



**ABBES LAGHROUR UNIVERSITY
KHENCHELA**

DEPARTMENT OF ECOLOGY
AND ENVIRONMENT



ENVIRONMENTAL POLLUTION

INTENDED FOR THIRD YEAR OF THE BACHELOR'S DEGREE IN ECOLOGY
AND THE ENVIRONMENT

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Foreword

This handout is intended for third-year students in Ecology and Environment and provides a structured introduction to pollution and its ecological implications. It examines the main forms of environmental pollution, their sources, their mechanisms of dispersion and circulation in the biosphere, and their effects on air, water, soil, ecosystems, and living organisms.

The objective of this document is to support students in understanding the scientific principles underlying pollutant behaviour, including transport, transformation, accumulation, and persistence in environmental systems. It also aims to strengthen the analytical skills required to study pollution as a major ecological issue and to approach environmental degradation from a rigorous and interdisciplinary perspective.

Particular attention is given to the relationship between human activities and ecological imbalance. Energy production, industrial development, agriculture, urbanization, and waste generation all contribute to the degradation of environmental quality and may affect biodiversity, ecosystem functioning, and natural resources. Understanding these interactions is essential for evaluating environmental risks and for developing appropriate strategies of prevention, monitoring, and management.

This handout is designed as a complementary academic resource for learning, revision, and further study.

Dr. Somia LAKHDARI

Table of contents

Chapter 1: Pollution and Ecological Implications.....	5
I.1.Definitions.....	5
I.2. Classification of Pollution.....	6
I.2.1 According to the nature of the polluting agent	7
I.2.2 From an ecological point of view	8
I.2.3 From a toxicological point of view	8
I.3.Current Causes of Pollution	8
I.4.Types of Pollution.....	9
I.4.1 Air pollution.....	9
I.4.2 Soil pollution.....	9
I.3 Water pollution	9
I.4.4 Pollution according to polluting agents	10
I.5. Consequences of Pollution.....	10
I.5.1 Consequences for health	10
I.5.2 Consequences for the environment	11
I.6. How to Fight Pollution.....	11
I.6.1 Recycling	11
I.6.2 Steps in recycling.....	14
I.6.3 Water treatment.....	14
I.6.4 Renewable energies	14
I.6.5 Responsible behaviour	14
Chapter 2: Mechanisms of Dispersion and Circulation of Polluting Substances in the Biosphere	17
II.3. Biogeochemical Processes.....	24
II.4. Accumulation.....	29
II.5. Distribution of Pollutants.....	30
II.6. Transfer and Concentration of Pollutants in Biomass	30
II.7. Elimination, Decomposition, and Persistence	34
Chapter 3: Atmospheric Pollution.....	37
III.1. Origin of the Main Atmospheric Pollutants	37
III.1.1. Combustion of Fossil Fuels.....	38

III.1.2. Transport	38
III.1.3. Industrial Activities	39
III.1.4. Agriculture and Livestock	39
III.2. Polluting Substances	40
Chapter 4: Soil Pollution	56
IV.1. Definition	56
IV.2. Forms and Consequences of Soil Pollution Caused by Modern Agriculture	57
IV.2.1. Pollution by Fertilizers	58
IV.2.2. Pollution by Pesticides	60
IV.3. Pollution by Contaminants of Industrial Origin	62
IV.3.1. Heavy Metals and Trace Elements	62
IV.3.2. Hydrocarbons and Petroleum Products	63
IV.3.3. Chlorinated Solvents	63
IV.3.4. Persistent Organic Pollutants	64
IV.3.5. Industrial Waste and Sludge	64
IV.3.6. Consequences of Industrial Soil Pollution	65
IV.3.7. Prevention and Remediation	65
Chapter 5: Water Pollution	68
V.1. Introduction: Water Resources	68
V.4. Domestic and Urban Pollution	77
V.5. Pollution of Agricultural Origin	78
V.6. Pollution of Atmospheric Origin	79
V.7. Natural Pollution	80
Chapter 6: Nuclear Pollution	83
VI.1. Introduction	83
VI.2. Sources of Radioactive Pollution	85
VI.3. Ways and Means of Human Exposure	90
VI.4. Biological Effects of Ionizing Radiation	93
VI.5. Prevention, Protection, and Management	94
REFERENCES	97

CHAPTER 1

Chapter 1: Pollution and Ecological Implications

I.1.Definitions

Pollution is any anthropogenic modification of an ecosystem that results in a change in the concentration of natural chemical constituents, or that results from the introduction into the biosphere of artificial chemical substances. It may also correspond to a disturbance of energy flow, radiation intensity, matter circulation, or the introduction of exotic species into a natural biocenosis.

A pollutant can be defined as a biological, physical or chemical alteration agent which, above a certain threshold or standard, develops negative impacts on part or all of an ecosystem or on the environment in general.

The term nuisance refers to technical factors, such as noise, traffic and solid waste, or social factors, such as congestion and neighbourhood disturbance, that reduce quality of life. Unlike pollution, nuisances do not necessarily cause harmful effects on human health and may be without direct ecological consequences.

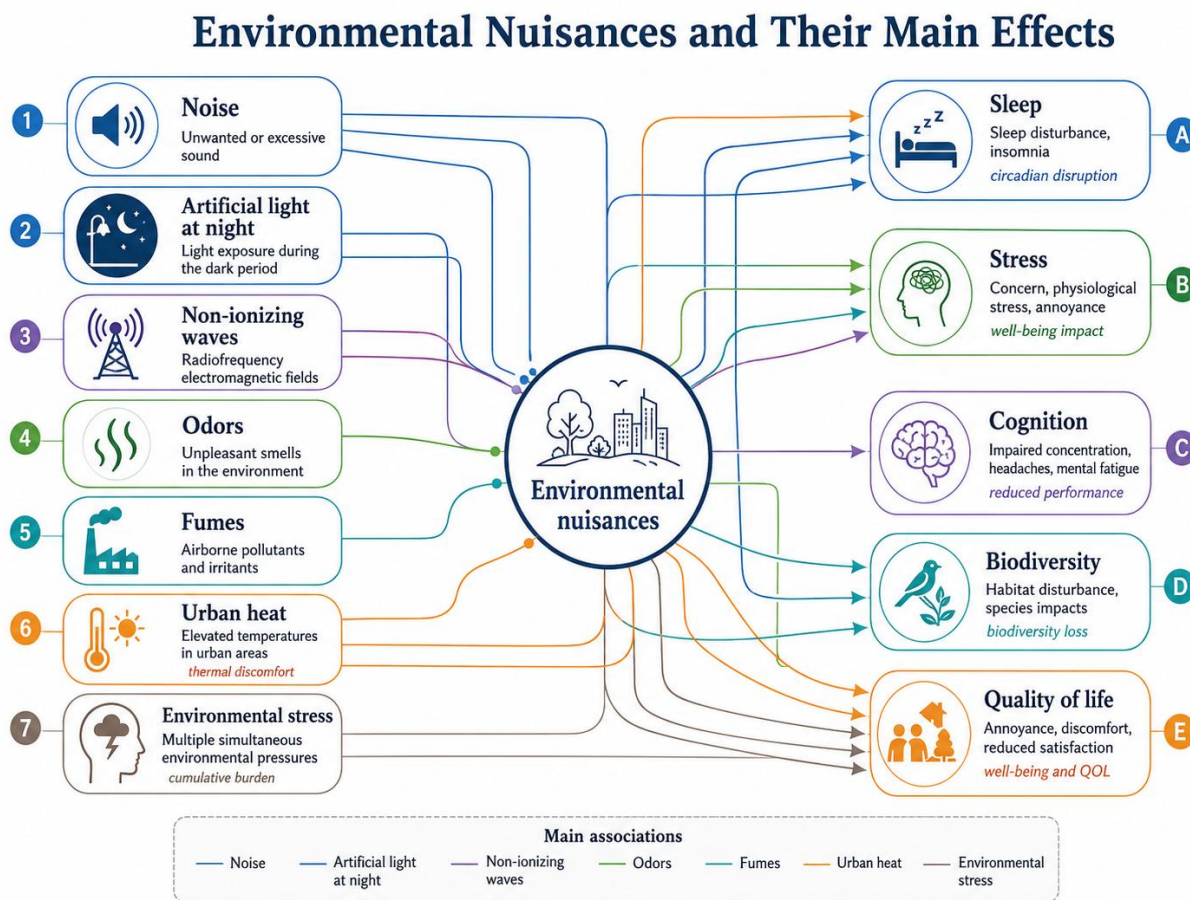


Figure I.1. Environmental nuisances and their main effects on human well-being and ecosystems. (original)

I.2. Classification of Pollution

Pollution can be classified according to several criteria. This classification is important because it allows the identification of sources, pathways of exposure, environmental compartments affected and possible control measures.

Table 1 Main criteria used to classify pollution

Criterion	Classes	Ecological significance
Nature of pollutant	Physical; chemical; biological	Distinguishes radiation, heat, noise, chemicals, pathogens, and invasive organisms.
Receiving medium	Air; water; soil/sediment; biota	Clarifies exposure pathways and monitoring strategies.
Source pattern	Point source; diffuse/non-point source	Point sources are localized and easier to regulate; diffuse sources are widespread and cumulative.
Temporal behaviour	Acute; chronic; intermittent	Determines whether damage results from short peaks or long-term exposure.
Persistence	Readily degradable; moderately persistent; persistent	Controls residence time, long-range transport, and legacy contamination.
Exposure route	Inhalation; ingestion; dermal/contact; root uptake; branchial uptake	Links environmental contamination to organism-level dose and effects.

I.2.1 According to the nature of the polluting agent

- Physical pollution: ionizing radiation, artificial warming of the environment by a technological heat source, noise, light and electromagnetic disturbances.
- Chemical pollution: mineral substances, abiotic organic substances or biochemical substances introduced into the environment in abnormal quantities.

- Biological pollution: pathogenic microorganisms and populations of invasive exotic species artificially introduced by humans.

I.2.2 From an ecological point of view

From an ecological perspective, pollution can be classified according to the environment or biosphere compartment in which it is emitted and where it disturbs living communities: air and the atmosphere, water and the hydrosphere, and soil and the pedosphere. This classification is useful because the fate of a pollutant depends strongly on the compartment into which it is released.

I.2.3 From a toxicological point of view

The toxicological classification considers the medium or pathway through which pollutants contaminate organisms. In plants, contamination may occur by stomatal absorption, foliar absorption or root translocation. In animals, contamination may occur by inhalation in terrestrial species, transbranchial absorption in aquatic species, ingestion through the oral route, or transcutaneous penetration after contact of the skin or integument with the pollutant.

I.3.Current Causes of Pollution

I.3.1 Energy production

Energy production is one of the principal causes of pollution. The main air pollutants produced by combustion are sulfur dioxide (SO₂), nitrogen oxides (NO_x) and solid particles. These emissions contribute to acid rain, photochemical smog and particulate pollution.

I.3.2 Diversification of chemical pollutants and accumulation of waste

Since the end of the Second World War, organic chemistry has made available a very large number of new synthetic molecules. In the 1990s, about 120,000 molecules were estimated to be commercialized worldwide, with hundreds to thousands of new chemical substances entering the market every year. Among these products are plastics, detergents and many synthetic compounds.

One of the most serious aspects of global pollution by synthetic chemical substances is the increase in releases of persistent organic pollutants (POPs). These include polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, polychlorinated biphenyls (PCBs), organochlorine pesticides and dioxins. Their persistence, toxicity and capacity for bioaccumulation make them particularly problematic for ecosystems and human health.

I.3.3 Pollution due to intensive agriculture and livestock farming

A major cause of biosphere pollution is the development of intensive agriculture and livestock production. The use of synthetic pesticides such as insecticides, fungicides and herbicides, together with mineral fertilization using nitrogen, phosphate and potassium salts, has greatly increased crop yields. However, these products, along with animal excreta, can generate diffuse pollution of surface waters, coastal waters and groundwater.

I.4.Types of Pollution

I.4.1 Air pollution

Atmospheric pollution can be defined as the presence of impurities in the air that may cause significant discomfort to humans and damage to property. Air pollution is strongly influenced by climatic and meteorological parameters, particularly wind, temperature, humidity and atmospheric pressure.

I.4.2 Soil pollution

Soil pollution may be diffuse or local. It may originate from industrial activities or from agricultural practices, particularly the massive use of fertilizers and pesticides that infiltrate the soil. Agricultural pollution may affect human health by contaminating groundwater and by bioaccumulation in crops grown on polluted soils.

I.4.3. Water pollution

Water pollution may have several origins. Industrial agriculture can release substances contained in fertilizers, such as nitrate ions (NO₃⁻), and phytosanitary products that may pollute

groundwater and lead to the closure of drinking-water collection points. Industrial activities mainly release chemicals and hydrocarbons. Wastewater can provide a favourable medium for bacterial development and, if not properly treated, may become an important source of water pollution. Chemical oxygen demand (COD) and biological oxygen demand (BOD) are useful indicators for evaluating organic pollution in water.

I.4.4 Pollution according to polluting agents

- Transport-related pollution, including automobile pollution and pollution caused by aircraft.
- Radioactive pollution, involving radioactive products, for example phosphogypsum or nuclear accidents.
- Electromagnetic pollution, related to ionizing and non-ionizing radiation.
- Thermal pollution, caused by abnormal heat input into natural environments.
- Light pollution, defined as abnormal or disturbing nocturnal light and the ecological consequences of artificial lighting on fauna, flora, ecosystems and human health.
- Pollution linked to tourism, leisure activities, festivities, space debris, weapons and explosives.

I.5. Consequences of Pollution

Pollution may result in the greenhouse effect, acid rain and modification of the ozone layer. Its consequences are not limited to human health; they also affect biodiversity, ecosystem functioning and the services that ecosystems provide.

I.5.1 Consequences for health

Water pollution can have serious consequences for human health. Diseases caused by polluted water still kill many people each year, particularly in poor countries. These diseases may result from drinking contaminated water or from simple skin contact with polluted water. Air pollution may cause premature death and chronic health effects. Environmental contaminants, especially chemical products, may also contribute to some cancers.

I.5.2 Consequences for the environment

Chemical, physical and biological pollution modifies the environment. Depending on its nature, pollution affects the physiology and behaviour of exposed organisms or changes the characteristics of biotopes. Ultimately, it can modify the composition and structure of populations.

- Alteration of environments: chemical substances such as heavy metals and endocrine disruptors, as well as physical effects such as heat, light and radioactivity, may weaken organisms and reduce their reproductive capacity.
- Modification of species presence: changes in environmental conditions can cause the local disappearance of certain species and the development of others. The introduction of invasive species increases these imbalances.
- Loss of biodiversity and impact on humans: ecosystem degradation often results in biodiversity loss and disturbance of ecological services, leading to a general deterioration of the living environment for organisms and human activities.

I.6. How to Fight Pollution

I.6.1 Recycling

Recycling is the reuse of materials after a first use. It is a waste-treatment process that allows materials from industrial and household waste to be reintroduced into the production cycle. A common example is the manufacture of new bottles from used glass bottles. Human-organized recycling must be distinguished from natural biogeochemical cycles.

Recycling has two major ecological consequences: it reduces the volume of waste and preserves natural resources by avoiding the extraction of new raw materials. There are three main families of recycling techniques: chemical recycling, mechanical recycling and organic recycling.

- Chemical recycling uses chemical reactions to treat waste and separate components.
- Mechanical recycling transforms waste using machines, for example by crushing, grinding or shredding.

- Organic recycling uses composting or fermentation to produce fertilizers or fuels such as biogas.

WASTE MANAGEMENT HIERARCHY

The preferred approach to manage waste
in order of environmental impact

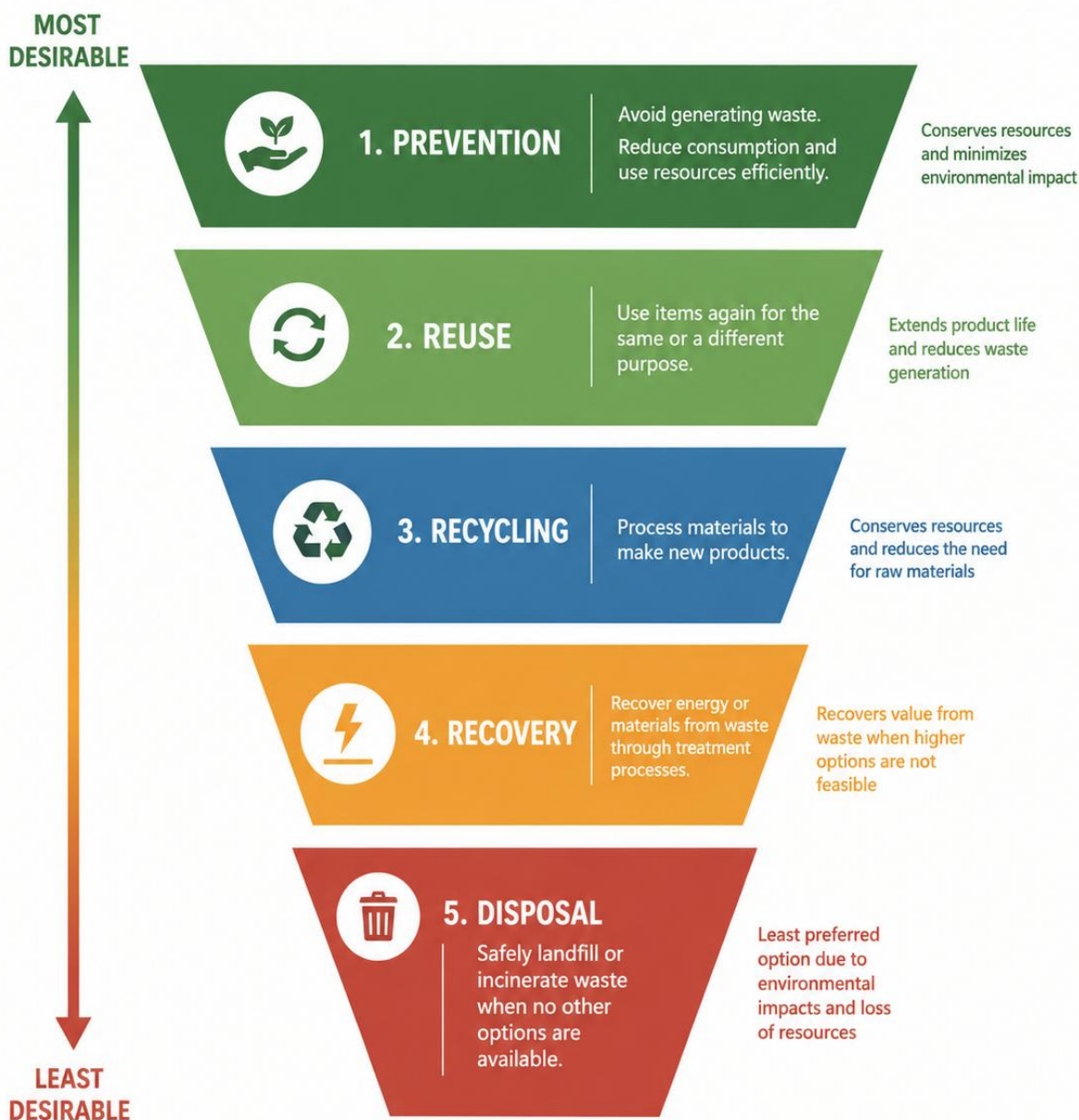


Figure I.2. Waste management hierarchy: prevention, reuse, recycling, recovery and disposal.(original)

I.6.2 Steps in recycling

1. Waste collection: recycling operations begin with collection. Non-recyclable waste is incinerated or buried in controlled landfill sites, while recyclable waste is directed toward transformation.
2. Transformation: after sorting, waste is sent to factories where it enters specific transformation chains and comes out as material ready for use.
3. Marketing and consumption: recycled products are used to generate energy or to manufacture new products, which may later be collected and recycled again.

I.6.3 Water treatment

Water recycling first uses classical treatment methods. Water passes through screens that retain large impurities, then through basins where fats and floating materials are removed. It is then aerated so that microorganisms can degrade organic matter, settled in basins, filtered through sand beds and finally disinfected using chlorine or ultraviolet radiation to eliminate infectious germs. Additional treatments are applied according to the desired water quality.

