UNIT 3: ENERGY-TRANSFORMATION

3.1 Cellular Metabolism

Living cells are dynamic and constantly active. They engage in various processes including assembling and breaking down macromolecules, transporting substances across membranes, and transmitting genetic instructions. All these cellular activities require energy. This energy is extracted from the environment and used to perform essential life functions such as movement, growth, development, and reproduction.

Metabolism is the term used to describe the sum of all chemical reactions occurring within a cell. These reactions are crucial as they allow cells to produce energy for vital processes and to synthesize new organic materials. Metabolism can be broadly classified into two types of reactions:

1. **Anabolism**:
   - **Definition**: Anabolism refers to the set of metabolic pathways that construct complex molecules from simpler ones. It is a constructive process that builds macromolecules like proteins, nucleic acids, and polysaccharides.
   - **Characteristics**:
     - **Energy Requirement**: Anabolic reactions require energy to proceed. This energy is used to form bonds between smaller molecules to create larger, complex molecules.
     - **Endergonic Nature**: These reactions are endergonic, meaning they absorb energy from the surroundings.
     - **Example**: Photosynthesis in plants is an example of an anabolic process where simple molecules like carbon dioxide and water are used to produce glucose and oxygen.
2. **Catabolism**:
   - **Definition**: Catabolism is the set of metabolic pathways that break down complex molecules into simpler ones. This process involves the degradation of macromolecules like proteins, fats, and carbohydrates.
   - **Characteristics**:
     - **Energy Release**: Catabolic reactions release energy by breaking down complex molecules into simpler ones. This energy is often captured in the form of ATP (adenosine triphosphate).
     - **Exergonic Nature**: These reactions are exergonic, meaning they release energy into the surroundings.

- **Example**: Cellular respiration is a catabolic process where glucose is broken down to release energy, which is used to produce ATP.

Comparison of Anabolic and Catabolic Pathways:

Aspect	Anabolism	Catabolism
Function	Constructs complex molecules	Breaks down complex molecules
Energy Requirement	Requires energy (endergonic)	Releases energy (exergonic)
Processes	Photosynthesis	Cellular respiration
Molecular Impact	Builds macromolecules (e.g., proteins)	Degrades macromolecules (e.g., glucose)

3.2 Photosynthesis

Photosynthesis is a crucial process that allows plants and some other organisms to convert light energy into chemical energy. This process occurs in the chloroplasts of plant cells and involves two main stages: the light-dependent reactions and the light-independent reactions (Calvin Cycle).

1. **Light-Dependent Reactions**:
   - **Purpose**: Convert solar energy into chemical energy.
   - **Process**:
     - **Photon Absorption**: Chlorophyll pigments absorb light, which excites electrons to a higher energy state.
     - **Water Splitting**: Water molecules are split into oxygen, protons, and electrons. Oxygen is released as a byproduct.
     - **Electron Transport Chain**: Excited electrons travel through a series of proteins in the thylakoid membrane, transferring energy that is used to pump protons into the thylakoid lumen, creating a proton gradient.
     - **ATP Formation**: The proton gradient drives ATP synthase to produce ATP from ADP and inorganic phosphate.
     - **NADPH Formation**: Electrons reduce NADP+ to NADPH.
   - **Types of Photophosphorylation**:
     - **Non-Cyclic Photophosphorylation**: Produces ATP, NADPH, and oxygen. Involves both Photosystem II and Photosystem I.
     - **Cyclic Photophosphorylation**: Produces only ATP. Involves only Photosystem I.
2. **Light-Independent Reactions (Calvin Cycle)**:

    - **Purpose**: Use chemical energy from the light-dependent reactions to convert carbon dioxide into glucose.
    - **Process**:
        - **Carbon Fixation**: Carbon dioxide is attached to a five-carbon sugar called ribulose-1,5-bisphosphate (RuBP) by the enzyme Rubisco, forming a six-carbon compound that quickly splits into two three-carbon molecules (3-PGA).
        - **Reduction**: ATP and NADPH are used to convert 3-PGA into glyceraldehyde-3-phosphate (G3P), a three-carbon sugar.
        - **Regeneration**: Some G3P molecules are used to regenerate RuBP, allowing the cycle to continue. Other G3P molecules are used to form glucose and other carbohydrates.

Photosynthetic Pigments:

- **Chlorophylls**: The primary pigments responsible for capturing light energy. Chlorophyll a absorbs blue and red light, while chlorophyll b absorbs additional wavelengths of light.
- **Carotenoids**: Accessory pigments that capture light energy and pass it to chlorophyll. They include compounds like carotene and xanthophylls.
- **Phycobilins**: Water-soluble pigments found in certain algae and cyanobacteria.

