Chapter 10: Photosynthesis

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PHOTOSYNTHESIS: Definition

- A series of chemical reactions in which the energy of sunlight is used to synthesize high-energy organic molecules, normally carbohydrates (such as glucose), from low-energy inorganic molecules, normally carbon dioxide and water.

- Photosynthesis converts sunlight energy to the chemical energy of food.

Summary of Photosynthesis

$$6\text{H}_2\text{O} + 6\text{CO}_2 \xrightarrow{\text{light energy}} 6\text{O}_2 + \text{C}_6\text{H}_{12}\text{O}_6$$

water carbon dioxide enzymes oxygen glucose
PHOTOSYNTHETIC ORGANISMS

Photosynthetic organisms (photoautotrophs) use sunlight energy to drive the synthesis of organic molecules from carbon dioxide and (in most cases) water. They feed not only themselves, but the entire living world.

- **Plants**
- Multicellular *Algae* (Kelp) and some unicellular *protists*
- Some Prokaryotes (cyanobacteria; purple-sulfur bacteria)
Photosynthesis: The Process that Feeds the Biosphere

- All organisms must acquire energy from the environment for their survival.

- **Autotrophs** (producers; “self-feeders”)
  - They sustain themselves without eating anything derived from other organisms. Autotrophs produce their organic molecules from $\text{CO}_2$ and other inorganic molecules obtained from the environment.
  - **Examples**: plants, algae, some protists, some prokaryotes (bacteria)
  - Many are **photoautotrophs**, they use light as a source of energy to synthesizes organic substances.

- **Heterotrophs** (consumers; “other-feeders”)
  - Unable to make their own food, they live on compounds produced by other organisms. They are **not** photosynthetic organisms.
  - **Examples**: animals, fungi, most protist species, most prokaryotes
BIOLOGY I.  Chapter 10

– Photosynthesis

Flow of Energy Through an Ecosystem

- **Producers** transform the sun’s energy to chemical energy by means of *photosynthesis*. Nutrients are then transferred from producers to **consumers** (organisms, such as animals, that feed on producers and other consumers) and from consumers to consumers.

- **Decomposers** such as fungi break down the organic molecules of dead organisms, making these nutrients available for reuse.

- Some energy is “lost” as heat, thereby becoming unavailable to the ecosystem to do work; therefore, organisms need a constant input of energy to perform the activities of life.

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The Importance of Photosynthesis: Photosynthesis is critical to human kind in many ways.

- Photosynthesis produces an enormous amount of carbohydrates, which are used by the majority of living things for growth, repair, and cellular work.
- Photosynthesizers also produce great amounts of oxygen as a by-product.
  - Oxygen is required by many organisms for cellular respiration.
  - Oxygen forms an ozone shield high in the atmosphere that filters out ultraviolet radiation and makes terrestrial life possible.
- The products of photosynthesis serve as a source of building materials, fabrics, paper, and pharmaceuticals.
- Photosynthesis consumes carbon dioxide from the atmosphere, which is otherwise a toxic gas if it is present in excess.
Energy flows into an ecosystem as sunlight and ultimately leaves as heat, while the chemical elements essential to life are recycled.

**Photosynthesis** (by algae, plants and some bacteria) generates oxygen and organic molecules used by the mitochondrion of eukaryotic organisms as fuel for **cellular respiration**. Respiration breaks this fuel down, generating ATP. The waste products of respiration, carbon dioxide and water, are the raw materials for photosynthesis.
Chloroplasts: The Site of Photosynthesis in Plants

- In **algae** and **plants**, photosynthesis takes place in the **chloroplasts**, membrane-bounded organelles.
- The **leaves** are the major sites of photosynthesis in most plants, but all green parts of a plant, including green stems and unripened fruit have chloroplasts.
- The leaves contain **mesophyll** tissue in which cells are specialized for photosynthesis.
The Location of Photosynthesis in Plants

- **Leaves** are the major organs of photosynthesis in plants. Inside plant cells, the **chloroplast** is the organelle where photosynthesis occurs.
- **Mesophyll**: The ground tissue of a leaf; specialized for photosynthesis.
- **Stoma** (plural, *stomata*): A microscopic pore that allow gas exchange between the environment and the interior of the plant.
- **Thylakoid**: A flattened membranous sac whose membrane contains the pigment **chlorophyll** for photosynthesis and ATP-synthesizing enzymes.
- **Stroma**: Within the chloroplast, the dense fluid surrounding the thylakoid membrane; involved in synthesis of organic molecules from carbon dioxide and water.
Eukaryotic Cell Organelles: The Chloroplast in Plants and Algae

- The membranous organelle that performs **photosynthesis** (capture of sun light energy to convert it into chemical energy in carbohydrates), in **algae** and **plants**.
- It has internal membranes called **thylakoids** that contain the photosynthetic pigment **chlorophyll**. The fluid outside the thylakoids is the **stroma**.

