UNIT 5: INTRODUCTION TO ENVIRONMENTAL CHEMISTRY

Introduction Environmental chemistry is the study of the chemical processes occurring in the environment and their effects on living organisms and ecosystems. It involves understanding how chemicals move through and interact with the atmosphere, hydrosphere, lithosphere, and biosphere, as well as the impacts of human activities on these processes.

Components of the Environment The environment is divided into four main compartments:

1. **Atmosphere**: The layer of gases surrounding Earth, consisting of 78% nitrogen, 21% oxygen, and trace amounts of other gases. It regulates temperature, protects against harmful radiation, and supports life through various chemical reactions. For example:
    - Nitric oxide (NO) reacts with oxygen (O_2) to form nitrogen dioxide (NO_2) under ultraviolet (UV) light.
    - Sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) can form acids (e.g., sulfuric acid) that contribute to acid rain.
    - Chlorofluorocarbons (CFCs) break down in the atmosphere, releasing chlorine atoms that deplete the ozone layer.
2. **Hydrosphere**: Includes all forms of water on Earth—oceans, lakes, rivers, glaciers, and groundwater. It covers about 71% of the planet's surface, with only 1% being freshwater. Key chemical reactions in the hydrosphere include:
    - Ammonia (NH_3) from agriculture and industry can be toxic to aquatic life.
    - Nitrification converts ammonia to nitrites (NO_2^-) and nitrates (NO_3^-), impacting aquatic ecosystems and causing eutrophication.
3. **Lithosphere**: The Earth's crust and upper mantle, containing rocks and soil. Chemical processes here include:
    - The oxidation of iron carbonates ($FeCO_3$) by bacteria.
    - Chemical weathering, such as the hydration of iron oxides (Fe_2O_3).
4. **Biosphere**: The zone of life on Earth, encompassing all ecosystems where living organisms interact with each other and their environment. Important biochemical cycles include:
    - **Photosynthesis**: Plants convert carbon dioxide (CO_2) and water into glucose and oxygen using sunlight.
    - **Respiration**: Organisms break down glucose to release energy, producing CO_2 and water.

Natural Cycles Several natural cycles are crucial for maintaining environmental balance:

1. **Hydrologic Cycle**: Describes the continuous movement of water through evaporation, condensation, precipitation, and infiltration.
2. **Oxygen Cycle**: Involves the exchange of oxygen between the atmosphere, biosphere, and lithosphere. Key processes include photosynthesis and respiration.
3. **Nitrogen Cycle**: Focuses on the transformation of nitrogen in various forms (e.g., ammonia, nitrate) through processes like fixation, nitrification, and denitrification. Human activities, such as burning fossil fuels, impact this cycle by increasing nitrogen oxides in the atmosphere.
4. **Phosphorus Cycle**: Essential for plant growth, involving the movement of phosphorus through the soil, water, and organisms. It includes the transformation of inorganic phosphorus into organic forms and its return to the soil upon decomposition.
5. **Sulfur Cycle**: Manages sulfur through various chemical forms and processes, including atmospheric oxidation and microbial transformations. Sulfur is crucial for life but can contribute to environmental issues like acid rain.
6. **Carbon Cycle**: Describes how carbon is exchanged between the atmosphere, living organisms, and the earth. Key processes include photosynthesis, respiration, and the combustion of fossil fuels, which release carbon dioxide and contribute to global warming.

Understanding these cycles and their interactions helps in managing environmental impacts and addressing issues like pollution and climate change.

Concepts Related to Environmental Chemistry

Pollutant:

- **Definition:** A substance whose concentration has increased due to human activities and that ultimately has detrimental effects on the environment.
- **Examples:** Sulfur dioxide (SO_2), carbon dioxide (CO_2), ozone (O_3), lead (Pb), mercury (Hg), excess heat, light, and sound.

Contaminant:

- **Definition:** A substance that does not naturally occur in the environment but is introduced due to human activities. It becomes a pollutant when it harms human health or the environment.
- **Examples:** Contaminants in bodies of water, on humans, trees, animals, and fish.