Importance of Photosynthesis:

- **Oxygen Production**: Oxygen is released as a byproduct, which is essential for aerobic respiration in most living organisms.
- **Carbon Cycle**: Photosynthesis contributes to the global carbon cycle by converting atmospheric CO2 into organic compounds.
- **Energy Source**: Provides the primary energy source for plants and indirectly supports most other organisms through the food chain.

In summary, metabolism encompasses all biochemical processes within a cell, including anabolism and catabolism. Photosynthesis is a vital metabolic pathway that converts light energy into chemical energy, sustaining life by producing oxygen and organic compounds.

3.3 Contributions of Photosynthesis for the Continuity of Life, Oxygen and Carbon Dioxide Balance, and Global Warming

Photosynthesis plays a crucial role in sustaining life on Earth and maintaining the balance of gases in our atmosphere. Its contributions are significant in several key areas:

1. **Oxygen Production**:
   - **Primary Source**: Photosynthesis is the primary process through which oxygen is produced. During this process, plants, algae, and some bacteria convert carbon dioxide (CO_2) and water (H_2O) into glucose ($C_6H_{12}O_6$) and oxygen (O_2) using sunlight.
   - **Replenishment**: The oxygen produced by photosynthesis is essential for the survival of aerobic organisms, including humans. Plants continuously replenish the oxygen in the atmosphere, ensuring a steady supply for respiration.
2. **Food Production**:
   - **Direct and Indirect Dependence**: All food originates from photosynthesis. Plants convert sunlight into energy and produce carbohydrates, which serve as food for herbivores. These herbivores are, in turn, consumed by carnivores. Thus, photosynthesis forms the base of the food chain.
   - **Fossil Fuels**: Many of our modern energy sources, such as coal, oil, and natural gas, are ancient products of photosynthesis. Millions of years ago, plants absorbed CO_2 and sunlight to produce organic matter. This matter eventually became fossil fuels through geological processes.
3. **Carbon Dioxide and Oxygen Balance**:
   - **Carbon Sequestration**: Photosynthesis helps remove CO_2 from the atmosphere. Plants absorb CO_2 during photosynthesis and convert it into glucose, reducing the greenhouse gas concentration in the air.
   - **Balance Maintenance**: The balance between CO_2 and O_2 in the atmosphere is vital for regulating Earth's climate and supporting life. Photosynthesis helps maintain this balance by converting CO_2 into O_2 and organic matter.
4. **Impact on Global Warming**:
   - **Reduction of Greenhouse Gases**: By absorbing CO_2, photosynthesis mitigates the effects of global warming. CO_2 is a major greenhouse gas that contributes to climate change by trapping heat in the atmosphere. By reducing CO_2 levels, photosynthesis helps slow down the rate of global warming.
   - **Ongoing Need for Solar Energy**: Photosynthesis relies on sunlight to drive the conversion of CO_2 into glucose and O_2. This process is essential for recycling carbon, oxygen, and hydrogen in the environment. Continuous solar energy input is necessary to support this cycle and maintain the balance of gases.

In summary, photosynthesis is vital for life on Earth. It produces oxygen, supports the food chain, helps balance atmospheric gases, and plays a crucial role in mitigating global warming by removing carbon dioxide from the atmosphere.

3.4 Cellular Respiration

Cellular respiration is a crucial process by which cells convert glucose into energy. This energy is stored in a compound called ATP (Adenosine Triphosphate) and used for various cellular activities.

ATP and Energy Transfer

ATP consists of adenosine attached to three phosphate groups. The bonds between these phosphate groups, known as phosphoanhydride bonds, store high amounts of energy. When a phosphate group is removed through hydrolysis, ATP converts to ADP (Adenosine Diphosphate), releasing energy that the cell can use. Removing another phosphate group from ADP forms AMP (Adenosine Monophosphate), also releasing energy. AMP can be recycled back to ADP or ATP, maintaining a constant supply of energy in cells.

Coupled Reactions

Many biochemical reactions involve energy changes. Exothermic reactions release energy, while endothermic reactions require energy. To make these reactions efficient, they are often "coupled," meaning an exothermic reaction provides the energy needed for an endothermic reaction. A common example is the hydrolysis of ATP, which releases energy used for muscle contraction.

Example:

- **Hydrolysis of ATP:** ATP + H_2O → ADP + P + Energy
- **Muscle Contraction:** Relaxed muscle + Energy → Contracted muscle

Similarly, creatine phosphate can provide energy to regenerate ATP.

Example:

- **Hydrolysis of Creatine Phosphate:** Creatine-P + H_2O → Creatine + Pi + Energy
- **Regeneration of ATP:** ADP + Pi + Energy → ATP + H_2O

Stages of Cellular Respiration

Cellular respiration consists of several stages:

1. **Glycolysis:** Occurs in the cytosol and does not require oxygen. It breaks down glucose into two molecules of pyruvate, producing a small amount of ATP and NADH.
2. **Pyruvate Oxidation:** Pyruvate is converted into Acetyl-CoA in the mitochondria. This step produces NADH and releases carbon dioxide.