**FIGURE 4.16. Chloroplast.**

Chloroplasts carry out photosynthesis.

Generalized drawing of a chloroplast in which the outer and inner membranes have been cut away to reveal the grana, each of which is a stack of membranous sacs called thylakoids. In some grana, but not all, it is obvious that thylakoid spaces are interconnected.
FIGURE 7.2. Leaves and Photosynthesis.
Photosynthesis and the Nature of Sunlight

- Photosynthesis uses solar energy in the *visible-light* range of the *electromagnetic spectrum*, the entire spectrum of *electromagnetic radiation* or *energy*, from gamma rays to radio waves (less than a nanometer to more than a kilometer).
  - Electromagnetic waves are disturbances of electric and magnetic fields. These waves self-propagate in a vacuum or in matter.

- **Wavelength** is the distance between the crests of electromagnetic waves.
  - The wavelengths of light operating in photosynthesis occur in the visible spectrum between 400 (violet) and 700 nanometers (red).
  - *Electromagnetic radiation with shorter wavelengths* carry more energy.
Energy undulates across space in waves. The distance between crests of two successive waves is a **wavelength** and is measured in nanometers. About 2.5 million nanometers fit in one inch. Visible light is a very small part of the spectrum which includes all electromagnetic waves. Like many other organisms, we perceive visible light wavelengths as colors.
Figure 10.6 – The electromagnetic spectrum. White light is a mixture of all wavelengths of visible light. A prism can sort white light into its component colors by bending light of different wavelengths at different angles. (Droplets of water in the atmosphere can act as prisms, forming a rainbow). Visible light drives photosynthesis.
Photosynthetic Pigments: The Light Receptors

*Photosynthetic pigments* are molecules that absorb wavelengths of light.

The pigments found in chloroplasts are capable of absorbing various portions of visible light; this is called their *absorption spectrum* (a graph showing a pigment’s light absorption versus wavelength).

- **Chlorophylls** *a* and *b* absorb violet, blue, and red light best. Because green light is transmitted and reflected by chlorophyll, plant leaves appear green to us.

- Accessory pigments:
  - **Carotenoids** absorb light in the violet-blue-green range and reflect red, orange and yellow wavelengths.
Visible light contains forms of energy that differ according to wavelength and color. (a) The photosynthetic pigments in chlorophylls *a* and *b* and the carotenoids absorb certain wavelengths within visible light. This is their absorption spectrum. (b) The action spectrum for photosynthesis in plants—the wavelengths that are used when photosynthesis is taking place—matches well the sum of the absorption spectrums for chlorophylls *a* and *b* and the carotenoids.
Why Leaves are Green: Interaction of Light with Chloroplasts

- The chlorophyll molecules of chloroplasts absorb violet-blue and red-orange light (the colors most effective in driving photosynthesis) and reflect or transmit green light. This is why leaves appear green.
### Table 6.1 Major Photosynthetic Pigments

<table>
<thead>
<tr>
<th>Pigments</th>
<th>Reflected Colors</th>
<th>Present In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorophyll a</td>
<td>Yellow–green</td>
<td>Main pigment in all plants, algae, cyanobacteria</td>
</tr>
<tr>
<td>Chlorophyll b</td>
<td>Blue–green</td>
<td>Plants, green algae, cyanobacteria</td>
</tr>
<tr>
<td>Carotenoids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carotenes,</td>
<td>Yellow, orange,</td>
<td>Plants, algae, cyanobacteria</td>
</tr>
<tr>
<td>lycopenes</td>
<td>red</td>
<td></td>
</tr>
<tr>
<td>Xanthophylls</td>
<td>Yellow, brown</td>
<td>Plants, algae, cyanobacteria</td>
</tr>
<tr>
<td>Phycobilins</td>
<td>Red</td>
<td>Red algae, cyanobacteria</td>
</tr>
</tbody>
</table>
Preview of Photosynthesis: A Simplified Summary