I.6.4 Renewable energies

Renewable energies are energy sources other than hydrocarbons, coal and nuclear energy. They come from natural phenomena and are often called clean or green energies. They mainly originate from solar radiation, the water cycle, winds, the internal heat of the Earth, and the Earth-Moon system. Solar energy, hydropower, wind energy, wood combustion under sustainable forest management, geothermal energy and tidal energy are important examples.

I.6.5 Responsible behaviour

Protecting nature and avoiding environmental degradation also depend on responsible daily behaviour: buying recycled paper, taking showers rather than baths, reducing heating, repairing objects, thinking before throwing items away, donating reusable objects, using low-consumption

bulbs, avoiding waste, sorting waste, choosing walking or public transport and building homes in an ecological manner.

CHAPTER 2

Chapter 2: Mechanisms of Dispersion and Circulation of Polluting Substances in the Biosphere

Polluting substances released into the environment rarely remain confined to the place where they are emitted. Once introduced into the biosphere, they can be transported, transformed, accumulated, diluted, deposited, degraded, or transferred from one environmental compartment to another. These compartments include the atmosphere, hydrosphere, lithosphere, pedosphere, and biosphere. The study of pollutant dispersion and circulation is therefore essential for understanding environmental contamination, ecological risk, and the long-term consequences of human activities.

The movement of pollutants depends on several interacting factors. First, the intrinsic physicochemical properties of the pollutant determine whether it will dissolve in water, evaporate into the atmosphere, adsorb onto soil particles, accumulate in organisms, or persist for long periods. Second, environmental conditions such as temperature, pH, wind, rainfall, soil texture, organic matter content, water flow, and biological activity influence the fate of pollutants. Finally, ecological processes such as uptake by plants, ingestion by animals, microbial degradation, and movement through food chains contribute to the redistribution of contaminants within ecosystems.

Pollutants may circulate locally, regionally, or globally. A pollutant emitted from an industrial chimney may affect the surrounding urban area, but if it is sufficiently persistent and mobile, it can also be transported over hundreds or thousands of kilometres. Similarly, a pesticide applied to agricultural soil may remain in the upper soil layer, leach toward groundwater, be transported by runoff into rivers, volatilize into the atmosphere, or enter plants and animals. Understanding these mechanisms allows ecologists and environmental scientists to predict pollution pathways, identify vulnerable ecosystems, and propose appropriate prevention and remediation strategies.

II.1. Physical Properties

The dispersion, mobility, persistence, and toxicity of pollutants depend strongly on their physical and chemical properties. These properties control the way pollutants behave after their release into the environment. Some pollutants remain close to their source, whereas others can move easily through air, water, soil, and living organisms. The most important properties include water

solubility, vapour pressure, volatility, persistence, degradation rate, half-life, density, particle size, adsorption capacity, and affinity for organic matter or lipids.

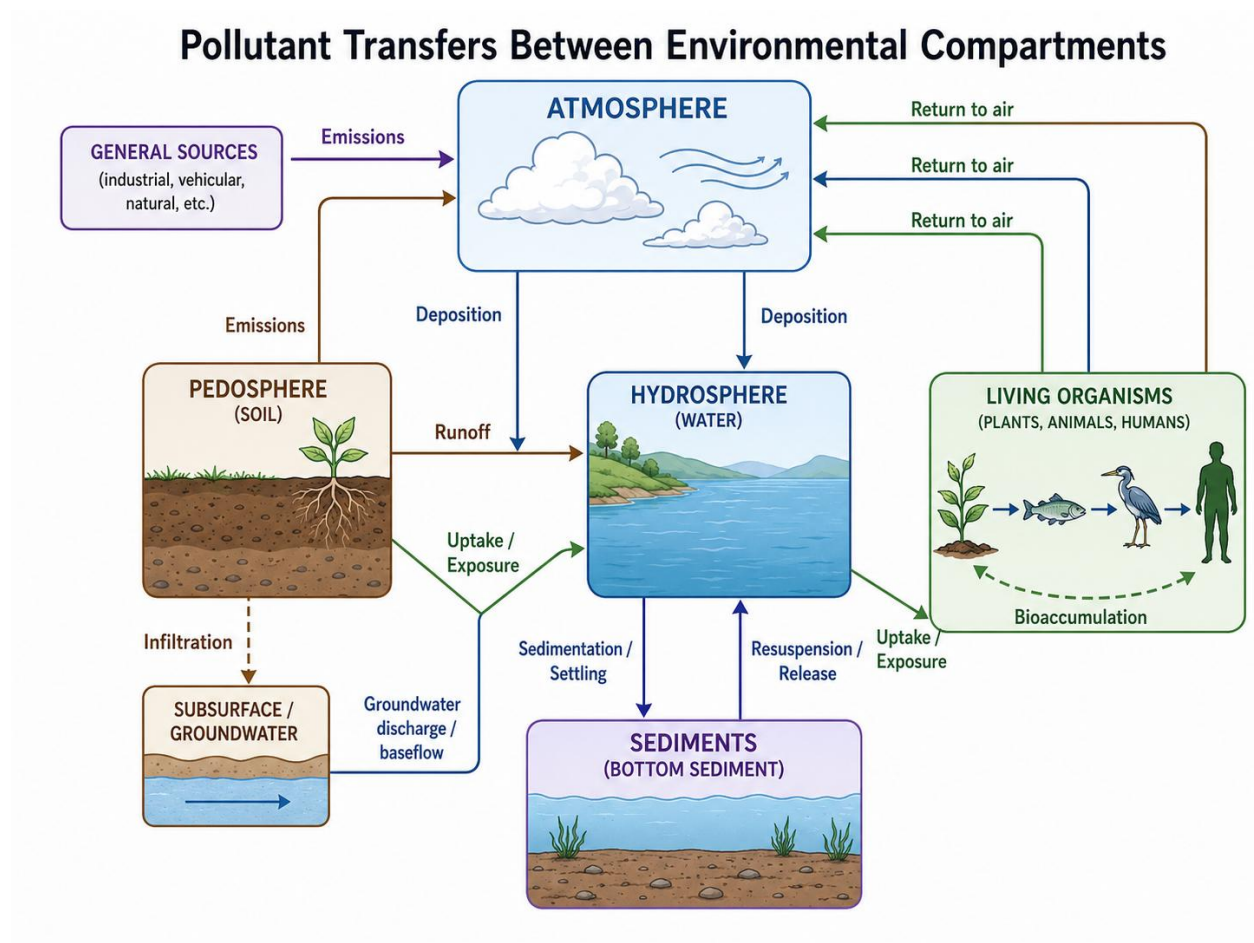


Figure II.1. Pollutant transfers between environmental compartments of the biosphere.(original)

II.1.1. Water Solubility

Water solubility is the ability of a substance to dissolve in water. It is generally expressed in milligrams per litre (mg/L), often at a reference temperature of 20°C. This property is very important because water is one of the main transport media in the biosphere. Rainwater, rivers, lakes, groundwater, soil solution, and marine systems can all transport dissolved pollutants.

Highly soluble pollutants are generally more mobile in aquatic environments. They can be easily leached from soil into groundwater or transported by surface runoff into rivers and lakes. For example, nitrate ions derived from nitrogen fertilizers are highly soluble. As a result, they can

move rapidly through the soil profile and contaminate groundwater. This is a major environmental problem in agricultural regions.

In contrast, poorly soluble pollutants tend to remain associated with solid particles, sediments, soil organic matter, or biological tissues. Many hydrophobic organic pollutants, such as some pesticides, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls, have low water solubility. Instead of remaining dissolved in water, they bind to suspended particles or sediments and may persist for long periods in aquatic ecosystems.

Solubility is also affected by environmental conditions. Temperature, pH, salinity, and the presence of dissolved organic matter can modify the solubility of pollutants. For example, some metals become more soluble and more toxic under acidic conditions, which explains why acidification can increase metal mobility in soils and aquatic systems.

II.1.2. Vapour Pressure and Volatility

Vapour pressure is the pressure exerted by the vapour of a substance when it is in equilibrium with its liquid or solid phase at a given temperature. It indicates the tendency of a compound to evaporate. A substance with high vapour pressure evaporates easily and can enter the atmosphere rapidly. A substance with low vapour pressure is less volatile and tends to remain in soil, water, or sediments.

Volatility is important for understanding air pollution and the atmospheric transport of contaminants. Volatile organic compounds, solvents, fuels, and some pesticides may evaporate after their release and become atmospheric pollutants. Once in the air, they may be transported by winds, transformed by sunlight, or participate in the formation of secondary pollutants such as tropospheric ozone and photochemical smog.

Temperature strongly influences vapour pressure. When temperature increases, the vapour pressure of a liquid generally increases, leading to greater evaporation. This explains why pesticide volatilization, solvent evaporation, and hydrocarbon emissions are often more intense during warm periods.

Vapour pressure can be approximately calculated using relationships derived from thermodynamic equations such as the Clapeyron equation. For water, commonly used values

include a molar mass of 0.018 kg/mol, a latent heat of vaporization of 2.26×10^6 J/kg, a reference pressure of 1013 mbar, and a boiling temperature of 373 K. Although such calculations are more frequently used in physical chemistry, they are useful in environmental sciences because they help estimate the tendency of substances to pass from liquid or solid phases into the atmosphere.

II.1.3. Persistence and Remanence

Persistence, also called remanence, refers to the ability of a pollutant to remain in the environment without being rapidly degraded, transformed, or eliminated. Persistent pollutants are particularly dangerous because they can accumulate over time and cause long-term ecological effects even when emissions are relatively low.

A persistent pollutant may remain in soil, water, sediment, or living organisms for months, years, or even decades. Examples include certain organochlorine pesticides, polychlorinated biphenyls, dioxins, some heavy metals, and radionuclides. Unlike many organic substances, metals do not degrade into harmless compounds. They may change chemical form, but the element itself remains present in the environment.

Persistence depends on both the chemical structure of the pollutant and environmental conditions. Molecules with stable chemical bonds, low biodegradability, high hydrophobicity, or strong adsorption to soil particles tend to persist longer. Cold temperatures, lack of oxygen, low microbial activity, and low sunlight penetration can also slow degradation.

Persistent pollutants are important from an ecological point of view because they may remain available for uptake by organisms, accumulate in food chains, and cause delayed effects. Even if emissions stop, the pollutant may continue to affect ecosystems for a long period.

II.1.4. Degradation Rate and Half-Life

The degradation rate describes how quickly a pollutant is broken down or transformed in the environment. Degradation can occur through physical, chemical, or biological processes. Physical processes include dilution, volatilization, and sedimentation. Chemical processes include hydrolysis, oxidation, reduction, and photolysis. Biological degradation is mainly carried out by microorganisms such as bacteria and fungi.

The half-life, also known as DT50, is the time required for 50% of the initial amount of a pollutant to disappear, either through degradation, transformation, or removal. A short half-life indicates that the pollutant is rapidly eliminated, while a long half-life indicates persistence.

For example, a pesticide with a half-life of a few days will usually have a limited period of activity in the environment. However, a pesticide with a half-life of several months may remain in soil long after application and may affect non-target organisms. In aquatic ecosystems, a long half-life may increase the risk of chronic exposure for fish, invertebrates, algae, and microorganisms.

It is important to note that disappearance does not always mean detoxification. Sometimes a pollutant is transformed into another compound that may be equally toxic or even more toxic than the original substance. For example, some pesticides produce degradation products that remain biologically active.

II.1.5. Adsorption and Partitioning

Adsorption is the process by which pollutants attach to the surface of solid particles such as clay minerals, organic matter, sediments, and suspended particles. This process plays a major role in soils and aquatic systems. Pollutants that adsorb strongly are less mobile in water but may accumulate in sediments or soils.

Partitioning refers to the distribution of a pollutant between different environmental phases, such as air, water, soil, sediment, and biological tissues. A pollutant may be partly dissolved in water, partly adsorbed to particles, and partly accumulated in organisms. This distribution depends on properties such as solubility, vapour pressure, hydrophobicity, and affinity for organic carbon.

Hydrophobic pollutants tend to bind strongly to organic matter and lipids. This increases their potential for bioaccumulation. In contrast, hydrophilic pollutants are more likely to remain dissolved in water and move through hydrological pathways.

II.2. Lifetime of Substances

Each pollutant has a specific lifetime in the environment. The lifetime is the period during which a pollutant remains present before being removed, degraded, transformed, or deposited. In

atmospheric chemistry, the lifetime is often defined as the time after which the quantity of a pollutant is divided by the mathematical constant e , approximately 2.72. The longer the lifetime, the greater the potential for long-distance transport and accumulation.

Pollutants with short lifetimes generally affect areas close to their emission sources. For example, sulfur dioxide may be removed from the atmosphere within a few days by oxidation and precipitation. Pollutants with longer lifetimes can be transported over regional, continental, or global scales. Carbon monoxide, methane, some halogenated compounds, and persistent organic pollutants can travel far from their sources.

The lifetime of a pollutant depends on several factors, including chemical reactivity, atmospheric conditions, sunlight intensity, precipitation, temperature, and the presence of other reactive substances. In the atmosphere, pollutants may react with hydroxyl radicals, ozone, nitrate radicals, or other oxidants. In water and soil, they may be degraded by microorganisms or transformed by chemical reactions.

The concept of lifetime is closely linked to the concept of accumulation. If a pollutant is emitted continuously and its lifetime is long, its concentration may increase over time. This is particularly important for greenhouse gases and persistent organic pollutants.

II.2.1. Atmospheric Mixing Time

The mixing time is the period required for a substance to become homogeneously distributed over part or all of the atmosphere. Mixing is controlled by wind, turbulence, convection, and large-scale atmospheric circulation.

For distribution within one hemisphere, the mixing time is generally about one to two months. For interhemispheric mixing, it may take one to two years. This difference is due to the structure of global atmospheric circulation and the limited exchange between the northern and southern hemispheres.

Methane is a good example of a pollutant with a relatively long atmospheric lifetime. Although methane emissions are concentrated in specific regions, such as wetlands, rice fields, livestock areas, landfills, and fossil fuel extraction zones, methane becomes relatively well mixed in the

global atmosphere. This explains why methane contributes to global climate change rather than only local pollution.

II.2.2. Removal of Pollutants from the Atmosphere

Pollutants can disappear from the atmosphere through several mechanisms. The first mechanism is chemical transformation. A pollutant may react with other atmospheric compounds and form a new substance. For example, sulfur dioxide can be oxidized to sulfate, and nitrogen oxides can contribute to nitric acid formation.

The second mechanism is wet deposition, also called washout or rainout. In this process, pollutants are captured by water droplets and removed from the atmosphere by rain, snow, or fog. Wet deposition is an important pathway for acid rain formation and for the transfer of atmospheric pollutants to soils and aquatic systems.

The third mechanism is dry deposition. Pollutants may settle directly onto surfaces such as vegetation, soil, buildings, or water bodies. Particles, gases, and aerosols may be deposited by gravity, turbulence, or contact with surfaces.

The fourth mechanism is gravitational settling, which mainly affects larger particles. Heavy particles fall more rapidly than fine particles. Fine particles can remain suspended for longer periods and travel greater distances.

II.2.3. Approximate Atmospheric Lifetimes of Some Pollutants

Pollutant	Approximate atmospheric lifetime	Environmental significance
Nitrogen oxides (NO_x)	About 15 days	Contribute to photochemical smog, ozone formation, and acid deposition
Sulfur dioxide (SO₂)	About 5 days	Precursor of sulfuric acid and sulfate particles; contributes to acid rain
Fine particles	Several weeks	Can be transported over long distances and affect health, visibility, and climate
Volatile organic compounds (VOCs)	0.5 to 60 days	Participate in ozone and secondary organic aerosol formation
Carbon monoxide (CO)	About 2 months	Influences atmospheric oxidation capacity and can be transported regionally
Methane (CH₄)	Several years	Well mixed globally and contributes to greenhouse effect
Some CFCs	Several decades	Reach the stratosphere and contribute to ozone layer depletion

The lifetime of pollutants is therefore a key parameter for environmental monitoring, atmospheric modelling, and pollution control strategies.

II.3. Biogeochemical Processes

Biogeochemical processes describe the circulation and transformation of substances through biological, geological, chemical, and physical pathways. Pollutants released into the biosphere are affected by these processes in the same way as natural elements, but their effects may be harmful when their concentrations exceed ecological tolerance thresholds.

A pollutant may move from the atmosphere to soil through deposition, from soil to water through leaching and runoff, from water to sediments through sedimentation, and from sediments to organisms through ingestion or absorption. It may also be transformed chemically or biologically at each stage. Therefore, pollution is not a static phenomenon. It is dynamic and depends on the continuous exchange between environmental compartments.

The main pathways of pollutant circulation include atmospheric circulation, hydrospheric movement, soil transfer, biological uptake, accumulation, and trophic transfer.

II.3.1. Atmospheric Circulation

Atmospheric circulation is one of the most important mechanisms of pollutant dispersion. The atmosphere can transport gaseous pollutants, aerosols, dust particles, smoke, volatile organic compounds, and fine particulate matter. Because air masses move continuously, atmospheric pollution may spread rapidly from emission sources to distant regions.

The troposphere is the most important atmospheric layer for pollutant dispersion because it contains most weather phenomena, including winds, clouds, precipitation, turbulence, and convection. Pollutants emitted at ground level, such as vehicle exhaust gases, industrial emissions, and domestic heating fumes, are first dispersed in the lower troposphere. Their concentration depends on emission intensity, wind speed, atmospheric stability, topography, and temperature inversions.

When wind speeds are high, pollutants are diluted and transported away from the emission source. When winds are weak, pollutants may accumulate near the ground, especially in urban and industrial areas. Atmospheric stability also plays an important role. Under stable conditions, vertical mixing is limited and pollutants remain concentrated close to the surface. Under unstable conditions, warm air rises and carries pollutants upward, favouring dilution.

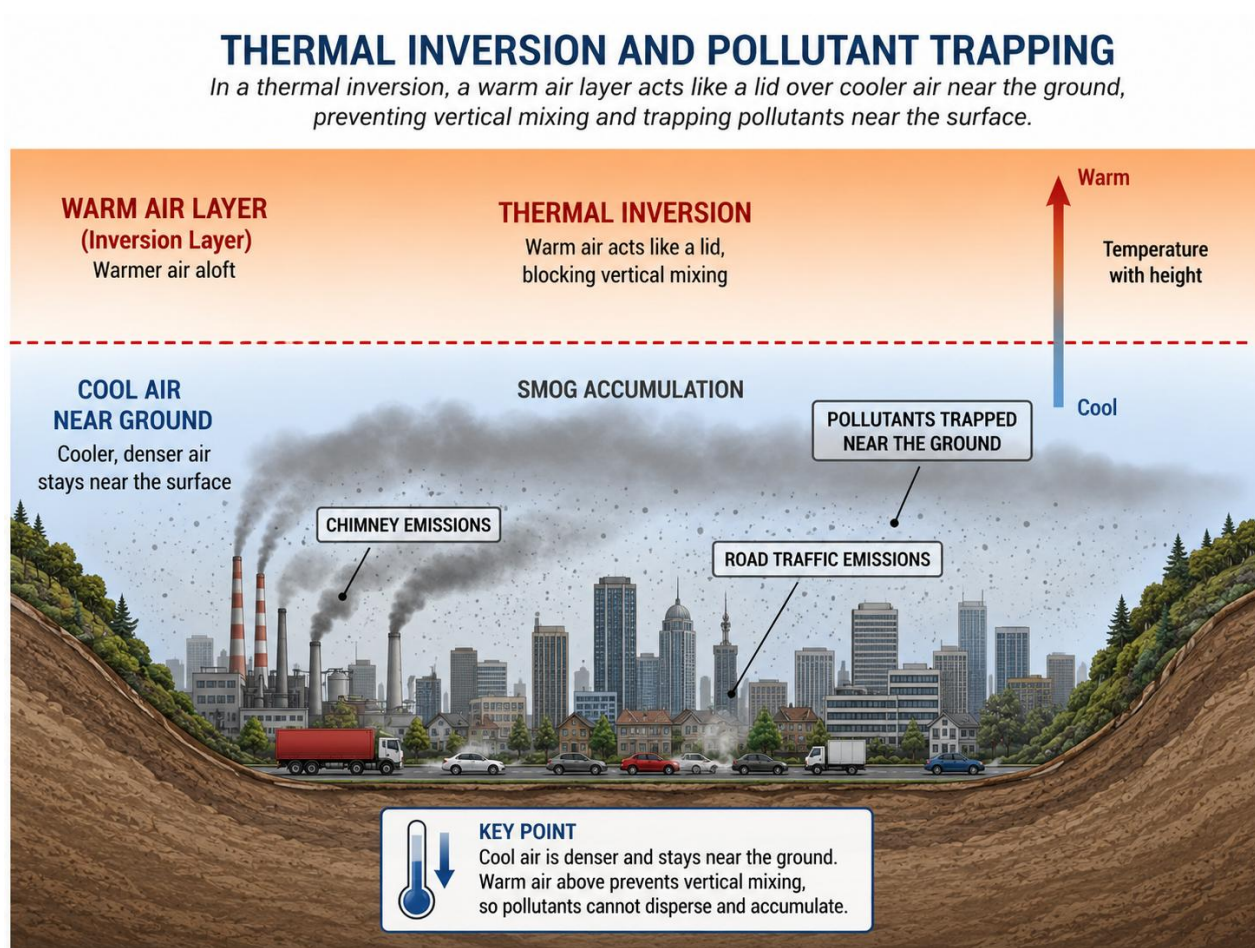


Figure II.2. Thermal inversion and trapping of atmospheric pollutants near the ground.(original)

II.3.1.1. Horizontal Circulation

Horizontal circulation refers to the transport of pollutants by winds over the Earth's surface. Wind direction and wind speed determine the trajectory and distance of pollutant movement. Pollutants emitted in one region may be transported to another region where they can cause ecological and health impacts.

