Salinity:** In estuarine and marine ecosystems, salinity influences the bioavailability of ions and metals, altering accumulation patterns. Cadmium and zinc, for example, exhibit different uptake kinetics in freshwater versus brackish water species (Huang et al., 2021).
- **Dissolved Oxygen and Water Flow:** Oxygen levels and hydrodynamics affect the chemical form of pollutants and their accessibility to organisms. Low-oxygen sediments often increase the bioavailability of metals such as iron and manganese, facilitating uptake by benthic invertebrates (Zhang et al., 2023).

VI.8.3.2. Biotic Factors

- **Species Metabolic Rate:** Organisms with slower metabolism tend to accumulate higher concentrations of persistent pollutants because elimination is reduced. Sedentary bivalves, for example, often show higher PCB concentrations than more active fish species in the same habitat (Bargagli, 2020).
- **Trophic Level:** Predators experience biomagnification, where pollutant concentrations increase at higher levels of the food chain. Mercury levels in top predators, such as tuna or eagles, are significantly higher than in primary consumers (Buesseler et al., 2022).
- **Age and Size:** Older and larger individuals have had longer exposure periods, resulting in greater pollutant accumulation. For instance, large predatory fish such as sharks or swordfish show higher concentrations of methylmercury compared to juveniles (Li et al., 2022).
- **Feeding Habits:** The diet of an organism directly influences pollutant intake. Filter-feeding mussels accumulate waterborne heavy metals; carnivorous fish concentrate organic pollutants from prey; herbivorous mammals may accumulate soil-borne metals from vegetation (Huang et al., 2021).

Example: In freshwater ecosystems affected by industrial effluents, benthic invertebrates in low-oxygen sediments showed a 2–3 fold higher accumulation of cadmium and lead compared to organisms in well-oxygenated areas, demonstrating the combined effect of abiotic (oxygen, sediment type) and biotic (feeding habits, trophic position) factors (Zhang et al., 2023)

VI.8.4. Biological Characteristics of Organisms

The accumulation of pollutants in organisms is strongly influenced by their intrinsic biological traits:

- **Lipid content:** Lipophilic pollutants (e.g., PCBs, dioxins) preferentially accumulate in fatty tissues.
- **Detoxification enzymes:** The presence and activity of enzymes such as cytochrome P450 can metabolize or transform contaminants, affecting retention.
- **Excretion pathways:** Efficient excretory mechanisms reduce internal pollutant levels, whereas slower excretion favors bioaccumulation.
- **Bioindicator species:** Certain organisms, such as mussels (*Mytilus spp.*), earthworms (*Lumbricus terrestris*), or hyperaccumulator plants (e.g., *Brassica juncea*), are particularly effective for monitoring metal or hydrocarbon pollution due to their high accumulation capacity (Huang et al., 2021; Li et al., 2022).

VI.8.5. Duration of Contamination

- The **length of exposure** is directly proportional to bioaccumulation; even low-level contamination over time can lead to high tissue concentrations.
- **Chronic low-dose exposure** can cause cumulative toxicity, affecting growth, reproduction, immune function, and survival.
- **Example:** Long-term mercury exposure in benthic fish species (*Fundulus heteroclitus*) results in muscle bioaccumulation, leading to behavioral and reproductive impairments (Dar et al., 2021).

VI.8.6. Examples of Pollutants and Bioaccumulating Organisms

The following table illustrates representative examples of pollutants, the organisms in which they bioaccumulate, their primary target tissues, and the observed biological effects. It highlights how different chemical substances interact with specific species and tissues, emphasizing the importance of organismal traits, exposure duration, and pollutant characteristics in determining the extent and consequences of bioaccumulation. Such data are essential for environmental monitoring, ecological risk assessment, and the selection of effective bioindicator species.**Table 22**

Table 22. Representative Pollutants, Bioaccumulating Organisms, Target Tissues, and Observed Biological Effects

Pollutant	Organism	Tissue Target	Observed Effect
Mercury (Hg)	*Fundulus heteroclitus*	Muscle	Neurotoxicity, reproductive impairment
Cadmium (Cd)	Earthworm (*Lumbricus terrestris*)	Kidney, liver	Growth inhibition, enzyme disruption
PCBs	Fish (*Oncorhynchus mykiss*)	Fat tissue	Endocrine disruption, immunotoxicity
Dioxins	Birds (*Haliaeetus leucocephalus*)	Fat and liver	Reproductive failure, teratogenicity

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