Using molecular formulas, we can summarize the complex series of chemical reactions in photosynthesis with this chemical equation:

$$6 \text{CO}_2 + 12 \text{H}_2\text{O} + \text{Light energy} \rightarrow C_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 + 6 \text{H}_2\text{O}$$

(carbon dioxide) (water) (from the sun) (glucose) (oxygen) (water)

dioxide)

We can simplify the chemical equation by indicating only the net consumption of water:

$$6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{Sunlight energy} \rightarrow C_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2$$

(carbon dioxide) (water) (and enzymes) (glucose) (oxygen)
Preview of Photosynthesis: *A Simplified Summary*

The atoms from carbon dioxide (CO$_2$) are shown in orange-red, and the atoms from water (H$_2$O) are shown in blue.
The Two Stages of Photosynthesis: A Preview

In plants, photosynthesis occurs in the chloroplasts, using two major reaction sequences:

1. The light-reactions (light-dependent or light-driven reactions) (the photo part of photosynthesis), in the thylakoid membranes.

2. The Calvin cycle (light-independent reactions or carbon-fixation) (the synthesis part), in the stroma (fluid of the chloroplast) in plants.
Photosynthesis consists of light reactions ("photo" part of photosynthesis) and Calvin cycle reactions (the "synthesis" part; or light-independent reactions). The light reactions, which use solar energy to produce ATP and NADPH, occur in the thylakoids (oxygen is released). These molecules are used in the Calvin cycle reactions (in the stroma) to reduce carbon dioxide to carbohydrate (CH₂O).

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PHOTOSYNTHESIS: Light Reactions (Light-Dependent Reactions)

- The primary function of the light reactions is to convert solar energy to the chemical energy of ATP and NADPH; they occur in the thylakoids (flattened membranous sacs containing chlorophyll) of the chloroplast.

- Two complexes called photosystems I and II, (or P700 and P680), are the light-capturing units consisting of a protein complex called the reaction center, surrounded by light-harvesting complexes. The two photosystems absorb light best at different wavelengths.

- Light excites electrons in chlorophyll molecules in the light-harvesting complexes, and transfers the energetic electrons to electron transport chains. The energy of these electrons drives the processes in the light reactions.
How a Photosystem Harvests Light

- When a photon (particle of visible light) strikes a pigment molecule in a light-harvesting complex, the energy is passed from molecule to molecule until it reaches the reaction center complex. Here, an excited electron from the special pair of chlorophyll a molecules is transferred to the primary electron acceptor.
PHOTOSYNTHESIS: Light Reactions

- **Linear Electron Flow (Noncyclic Pathway)**
  - A route of electron flow that involves both photosystems (I and II) and produces ATP, NADPH, and O$_2$. The net electron flow is from H$_2$O to NADP$^+$. 

- **Cyclic Electron Flow**
  - A route of electron flow that employs only photosystem I, producing ATP but not NADPH or O$_2$.

  ✓ Cyclic electron flow can occur in photosynthetic bacteria that have photosystem I but not photosystem II, and also some organisms that possess both photosystems, including prokaryotes.
PHOTOSYNTHESIS: Summary of Light Reactions

1) **Photosystem II (P680) generates ATP.**
   - Some of the energy from the electrons is used to pump hydrogen ions into the thylakoids. The hydrogen ion concentration is therefore higher inside the thylakoids than in the stroma outside. **Hydrogen ions** move down this concentration gradient through **ATP-synthases** (ATP-synthesizing enzymes) in the thylakoid membranes, providing the energy to drive **ATP synthesis** (by **chemiosmosis**).

2) **Photosystem I (P700) generates NADPH.**
   - Some of the energy, in the form of **energetic electrons**, is added to electron-carrier molecules of NADP\(^+\) to make the highly energetic carrier **NADPH**.

3) **Splitting water maintains the flow of electrons through the photosystems.**
   - Some of the energy is used to **split water** molecules, generating **electrons**, **hydrogen ions**, and **oxygen**.
PHOTOSYNTHESIS: Light Reactions

*** Figure 7-4 (next slide):

1) Light is absorbed by **photosystem II**, and the energy is passed to electrons in the **reaction center chlorophyll** molecules.