In Western Europe, for example, westerly winds may transport pollutants toward the east. Sulfur oxides and nitrogen oxides emitted by industrialized regions can be transported over long distances and contribute to acid deposition in areas far from the original source. Scandinavian lakes have historically been affected by acidifying pollutants transported from industrial regions of Western and Central Europe.

In West Africa, the north-easterly trade wind known as the Harmattan transports Saharan dust toward southern regions, especially between December and February. This dust may contain mineral particles, organic matter, microorganisms, and sometimes pathogenic agents. The Harmattan illustrates how natural atmospheric circulation can transport particles over large distances and influence air quality, visibility, respiratory health, and ecosystem functioning.

Horizontal circulation also explains the global distribution of some pollutants. Persistent organic pollutants and mercury, for example, can be transported from industrial regions to remote areas such as mountain ecosystems, polar regions, and oceans. This phenomenon shows that pollution is not only a local issue but also a global ecological problem.

II.3.1.2. Vertical Circulation

Vertical circulation refers to the upward or downward movement of air masses. It is mainly controlled by temperature differences, atmospheric instability, convection, and turbulence. When the ground is heated, the air near the surface becomes warmer and less dense. It rises and can transport pollutants to higher altitudes.

During unstable atmospheric conditions, ascending air currents may carry pollutants to great heights. In strong convection systems, some pollutants can reach the upper troposphere. Once at higher altitudes, they may be transported horizontally over long distances. The combination of vertical and horizontal circulation therefore increases the spatial scale of pollution.

Vertical movement also plays a role in the exchange of pollutants between atmospheric layers. However, dispersion is generally slower in the stratosphere because wind speeds and mixing processes differ from those in the troposphere. Pollutants that reach the stratosphere may remain there for long periods. This is particularly important for chlorofluorocarbons, which are stable enough to reach the stratosphere, where they contribute to ozone layer depletion.

Nevertheless, pollutants do not remain indefinitely in the atmosphere. They may return to the Earth's surface through dry deposition, wet deposition, gravitational settling, or chemical transformation.

II.3.2. Movements of the Hydrosphere

The hydrosphere includes all water reservoirs on Earth, such as oceans, seas, rivers, lakes, groundwater, glaciers, soil water, and atmospheric water vapour. Water is a major vector for pollutant transport because it can dissolve, suspend, carry, dilute, and redistribute contaminants.

Pollutants enter the hydrosphere through different pathways. Industrial wastewater, domestic sewage, agricultural runoff, atmospheric deposition, oil spills, mining drainage, and landfill leachate are major sources of water contamination. Once in aquatic systems, pollutants can be transported downstream, diluted, transformed, deposited in sediments, or taken up by organisms.

Surface runoff occurs when rainfall or irrigation water flows over the land surface and carries pollutants into rivers, lakes, and reservoirs. This process is particularly important in agricultural areas, where fertilizers, pesticides, animal waste, and soil particles can be washed into aquatic ecosystems.

Leaching occurs when water infiltrates through the soil and transports soluble pollutants downward toward groundwater. Highly soluble substances such as nitrates are especially vulnerable to leaching. Groundwater contamination is often difficult to detect and remediate because pollutants may move slowly but persist for long periods.

In rivers, pollutants are transported by water flow. Their concentration may decrease by dilution, but dilution does not eliminate pollution. In lakes and reservoirs, water movement is slower, which may favour sedimentation and accumulation. In marine environments, currents, tides, waves, and coastal circulation influence the distribution of pollutants such as hydrocarbons, plastics, nutrients, and heavy metals.

II.3.3. Transfer of Substances in Soil

Soil is a complex environmental compartment composed of mineral particles, organic matter, water, air, and living organisms. It acts both as a sink and a source of pollutants. Some pollutants are retained in soil, while others are transferred to water, plants, or the atmosphere.

The behaviour of pollutants in soil depends on soil texture, structure, pH, organic matter content, clay content, moisture, microbial activity, and redox conditions. Clay-rich soils and soils rich in organic matter generally have a higher capacity to retain pollutants. Sandy soils, in contrast, are more permeable and allow faster leaching.

Pollutants may be retained in soil through adsorption, precipitation, complexation, or incorporation into organic matter. Heavy metals, for example, may bind to clay minerals, iron and manganese oxides, or organic matter. However, changes in pH or redox conditions can remobilize these metals and increase their bioavailability.

Organic pollutants may degrade in soil through microbial activity. Microorganisms can use some organic compounds as carbon or energy sources. However, degradation depends on the chemical structure of the pollutant and environmental conditions. Some compounds are easily biodegradable, while others are resistant and persist for long periods.

Soil also plays a filtering role. It can reduce the movement of pollutants toward groundwater. However, when the retention capacity of soil is exceeded or when pollutants are highly soluble, contamination can spread beyond the soil and affect aquatic systems.

II.4. Accumulation

Accumulation refers to the progressive increase of pollutant concentration in an environmental compartment or organism over time. It occurs when the input of a pollutant exceeds its removal, degradation, dilution, or elimination. Accumulation can occur in air, water, soil, sediments, plants, animals, and humans.

In the atmosphere, accumulation may occur when pollutants have long lifetimes and are emitted continuously. Greenhouse gases such as carbon dioxide, methane, and nitrous oxide accumulate because their removal processes are slower than their emissions.

In soil, accumulation may result from repeated application of fertilizers, pesticides, sewage sludge, industrial dust, or contaminated irrigation water. Heavy metals can accumulate in agricultural soils because they do not degrade. Over time, they may reach concentrations harmful to microorganisms, plants, animals, and humans.

In aquatic systems, sediments are important accumulation zones. Hydrophobic organic pollutants and metals often bind to particles and settle at the bottom of rivers, lakes, and oceans. Sediments may store pollutants for long periods, but they can also become secondary sources of contamination when disturbed by floods, dredging, storms, changes in pH, or oxygen depletion.

In organisms, accumulation occurs when uptake exceeds elimination. This is especially important for persistent and lipophilic substances. Accumulated pollutants may affect reproduction, growth, immunity, behaviour, and survival.

II.5. Distribution of Pollutants

The distribution of pollutants refers to their spatial and temporal presence in the environment. Pollutants are rarely distributed uniformly. Their distribution depends on emission sources, transport mechanisms, environmental conditions, chemical properties, and biological interactions.

Spatial distribution may be local, regional, or global. Local pollution is usually found near emission sources such as roads, factories, mines, farms, landfills, or wastewater outlets. Regional pollution may result from atmospheric transport, river networks, or agricultural runoff. Global pollution concerns substances that can travel long distances and persist in the environment, such as greenhouse gases, mercury, and persistent organic pollutants.

Temporal distribution also varies. Some pollutants are released continuously, such as domestic wastewater contaminants. Others are released seasonally, such as pesticides used during agricultural periods. Some pollution events are accidental and sudden, such as oil spills, industrial leaks, or nuclear accidents.

Environmental heterogeneity also influences pollutant distribution. In soil, pollutants may concentrate in the upper horizons or migrate downward. In aquatic systems, they may remain dissolved, adsorb onto particles, accumulate in sediments, or concentrate in organisms. In the atmosphere, pollutants may be diluted by wind or trapped by temperature inversions.

Mapping pollutant distribution is important for environmental monitoring. It helps identify pollution hotspots, vulnerable ecosystems, exposure pathways, and priority areas for remediation.

II.6. Transfer and Concentration of Pollutants in Biomass

Living organisms are not passive elements in polluted environments. They absorb, transform, store, eliminate, and transfer pollutants. The transfer of pollutants into biomass is one of the most

important ecological processes because it directly connects environmental contamination with biological effects.

Pollutants can enter organisms through different routes. Plants may absorb pollutants through roots from soil solution or through leaves from atmospheric deposition. Aquatic organisms may absorb dissolved pollutants through gills, skin, or ingestion of contaminated food. Terrestrial animals may be exposed through inhalation, ingestion, dermal contact, or consumption of contaminated prey.

Once inside the organism, pollutants may be metabolized, stored, excreted, or transferred to offspring. Some pollutants accumulate in specific organs. Heavy metals may concentrate in the liver, kidneys, bones, or nervous tissue. Lipophilic organic pollutants often accumulate in fatty tissues. Radionuclides may behave like essential elements and become incorporated into bones, muscles, or thyroid tissue depending on their chemical nature.

II.6.1. Dispersion by Living Organisms

Living organisms can contribute to pollutant dispersion by moving from one place to another. A contaminated animal may migrate to a different region and become prey for another organism. In this way, pollutants can move across ecosystems and food webs.

Birds, fish, mammals, insects, and humans can all participate in the biological transport of pollutants. Migratory species are particularly important because they connect distant habitats. For example, fish may accumulate contaminants in polluted waters and later be consumed by birds or humans far from the original pollution source.

This biological dispersion demonstrates that ecosystems are interconnected. Pollution in one biocenosis may affect another biocenosis through trophic relationships and organism movement.

II.6.2. Bioconcentration

Bioconcentration is the accumulation of a pollutant by an organism directly from the surrounding environment, without considering dietary intake. It is especially important in aquatic organisms that absorb dissolved pollutants from water through gills or body surfaces.

Many organisms can accumulate substances in their tissues at concentrations higher than those present in the surrounding medium. These substances may include natural elements, synthetic organic compounds, heavy metals, and radionuclides. Brown algae, such as kelps, can concentrate iodine at levels higher than those found in seawater. This capacity has historically been used for iodine extraction.

Organisms such as lichens, mosses, bivalves, annelids, and some algae are often used as bioindicators because they accumulate pollutants and reflect the contamination level of their environment. For example, lichens are useful indicators of atmospheric pollution because they absorb substances directly from the air and are sensitive to sulfur dioxide and heavy metals.

The bioconcentration factor is used to quantify this process. It is the ratio between the concentration of a pollutant in an organism and its concentration in the surrounding environment.

II.6.3. Bioaccumulation

Bioaccumulation is the progressive accumulation of pollutants in an organism from all exposure routes, including water, air, soil, and food. It occurs when the rate of pollutant uptake is higher than the rate of elimination.

Bioaccumulation is particularly important for persistent, poorly biodegradable, and fat-soluble substances. These compounds are difficult for organisms to eliminate and may remain stored in tissues for long periods. Heavy metals may accumulate in liver cells, while lipophilic molecules may accumulate in adipose tissue.

Bioaccumulation can cause chronic toxicity. Even when environmental concentrations are low, long-term exposure may lead to harmful internal concentrations. Effects may include reduced growth, reproductive failure, immune suppression, endocrine disruption, neurological damage, and increased mortality.

II.6.4. Biomagnification

Biomagnification is the increase in pollutant concentration from one trophic level to the next in a food chain. It occurs when predators consume contaminated prey and retain part of the pollutant in their tissues. As a result, top predators often have the highest concentrations.

A classic example is methylmercury in aquatic food chains. Methylmercury may be present at low concentrations in water, but it is absorbed by plankton, then transferred to small fish, large predatory fish, fish-eating birds, and humans. At each trophic level, the concentration increases.

Biomagnification creates a concentration pyramid that is opposite to the biomass pyramid. While biomass usually decreases from producers to top predators, pollutant concentration may increase. This makes top predators, including humans, particularly vulnerable to persistent pollutants.

The transfer factor is used to describe pollutant transfer between trophic levels. It is the ratio between the concentration of a pollutant in an organism at trophic level $n+1$ and its concentration in the organism at trophic level n .

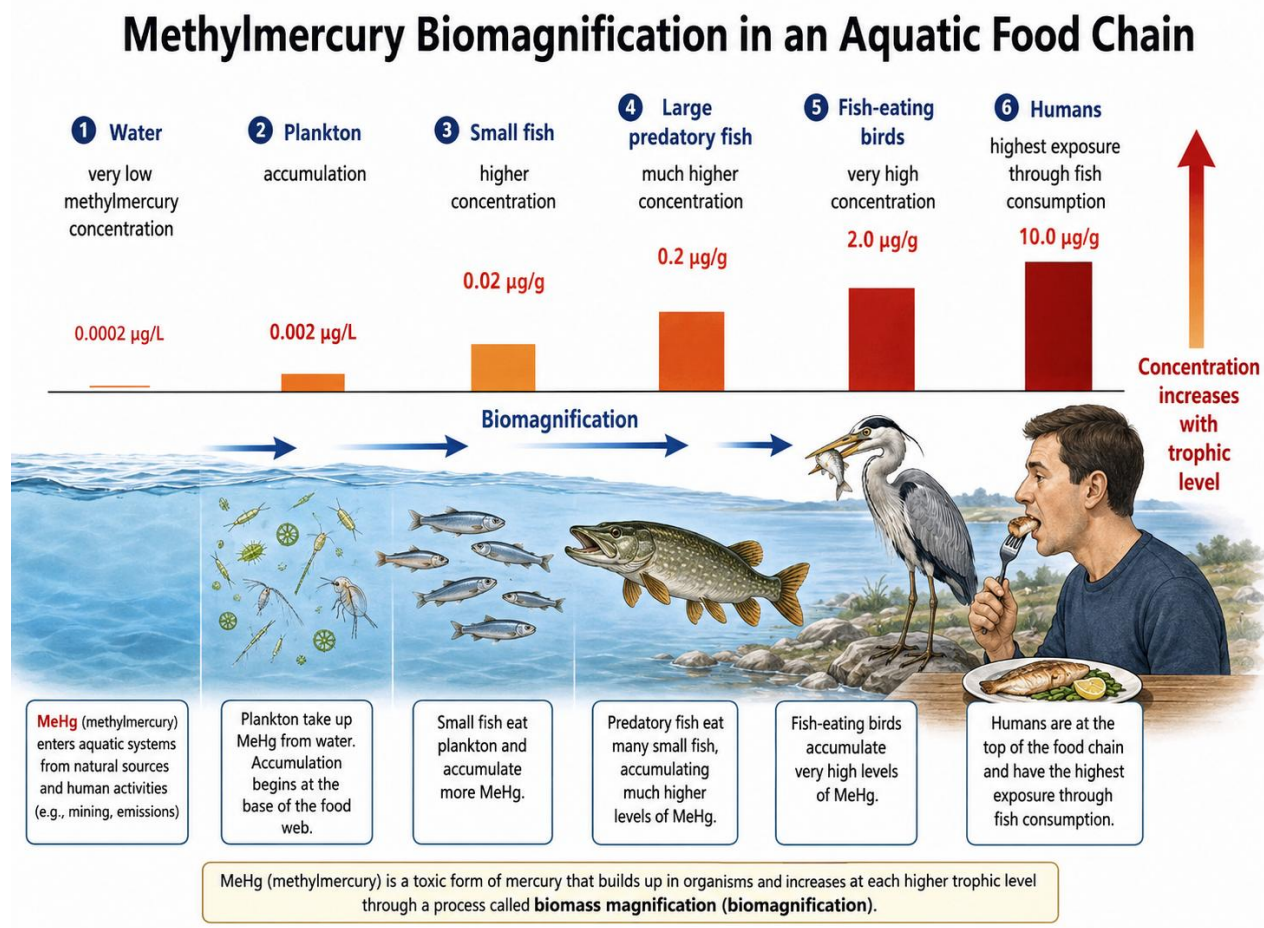


Figure II.3. Biomagnification of methylmercury in an aquatic food chain. (original)

II.7. Elimination, Decomposition, and Persistence

The environmental fate of pollutants depends not only on their dispersion and accumulation but also on their elimination and decomposition. Some pollutants are rapidly removed or degraded, while others persist for long periods and continue to affect ecosystems.

II.7.1. Elimination Processes

Elimination refers to the removal of pollutants from a given environmental compartment. In the atmosphere, pollutants may be eliminated by wet deposition, dry deposition, chemical reactions, or gravitational settling. In water, elimination may occur through dilution, sedimentation, volatilization, biodegradation, photodegradation, or adsorption onto suspended particles. In soil, pollutants may be eliminated by leaching, plant uptake, microbial degradation, volatilization, or erosion.

In living organisms, elimination may occur through excretion, metabolism, respiration, moulting, reproduction, or growth dilution. However, elimination is not always efficient. Persistent and lipophilic pollutants are often eliminated slowly, which favours bioaccumulation.

II.7.2. Decomposition and Degradation

Decomposition is the breakdown of pollutants into simpler compounds. It can be biological, chemical, or photochemical.

Biological degradation is mainly carried out by microorganisms. Bacteria and fungi can degrade many organic pollutants, especially when environmental conditions are favourable. Oxygen availability, temperature, moisture, nutrients, and pH influence microbial activity.

Chemical degradation includes hydrolysis, oxidation, reduction, and reactions with acids or bases. For example, some pesticides are hydrolysed in water, while other compounds are oxidized in the atmosphere.

Photodegradation occurs when sunlight breaks chemical bonds. This process is important at the surface of soils, waters, and atmospheric particles. However, pollutants buried in sediments or deep soil layers are less exposed to light and may persist longer.

II.7.3. Persistence and Ecological Risk

Persistence becomes an ecological problem when a pollutant remains active in the environment long enough to cause chronic exposure. Persistent pollutants may accumulate in soils, sediments, and organisms. They may also be transported far from their original source.

The most problematic persistent pollutants usually share several characteristics: chemical stability, low biodegradability, low water solubility, high affinity for organic matter or lipids, and resistance to environmental degradation. Persistent organic pollutants, heavy metals, and radionuclides are among the most concerning groups.

Metals and radionuclides require special attention because they cannot be destroyed like organic molecules. They may change chemical form, become immobilized, or be transferred between compartments, but the element itself remains present. Therefore, remediation often aims to reduce mobility, bioavailability, or exposure rather than eliminate the contaminant completely.

II.7.4. Importance for Environmental Management

Understanding elimination, decomposition, and persistence is essential for pollution management. Pollutants with short half-lives may require control near emission sources, while persistent pollutants require long-term monitoring and prevention. Remediation strategies must be adapted to the pollutant type and environmental conditions.

For biodegradable organic pollutants, biological treatment may be effective. For volatile pollutants, containment and air treatment may be necessary. For metals, immobilization, phytoremediation, soil washing, or excavation may be considered. For radionuclides, strict containment, monitoring, and controlled storage are essential.

In conclusion, the dispersion and circulation of pollutants in the biosphere result from complex interactions between physical properties, atmospheric and hydrological transport, soil processes, biological uptake, accumulation, and degradation. A pollutant released into one compartment may ultimately affect many others. Therefore, pollution must be studied using an integrated ecological approach that considers the whole biosphere rather than isolated environmental compartments.