Sink:

- **Definition:** A medium that interacts with and retains pollutants or converts them chemically.

Dissolved Oxygen (DO):

- **Definition:** Oxygen that is dissolved in water, essential for aquatic life.
- **Optimum Levels:** 4 – 8 mg/L. Levels below 4 mg/L indicate pollution and unfit water for consumption.

Biological Oxygen Demand (BOD):

- **Definition:** A measure of the oxygen needed to decompose organic matter in water.
- **Measurement:** Determined by measuring DO at the beginning and end of a 5-day period in a sealed sample. It reflects the oxygen consumed due to the oxidation of dissolved organic matter (DOM).

Threshold Limit Value (TLV):

- **Definition:** The maximum level of a toxic pollutant in the atmosphere that a healthy person can be exposed to over an 8-hour workday without adverse effects.
- **Determination:** Based on animal experiments, medical knowledge, and environmental studies.

Exercise 5

1. **Hydrosphere Components:**
    - **Definition:** The hydrosphere includes all water bodies on Earth, such as oceans, rivers, lakes, and glaciers.
    - **Examples:** Oceans, rivers, lakes, glaciers.
2. **CFCs and Ozone Depletion:**
    - **Reaction:** Chlorofluorocarbons (CFCs) deplete the ozone layer by breaking down in the upper atmosphere under UV radiation:

      $CF2Cl2 \xrightarrow{UV} CF_2Cl + Cl^{\cdot}$

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

3. **Oxygen Cycle Reactions:**
    - **Degradation of Organic Material:**

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

    - **Photosynthesis:**

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

4. **Nitrogen Fixation:**
    - **By Bacteria:**

      $$N_2+8H^++8e^- \rightarrow 2NH_3+H_2$$

    - **By Algae:**

      $$N_2+H_2O \rightarrow NH_3+O_2$$

5. **Pollutant:**
    - **Definition:** A substance whose concentration has increased due to human activity and harms the environment.
    - **Examples:** Sulfur dioxide (SO_2), carbon monoxide (CO), lead (Pb).
6. **Threshold Limit Value (TLV):**
    - **Definition:** The maximum level of a toxic pollutant to which a person can be exposed for an 8-hour workday without adverse health effects.
7. **Hydrological Cycle:**
    - **Definition:** The continuous movement of water on, above, and below the surface of the Earth. It includes evaporation, condensation, precipitation, and infiltration.
8. **Biological Oxygen Demand (BOD):**
    - **Definition:** A measure of the amount of oxygen required by microorganisms to decompose organic matter in water.
    - **Experimental Measurement:** Measured by the difference in dissolved oxygen (DO) at the beginning and end of a 5-day period in a sealed sample.

Environmental Pollution

Pollution:

- **Definition:** The discharge of harmful substances or energy into the environment causing undesirable changes and harm to ecosystems and human health.

Types of Pollution:

- **Air Pollution:** Caused by contaminants like sulfur dioxide, nitrogen oxides, carbon monoxide, and particulate matter.
- **Water Pollution:** Results from untreated sewage, industrial waste, and pollutants like nitrates and phosphates.
- **Land Pollution:** Caused by the spillage of chemicals, heavy metals, and non-biodegradable waste.

Air Pollution Examples:

- **Sulfur Dioxide (SO_2):** Causes respiratory problems and acid rain.
- **Nitrogen Oxides (NO_x):** Contribute to ozone depletion and photochemical smog.
- **Carbon Monoxide (CO):** Impairs vision and reduces blood oxygen levels.
- **Particulates:** Irritate the lungs and affect breathing.
- **Chlorofluorocarbons (CFCs):** Deplete the ozone layer, increasing UV radiation.

Water Pollution Examples:

- **Domestic Sewage:** Leads to eutrophication, decreasing oxygen levels in water.
- **Solid Waste:** Includes garbage and e-waste, causing pollution in water systems.
- **Fertilizers and Pesticides:** Contribute to nutrient overload and harmful algal blooms.
- **Heavy Metals (e.g., Lead):** Toxic to aquatic life and humans.