2) Energized electrons leave the reaction center.

3) The electrons move into adjacent **electron transport chain**.

4) The chain passes the electrons along, and some of their energy is used to drive **ATP synthesis by chemiosmosis** (and through photophosphorylation of ADP). Energy depleted electrons replace those lost by photosystem I.

5) Light strikes **photosystem I**, and the energy is passed to electrons in the **reaction center chlorophyll** molecules.

6) Energized electrons leave the reaction center.

7) The electrons move into the **electron transport chain**.

8) The energetic electrons from photosystem I are captured in molecules of **NADPH**.

9) The electrons lost from the reaction center of photosystem II are replaced by electrons obtained from splitting **water**, a reaction that also releases **oxygen**, and **H⁺** used to form NADPH.
FIGURE 7-4. The light-dependent reactions of photosynthesis.
Figure 10.13. How linear electron flow during the light reactions of photosynthesis generates ATP and NADPH.
A Mechanical Analogy for the Light Reactions

The light reactions use solar power to generate ATP and NADPH, which provide chemical energy and reducing power, respectively, to the carbohydrate-synthesizing reactions of the Calvin cycle.
In both kinds of organelles, **electron transport chains** pump protons (H\(^+\)) across a membrane from a region of low H\(^+\) concentration (light gray in this diagram) to one of high H\(^+\) concentration (dark gray). The protons then diffuse back across the membrane through **ATP synthase**, driving the synthesis of ATP.
Each thylakoid membrane within a granum produces NADPH and ATP. Electrons move through sequential molecular complexes within the thylakoid membrane, and the last one passes electrons to NADP\(^+\), after which it becomes NADP. A carrier at the start of the electron transport chain pumps hydrogen ions from the stroma into the thylakoid space. When hydrogen ions flow back out of the space into the stroma through the ATP synthase complex, ATP is produced from ADP + P (photophosphorylation).
BIOLOGY I. Chapter 10 – Photosynthesis

Figure 10.17. The light reactions and chemiosmosis: the organization of the thylakoid membrane.

Photosynthesis

STROMA (Low H⁺ concentration)

Photosystem II

Cytochrome complex

Photosystem I

THYLAKOID SPACE (High H⁺ concentration)

H₂O

O₂

1/2 O₂
+2 H⁺

2 H⁺

NADP⁺ reductase

NADP⁺ + 2H⁺

NADPH + H⁺

To Calvin cycle

STROMA (Low H⁺ concentration)

Thylakoid membrane

ATP synthase

ADP + Pᵢ → ATP

H⁺
PHOTOSYNTHESIS: Calvin Cycle
(Light-Independent or Carbon Fixation Reactions)

- The main purpose of the Calvin cycle, or light-independent reactions: ATP and NADPH (produced in the light reactions) provide the energy that drives the synthesis of carbohydrate (glucose) from CO₂ and H₂O.

  - These reactions occur in the stroma (fluid material) of the chloroplasts of algae and plants, or the cytoplasm of photosynthetic bacteria (such as cyanobacteria).
  - * The Calvin cycle is anabolic, building sugar (carbohydrate) from smaller molecules and consuming energy.

- These light-independent reactions are also called the Calvin-Benson, or C₃ cycle. The Calvin cycle has three major phases (see next slide).
PHOTOSYNTHESIS: Calvin Cycle (Light-Independent Reactions)

1) Carbon fixation (CO$_2$ uptake)
   - Carbon dioxide and water combine with ribulose bisphosphate (RuBP) to form 3-phosphoglycerate (3-PG or PGA). The enzyme that catalyzes this first step is RuBP carboxylase, or rubisco.

2) Synthesis of G3P (CO$_2$ reduction).
   - 3-PG is converted to glyceraldehyde-3-phosphate (G3P or PGAL), using energy from ATP and NADPH.
   - *** The G3P spun off from the Calvin cycle becomes the starting material for synthesis of glucose, and other carbohydrates including sucrose, starch, and cellulose, as well as other organic molecules. These reactions occur primarily outside of the chloroplast.