CHAPTER 3

Chapter 3: Atmospheric Pollution

Atmospheric pollution is one of the most important environmental problems affecting modern societies and natural ecosystems. It refers to the presence of harmful substances in the air at concentrations capable of causing negative effects on human health, animals, vegetation, materials, climate, and the general functioning of ecosystems. Air pollution may result from natural processes, such as volcanic eruptions, forest fires, dust storms, biological emissions, and sea spray, but in contemporary environmental science, it is mainly associated with human activities.

The atmosphere is a dynamic compartment of the biosphere. It is constantly affected by winds, temperature variations, humidity, pressure, solar radiation, and chemical reactions. Because of this dynamic nature, pollutants released into the air can be transported over short or long distances. Some pollutants affect only the area close to their emission source, while others can move over regional, continental, or even global scales. Atmospheric pollution is therefore not only a local urban problem but also a regional and planetary ecological issue.

Atmospheric pollution can be studied according to three major spatial scales. At the local scale, pollutants emitted by transport, domestic heating, industries, and waste burning directly affect the quality of air breathed by populations. At the regional scale, pollutants can be transported by winds and transformed into secondary pollutants such as acid rain or photochemical smog. At the global scale, long-lived pollutants such as greenhouse gases and chlorofluorocarbons contribute to climate change and the depletion of the stratospheric ozone layer.

III.1. Origin of the Main Atmospheric Pollutants

The main atmospheric pollutants originate from both natural and anthropogenic sources. Natural sources existed before human industrial development, but anthropogenic emissions have greatly increased the quantity and diversity of pollutants in the atmosphere. The most important human sources include fossil fuel combustion, industrial activities, transport, agriculture, waste treatment, domestic heating, solvent use, and chemical manufacturing.

III.1.1. Combustion of Fossil Fuels

The combustion of coal, petroleum products, and natural gas is one of the principal causes of atmospheric pollution. Fossil fuels are used for electricity production, industrial processes, heating, and transportation. Their combustion releases several pollutants, including carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen oxides, particulate matter, volatile organic compounds, and trace metals.

Sulfur dioxide is mainly produced when sulfur-containing fuels, such as coal and heavy fuel oil, are burned. Nitrogen oxides are formed during high-temperature combustion when nitrogen and oxygen from the air react. Carbon monoxide results from incomplete combustion, especially in poorly ventilated engines or inefficient combustion systems. Particles are released as soot, ash, smoke, or fine aerosols.

These pollutants have multiple environmental consequences. Sulfur dioxide and nitrogen oxides contribute to acid rain. Nitrogen oxides and volatile organic compounds participate in the formation of tropospheric ozone. Carbon dioxide contributes to the greenhouse effect. Particulate matter affects air quality, visibility, climate, and respiratory health.

III.1.2. Transport

Transport is a major source of air pollution, especially in urban areas. Road traffic emits carbon monoxide, nitrogen oxides, volatile organic compounds, benzene, particulate matter, and polycyclic aromatic hydrocarbons. Diesel engines are particularly important sources of fine particles and black carbon. Petrol engines emit volatile organic compounds and carbon monoxide, especially during incomplete combustion.

The intensity of traffic pollution depends on vehicle number, fuel quality, engine type, driving conditions, traffic congestion, and emission control technologies. In cities, pollutants from vehicles can accumulate near roads and affect pedestrians, residents, children, and workers exposed to traffic emissions.

Aircraft, ships, and trains also contribute to atmospheric pollution. Maritime transport emits sulfur oxides, nitrogen oxides, particulate matter, and heavy metals, especially when heavy fuel oils are used. Aviation contributes to nitrogen oxides, carbon dioxide, water vapour, and contrail formation in the upper troposphere.

III.1.3. Industrial Activities

Industrial activities release a wide variety of atmospheric pollutants depending on the type of production. Metallurgical industries emit metals such as lead, cadmium, mercury, nickel, chromium, arsenic, and zinc. Cement factories release dust, nitrogen oxides, sulfur dioxide, and carbon dioxide. Chemical industries may emit volatile organic compounds, solvents, acids, ammonia, chlorine compounds, and persistent organic pollutants.

Refineries and petrochemical industries are important sources of hydrocarbons, sulfur compounds, nitrogen oxides, and volatile organic compounds. Waste incineration may emit particles, metals, dioxins, furans, hydrochloric acid, and other toxic compounds if not properly controlled.

Industrial pollution can affect local air quality and also contribute to regional pollution when emissions are transported by winds. The ecological impact depends on emission intensity, pollutant toxicity, atmospheric conditions, and the vulnerability of surrounding ecosystems.

III.1.4. Agriculture and Livestock

Agriculture is also a source of atmospheric pollution. The use of nitrogen fertilizers leads to emissions of ammonia and nitrous oxide. Ammonia can react in the atmosphere with acidic compounds to form secondary particulate matter, especially ammonium sulfate and ammonium nitrate. Nitrous oxide is a powerful greenhouse gas.

Livestock production releases methane from enteric fermentation, especially in ruminants, and ammonia from animal waste. Manure storage and spreading may release ammonia, methane, nitrous oxide, and odorous compounds. Pesticide spraying can also introduce volatile or semi-volatile chemical compounds into the atmosphere.

Agricultural burning, including the burning of crop residues, produces smoke, carbon monoxide, carbon dioxide, particulate matter, nitrogen oxides, and organic compounds. These emissions can significantly degrade air quality, especially during dry seasons.

III.1.5. Domestic Sources and Waste

Domestic activities contribute to atmospheric pollution through heating, cooking, waste burning, use of solvents, cleaning products, paints, aerosols, and household chemicals. In some regions, the burning of wood, coal, or waste for heating and cooking produces high levels of indoor and outdoor pollution.

Open burning of waste is particularly harmful because it can release particles, dioxins, furans, heavy metals, hydrochloric acid, and other toxic substances. Poor waste management can therefore become an important source of local atmospheric contamination.

III.1.6. Natural Sources

Natural sources also contribute to the composition of the atmosphere. Volcanoes emit sulfur dioxide, carbon dioxide, ash, and various gases. Forest fires release smoke, particles, carbon monoxide, nitrogen oxides, and organic compounds. Dust storms transport mineral particles over long distances. Oceans emit sea salt aerosols and sulfur compounds. Vegetation emits biogenic volatile organic compounds such as terpenes and isoprene.

Natural emissions are part of Earth's biogeochemical cycles. However, they may become problematic when combined with anthropogenic pollution or when climate change increases the frequency and intensity of fires, droughts, and dust events.

III.2. Polluting Substances

Atmospheric pollutants are very diverse. They may be gases, liquids, solid particles, aerosols, metals, organic compounds, or radioactive substances. They can also be classified as primary or secondary pollutants.

Primary pollutants are emitted directly into the atmosphere from identifiable sources. Examples include sulfur dioxide, carbon monoxide, nitrogen oxides, particulate matter, volatile organic compounds, heavy metals, and some hydrocarbons.

Secondary pollutants are not emitted directly. They are formed in the atmosphere through chemical and photochemical reactions involving primary pollutants. Ozone, secondary aerosols, nitric acid, sulfuric acid, and some oxidized organic compounds are examples of secondary pollutants.

III.2.1. Different Types of Pollutants

Several pollutants are regulated and continuously monitored because of their importance for air quality and health. The main monitored pollutants include sulfur dioxide, carbon monoxide, nitrogen dioxide, ozone, particulate matter, benzene, and lead. Other substances are also monitored or regulated in many air quality programmes, including polycyclic aromatic hydrocarbons, cadmium, arsenic, nickel, and mercury.

Sulfur Dioxide: SO₂

Sulfur dioxide is mainly produced by the combustion of sulfur-containing fossil fuels, especially coal and heavy fuel oil. It is also emitted by some industrial processes, refineries, smelters, and volcanic activity. In the atmosphere, sulfur dioxide can be oxidized to sulfuric acid and sulfate particles. This process contributes to acid rain and fine particulate matter formation.

Sulfur dioxide irritates the respiratory system and can aggravate asthma and bronchitis. Ecologically, it can damage vegetation, acidify soils and water bodies, and contribute to forest decline.

Carbon Monoxide: CO

Carbon monoxide is a colourless and odourless gas produced by incomplete combustion. Major sources include vehicle engines, domestic heating, biomass burning, forest fires, and industrial combustion. In urban areas, road traffic is often the main source.

Carbon monoxide is toxic because it binds strongly to haemoglobin in the blood, reducing oxygen transport. In the atmosphere, it also influences atmospheric chemistry by reacting with hydroxyl radicals, thereby affecting the lifetime of methane and other gases.

Nitrogen Dioxide: NO₂

Nitrogen dioxide belongs to the group of nitrogen oxides. It is mainly emitted from combustion processes, especially vehicle engines, power plants, and industrial activities. Nitrogen dioxide is an important air pollutant because it contributes to respiratory irritation, acid rain, and the formation of tropospheric ozone and secondary particulate matter.

NO₂ is also a key indicator of traffic-related air pollution. High concentrations are often recorded near busy roads and urban centres.

Ozone: O₃

Ozone is a particular pollutant because its effects depend on its location in the atmosphere. In the stratosphere, ozone is beneficial because it absorbs harmful ultraviolet radiation. In the troposphere, however, ozone is a harmful secondary pollutant.

Tropospheric ozone forms when nitrogen oxides and volatile organic compounds react under sunlight. It is a major component of photochemical smog. Ozone irritates the respiratory system, reduces lung function, damages plant tissues, and decreases crop yields.

Particulate Matter: PM₁₀ and PM_{2.5}

Particulate matter refers to small solid or liquid particles suspended in the air. PM₁₀ includes particles with an aerodynamic diameter smaller than 10 micrometres, while PM_{2.5} includes particles smaller than 2.5 micrometres. Fine particles are especially dangerous because they can penetrate deep into the respiratory system.

Particles may be emitted directly from combustion, traffic, industry, construction, soil erosion, and natural dust. They may also form secondarily in the atmosphere from gases such as sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds.

Benzene: C₆H₆

Benzene is an aromatic volatile organic compound emitted by vehicle exhaust, fuel evaporation, industrial processes, petroleum refining, tobacco smoke, and solvent use. It is toxic and carcinogenic. Long-term exposure may affect blood formation and increase the risk of leukemia.

Lead: Pb

Lead is a toxic metal that can be emitted from industrial processes, metal production, waste incineration, and historically from leaded gasoline. Although the removal of lead from gasoline has reduced emissions in many countries, lead remains an important pollutant near industrial sources and contaminated sites.

Lead affects the nervous system, especially in children. It can also accumulate in soils and enter food chains.

Other Pollutants

Other important atmospheric pollutants include polycyclic aromatic hydrocarbons, cadmium, arsenic, nickel, and mercury. These substances are often associated with industrial emissions, combustion processes, waste incineration, metal processing, and fossil fuel use. Many of them are toxic, persistent, carcinogenic, or capable of bioaccumulation.

III.2.2. Organic Compounds

Organic compounds are carbon-containing substances that may be released into the atmosphere from natural and anthropogenic sources. In air pollution studies, special attention is given to volatile organic compounds and persistent organic pollutants because of their toxicity, reactivity, and role in atmospheric chemistry.

a. Volatile Organic Compounds

Volatile organic compounds are organic substances that can evaporate easily at normal environmental temperatures. They are emitted by fuels, solvents, paints, adhesives, industrial processes, vehicle exhaust, vegetation, and household products.

VOCs play an important role in the formation of tropospheric ozone and photochemical smog. In the presence of sunlight and nitrogen oxides, they undergo chemical reactions that generate oxidants harmful to humans, plants, and materials.

The main families of volatile organic compounds include:

Alkanes are saturated hydrocarbons. They are relatively abundant and include compounds such as propane and butane. They are emitted by fuels, natural gas, and petroleum products.

Alkenes contain double bonds and are generally more reactive than alkanes. Their reactivity allows them to participate actively in photochemical reactions.

Dienes and terpenes contain multiple double bonds. Terpenes may be emitted naturally by vegetation, especially forests, but they can react in the atmosphere to form secondary organic aerosols.

Mono- and polycyclic aromatic compounds include benzene, toluene, ethylbenzene, xylene, and polycyclic aromatic hydrocarbons. Many aromatic compounds are toxic, and some are carcinogenic.

Oxygenated compounds include aldehydes, ketones, esters, and alcohols. They may be emitted directly or formed secondarily by atmospheric oxidation reactions.

VOCs differ greatly in toxicity and reactivity. Some compounds are mainly important because they contribute to ozone formation, while others are directly harmful to human health.

b. Persistent Organic Pollutants

Persistent organic pollutants are organic compounds that resist degradation, remain in the environment for long periods, can be transported over long distances, accumulate in living organisms, and may cause toxic effects. They are often toxic even at low concentrations.

Many POPs are industrial residues or by-products. They may be mutagenic, carcinogenic, endocrine-disrupting, or toxic to reproduction. Because they are often lipophilic, they accumulate in fatty tissues and biomagnify through food chains.

Important examples include trichloroethylene, trichloroethane, tetrachloroethylene, dioxins, furans, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and hexachlorobenzene.

Dioxins and furans are often produced unintentionally during combustion processes, especially when chlorine-containing materials are burned under poor conditions. PCBs were used in electrical equipment and industrial applications but are now restricted or banned in many countries. PAHs are formed during incomplete combustion of organic matter, including fossil fuels, wood, coal, and waste.

The ecological risk of POPs is high because they can contaminate remote areas far from emission sources. They may be found in sediments, soils, wildlife, and human tissues. Their persistence makes prevention more effective than remediation.

III.2.3. Trace Metal Elements

Trace metal elements, often called heavy metals, are metallic or metalloid elements present at low concentrations in the environment but capable of producing toxic effects when their concentration increases. They may be emitted into the atmosphere as particles, vapours, or compounds attached to dust and aerosols.

Some trace metals are essential for living organisms at very low concentrations, such as copper, zinc, iron, and nickel. However, they can become toxic when concentrations exceed physiological needs. Other metals, such as lead, cadmium, and mercury, have no known biological benefit and are toxic even at low exposure levels.

Trace metals are not biodegradable. They may change chemical form, but the element itself persists in the environment. This makes them important long-term pollutants.

Mercury

Mercury is unique because it is the only metal that is liquid at room temperature. It is volatile and can easily combine with other compounds. Atmospheric mercury may be emitted by coal combustion, waste incineration, mining, metal processing, and natural processes such as volcanic activity.

Mercury can be transported over long distances in the atmosphere. Once deposited in aquatic environments, it can be transformed by microorganisms into methylmercury, a highly toxic organic form that bioaccumulates and biomagnifies in food chains. Predatory fish and fish-eating animals may contain high levels of methylmercury.

Mercury affects the nervous system and is particularly dangerous for developing organisms.

Lead

Lead is a major atmospheric pollutant historically associated with leaded gasoline. Although emissions from gasoline have decreased in many regions, lead may still be emitted by metal industries, battery recycling, waste incineration, mining, and contaminated dust.

Lead particles can be deposited on soils, vegetation, and water surfaces. Once deposited, lead can persist for long periods and may enter food chains. Human exposure can affect the nervous system, blood formation, kidneys, and child development.

Cadmium

Cadmium is mainly emitted by waste incineration, metallurgy, fossil fuel combustion, phosphate fertilizer production, and industrial processes. It can attach to fine particles and be transported in the atmosphere before deposition.

Cadmium accumulates in soils and can be taken up by plants. It may enter the food chain through cereals, vegetables, and animal products. Chronic exposure affects kidneys, bones, and other organs. From an ecological point of view, cadmium can disturb microbial activity, plant growth, and soil fertility.

Arsenic, Nickel, and Other Metals

Arsenic, nickel, chromium, copper, zinc, and other metals may be emitted by industrial activities, combustion, mining, smelting, and waste treatment. Their toxicity depends on their chemical form, concentration, exposure route, and environmental conditions.

In ecosystems, metal pollution can reduce biodiversity, inhibit microbial processes, affect plant growth, and contaminate aquatic and terrestrial food chains.

III.2.4. Particles

Particles are one of the most complex categories of air pollutants. They include a wide variety of solid and liquid substances suspended in the atmosphere. Their composition may include mineral dust, soot, organic carbon, elemental carbon, sulfates, nitrates, ammonium, metals, sea salt, biological particles, pollen, spores, and secondary organic compounds.

The impact of particles depends on their size, concentration, chemical composition, shape, and surface properties. Particle size is particularly important because it determines how long particles remain suspended in air, how far they travel, and where they deposit in the respiratory system.

Particles are usually classified according to their aerodynamic diameter:

Total suspended particulates, or TSP, represent the total mass of particles suspended in air.

PM10 refers to particles with an aerodynamic diameter smaller than 10 micrometres. These particles can enter the respiratory tract.

PM2.5 refers to fine particles with an aerodynamic diameter smaller than 2.5 micrometres. They can penetrate deep into the lungs and reach the alveolar region.

PM1.0 refers to particles with an aerodynamic diameter smaller than 1 micrometre. These particles remain suspended for long periods and may be transported over long distances.

Ultrafine particles have an aerodynamic diameter smaller than 0.1 micrometre. They are numerous in combustion emissions and may enter the bloodstream.

Nanoparticles are extremely small particles, often smaller than 0.05 or 0.03 micrometre. Their small size gives them a large surface area relative to their mass, which can increase their chemical reactivity.

Sources of Particles

Particles may be primary or secondary. Primary particles are emitted directly into the air. They come from vehicle exhaust, industrial chimneys, construction activities, soil erosion, mining, biomass burning, sea spray, and volcanic eruptions.

Secondary particles form in the atmosphere from gaseous precursors. Sulfur dioxide can form sulfate particles, nitrogen oxides can form nitrate particles, ammonia can form ammonium salts, and volatile organic compounds can form secondary organic aerosols.

Environmental and Health Importance of Particles

Particles reduce visibility, influence cloud formation, affect the radiation balance of the atmosphere, and can contribute to climate change. Some particles reflect sunlight and have a cooling effect, while black carbon absorbs radiation and contributes to warming.

Particles also affect ecosystems through deposition. When deposited on leaves, they may block stomata and reduce photosynthesis. When deposited on soil and water, they may introduce metals, nutrients, acids, and organic pollutants.

From a health point of view, fine and ultrafine particles are particularly dangerous because they can penetrate deeply into the respiratory system. They are associated with respiratory diseases, cardiovascular problems, inflammation, asthma aggravation, and premature mortality.

III.2.5. Chlorofluorocarbons

Chlorofluorocarbons, or CFCs, are synthetic compounds containing carbon, chlorine, and fluorine atoms. They are also known as Freons. They were widely used because they are non-flammable, chemically stable, non-corrosive, and relatively non-toxic at ground level. For several decades, they were used as refrigerants in refrigerators and air conditioners, as propellants in aerosol sprays, as foam-blowing agents, and as solvents for cleaning electronic components.

The same stability that made CFCs useful also made them environmentally dangerous. Because they are stable in the lower atmosphere, they can persist long enough to reach the stratosphere. In the stratosphere, ultraviolet radiation breaks them down and releases chlorine atoms. These chlorine atoms participate in catalytic reactions that destroy ozone molecules.

The destruction of stratospheric ozone reduces the ability of the ozone layer to absorb ultraviolet radiation. Increased ultraviolet radiation at the Earth's surface can affect human health, animals,

plants, and aquatic ecosystems. It may increase the risk of skin cancer, eye damage, immune system effects, and reduced productivity in sensitive organisms.

CFCs are also greenhouse gases. Although their concentrations are lower than carbon dioxide, their global warming potential is high. Their regulation has therefore been important for both ozone layer protection and climate protection.

III.3. Effects of the Different Substances

Atmospheric pollutants have multiple effects depending on their nature, concentration, exposure duration, and environmental conditions. Their impacts may concern human health, animals, plants, ecosystems, materials, visibility, climate, and atmospheric chemistry.

III.3.1. Effects on Human Health

Air pollution affects the respiratory, cardiovascular, nervous, immune, and reproductive systems. The most sensitive groups include children, elderly people, pregnant women, people with asthma or chronic respiratory diseases, people with cardiovascular diseases, and individuals living near major emission sources.

Short-term exposure to high pollution levels can cause irritation of the eyes, nose, and throat, coughing, breathing difficulties, asthma attacks, headaches, and increased hospital admissions. Pollution episodes are often associated with increased cardiovascular and respiratory events.