Land Pollution Examples:

- **Garbage:** Results from inadequate disposal and causes accumulation in landfills.
- **Plastic:** Non-biodegradable and remains in the soil, affecting plant growth.
- **Mercury:** From mining and improper disposal of mercury-containing items.

Methods to Reduce Pollution:

- **Air Pollution:** Use public transport, recycle, reduce plastic use, and avoid chemical products.
- **Water Pollution:** Treat wastewater, recycle, and use organic fertilizers.
- **Land Pollution:** Reduce, reuse, and recycle non-biodegradable materials.

These concepts and examples highlight the impact of human activities on the environment and emphasize the importance of adopting practices to mitigate pollution.

Global Warming and Climate Change: A Chemical Perspective

Importance of Chemistry in Climate Change

Chemistry plays a crucial role in understanding and addressing climate change. Human activities significantly impact the environment, and climate change is a pressing global issue. The primary driver of global warming is the emission of greenhouse gases (GHGs) into the atmosphere, resulting from various chemical reactions and industrial processes.

Key Chemical Reactions and Greenhouse Gases

1. **Combustion Reactions:**
    - Combustion of fossil fuels is a major source of greenhouse gases. The general reaction can be represented as:

      $CX_Y+O_2 \rightarrow CO_2+H_2O+Heat$

      Here, CX_Y represents a hydrocarbon, where X and Y are the numbers of carbon and hydrogen atoms. This reaction produces carbon dioxide (CO_2) and water, contributing to the greenhouse effect.
2. **Industrial Emissions:**
    - Certain chemicals, like chlorofluorocarbons (CFCs) and solvents, also contribute to global warming. These are either manufactured or used in various industrial applications.
3. **Natural Sources:**
    - Methane (CH_4) is a natural greenhouse gas produced by biological processes, such as those occurring in oceans and wetlands.
4. **Human Activities:**

- Carbon dioxide (CO_2) from burning fossil fuels is a significant concern. Since 1900, CO_2 emissions have increased substantially due to industrialization and energy consumption.

Greenhouse Effect

The greenhouse effect is the warming of Earth's surface due to certain gases in the atmosphere that trap infrared radiation. Without these gases, Earth's average temperature would be around -18°C. However, the presence of greenhouse gases like CO_2, CH_4, and H_2O raises the temperature to a more hospitable 15°C.

- **CO_2 and H_2O** absorb infrared radiation effectively, warming the Earth.
- **N_2 and O_2** do not absorb infrared radiation and, therefore, do not contribute to the greenhouse effect.

Major Greenhouse Gases and Their Contributions

1. **Carbon Dioxide (CO_2):**
    - Emitted from burning fossil fuels, deforestation, and cement production.
    - Contributes about 52.92% to global warming.
    - Stays in the atmosphere for 200 years or more.
2. **Methane (CH_4):**
    - Produced by livestock, agriculture, and fossil fuel extraction.
    - Contributes about 14.88% to global warming.
    - Lasts approximately 12 years in the atmosphere.
3. **Halogenated Compounds (CFCs & HCFCs):**
    - Used in refrigeration and air conditioning.
    - Contribute around 10.78% to global warming.
    - Can last from months to thousands of years in the atmosphere.
4. **Tropospheric Ozone (O_3):**
    - Formed from reactions between CO, NO_2, and VOCs.
    - Contributes about 10.72% to global warming.
    - Has a shorter atmospheric lifetime (months).
5. **Nitrous Oxide (N_2O):**
    - Emitted from fertilizers and fuel use.
    - Contributes about 10.70% to global warming.
    - Remains in the atmosphere for up to 114 years.

Green Chemistry and Cleaner Production

Green Chemistry aims to reduce the environmental impact of chemical processes and products. It focuses on designing products and processes that minimize waste and use safer chemicals.