3) Regeneration of RuBP (the CO$_2$ acceptor).
   - Ten molecules of G3P are used to regenerate six molecules of RuBP again using ATP energy.
Figure 10.18. The Calvin cycle.
FIGURE 7.8. The Calvin Cycle Reactions.

The Calvin Cycle involves the fixation of CO₂ and the conversion of 3 CO₂ into glucose. The cycle consists of three main stages: CO₂ fixation, reduction, and regeneration of RuBP.

- **CO₂ fixation**: The cycle starts with the fixation of CO₂ to form a 6-carbon intermediate, which is then reduced to form 3 C₃ molecules.
- **Reduction**: Each C₃ molecule is reduced to form 6 3-phosphoglycerate (3PG) molecules, which are then converted to glyceraldehyde-3-phosphate (G3P). 6 NADPH and 6 ATP are produced in this stage.
- **Regeneration**: The 6 G3P molecules are converted back into 6 RuBP molecules, each of which can fix another CO₂ molecule. This process requires 3 ADP and 3 P to form 3 ATP.

The cycle is summarized as follows:

- 3 RuBP → 6 3PG
- 6 3PG → 6 G3P
- 6 G3P → 6 RuBP + 3 ADP + 3 P → 3 ATP

The cycle results in a net gain of one G3P and two ATP, which can be used to synthesize glucose.
PHOTOSYNTHESIS: Calvin Cycle – *Fate of G3P*

- **G3P** is the first reactant in a number of plant cell metabolic pathways.
- Two G3Ps are needed to form *glucose-phosphate*; **glucose** is often considered the end product of photosynthesis.
- **Sucrose** is the transport sugar in plants; **starch** is the storage form of glucose; and **cellulose** is a major constituent of plant cell walls.
Animation: Calvin-Benson Cycle (Light-Independent Reactions)
Other Types of Photosynthesis in Hot, Arid Climates

- Plants that carry on photosynthesis as described, via the Calvin cycle, are called \( C_3 \) plants. The first stable product of photosynthesis is the 3-carbon molecule \( 3PG \).
  - The majority of plants are \( C_3 \) plants.

- Photorespiration:
  - This is a series of reactions that occurs in plants when carbon dioxide levels are depleted but oxygen continues to accumulate, and the enzyme RuBP carboxylase (rubisco) fixes oxygen instead of carbon dioxide. On dry, hot days, \( C_3 \) plants close their stomata (pores on leaves, for exchange of water and \( \text{CO}_2 \)), conserving water. Oxygen from the light reactions builds up.
  - This process is called photorespiration because in the presence of light (\textit{photo}), oxygen is taken up and \( \text{CO}_2 \) is released (\textit{respiration}). (No ATP or carbohydrates are produced).
Other Types of Photosynthesis

- **C₄ Photosynthesis:**
  - In **C₄ plants**, as opposed to the C₃ plants just described, the enzyme **PEPCase** (PEP carboxylase) fixes carbon dioxide to PEP (phosphoenolpyruvate, a C₃ molecule) to form a 4-carbon molecule, **oxaloacetate**, within mesophyll cells. A reduced form of this molecule (malate) is pumped into bundle sheath cells, where CO₂ is released to the Calvin cycle.

  - **Advantage:** **C₄ plants** can avoid photorespiration, which is wasteful because it is not part of the Calvin cycle. It does not occur in **C₄ plants** because PEPCase, unlike RuBP carboxylase, does not combine with O₂. Even when stomata are closed, CO₂ is delivered to the Calvin cycle in the bundle sheath cells.
Carbon Dioxide Fixation in C₃ and C₄ Plants

- In C₃ plants, CO₂ is taken up by the Calvin cycle directly in mesophyll cells.

- C₄ plants form a C₄ molecule in mesophyll cells prior to releasing CO₂ to the Calvin cycle in bundle sheath cells. There is a partitioning of pathways in space.