Long-term exposure is more serious because it can increase the risk of chronic bronchitis, reduced lung function, cardiovascular disease, stroke, lung cancer, and premature mortality. Fine particles, nitrogen dioxide, ozone, benzene, PAHs, and heavy metals are among the pollutants of greatest concern for chronic health effects.

Carbon monoxide reduces oxygen transport in the blood. Benzene is carcinogenic. Lead affects the nervous system, especially in children. Mercury affects neurological development. Cadmium affects kidneys and bones. Fine particles penetrate deep into the lungs and can contribute to systemic inflammation.

III.3.2. Effects on Vegetation

Vegetation is highly sensitive to atmospheric pollution. Pollutants can enter leaves through stomata, deposit on leaf surfaces, alter photosynthesis, damage tissues, and reduce growth. Ozone is one of the most harmful air pollutants for plants. It enters leaves through stomata and produces oxidative stress, which damages cell membranes and reduces photosynthetic capacity.

Sulfur dioxide and nitrogen oxides may cause leaf injury, chlorosis, necrosis, and growth reduction. Acid rain damages leaves, acidifies soils, leaches essential nutrients, and mobilizes toxic metals such as aluminium. Particulate matter can cover leaf surfaces, block stomata, reduce light absorption, and interfere with gas exchange.

Crop plants exposed to ozone and other pollutants may show reduced yield and quality. Forest trees may become more vulnerable to drought, pests, diseases, and nutrient imbalance.

III.3.3. Effects on Animals

Animals can be affected by air pollution through inhalation, ingestion of contaminated food, or exposure to polluted water and soil after atmospheric deposition. Respiratory irritation, reduced immune resistance, reproductive effects, and bioaccumulation of toxic substances may occur.

Wildlife may be exposed to persistent organic pollutants and heavy metals deposited from the atmosphere. These pollutants can accumulate in food webs and affect top predators. Birds, fish-eating mammals, and carnivores are particularly vulnerable to biomagnification.

III.3.4. Effects on Aquatic and Terrestrial Ecosystems

Atmospheric pollution affects ecosystems not only through direct exposure but also through deposition. Sulfur and nitrogen compounds deposited by rain or dry deposition can acidify soils and water bodies. Acidification reduces biodiversity, affects fish reproduction, damages aquatic invertebrates, and changes species composition.

Nitrogen deposition can also cause eutrophication in sensitive ecosystems. Excess nitrogen favours fast-growing species and may reduce plant diversity in grasslands, wetlands, and forests. In aquatic ecosystems, nitrogen enrichment can contribute to algal blooms and oxygen depletion.

Heavy metals and persistent organic pollutants deposited from the atmosphere can accumulate in soils, sediments, and organisms. They may affect microbial processes, nutrient cycling, decomposition, and food web structure.

III.3.5. Acid Rain

Acid rain results mainly from sulfur dioxide and nitrogen oxides. These gases react in the atmosphere to form sulfuric acid and nitric acid. They are then deposited by rain, snow, fog, or dry deposition.

Acid rain can acidify lakes and rivers, leading to fish mortality and loss of aquatic biodiversity. It can acidify soils, leach calcium, magnesium, and potassium, and mobilize aluminium, which is toxic to roots and aquatic organisms. It also damages buildings, monuments, metals, and cultural heritage materials.

Forests exposed to acid deposition may show leaf yellowing, reduced growth, root damage, nutrient deficiency, and increased sensitivity to stress.

Acid Rain Formation and Its Environmental Effects

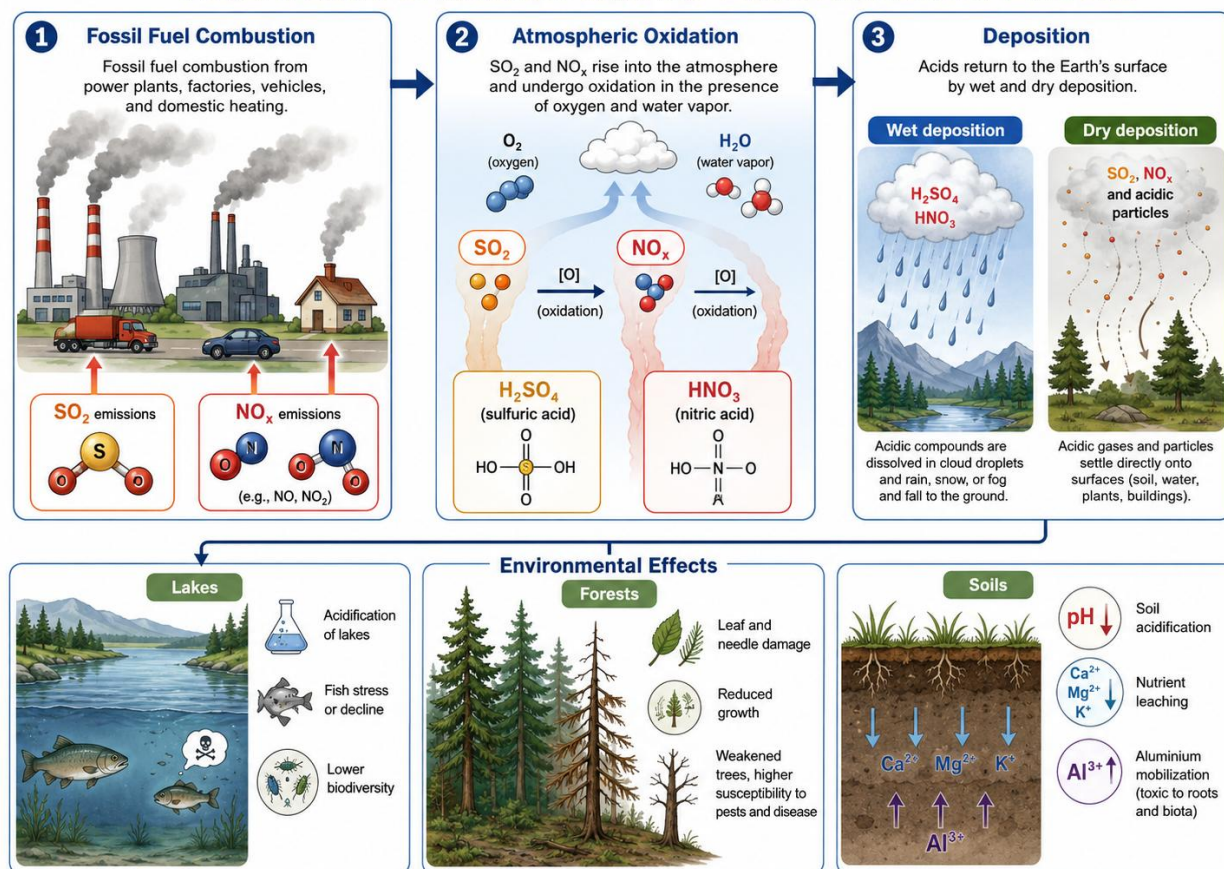


Figure III.1. Formation of acid rain and its environmental effects on lakes, forests and soils. (original)

III.3.6. Photochemical Smog and Tropospheric Ozone

Photochemical smog forms when nitrogen oxides and volatile organic compounds react under sunlight. It is common in urban and industrial areas, especially during warm and sunny weather. Tropospheric ozone is a major component of photochemical smog.

Photochemical smog causes eye irritation, respiratory problems, reduced visibility, and damage to vegetation. It is particularly harmful during pollution episodes because ozone concentrations can rise rapidly under favourable meteorological conditions.

III.3.7. Greenhouse Effect and Climate Change

Some atmospheric pollutants are greenhouse gases. Carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons absorb infrared radiation and contribute to the warming of the lower atmosphere.

The natural greenhouse effect is essential for life on Earth, but human activities have increased greenhouse gas concentrations, strengthening this effect and contributing to climate change. Climate change may alter precipitation patterns, increase heat waves, intensify droughts and floods, affect agricultural productivity, disturb ecosystems, and threaten biodiversity.

Air pollution and climate change are closely linked because many emission sources produce both air pollutants and greenhouse gases.

III.3.8. Ozone Layer Depletion

The stratospheric ozone layer protects life on Earth by absorbing a large part of harmful ultraviolet radiation. Chlorofluorocarbons and other halogenated compounds can reach the stratosphere and release chlorine or bromine atoms that destroy ozone molecules.

Ozone depletion increases ultraviolet radiation reaching the Earth's surface. This can increase skin cancer risk, eye diseases, immune system effects, and damage to plants, phytoplankton, and aquatic food webs.

III.3.9. Effects on Materials and Visibility

Air pollutants can damage buildings, monuments, metals, paints, rubber, textiles, and cultural heritage. Sulfur dioxide and acid rain corrode limestone, marble, and metals. Ozone can degrade rubber and some polymers. Particulate matter blackens building surfaces and reduces aesthetic value.

Particles and photochemical smog reduce atmospheric visibility by scattering and absorbing light. This is common in polluted urban areas and regions affected by dust, smoke, or industrial aerosols.

Conclusion

Atmospheric pollution is a complex environmental issue involving many sources, substances, transformations, and effects. The main pollutants include sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, particulate matter, benzene, lead, heavy metals, volatile organic compounds, persistent organic pollutants, and chlorofluorocarbons. These pollutants may be emitted directly or formed in the atmosphere through chemical reactions.

Their effects are observed at several levels: human health, vegetation, animals, aquatic ecosystems, soils, climate, the ozone layer, materials, and visibility. Because atmospheric pollution can move from local to global scales, its management requires continuous monitoring, emission reduction, cleaner technologies, sustainable transport, renewable energy, industrial control, and ecological awareness.

CHAPTER 4

Chapter 4: Soil Pollution

Soil is one of the most important natural resources of the biosphere. It is not only a physical support for vegetation, but also a living and dynamic system where mineral particles, organic matter, water, air, microorganisms, roots, and soil fauna interact continuously. Soil plays essential ecological functions: it supports plant growth, stores and recycles nutrients, regulates water infiltration and runoff, filters pollutants, participates in carbon storage, and provides habitat for a very large diversity of organisms.

Soil is also an interface between the atmosphere, hydrosphere, lithosphere, and biosphere. For this reason, it receives substances from many sources: atmospheric deposition, irrigation water, agricultural inputs, industrial emissions, waste disposal, urban runoff, and biological residues. Some of these substances are useful for soil fertility when present in appropriate quantities, but they become pollutants when they accumulate excessively or when they are toxic, persistent, or poorly degradable.

Soil pollution is a major environmental problem because contaminated soil can become both a reservoir and a secondary source of pollution. Pollutants stored in soil may remain for long periods, be transferred to groundwater, be absorbed by plants, enter food chains, affect soil organisms, or be transported by erosion and runoff toward aquatic ecosystems. Unlike air or surface water pollution, soil pollution is often less visible and may remain undetected for many years. However, its ecological and health consequences can be severe and long-lasting.

IV.1. Definition

Soil pollution can be defined as the introduction, accumulation, or presence of chemical, physical, or biological contaminants in soil at concentrations that alter its natural composition, disturb its ecological functions, reduce its fertility, or create risks for living organisms and human health.

A soil is considered polluted when the concentration of one or several substances exceeds the natural background level or an acceptable environmental threshold. These substances may be organic, mineral, biological, or radioactive. Soil pollution may result from direct contamination,

such as pesticide application or industrial waste dumping, or indirect contamination, such as atmospheric deposition of pollutants emitted by factories, vehicles, or waste incineration.

Soil pollution affects the physical, chemical, and biological quality of soil. Physical degradation may include compaction, sealing, erosion, or accumulation of solid waste. Chemical pollution may involve heavy metals, pesticides, hydrocarbons, nitrates, phosphates, solvents, salts, acids, or persistent organic pollutants. Biological pollution may involve pathogenic microorganisms introduced through untreated wastewater, manure, sewage sludge, or animal waste.

The seriousness of soil pollution depends on several factors, including the nature of the pollutant, its concentration, persistence, mobility, toxicity, bioavailability, and interaction with soil components. Some pollutants are easily degraded by microorganisms, while others persist for decades. Some substances remain fixed in soil particles, while others migrate toward groundwater or are absorbed by plants.

Soil pollution can be classified according to different criteria. According to its origin, it may be agricultural, industrial, urban, domestic, mining, atmospheric, or accidental. According to its spatial distribution, it may be local, when contamination is concentrated around a specific source, or diffuse, when pollutants are spread over large areas. According to the pollutant type, it may be organic, inorganic, biological, radioactive, or mixed.

The ecological consequences of soil pollution are numerous. It can reduce microbial activity, disturb nutrient cycles, decrease soil fertility, inhibit plant growth, contaminate crops, reduce biodiversity, and alter ecosystem productivity. From a health perspective, polluted soils may expose humans to contaminants through direct contact, inhalation of dust, consumption of contaminated food, or drinking polluted groundwater.

IV.2. Forms and Consequences of Soil Pollution Caused by Modern Agriculture

Modern agriculture has greatly increased crop production through the use of fertilizers, pesticides, irrigation, mechanization, and intensive livestock systems. However, when agricultural practices are poorly controlled or excessive, they can become an important source of soil pollution. Agricultural pollution is often diffuse because it affects large cultivated areas rather than a single point source.

The main agricultural sources of soil pollution include mineral fertilizers, organic manure, pesticides, herbicides, fungicides, insecticides, irrigation water of poor quality, plastic residues, veterinary products, and animal waste. These inputs may modify soil chemistry, increase nutrient imbalance, introduce toxic substances, disturb soil organisms, and contaminate water resources.

IV.2.1. Pollution by Fertilizers

Fertilizers are used to improve soil fertility and increase crop yield by supplying essential nutrients such as nitrogen, phosphorus, and potassium. They may be mineral fertilizers, such as ammonium nitrate, urea, superphosphate, and potassium salts, or organic fertilizers, such as manure, compost, and sewage sludge. When applied in appropriate quantities, fertilizers contribute to plant growth. However, excessive or inappropriate use can cause serious environmental problems.

Nitrogen fertilizers are among the most important sources of agricultural pollution. After application, nitrogen can be transformed in soil through mineralization, nitrification, denitrification, volatilization, and leaching. Nitrate ions are highly soluble and weakly retained by soil particles. As a result, they can easily move downward with infiltrating water and contaminate groundwater. High nitrate concentrations in drinking water represent a risk to human health and indicate agricultural pressure on water resources.

Excess nitrogen in soil may also be transferred to rivers and lakes through runoff and drainage. This contributes to eutrophication, a process characterized by excessive growth of algae and aquatic plants. When this organic matter decomposes, dissolved oxygen decreases, which can lead to fish mortality and degradation of aquatic ecosystems.

Phosphate fertilizers can also contribute to environmental pollution. Phosphorus is less mobile than nitrate because it tends to bind to soil particles, especially clay minerals and iron or aluminium oxides. However, soil erosion can transport phosphorus-rich particles into surface waters. In aquatic ecosystems, phosphorus is often a limiting nutrient, so even small increases can stimulate algal blooms and eutrophication.

Fertilizers may also introduce impurities into soil. Some phosphate fertilizers contain trace metals such as cadmium, lead, arsenic, chromium, or uranium in variable amounts. Repeated application

over long periods can lead to gradual accumulation of these elements in agricultural soils. This accumulation may reduce soil quality and increase the risk of transfer to crops.

Organic fertilizers and animal manure can improve soil structure and organic matter content, but they may also become sources of pollution when applied excessively. They may introduce pathogens, antibiotics, hormones, heavy metals, salts, and excess nutrients. Intensive livestock farming produces large quantities of manure, which can exceed the absorption capacity of surrounding soils.

The consequences of fertilizer pollution include soil acidification, salinization, nutrient imbalance, groundwater contamination, eutrophication, greenhouse gas emissions, and reduction of soil biodiversity. Excess nitrogen can increase emissions of nitrous oxide, a powerful greenhouse gas. Soil acidification may reduce nutrient availability and increase the mobility of toxic metals such as aluminium.

Good fertilizer management is therefore essential. It includes calculating nutrient needs according to crop requirements, soil testing, avoiding excessive application, applying fertilizers at appropriate periods, using slow-release fertilizers, maintaining vegetation cover, and reducing nutrient losses through runoff and leaching.

Contaminant Entry Pathways in Agricultural Soil

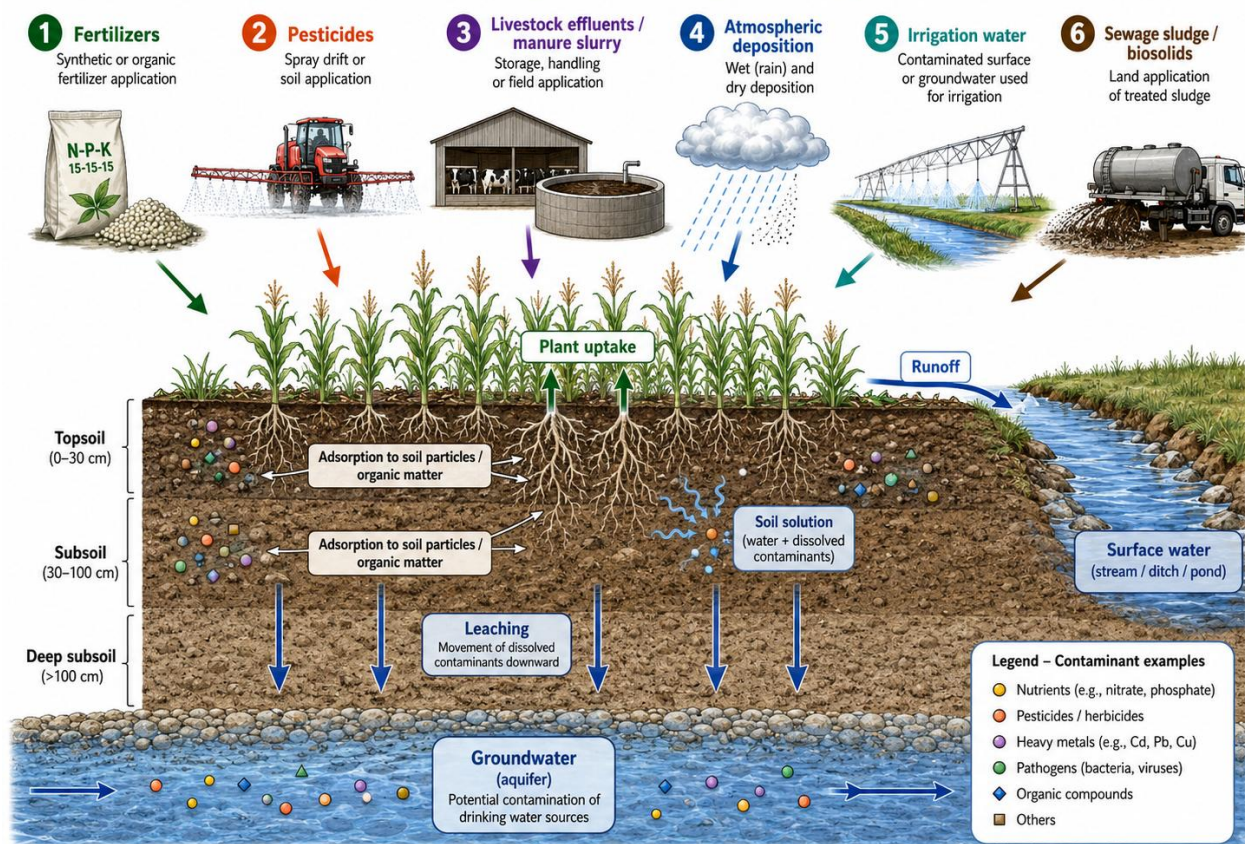


Figure IV.1. Main contaminant entry pathways in agricultural soils.(original)

IV.2.2. Pollution by Pesticides

Pesticides are chemical or biological substances used to control organisms considered harmful to crops, livestock, or stored products. They include insecticides, herbicides, fungicides, nematicides, rodenticides, and other plant protection products. Pesticides have played an important role in increasing agricultural productivity, but they are also among the most significant sources of soil contamination.