Key Principles:

1. **Prevention:** Avoid creating waste rather than managing it after production.
2. **Atom Economy:** Maximize the incorporation of all materials used into the final product.
3. **Less Hazardous Chemical Synthesis:** Use methods that minimize toxicity.
4. **Design of Safer Chemicals:** Create chemicals that are safe for both humans and the environment.
5. **Safer Solvents and Auxiliaries:** Replace toxic solvents with safer alternatives.
6. **Design for Energy Efficiency:** Optimize energy use and minimize energy consumption.
7. **Use of Renewable Feedstock:** Utilize renewable resources instead of depleting ones.
8. **Reduce Derivatives:** Minimize unnecessary derivatives in chemical processes.
9. **Catalysis:** Employ catalysts to improve efficiency and reduce waste.
10. **Design for Degradation:** Ensure products break down into non-toxic substances after use.
11. **Real-time Analysis for Pollution Prevention:** Monitor processes in real-time to prevent pollution.
12. **Inherently Safer Chemistry for Accident Prevention:** Choose safer chemicals and processes to reduce risks.

By implementing these principles, industries can contribute to mitigating climate change while promoting sustainability and safety.

Cleaner Production in Chemistry

Definition and Ideal Attributes

Cleaner production aims to design chemical processes and products that minimize environmental impacts. Ideally, a chemical reaction should:

- Be **safe** for workers and the environment
- Be **simple** and efficient
- Be **selective** in producing the desired product
- Achieve a **high yield**
- Be **energy-efficient**
- Use **renewable** or **recyclable** materials
- Produce **minimal hazardous byproducts** or manage them effectively

In practice, achieving all these attributes simultaneously is challenging. Chemists and engineers strive to find environmentally preferable reaction pathways that balance these desirable attributes.

Goals of Green Chemistry from Cleaner Production Perspective

1. **Reduce Environmental Impact:** Choose materials and chemical transformations that minimize adverse effects on the environment.
2. **Renewable Materials:** Develop processes using renewable (plant-based) raw materials instead of non-renewable (fossil-derived) ones.
3. **Less Toxic Products:** Create products that are less toxic or use less toxic raw materials.
4. **Rapid Degradation:** Ensure products degrade more readily in the environment.
5. **Reduce Hazardous Solvents:** Minimize the use of hazardous or environmentally persistent solvents in chemical processes.
6. **Improve Energy Efficiency:** Develop low-temperature and low-pressure processes using advanced catalysts.
7. **Minimize Byproducts:** Design reactions to reduce or eliminate byproducts, improving **atom economy**.

Atom Economy

Atom economy measures how effectively the atoms in the reactants are incorporated into the desired products. It is calculated as:

$$\text{Atom Economy}(\%)=\frac{\textit{Formula weight of the product}}{\text{Sum of formula weights of all reactants}}\times 100$$

Example Calculation

Consider the reaction:

$Fe_2O_3(s)+3CO(g)\rightarrow 2Fe(l)+3CO_2(g)$

Using atomic masses: Fe = 56, C = 12, O = 16,

1. Calculate the total formula weight of reactants:

   $(2\times 56)+(3\times(12+16))=112+84=196$

2. Calculate the total formula weight of products:

   $(2\times 56)+(3\times(12+16+16))=112+132=244$

3. Atom economy calculation:

   $\text{Atom Economy}=\frac{112}{196}\times 100=45.9\%$

Why Reactions with One Product Have Higher Atom Economy

Reactions producing only one product have 100% atom economy because all the reactant atoms are converted into the desired product, with no byproducts. For example, the synthesis of ammonia:

$N_2 + 3H_2 \rightarrow 2NH_3$

or ethene reacting with water to make ethanol:

$CH_2{=}CH_2 + H_2O \rightarrow CH_3CH_2OH$

Green Chemistry and Cleaner Production

- **Green Chemistry** is a movement to make chemical processes more environmentally friendly and sustainable.
- It involves considering the hazards of chemicals, their properties, and the environmental impact throughout the product lifecycle.