Figure 7.11. Carbon dioxide fixation in C₃ and C₄ plants.
C₄ Photosynthesis

- **C₄ leaf anatomy and the C₄ pathway.** The structure and biochemical functions of the leaves of C₄ plants are an evolutionary adaptation to hot, dry climates. This adaptation maintains a CO₂ concentration in the bundle sheath that favors photosynthesis over photorespiration.
Other Types of Photosynthesis

- **CAM Photosynthesis:** (CAM means crassulacean-acid metabolism)
  - The *Crassulaceae* is a family of flowering succulent (water-containing) plants that live in warm, dry regions of the world. CAM was first discovered in these plants, but now it is known to be prevalent among other types of plants.
  - In CAM plants, *the stomata (leaf pores) are open only at night*, conserving water.
  - PEPCase fixes CO$_2$ to PEP *only at night*, and the next day CO$_2$ is released and enters the Calvin cycle within the same cells.
  - This represents a *partitioning of pathways in time*: carbon dioxide fixation occurs at night, and the Calvin cycle occurs during the day.
CAM Photosynthesis: Carbon Dioxide Fixation in a CAM Plant

CAM plants, such as pineapple, fix CO₂ at night, forming a C₄ molecule that is released to the Calvin cycle during the day.

Pineapple and beavertail cactus are CAM plants.
Figure 10.20. C4 and CAM photosynthesis compared.
PHOTOSYNTHESIS

* What is the relationship between light reactions and Calvin cycle (light-independent reactions)?

- The light reactions produce the energy carrier ATP and the electron carrier NADPH.

- Energy from these carriers is used in the synthesis of organic molecules (such as glucose) during the Calvin cycle (light-independent reactions).

- The depleted carriers, ADP and NADP+, return to the light reactions for recharging.
Photosynthesis

• In **light reactions**, chlorophyll and other molecules in the thylakoids capture sun energy and convert some of it into chemical energy stored in energy-carrier molecules (**ATP** and **NADPH**). **Oxygen** gas is released as a by-product.

• In the **Calvin cycle (light-independent reactions)**, enzymes in the stroma use the chemical energy of the carrier molecules to drive the synthesis of **glucose** or other organic molecules (using **carbon dioxide** and **water**).

Figure pg. 118 (Audesirk, 7th Ed)
Photosynthesis consists of light reactions (“photo” part of photosynthesis) and Calvin cycle reactions (the “synthesis” part; or light-independent reactions). The light reactions, which use solar energy to produce ATP and NADPH, occur in the thylakoids (oxygen is released). These molecules are used in the Calvin cycle reactions (in the stroma) to reduce carbon dioxide to carbohydrate (CH$_2$O).
A Review of Photosynthesis

**Light reactions:**
- Are carried out by molecules in the thylakoid membranes
- Convert light energy to the chemical energy of ATP and NADPH
- Split $H_2O$ and release $O_2$ to the atmosphere

**Calvin cycle reactions:**
- Take place in the stroma
- Use ATP and NADPH to convert $CO_2$ to the sugar G3P
- Return ADP, inorganic phosphate, and NADP$^+$ to the light reactions

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**Diagram:**
- Photosystem II
- Electron transport chain
- Photosystem I
- Calvin cycle
- Light reactions
- Chloroplast
- $H_2O$
- $CO_2$
- NADP$^+$
- ADP
- $P_i$
- RuBP
- 3-Phosphoglycerate
- G3P
- Starch (storage)
- Amino acids
- Fatty acids
- Sucrose (export)
- $O_2$
Animation:
Overview of Photosynthesis:
Interrelationships of the Light Reactions and Calvin Cycle (Light-Independent Reactions)
# Summary of Photosynthesis

<table>
<thead>
<tr>
<th>Reaction Series</th>
<th>Summary of Process</th>
<th>Needed Materials</th>
<th>End Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-dependent reactions</td>
<td>Energy from sunlight used to split water, manufacture ATP, and reduce NADP⁺</td>
<td>Light energy; pigments (chlorophyll)</td>
<td>Electrons</td>
</tr>
<tr>
<td>(take place in thylakoid membranes)</td>
<td></td>
<td>Electrons, NADP⁺, H₂O, electron acceptors</td>
<td>NADPH, O₂</td>
</tr>
<tr>
<td>Photochemical reactions</td>
<td>Chlorophyll-activated; reaction center gives up photoexcited electron to electron acceptor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron transport</td>
<td>Electrons transported along chain of electron acceptors in thylakoid membranes; electrons reduce NADP⁺; splitting of water provides some H⁺ that accumulates inside thylakoid space</td>
<td>-Proton gradient, ADP + P, ATP synthase</td>
<td></td>
</tr>
<tr>
<td>Chemiosmosis</td>
<td>H⁺ permitted to diffuse across the thylakoid membrane down their gradient; they cross the membrane through special channels in ATP synthase complex; energy released is used to produce ATP</td>
<td></td>
<td>ATP</td>
</tr>
<tr>
<td>Carbon fixation reactions</td>
<td>Carbon fixation: Carbon dioxide used to make carbohydrate</td>
<td>Ribulose bisphosphate, CO₂, ATP, NADPH, necessary enzymes</td>
<td>Carbohydrates, ADP + P, NADP⁺</td>
</tr>
<tr>
<td>(take place in stroma)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Calvin cycle)</td>
<td></td>
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# A Comparison of Photosynthesis and Aerobic Cellular Respiration