After application, pesticides may follow several environmental pathways. A portion reaches the target organism, but another portion may remain in soil, volatilize into the atmosphere, be transported by runoff, leach into groundwater, adsorb onto organic matter or clay particles, or be absorbed by non-target organisms. Their fate depends on chemical properties such as solubility,

persistence, volatility, and adsorption coefficient, as well as soil conditions such as texture, pH, moisture, temperature, and organic matter content.

Some pesticides degrade rapidly, while others are persistent and can remain in soil for months or years. Persistent pesticides are particularly problematic because they may accumulate after repeated applications. Certain organochlorine pesticides, although banned or restricted in many countries, are still detected in soils because of their long persistence.

Pesticides can affect soil organisms directly. Soil contains bacteria, fungi, algae, protozoa, nematodes, earthworms, insects, and many other organisms that participate in decomposition, nutrient cycling, soil structure formation, and organic matter transformation. Pesticides may reduce microbial diversity, inhibit enzymatic activity, affect earthworm survival, and disturb soil food webs.

Herbicides can reduce plant diversity around cultivated fields by eliminating non-target vegetation. This may affect insects, birds, and other organisms that depend on these plants for food or habitat. Insecticides can harm beneficial insects, including pollinators and natural enemies of crop pests. Fungicides may affect beneficial soil fungi, including mycorrhizal fungi that help plants absorb nutrients.

Pesticide pollution can also affect water resources. Rainfall or irrigation may transport pesticides from soil to streams, rivers, lakes, and reservoirs. Some pesticides may leach toward groundwater, especially in sandy soils or when the water table is shallow. Contaminated water can affect aquatic organisms and may create risks for drinking water quality.

The effects of pesticides on human health depend on the type of compound, dose, exposure duration, and route of exposure. Farmers and agricultural workers are often the most exposed populations. Exposure may occur through inhalation, skin contact, or ingestion. Long-term exposure to certain pesticides has been associated with neurological, endocrine, reproductive, and carcinogenic effects.

Ecologically, pesticide pollution can reduce biodiversity, simplify food webs, disturb predator-prey relationships, and increase pest resistance. Repeated use of the same pesticide may select resistant pest populations, leading to increased pesticide use and a cycle of dependency.

Sustainable pesticide management requires integrated pest management. This approach combines biological control, crop rotation, resistant varieties, mechanical control, monitoring of pest populations, rational pesticide use, and preference for less persistent and less toxic products. The objective is not only to protect crops but also to preserve soil quality, biodiversity, water resources, and human health.

IV.3. Pollution by Contaminants of Industrial Origin

Industrial activities are major sources of soil pollution. Industrial contamination is often more localized than agricultural pollution, but it can be very intense and persistent. Polluted industrial sites may remain contaminated long after industrial activity has stopped. Former factories, refineries, mines, smelters, waste storage areas, military sites, and fuel stations are common examples of contaminated sites.

Industrial pollutants may reach soil through direct discharge, accidental spills, leakage from storage tanks, atmospheric deposition, waste dumping, wastewater infiltration, mining residues, or improper disposal of hazardous materials. Once in the soil, these pollutants may remain fixed, migrate toward groundwater, volatilize into soil air, or be absorbed by organisms.

IV.3.1. Heavy Metals and Trace Elements

Heavy metals and trace elements are among the most common industrial soil contaminants. They include lead, cadmium, mercury, arsenic, chromium, nickel, copper, zinc, and others. These elements are released by mining, metallurgy, battery production, metal plating, waste incineration, cement production, fossil fuel combustion, and chemical industries.

Unlike many organic pollutants, metals cannot be destroyed. They can only change chemical form or become more or less mobile and bioavailable. Their behaviour in soil depends on pH, organic matter, clay content, redox conditions, and the presence of oxides and carbonates.

Lead may accumulate near roads, industrial sites, smelters, and battery recycling areas. It is toxic to the nervous system and can affect children's development. Cadmium may originate from metallurgy, batteries, pigments, plastics, and phosphate fertilizers. It can be taken up by plants and accumulate in the food chain. Mercury can be transformed into methylmercury under certain

conditions and become highly toxic. Arsenic may be released from mining, pesticides, wood preservatives, and industrial processes.

High concentrations of metals in soil can inhibit microbial activity, reduce plant growth, contaminate crops, affect soil fauna, and create long-term risks for humans and animals.

IV.3.2. Hydrocarbons and Petroleum Products

Hydrocarbons are common soil pollutants near refineries, fuel stations, pipelines, garages, airports, industrial zones, and areas affected by oil spills. They include petrol, diesel, lubricating oils, crude oil, and various petroleum derivatives.

Hydrocarbon pollution modifies soil properties by reducing aeration, changing water infiltration, and affecting microbial communities. Some hydrocarbons are volatile and may contaminate soil air. Others are persistent and bind strongly to soil organic matter.

Particularly important hydrocarbons include BTEX compounds, which are benzene, toluene, ethylbenzene, and xylene. Benzene is carcinogenic and can migrate through soil and groundwater. Polycyclic aromatic hydrocarbons are produced by incomplete combustion and are found in tar, soot, oil residues, and industrial waste. Some PAHs are persistent, toxic, and carcinogenic.

Hydrocarbons can be degraded by microorganisms under favourable conditions, but degradation may be slow when compounds are complex, concentrations are high, oxygen is limited, or nutrients are insufficient.

IV.3.3. Chlorinated Solvents

Chlorinated solvents are used in degreasing, dry cleaning, metal cleaning, chemical industries, and electronic manufacturing. Examples include trichloroethylene, tetrachloroethylene, and other chlorinated hydrocarbons.

These compounds are important because they can penetrate soil and contaminate groundwater. Some are dense non-aqueous phase liquids, meaning they are heavier than water and can sink

through aquifers. This makes remediation difficult. Many chlorinated solvents are toxic, persistent, and potentially carcinogenic.

In soil, they may volatilize and migrate as vapours, creating risks for indoor air quality when buildings are constructed over contaminated sites. This phenomenon is known as vapour intrusion.

IV.3.4. Persistent Organic Pollutants

Industrial activities can release persistent organic pollutants such as PCBs, dioxins, furans, PAHs, and certain chlorinated pesticides. These substances are resistant to degradation, accumulate in organic matter, and may enter food chains.

PCBs were historically used in electrical transformers, capacitors, hydraulic fluids, and industrial equipment. Dioxins and furans are often formed unintentionally during combustion processes, especially waste incineration and industrial burning. PAHs are produced by incomplete combustion of coal, oil, wood, and organic matter.

Because of their persistence and toxicity, these pollutants represent long-term ecological risks. They may affect reproduction, immune function, endocrine systems, and development in wildlife and humans.

IV.3.5. Industrial Waste and Sludge

Industrial waste and sludge may contain complex mixtures of contaminants, including metals, acids, solvents, hydrocarbons, salts, organic pollutants, and pathogens. When waste is poorly stored or dumped directly onto land, contaminants can infiltrate soil and groundwater.

Some industrial residues may alter soil pH, salinity, and structure. Acidic waste can increase metal mobility, while alkaline waste can modify nutrient availability. Saline waste can reduce plant growth and cause soil degradation.

IV.3.6. Consequences of Industrial Soil Pollution

The consequences of industrial soil pollution are often severe and long-lasting. Polluted soils may lose their fertility and become unsuitable for agriculture, grazing, or urban use. Vegetation may be damaged or completely absent in highly contaminated areas. Soil microorganisms may be inhibited, reducing decomposition and nutrient cycling.

Industrial pollutants can migrate from soil to groundwater and contaminate drinking water resources. They can also be absorbed by plants and enter food chains. Dust from contaminated soils can be inhaled by humans and animals. In urban areas, contaminated former industrial sites can create risks when reused for housing, schools, parks, or agriculture.

The economic consequences are also important. Contaminated sites require investigation, monitoring, remediation, and land-use restrictions. Remediation can be expensive and technically complex.

IV.3.7. Prevention and Remediation

Prevention is the most effective strategy against industrial soil pollution. It requires strict control of industrial emissions, safe storage of chemicals, treatment of wastewater and solid waste, monitoring of industrial sites, environmental impact assessment, and rapid response to accidental spills.

Remediation techniques depend on the pollutant type, soil characteristics, contamination depth, land use, and environmental risk. Common approaches include excavation and removal of contaminated soil, soil washing, stabilization and solidification, bioremediation, phytoremediation, thermal treatment, chemical oxidation, and containment.

Bioremediation uses microorganisms to degrade organic pollutants such as hydrocarbons. Phytoremediation uses plants to extract, stabilize, or degrade pollutants. Stabilization reduces pollutant mobility and bioavailability. Excavation is rapid but costly and transfers contaminated soil to another location.

In conclusion, soil pollution caused by agriculture and industry represents a major threat to ecosystem functioning, food safety, water quality, biodiversity, and human health. Because soil formation is extremely slow, polluted soils must be considered as a long-term environmental

problem. Sustainable soil management requires prevention, monitoring, rational use of agricultural inputs, industrial regulation, and restoration of contaminated sites.

CHAPTER 5

Chapter 5: Water Pollution

Water is an essential natural resource for life, ecosystems, agriculture, industry, energy production, and human development. It is involved in all biological processes and plays a central role in the functioning of the biosphere. Aquatic environments such as rivers, lakes, wetlands, groundwater, seas, and oceans support a high diversity of organisms and provide important ecological services, including water purification, nutrient cycling, climate regulation, food production, and habitat formation.

Water pollution occurs when physical, chemical, biological, or radioactive substances are introduced into aquatic environments at concentrations that alter water quality, disturb aquatic organisms, reduce ecological functions, or create risks for human health. Pollution may affect surface water, groundwater, marine waters, and even atmospheric water through contaminated rain or fog.

Unlike some forms of visible environmental degradation, water pollution may be invisible at the beginning. Clear water is not always clean water. Some pollutants, such as nitrates, pesticides, heavy metals, pharmaceutical residues, or pathogenic microorganisms, may be present without changing the appearance of water. Therefore, water quality assessment requires physical, chemical, microbiological, and ecological analyses.

Water pollution is a major environmental issue because water is a mobile medium. Pollutants introduced at one point can be transported downstream, infiltrate groundwater, accumulate in sediments, enter aquatic food chains, or reach coastal and marine ecosystems. For this reason, water pollution often has consequences far beyond the original source of contamination.

V.1. Introduction: Water Resources

Water resources include all forms of water available in the environment. They are generally divided into surface water, groundwater, atmospheric water, glaciers, and marine water. Although water covers most of the Earth's surface, only a small fraction is directly available as freshwater for human use and terrestrial ecosystems.

Surface water includes rivers, streams, lakes, reservoirs, ponds, wetlands, and irrigation canals. These resources are directly exposed to pollution from runoff, wastewater discharge, industrial effluents, agricultural drainage, atmospheric deposition, and accidental spills. Surface water is often the first compartment affected by visible pollution.

Groundwater is stored in aquifers beneath the soil surface. It represents an important source of drinking water, irrigation water, and industrial supply. Groundwater is generally better protected than surface water because soil and geological layers can filter some pollutants. However, once groundwater becomes contaminated, remediation is difficult, slow, and expensive. Pollutants such as nitrates, pesticides, solvents, hydrocarbons, and heavy metals may persist in aquifers for long periods.

Marine water includes seas and oceans. Marine environments receive pollutants from rivers, coastal cities, industrial zones, ports, ships, oil platforms, atmospheric deposition, and offshore activities. Because oceans are large, pollution may be diluted, but dilution does not mean disappearance. Many pollutants accumulate in sediments, coastal zones, organisms, and food webs.

Water resources are renewed through the hydrological cycle. Evaporation, condensation, precipitation, infiltration, runoff, groundwater flow, and river discharge continuously redistribute water across the planet. However, human activities can disturb this cycle by overexploiting aquifers, modifying river flow, draining wetlands, increasing impermeable surfaces, and releasing pollutants.

The quality of water resources depends on natural factors and human pressures. Natural factors include geology, climate, vegetation, soil type, hydrology, and biological activity. Human pressures include urbanization, agriculture, industry, mining, wastewater discharge, deforestation, and poor waste management.

The protection of water resources is essential for sustainable development. Clean water is necessary for drinking, sanitation, food production, biodiversity conservation, and ecosystem stability. Water pollution reduces the availability of usable water and increases treatment costs. It can also cause disease, biodiversity loss, eutrophication, fish mortality, and long-term ecosystem degradation.

V.2. Different Sources of Water Pollution

Water pollution may originate from many sources. These sources can be classified according to their origin, spatial distribution, or type of discharge. A common distinction is made between point-source pollution and diffuse pollution.

Point-source pollution comes from a clearly identifiable location. Examples include wastewater treatment plant outlets, industrial discharge pipes, sewage networks, mining drainage points, and accidental releases from factories. Point-source pollution is easier to identify and monitor because the discharge location is known.

Diffuse pollution does not come from a single identifiable point. It results from the accumulation of pollutants over large areas and their transport by runoff, infiltration, or atmospheric deposition. Agricultural pollution is a typical example of diffuse pollution. Fertilizers, pesticides, manure, and soil particles may be washed from fields into rivers and groundwater after rainfall.

The main sources of water pollution include domestic and urban activities, agriculture, industry, atmospheric deposition, natural processes, mining, transport, tourism, and waste disposal.

V.2.1. Domestic Sources

Domestic pollution comes from households, schools, hospitals, hotels, restaurants, and other human settlements. It includes wastewater from toilets, bathrooms, kitchens, laundry, cleaning products, detergents, oils, food residues, and household chemicals. Domestic wastewater contains organic matter, nutrients, microorganisms, suspended solids, pharmaceuticals, disinfectants, and personal care products.

If domestic wastewater is discharged without treatment, it can reduce dissolved oxygen in water, spread pathogens, cause bad odours, increase turbidity, and promote eutrophication. In many developing regions, untreated sewage remains a major cause of waterborne diseases.

V.2.2. Urban Sources

Urban pollution includes runoff from streets, roofs, parking areas, markets, industrial zones, construction sites, and drainage networks. Rainwater washes pollutants deposited on urban surfaces and transports them into rivers, lakes, or coastal waters.

Urban runoff may contain hydrocarbons, oils, heavy metals, rubber particles, microplastics, litter, detergents, organic matter, nutrients, and pathogens. Roads are important sources of lead, zinc, copper, cadmium, hydrocarbons, and particles derived from vehicle wear, brake linings, tyres, and fuel residues.

Urbanization also increases impermeable surfaces, which reduces infiltration and increases runoff. This accelerates the transport of pollutants into aquatic systems and increases flood risk.

V.2.3. Agricultural Sources

Agriculture is one of the most important sources of water pollution, especially in rural and intensively cultivated regions. Agricultural pollutants include nitrates, phosphates, pesticides, herbicides, fungicides, animal waste, antibiotics, hormones, sediments, salts, and organic matter.

Fertilizers can be leached into groundwater or transported by runoff into rivers and lakes. Nitrates are particularly mobile because they dissolve easily in water. Phosphates are less mobile but can be transported with eroded soil particles. Excess nutrients can cause eutrophication.

Pesticides may contaminate water through runoff, leaching, spray drift, drainage, or accidental spills. Some pesticides are toxic to aquatic organisms even at low concentrations. Intensive livestock farming can also pollute water through manure runoff, pathogens, ammonia, organic matter, and veterinary residues.

V.2.4. Industrial Sources

Industrial activities release many types of pollutants depending on the production process. Industrial wastewater may contain heavy metals, acids, bases, solvents, hydrocarbons, dyes, detergents, salts, phenols, cyanides, persistent organic pollutants, and heated water.

Industries such as metallurgy, textiles, petrochemicals, paper production, food processing, mining, pharmaceuticals, and chemical manufacturing are major sources of water contamination if effluents are not properly treated.

Industrial pollution may be toxic, persistent, and difficult to degrade. Some industrial pollutants accumulate in sediments and organisms, creating long-term ecological risks.

V.2.5. Atmospheric Sources

The atmosphere can also be a source of water pollution. Pollutants emitted into the air may be deposited into aquatic ecosystems through rain, snow, fog, dust, or dry deposition. Sulfur dioxide and nitrogen oxides can form acid rain. Heavy metals, persistent organic pollutants, pesticides, and particles can also be transported by air and deposited into water bodies.

Atmospheric deposition can contaminate remote lakes, forests, mountains, and oceans far from emission sources. This demonstrates the connection between air pollution and water pollution.

V.2.6. Natural Sources

Water pollution may also have natural origins. Natural processes such as erosion, volcanic activity, decomposition of organic matter, mineral dissolution, saline intrusion, and natural radioactivity can modify water quality.

For example, water flowing through rocks may dissolve minerals and become rich in salts, iron, manganese, arsenic, fluoride, or sulfates. In arid and semi-arid regions, high evaporation can increase salinity. Floods and landslides can increase turbidity and transport large amounts of suspended matter.

Natural pollution is not caused directly by human activities, but human actions may intensify it. Deforestation, overgrazing, soil degradation, and climate change can increase erosion and sediment transport.

V.3. Main Types of Pollutants

Water pollutants can be classified according to their nature. The main types include fermentable organic matter, mineral nutrient elements such as nitrates and phosphates, trace metal elements, synthetic organic compounds, hydrocarbons, suspended solids, pathogenic microorganisms, radioactive substances, and thermal pollution.

V.3.1. Fermentable Organic Matter

Fermentable organic matter refers to biodegradable organic substances that can be decomposed by microorganisms. It comes mainly from domestic wastewater, food industries, slaughterhouses, agriculture, livestock waste, and organic residues.

When organic matter enters water, microorganisms use oxygen to decompose it. If the quantity of organic matter is high, oxygen consumption increases and dissolved oxygen decreases. This can lead to oxygen depletion, also called deoxygenation.

Dissolved oxygen is essential for fish, aquatic invertebrates, and many microorganisms. When oxygen levels become too low, sensitive species disappear and anaerobic processes may develop. Anaerobic decomposition produces unpleasant gases such as methane, hydrogen sulfide, and ammonia.

Organic pollution is commonly evaluated using biochemical oxygen demand and chemical oxygen demand. Biochemical oxygen demand measures the amount of oxygen required by microorganisms to degrade organic matter. Chemical oxygen demand measures the oxygen equivalent needed to oxidize organic substances chemically. High BOD and COD values indicate strong organic pollution.

The consequences of fermentable organic matter pollution include oxygen depletion, fish mortality, bad odours, proliferation of anaerobic bacteria, degradation of aquatic habitats, and loss of biodiversity.

V.3.2. Mineral Nutrient Elements: Nitrates and Phosphates

Nitrates and phosphates are essential nutrients for plant and algal growth. However, when they are present in excessive concentrations, they become pollutants. Their main sources include fertilizers, manure, domestic wastewater, detergents, sewage, and industrial effluents.

Nitrates are highly soluble and easily leached into groundwater. They are particularly problematic in agricultural areas where nitrogen fertilizers are applied intensively. High nitrate concentrations in drinking water may create health risks, especially for infants.

Phosphates are often associated with detergents, fertilizers, sewage, and eroded soil particles. In freshwater ecosystems, phosphorus is frequently the limiting nutrient. Therefore, an increase in phosphate concentration can strongly stimulate algal growth.

Excess nutrients cause eutrophication. This process begins with nutrient enrichment, followed by excessive growth of algae and aquatic plants. When algae die, their decomposition consumes dissolved oxygen. Oxygen depletion may cause fish mortality and the disappearance of sensitive aquatic organisms.

Eutrophication can also lead to the development of harmful algal blooms. Some cyanobacteria produce toxins that affect animals and humans. Eutrophic waters may become turbid, foul-smelling, and unsuitable for drinking, recreation, or aquatic life.