3. **Krebs Cycle (Citric Acid Cycle):** Acetyl-CoA enters the Krebs cycle in the mitochondria, combining with oxaloacetate to form citric acid. The cycle produces ATP, NADH, $FADH_2$, and releases carbon dioxide.
4. **Oxidative Phosphorylation:** Takes place in the mitochondria, involving the electron transport chain and chemiosmosis. Electrons from NADH and $FADH_2$ are transferred through proteins in the inner mitochondrial membrane, creating a proton gradient that drives ATP synthesis.

Energy Yield:

- Complete oxidation of one glucose molecule produces about 30-34 ATP molecules.

Non-Carbohydrate Sources of Energy

Cellular respiration can also use fats, proteins, and other carbohydrates. For instance:

- **Fats:** Broken down into glycerol and fatty acids. Fatty acids undergo beta-oxidation to form Acetyl-CoA.
- **Proteins:** Digested into amino acids, which can be converted into intermediates of glycolysis or the Krebs cycle.

Anaerobic Respiration (Fermentation)

In the absence of oxygen, pyruvate undergoes fermentation to regenerate NAD+ from NADH, allowing glycolysis to continue. There are two main types of fermentation:

- **Alcohol Fermentation:** Pyruvate is converted into ethanol and carbon dioxide, with NADH being oxidized back to NAD+.
- **Lactic Acid Fermentation:** Pyruvate is converted into lactic acid, regenerating NAD+.

Example of Alcohol Fermentation:

- Pyruvate → Acetaldehyde + CO_2 → Ethanol
- $NADH + H^+ \rightarrow NAD^+$

Cellular respiration ensures that cells have a continuous supply of ATP, supporting all cellular functions and maintaining energy balance.

Alcohol and Lactic Acid Fermentation

1. Alcohol Fermentation: Alcohol fermentation is a process used by yeasts and some bacteria to convert sugars into ethanol and carbon dioxide. This process occurs in the absence of oxygen (anaerobic conditions). It involves two main stages:

- **Glycolysis:** Glucose is broken down into pyruvate.
- **Fermentation:** Pyruvate is converted into ethanol (alcohol) and carbon dioxide. During this stage, NADH (produced in glycolysis) is oxidized to NAD+, which is then used in glycolysis to produce ATP.

2. Lactic Acid Fermentation: Lactic acid fermentation is a process that occurs in muscle cells and some bacteria. This process also happens under anaerobic conditions and involves:

- **Glycolysis:** Like in alcohol fermentation, glucose is broken down into pyruvate.
- **Fermentation:** Pyruvate is converted into lactic acid (or lactate). During this process, NADH is oxidized to NAD+.

Key Points:

- **Purpose of Lactic Acid Fermentation:** This process regenerates NAD+ from NADH, allowing glycolysis to continue producing ATP when oxygen is scarce. This is especially useful in muscle cells during intense exercise when oxygen levels drop.
- **Byproducts:** In humans, the byproduct is lactic acid, which can accumulate in muscles and cause fatigue. In bacteria, the byproducts are lactic acid and other compounds used in food production, such as yogurt and sour cream.
- **Applications:** Lactic acid fermentation is utilized in various food industries to produce dairy products.

Experimental Investigation:

To investigate fermentation rates, you can perform experiments using basic equipment or sophisticated fermenters. Below is a guide on how to conduct an investigation:

1. Effect of Temperature on Fermentation Rate:

- **Materials Needed:** Yeast suspension, glucose solution, fermentation tubes, water baths set at different temperatures.

- **Procedure:**
    - Label and prepare fermentation tubes with yeast and glucose.
    - Place the tubes in water baths at different temperatures (0°C, 22°C, 37°C, 70°C).
    - Monitor and measure the amount of CO_2 produced to determine the fermentation rate.

2. Effect of Different Substrates on Fermentation Rate:

- **Materials Needed:** Different types of sugars (glucose, fructose, sucrose, lactose), yeast suspension, fermentation tubes.
- **Procedure:**
    - Prepare fermentation tubes with different sugars.
    - Measure the volume of CO_2 produced to compare fermentation rates.

3. Effect of Substrate Concentration on Fermentation Rate:

- **Materials Needed:** Different concentrations of glucose solution, yeast suspension, fermentation tubes.
- **Procedure:**
    - Prepare fermentation tubes with varying concentrations of glucose.
    - Measure the volume of CO_2 produced to assess how concentration affects fermentation.

Important Considerations:

- **Independent Variable:** The factor you change in the experiment (e.g., temperature, type of sugar).
- **Dependent Variable:** The factor you measure (e.g., volume of CO_2 produced).
- **Control Variables:** Factors kept constant (e.g., yeast concentration, initial volume of solution) to ensure accurate results.

Data Collection:

- Record the start and end times, measure the volume of CO_2 produced, and calculate the fermentation rate for each condition.