**TABLE 9-2**

<table>
<thead>
<tr>
<th><strong>Type of metabolic reaction</strong></th>
<th><strong>Photosynthesis</strong></th>
<th><strong>Aerobic Respiration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>Anabolism</td>
<td>Catabolism</td>
</tr>
<tr>
<td>End products</td>
<td>CO₂, H₂O</td>
<td>C₆H₁₂O₆, O₂</td>
</tr>
<tr>
<td>Which cells have these processes?</td>
<td>Cells that contain chlorophyll (certain cells of plants, algae, and some bacteria)</td>
<td>Every actively metabolizing cell has aerobic respiration or some other energy-releasing pathway</td>
</tr>
<tr>
<td>Sites involved (in eukaryotic cells)</td>
<td>Chloroplasts</td>
<td>Cytosol (glycolysis); mitochondria</td>
</tr>
<tr>
<td>ATP production</td>
<td>By photophosphorylation (a chemiosmotic process)</td>
<td>By substrate-level phosphorylation and by oxidative phosphorylation (a chemiosmotic process)</td>
</tr>
<tr>
<td>Principal electron transfer compound</td>
<td>NADP⁺ is reduced to form NADPH*</td>
<td>NAD⁺ is reduced to form NADH*</td>
</tr>
<tr>
<td>Location of electron transport chain</td>
<td>Thylakoid membrane</td>
<td>Mitochondrial inner membrane (cristae)</td>
</tr>
<tr>
<td>Source of electrons for electron transport chain</td>
<td>In noncyclic electron transport: H₂O (undergoes photolysis to yield electrons, protons, and oxygen)</td>
<td>Immediate source: NADH, FADH₂</td>
</tr>
<tr>
<td>Terminal electron acceptor for electron transport chain</td>
<td>In noncyclic electron transport: NADP⁺ (becomes reduced to form NADPH)</td>
<td>Ultimate source: glucose or other carbohydrate</td>
</tr>
</tbody>
</table>

* NADPH and NADH are very similar hydrogen (i.e., electron) carriers, differing only in a single phosphate group. However, NADPH generally works with enzymes in anabolic pathways, such as photosynthesis. NADH is associated with catabolic pathways, such as cellular respiration.
Above: In photosynthesis, water is oxidized and oxygen is released; in cellular respiration, oxygen is reduced to water.

Middle: Both processes have an electron transport chain located within membranes (the grana of chloroplasts and the cristae of mitochondria), where ATP is produced by chemiosmosis.

Below: Both have enzyme-catalyzed reactions within the semifluid interior. In photosynthesis, CO₂ is reduced to a carbohydrate; in cellular respiration, a carbohydrate is oxidized to CO₂.
In **photosynthesis**, chloroplasts in green plants use the energy of sunlight to synthesize high-energy carbon compounds such as **glucose** from low-energy molecules of **water** and **carbon dioxide**. Plants themselves, and other organisms that eat plants or one another, extract energy from these organic molecules by **cellular respiration**, yielding **water** and **carbon dioxide** again. **This energy in turn drives all the reactions of life.**
Energy flows into an ecosystem as sunlight and ultimately leaves as heat, while the chemical elements essential to life are recycled. **Photosynthesis** (by plants and algae) generates oxygen and organic molecules used by the mitochondrion of eukaryotic organisms as fuel for **cellular respiration**. Respiration breaks this fuel down, generating ATP. The waste products of respiration, carbon dioxide and water, are the raw materials for photosynthesis.
Animation:
Link Between Photosynthesis and Cellular Respiration

CLICK TO PLAY
References