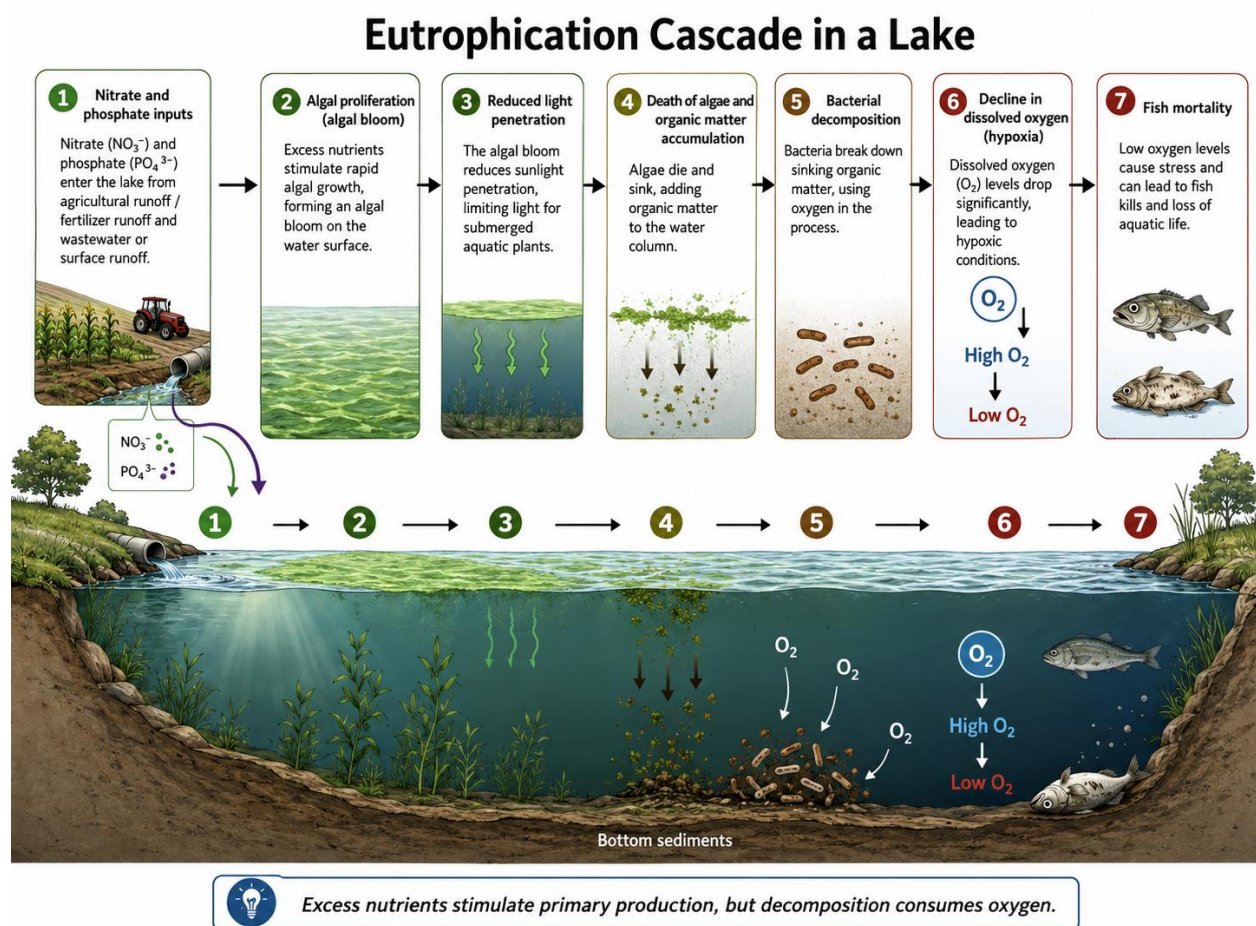


Figure V.1. Eutrophication cascade in a lake caused by nitrate and phosphate enrichment.(original)

V.3.3. Trace Metal Elements

Trace metal elements include metals and metalloids such as mercury, lead, cadmium, arsenic, chromium, nickel, copper, zinc, and manganese. Some of these elements are essential at low concentrations, but they become toxic when present in excess. Others, such as lead, cadmium, and mercury, are toxic even at very low concentrations.

Metals enter water through industrial effluents, mining drainage, urban runoff, atmospheric deposition, waste disposal, corrosion of pipes, and natural rock weathering. Unlike many organic pollutants, metals do not degrade. They may change chemical form, precipitate, adsorb onto particles, accumulate in sediments, or become bioavailable under certain conditions.

The toxicity of metals depends on their concentration, chemical form, pH, hardness, redox conditions, and organic matter content. Acidic water often increases metal solubility and toxicity. For example, mercury can be transformed by microorganisms into methylmercury, a highly toxic form that bioaccumulates in aquatic food chains.

Trace metals can affect fish, invertebrates, algae, microorganisms, and humans. They may cause neurological effects, kidney damage, reproductive problems, growth inhibition, enzyme disturbance, and mortality. In ecosystems, metal pollution can reduce biodiversity and modify food web structure.

V.3.4. Synthetic Organic Compounds

Synthetic organic compounds are chemical substances produced by human activities. They include pesticides, herbicides, industrial solvents, pharmaceuticals, hormones, detergents, plasticizers, dyes, flame retardants, and persistent organic pollutants.

Many synthetic organic compounds are considered micropollutants because they occur in water at very low concentrations, often in micrograms or nanograms per litre. However, even low concentrations may have ecological effects, especially with chronic exposure.

Some synthetic compounds are toxic, persistent, bioaccumulative, or endocrine-disrupting. Endocrine disruptors can interfere with hormonal systems and affect reproduction, development,

and behaviour in aquatic organisms. Pharmaceutical residues and hormones from wastewater may affect fish and invertebrate populations.

Pesticides are especially important in agricultural watersheds. They can reach aquatic ecosystems through runoff, leaching, drainage, and spray drift. Their effects depend on the molecule, concentration, exposure time, and sensitivity of organisms. Some insecticides are highly toxic to aquatic invertebrates, while herbicides may affect algae and aquatic plants.

Persistent organic pollutants, such as PCBs, dioxins, and some chlorinated pesticides, can remain in sediments for long periods and biomagnify through food chains.

V.3.5. Hydrocarbons

Hydrocarbons are organic compounds composed mainly of carbon and hydrogen. They are associated with petroleum, fuels, oils, lubricants, road runoff, industrial activities, shipping, refineries, and accidental spills.

Hydrocarbon pollution may occur in rivers, lakes, groundwater, and marine environments. Oil spills are among the most visible forms of hydrocarbon pollution. In marine ecosystems, hydrocarbons can cover the water surface, reduce oxygen exchange, coat birds and marine mammals, contaminate sediments, and affect plankton, fish, shellfish, and coastal habitats.

Some hydrocarbons are volatile and evaporate quickly, while others persist and bind to sediments. Polycyclic aromatic hydrocarbons are particularly concerning because some are toxic, mutagenic, and carcinogenic. They can be produced by incomplete combustion and are found in oil residues, soot, urban runoff, and industrial discharges.

Hydrocarbons can reduce photosynthesis in phytoplankton, damage fish eggs and larvae, affect respiratory surfaces, and alter food chains. In groundwater, petroleum hydrocarbons may form contaminant plumes that are difficult to remove.

V.4. Domestic and Urban Pollution

Domestic and urban pollution is mainly associated with human settlements. It includes wastewater, sewage, stormwater runoff, household chemicals, detergents, oils, pharmaceuticals, microplastics, and solid waste. In urban areas, water pollution is often complex because many pollutants are mixed together.

Domestic wastewater contains organic matter, suspended solids, nutrients, bacteria, viruses, protozoa, detergents, fats, food residues, pharmaceuticals, hormones, and cleaning products. If not treated before discharge, it can cause oxygen depletion, eutrophication, microbial contamination, and health risks.

Urban runoff is produced when rainwater flows over impermeable surfaces such as roads, roofs, parking areas, and sidewalks. This runoff collects pollutants deposited on surfaces and transports them into drainage systems and water bodies. It may contain hydrocarbons, heavy metals, particles, litter, microplastics, animal waste, salts, and nutrients.

One of the most serious risks of domestic pollution is microbiological contamination. Pathogenic microorganisms may cause waterborne diseases such as cholera, typhoid fever, hepatitis, dysentery, gastroenteritis, and other infections. This is particularly important in areas where wastewater treatment and sanitation systems are insufficient.

Urban pollution can also increase the temperature of runoff, especially when water flows over hot surfaces. Thermal changes can affect aquatic organisms by reducing dissolved oxygen and disturbing biological cycles.

Wastewater treatment is essential for reducing domestic and urban pollution. Treatment generally includes preliminary removal of large solids, primary sedimentation, biological treatment of organic matter, nutrient removal, filtration, and disinfection. Treated wastewater may be discharged into the environment or reused for irrigation, industrial purposes, or groundwater recharge under controlled conditions.

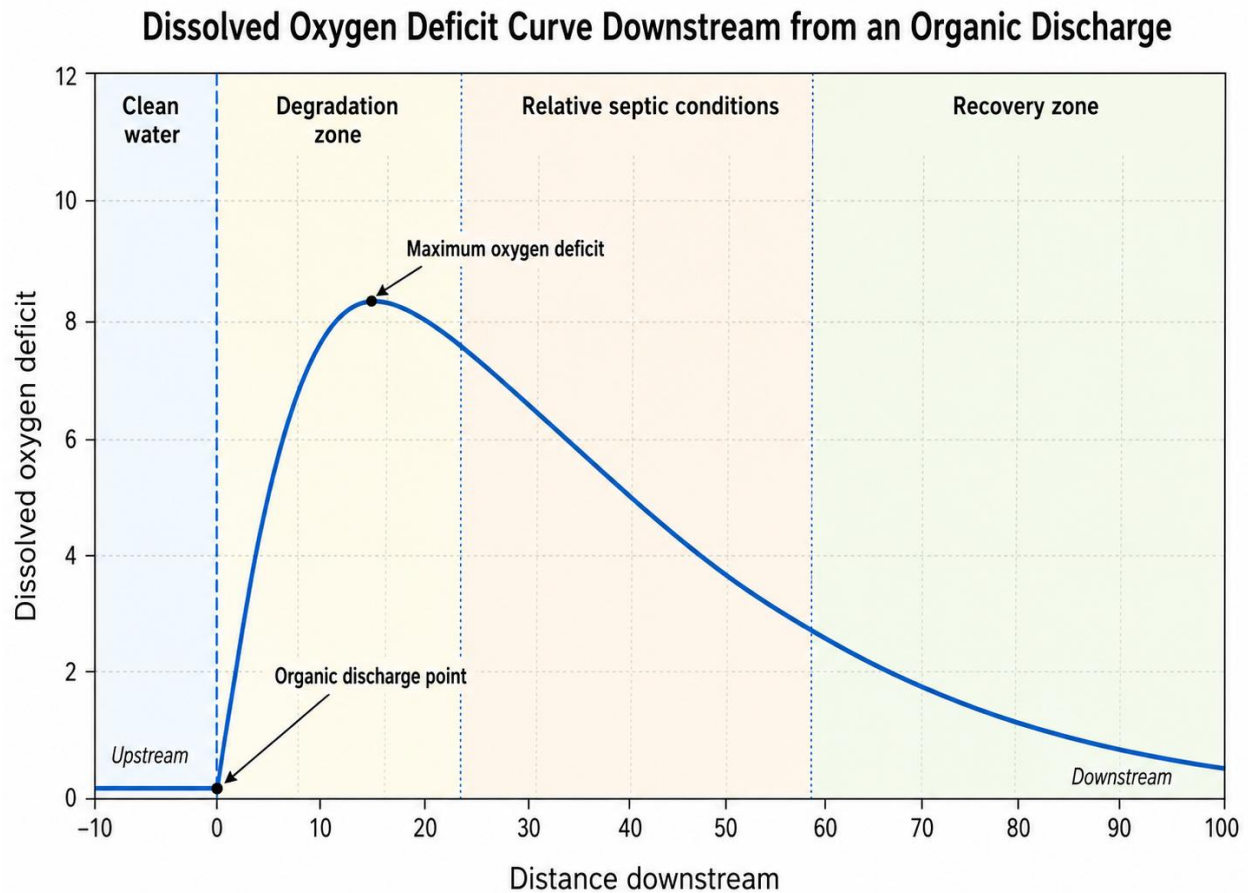


Figure V.2. Dissolved oxygen deficit curve downstream from an organic discharge. (original)

V.5. Pollution of Agricultural Origin

Agricultural pollution is one of the main causes of water quality degradation, especially in rural landscapes and intensive farming regions. It is generally diffuse, which makes it difficult to control. Pollutants are transported from fields, livestock areas, and irrigation systems to rivers, lakes, wetlands, and groundwater.

The main agricultural pollutants include nitrates, phosphates, pesticides, herbicides, manure, pathogens, veterinary drugs, antibiotics, hormones, sediments, and salts.

Fertilizers are a major source of nitrate and phosphate pollution. Nitrates leach easily into groundwater, while phosphates are transported mainly with eroded soil particles. Excess nutrients cause eutrophication and algal blooms in surface waters.

Pesticides used to control pests, weeds, and plant diseases can contaminate water through runoff, leaching, drainage, and atmospheric drift. Some pesticides are toxic to fish, amphibians, aquatic insects, algae, and microorganisms. Long-term exposure can affect reproduction, growth, behaviour, and survival.

Livestock farming can pollute water through manure, slurry, and animal waste. These materials contain organic matter, nutrients, pathogens, antibiotics, and hormones. When manure is applied excessively or stored improperly, pollutants can enter water bodies during rainfall.

Soil erosion is another important agricultural source of water pollution. When vegetation cover is reduced and soils are exposed, rainfall can detach and transport soil particles. Sediments increase turbidity, reduce light penetration, cover fish spawning areas, transport phosphorus and pesticides, and degrade aquatic habitats.

Irrigation can also contribute to salinization and pollution when water contains dissolved salts or when drainage is insufficient. In arid and semi-arid regions, evaporation concentrates salts in soil and drainage water, which may later contaminate surface or groundwater.

Reducing agricultural pollution requires good agricultural practices. These include rational fertilizer application, soil testing, buffer strips along rivers, crop rotation, cover crops, reduced pesticide use, integrated pest management, proper manure storage, erosion control, and efficient irrigation.

V.6. Pollution of Atmospheric Origin

Atmospheric pollution can become water pollution when airborne contaminants are deposited into aquatic ecosystems. Pollutants emitted into the air may return to the Earth's surface through wet deposition, such as rain, snow, and fog, or dry deposition, such as dust and particles settling on surfaces.

Acid rain is one of the best-known examples of atmospheric-origin water pollution. It forms when sulfur dioxide and nitrogen oxides react in the atmosphere to produce sulfuric and nitric acids. These acids are then deposited into lakes, rivers, soils, and forests. Acidification can reduce pH, mobilize toxic metals, damage aquatic organisms, and alter ecosystem structure.

Atmospheric deposition can also introduce heavy metals such as mercury, lead, cadmium, arsenic, and nickel into water bodies. Mercury is especially important because it can be converted into methylmercury in aquatic systems. Methylmercury bioaccumulates in fish and biomagnifies in food chains, creating risks for wildlife and humans.

Persistent organic pollutants can also be transported through the atmosphere and deposited into remote aquatic ecosystems. These substances may evaporate in warmer regions, travel through the atmosphere, and condense in colder regions. This process explains the presence of contaminants in polar and mountain ecosystems far from industrial sources.

Dust deposition can affect water quality by adding mineral particles, nutrients, microorganisms, or pollutants attached to particles. In some regions, Saharan dust can transport minerals and microorganisms over long distances.

Atmospheric-origin pollution demonstrates that the compartments of the biosphere are interconnected. Air pollution control is therefore necessary for protecting water resources.

V.7. Natural Pollution

Natural pollution refers to water quality degradation caused by natural processes rather than direct human activities. Although the term pollution is often associated with human causes, natural substances can also make water unsuitable for certain uses or harmful to organisms when present at high concentrations.

Natural sources of water pollution include rock weathering, volcanic emissions, erosion, decomposition of organic matter, saline intrusion, mineral dissolution, geothermal activity, floods, droughts, and natural radioactivity.

Geological formations can release substances into water. Groundwater may naturally contain high concentrations of iron, manganese, arsenic, fluoride, sulfates, chlorides, or other dissolved minerals. In some regions, arsenic contamination of groundwater is mainly linked to natural geological conditions, although human activities may worsen the problem.

Salinity can also have natural origins. In arid and semi-arid areas, high evaporation rates concentrate salts in surface water and groundwater. Coastal aquifers may be affected by seawater

intrusion, especially when freshwater pumping is excessive. Saline water reduces its suitability for drinking, irrigation, and many aquatic organisms.

Natural organic matter from decomposing vegetation can modify water colour, oxygen concentration, and chemical composition. In wetlands, decomposition may produce humic substances, methane, and reduced compounds. Under some conditions, natural oxygen depletion may occur.

Erosion is a natural process, but it can increase turbidity and sediment load in rivers and lakes. Floods can transport large quantities of sediments, organic matter, nutrients, and microorganisms. Volcanic activity may release acids, metals, ash, and gases that affect water quality.

Natural pollution is often intensified by human activities. Deforestation, overgrazing, poor land management, mining, excessive groundwater pumping, and climate change can increase erosion, salinization, sedimentation, and the release of naturally occurring contaminants.

Conclusion

Water pollution is a complex environmental problem involving many sources, pollutants, and ecological consequences. Water resources are vulnerable because water circulates continuously through the atmosphere, soil, surface systems, groundwater, and oceans. Pollutants may be transported, transformed, diluted, accumulated, or transferred into food chains.

The main sources of water pollution include domestic and urban wastewater, agricultural runoff, industrial effluents, atmospheric deposition, and natural processes. The major types of pollutants include fermentable organic matter, nutrients such as nitrates and phosphates, trace metals, synthetic organic compounds, hydrocarbons, pathogens, suspended matter, and heat.

The consequences of water pollution include oxygen depletion, eutrophication, toxicity, disease transmission, biodiversity loss, contamination of drinking water, degradation of aquatic habitats, and risks to human health. Protecting water quality requires wastewater treatment, sustainable agriculture, industrial regulation, monitoring, ecosystem restoration, and responsible management of water resources.

CHAPTER 6

Chapter 6: Nuclear Pollution

Nuclear pollution, also called radioactive pollution, is one of the most specific and sensitive forms of environmental pollution. It occurs when radioactive substances are introduced into the environment and become capable of exposing living organisms to ionizing radiation. Unlike many chemical pollutants, radioactive substances cannot be destroyed by ordinary physical, chemical, or biological treatment. They decrease only through radioactive decay, a natural process that may take from a few seconds to thousands of years depending on the radionuclide.

Radioactive pollution is often less visible and less understood than air, water, or soil pollution. However, it has received strict scientific and regulatory attention because ionizing radiation can affect living tissues, genetic material, ecosystems, food chains, and human health. The development of nuclear energy, the use of radioisotopes in medicine and research, industrial applications, military activities, and nuclear accidents have all increased the importance of radioactive pollution as an environmental issue.

From an ecological point of view, nuclear pollution must be studied like other types of pollution: by identifying sources, pathways of dispersion, exposure routes, biological effects, persistence, and risk management strategies. However, it also has specific characteristics related to radioactivity, irradiation, contamination, decay periods, and radioactive waste management.

VI.1. Introduction

Radioactive pollution is defined as the presence of radioactive substances in the environment at levels that may expose humans, animals, plants, or ecosystems to ionizing radiation. These substances may be present in air, water, soil, sediments, food, waste, or biological tissues. They may originate from natural sources, nuclear facilities, medical uses, industrial applications, military activities, or accidental releases.

The main characteristic of radioactive pollution is that the pollutant itself is a source of radiation. A radioactive substance emits ionizing radiation during its decay. This radiation can interact with living tissues and may damage cells or DNA. Exposure may be external, when the radioactive source remains outside the body, or internal, when radioactive substances enter the body through inhalation, ingestion, wounds, or skin contamination.

Radioactive substances may be dangerous even at very low concentrations. Some radionuclides can accumulate in specific organs because their chemical behaviour resembles that of essential elements. For example, iodine-131 can accumulate in the thyroid gland, strontium-90 behaves similarly to calcium and may accumulate in bones, and cesium-137 behaves similarly to potassium and can be distributed in soft tissues.

A major difference between radioactive pollution and many other forms of pollution is that radioactivity cannot be neutralized chemically or biologically. A radioactive atom remains radioactive until it decays into another element or isotope. Therefore, time is a central factor in radioactive pollution. Each radionuclide is characterized by a half-life, which is the time required for its radioactivity to decrease by half. Some radionuclides have very short half-lives, while others remain radioactive for thousands of years.

VI.1.1. Specific Characteristics of Radioactive Pollution

Radioactive pollution has several specific characteristics that distinguish it from other environmental contaminants.

First, radioactive substances emit ionizing radiation. This radiation may be alpha, beta, gamma, X-rays, or neutron radiation. Each type of radiation has different penetrating power and biological effects. Alpha particles have low penetration but are dangerous when inhaled or ingested. Gamma rays are highly penetrating and can expose the body externally.

Second, radioactive substances may cause both external and internal irradiation. External irradiation occurs when the body is exposed to radiation from a source outside it, such as contaminated soil or radioactive materials. Internal irradiation occurs when radionuclides enter the body and irradiate tissues from within.

Third, radioactive substances may be harmful at very low concentrations. This is especially true when radionuclides enter food chains or accumulate in sensitive organs. For this reason, strict standards are established for drinking water, food, occupational exposure, and environmental releases.

Fourth, radioactivity decreases according to exponential decay. This means that the activity of a radionuclide decreases progressively over time, but never disappears instantly. The persistence of radioactive contamination depends on the half-life of the radionuclide and its environmental mobility.

Fifth, radioactive pollution often requires long-term management. Some radioactive waste must be stored safely for decades, centuries, or even longer. This makes radioactive waste management one of the most important challenges of nuclear technology.

VI.1.2. Main Radionuclides of Environmental Importance

Several radionuclides are important in environmental pollution because of their persistence, mobility, biological uptake, or radiotoxicity. Among them are:

- ✓ Tritium, or hydrogen-3, which can be incorporated into water molecules.
- ✓ Carbon-14, which can enter organic matter and biological cycles.
- ✓ Cobalt-60, often associated with industrial and medical sources.
- ✓ Strontium-90, which behaves like calcium and may accumulate in bones.
- ✓ Cesium-137, which behaves like potassium and can contaminate soils, plants, animals, and humans.
- ✓ Americium-241, associated with nuclear activities and long-term contamination.
- ✓ Radium-226 and radon-222, naturally occurring radionuclides from the uranium series.
- ✓ Thorium and uranium decay-series radionuclides, which are naturally present in rocks and soils.

The environmental behaviour of radionuclides depends not only on their half-life but also on their chemical form, solubility, adsorption to particles, biological availability, and ability to move through water, soil, air, and food chains.

VI.2. Sources of Radioactive Pollution

Radioactive pollution may originate from natural or artificial sources. Natural radioactivity has always existed in the environment, while artificial radioactivity has increased due to human activities such as nuclear energy production, nuclear weapons testing, medical applications, industrial uses, and accidental releases.

VI.2.1. Natural Sources of Radiation

Human beings have always been exposed to natural radiation. This natural exposure comes from cosmic rays, radioactive elements in rocks and soils, radon gas, natural radionuclides in food and water, and radionuclides naturally present in the human body.

Cosmic radiation comes from space and reaches the Earth's atmosphere. The intensity of cosmic radiation increases with altitude and varies with latitude. People living at high altitudes or frequently travelling by aircraft may receive slightly higher exposure.

Terrestrial radiation comes from naturally occurring radionuclides in rocks, soils, and building materials. Uranium, thorium, radium, potassium-40, and their decay products contribute to natural radiation. The level of exposure varies according to local geology.

Radon-222 is one of the most important natural sources of radiation exposure. It is a radioactive gas produced by the decay of uranium and radium in soils and rocks. Radon can enter buildings through cracks in foundations, floors, walls, or water systems. Because it is inhaled, radon and its decay products can irradiate lung tissues. Indoor radon levels vary greatly depending on soil composition, building materials, ventilation, and construction type.

Natural radionuclides can also be present in water and food. Some groundwater may contain radium, uranium, thorium, or other radioactive elements at levels exceeding drinking-water recommendations. Potassium-40 and carbon-14 are naturally present in living organisms.

Natural radiation is important because it provides a reference level for comparing artificial radiation exposures. It also shows that radiation is not exclusively a technological phenomenon; it is part of the natural environment.

VI.2.2. Artificial Sources of Radioactive Contamination

Artificial radioactive contamination results from human activities. The most important artificial sources include nuclear weapon explosions, nuclear energy production, radioactive waste, medical and scientific uses of radioisotopes, industrial applications, and nuclear accidents.

VI.2.2.1. Nuclear Weapon Explosions

Nuclear weapon explosions produce large quantities of radionuclides. These include fission products, activation products, and radioactive materials dispersed by the explosion. After an atmospheric nuclear test, radioactive particles may be deposited on the Earth's surface as fallout.

Fallout may be local, regional, or global. Local fallout occurs within minutes or hours near the explosion site. Tropospheric fallout may be transported and deposited over weeks or months. Material injected into the stratosphere may remain there for years and be distributed globally.

The composition of fallout changes over time because radionuclides have different half-lives. Short-lived radionuclides decay rapidly, while long-lived radionuclides such as strontium-90 and cesium-137 can remain in the environment for decades.

Strontium-90 is of particular concern because it behaves like calcium and can accumulate in bones. Cesium-137 behaves like potassium and can be taken up by plants and animals. These radionuclides can enter food chains and expose human populations through contaminated food.

Nuclear weapon testing has therefore contributed historically to global radioactive contamination. It also demonstrated the capacity of atmospheric circulation to transport radioactive substances across continents and oceans.

VI.2.2.2. Radioactive Waste

Radioactive waste is produced during nuclear power generation, nuclear fuel processing, medical applications, industrial uses, and scientific research. The management of radioactive waste is a key issue because radioactivity cannot be destroyed chemically or biologically.

Radioactive waste is produced at several stages of the nuclear fuel cycle. It may arise during uranium mining, ore processing, fuel fabrication, reactor operation, spent fuel reprocessing, decommissioning of nuclear facilities, and disposal of contaminated materials.

The largest quantities of radioactive waste may come from mining and processing, but the most radioactive waste is often associated with spent nuclear fuel and reprocessing residues. These

wastes contain fission products and transuranic elements that may remain radioactive for very long periods.

Medical, industrial, and research applications also generate radioactive waste. This waste may have lower total radioactivity than nuclear fuel waste, but it is produced in many different locations, which makes collection, control, and disposal more complex.

Radioactive waste may be gaseous, liquid, solid, or particulate. Its management depends on its activity level, half-life, physical state, chemical nature, and potential environmental mobility.

VI.2.3. Waste and Effluents from Facilities in Normal Operation

Nuclear facilities may release small quantities of radioactive effluents during normal operation, under strict regulatory control. These releases may occur as gases, aerosols, liquid effluents, or solid waste.

There are two general management strategies for radioactive waste and effluents:

1. Dilution and controlled discharge when radioactivity is very low and within authorized limits.
2. Storage and isolation when radioactivity is higher or when the waste is long-lived.

The choice depends on the activity of the waste, its physical form, its half-life, and the potential risk to humans and ecosystems. Gaseous waste may require filtration and monitoring before release. Liquid waste may be treated, diluted, stored, or discharged under regulation. Solid waste may be compacted, conditioned, immobilized in cement or glass, and stored in controlled facilities.

The main objective is to prevent uncontrolled dispersion and to ensure that doses to workers, the public, and ecosystems remain below safety limits.

VI.2.4. Medical, Industrial, and Research Sources

Radioisotopes are widely used in medicine for diagnosis and treatment. Nuclear medicine uses radionuclides for imaging, scintigraphy, radiotherapy, and laboratory analysis. These activities generate radioactive waste such as contaminated syringes, vials, protective materials, biological samples, and liquids.

Industrial uses include radiography, sterilization, thickness measurement, tracing, and control of industrial processes. Research laboratories use radioisotopes in biology, chemistry, environmental science, and physics. Although these sources are generally controlled, they require careful waste management and radiation protection.

VI.2.5. Accidental Sources

Nuclear accidents can release radioactive substances into the environment. The most well-known accidents include Chernobyl and Fukushima. Accidental releases may contaminate air, soil, water, vegetation, livestock, food products, and marine environments.

The environmental consequences of a nuclear accident depend on the type and quantity of radionuclides released, weather conditions, distance from the source, deposition patterns, land use, and emergency response. Rainfall during radioactive plume passage can increase local deposition and create contamination hotspots.

Accidents demonstrate the importance of monitoring, emergency planning, food control, evacuation measures, and long-term environmental assessment.

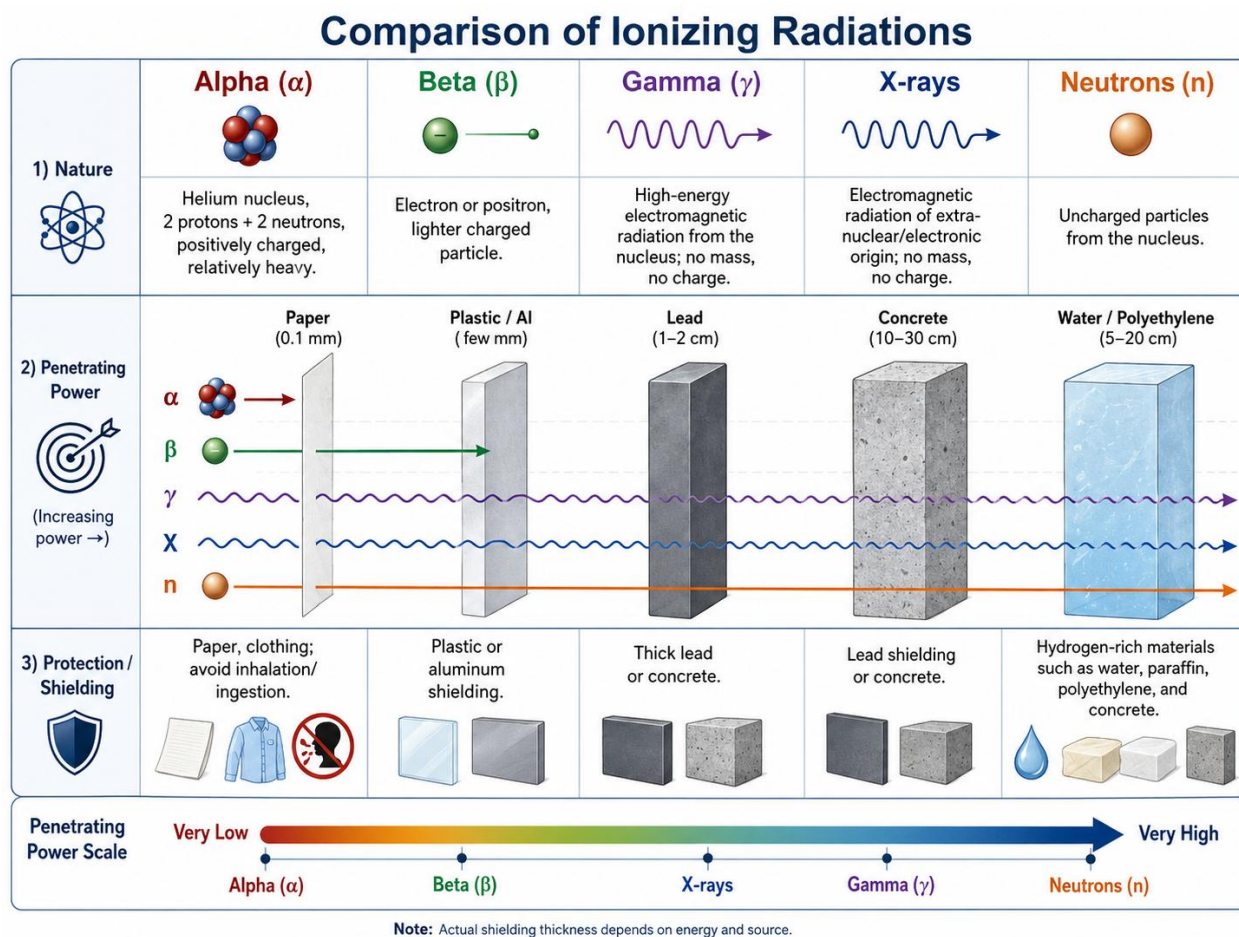


Figure VI.1. Comparison of ionizing radiations: nature, penetrating power and shielding materials.(original)

VI.3. Ways and Means of Human Exposure

Humans may be exposed to radioactive substances through several pathways. Exposure depends on the source, type of release, radionuclide properties, environmental transport, and human behaviour. The main routes of exposure are skin contact, inhalation, ingestion, and external irradiation.

Radioactive substances may contaminate the skin, hair, clothing, or open wounds. They may be inhaled as gases, vapours, aerosols, dust, or particles. They may be ingested through contaminated food or drinking water. They may also irradiate the body externally when present in soil, buildings, sediments, water, or objects.

The pathways of exposure differ according to the environmental compartment affected. Radioactive substances may be released into air, rivers, lakes, seas, oceans, or soil. Each pathway creates specific risks.

VI.3.1. Airborne Disposal and Atmospheric Exposure

Radioactive substances released into the air can be transported by wind and atmospheric circulation. Gaseous radionuclides may cause external irradiation or be inhaled. Aerosols and particles can contaminate the respiratory system when inhaled. Some particles may remain in the lungs, while others may pass into the bloodstream depending on their solubility and size.

Atmospheric deposition transfers radioactive substances from air to soil, vegetation, water bodies, and buildings. Rain can increase deposition by washing radioactive particles out of the atmosphere.

A classic example is iodine-131. When released into the atmosphere, iodine-131 can be deposited on pasture grass. Cows eating contaminated grass absorb iodine, which is then secreted into milk. Humans, especially children, may consume contaminated milk. Because iodine accumulates in the thyroid gland, this pathway is particularly important after nuclear accidents.

Cesium-137 can also be deposited on soils and plants. It may enter agricultural products, meat, milk, mushrooms, and wild foods. Long-term monitoring of food chains is therefore necessary after significant releases.

VI.3.2. Discharge into Rivers and Lakes

Radioactive substances discharged into rivers and lakes may expose humans and organisms through direct contact, drinking water, irrigation, fishing, sediments, and aquatic food chains.

External exposure may occur during swimming, fishing, or water sports if the water or sediments are contaminated. However, internal contamination is often more important because radionuclides may be ingested through drinking water or contaminated food.

Aquatic organisms can accumulate radionuclides from water, sediments, or food. Fish, molluscs, aquatic plants, and invertebrates may become contaminated. Humans may then be exposed by consuming these organisms. Irrigation with contaminated water can transfer radionuclides to crops and soils.

Sediments play an important role because they can store radionuclides for long periods. Disturbance of sediments by floods, dredging, storms, or biological activity can remobilize contamination.

VI.3.3. Discharge into Seas and Oceans

Seas and oceans have a very large dilution capacity, but dilution does not eliminate radioactive pollution. Marine disposal has historically been considered because the ocean can disperse and dilute contaminants. However, radioactive substances may still accumulate in sediments, marine organisms, and coastal zones.

Liquid radioactive effluents may be discharged into coastal waters under strict regulation. Solid radioactive waste has also been historically disposed of in the deep sea in sealed containers, although this practice is now highly restricted or prohibited in many contexts.

The return of marine radioactive contamination to humans may occur through three main pathways:

- A. Contamination of edible marine organisms such as fish, shellfish, algae, and crustaceans.
- B. Contamination of sediments and fishing equipment.
- C. Contamination of beaches and coastal areas.

Marine organisms may concentrate specific radionuclides depending on their physiology. For example, some algae can accumulate iodine, while fish may accumulate cesium. Seafood monitoring is therefore important in areas affected by radioactive releases.

VI.3.4. Disposal in Soil

Soil can receive radioactive substances through atmospheric deposition, waste disposal, accidental releases, irrigation with contaminated water, or burial of radioactive waste. Once in

soil, radionuclides may be retained, migrate downward, be absorbed by plants, or be transported by erosion and runoff.

The disposal of radioactive waste in soil or underground formations is possible only if long-term isolation can be guaranteed. Suitable sites may include deep geological formations, abandoned salt mines, clay formations, or engineered concrete structures. The objective is to prevent radionuclides from reaching groundwater, surface water, or living organisms.

Soil contamination is important because it can affect agriculture and food chains. Plants may absorb radionuclides through roots. Grazing animals may ingest contaminated plants and soil particles. Humans may be exposed through crops, milk, meat, and other food products.

The mobility of radionuclides in soil depends on soil pH, clay content, organic matter, moisture, mineral composition, and chemical form of the radionuclide. Cesium can bind strongly to clay minerals, while strontium may be more mobile and biologically available because it behaves like calcium.

VI.4. Biological Effects of Ionizing Radiation

Ionizing radiation can affect living organisms by damaging molecules, cells, and tissues. The most important target is DNA. Radiation may break chemical bonds, produce free radicals, and damage genetic material. Cells can sometimes repair this damage, but incorrect repair or severe damage may lead to mutations, cell death, cancer, or reproductive effects.

The biological effect depends on radiation dose, dose rate, type of radiation, exposure duration, affected tissue, age, and sensitivity of the organism. Rapidly dividing cells are generally more sensitive than slowly dividing cells. This explains why bone marrow, reproductive tissues, digestive epithelium, and developing embryos are highly radiosensitive.

VI.4.1. Acute Effects

Acute effects occur after exposure to high doses over a short period. They may include skin burns, radiation sickness, nausea, weakness, immune suppression, organ damage, and in extreme

cases death. Such exposures are generally associated with accidents, occupational incidents, or nuclear explosions.

VI.4.2. Chronic Effects

Chronic effects occur after long-term exposure to low or moderate doses. These effects may appear years after exposure. They include increased risk of cancer, genetic mutations, cataracts, reduced fertility, developmental effects, and possible immune system disturbances.

Internal contamination can be particularly important because radionuclides may remain in specific organs and irradiate tissues continuously. For example, iodine-131 affects the thyroid, strontium-90 affects bones, and plutonium may affect lungs or bones depending on exposure route.

VI.4.3. Effects on Ecosystems

Radioactive pollution can affect plants, animals, microorganisms, and ecosystem processes. High radiation levels may reduce reproduction, increase mutation rates, affect growth, modify behaviour, and change community composition.

However, ecological effects vary greatly according to dose and species sensitivity. Some organisms are more resistant than others. Microorganisms, insects, plants, mammals, birds, and aquatic organisms do not respond in the same way. Ecosystem-level effects may include reduced biodiversity, altered food webs, contamination of trophic chains, and long-term restrictions on land use.

VI.5. Prevention, Protection, and Management

Protection against radioactive pollution is based on prevention, monitoring, control of releases, safe waste management, emergency preparedness, and limitation of exposure.

The main principles of radiation protection are:

- Justification: any activity involving radiation should provide more benefit than harm.
- Optimization: exposure should be kept as low as reasonably achievable.

- Dose limitation: exposure must remain below established limits for workers and the public.

VI.5.1. Monitoring

Environmental monitoring includes measuring radioactivity in air, water, soil, sediments, vegetation, food, and living organisms. Monitoring helps detect contamination, evaluate exposure, and guide protective actions.

VI.5.2. Waste Management

Radioactive waste must be classified, conditioned, stored, transported, and disposed of according to its activity and half-life. Short-lived waste may be stored until its activity decreases. Long-lived waste requires secure isolation for long periods.

Waste management may involve shielding, containment, immobilization in cement or glass, storage in engineered facilities, and deep geological disposal.

VI.5.3. Emergency Measures

In case of a nuclear accident, protective measures may include evacuation, sheltering indoors, restriction of contaminated food and water, distribution of stable iodine tablets, decontamination, and long-term land-use control.

Stable iodine tablets may protect the thyroid by reducing the uptake of radioactive iodine, but they are useful only for specific exposure situations and must be taken according to public health instructions.

Conclusion

Nuclear pollution is a specific form of environmental pollution caused by radioactive substances capable of emitting ionizing radiation. It may originate from natural sources, nuclear weapons, nuclear power production, radioactive waste, medical and industrial uses, research activities, and accidents.

Its main environmental concern is that radioactivity cannot be destroyed chemically or biologically. It decreases only through radioactive decay, which may take from very short periods

to thousands of years. Radioactive substances can contaminate air, water, soil, sediments, food chains, and living organisms.

Human exposure may occur through inhalation, ingestion, skin contamination, or external irradiation. The ecological and health effects depend on the radionuclide, dose, exposure route, half-life, and biological behaviour. Effective management requires strict monitoring, safe waste disposal, prevention of releases, emergency preparedness, and long-term environmental protection.

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