

Chapter 10

Overview: The Process That Feeds the Biosphere

- **Photosynthesis** is the process that converts solar energy into chemical energy
- Directly or indirectly, photosynthesis nourishes almost the entire living world
- **Autotrophs** sustain themselves without eating anything derived from other organisms
- Autotrophs are the producers of the biosphere, producing organic molecules from CO₂ and other inorganic molecules
- Almost all plants are photoautotrophs, using the energy of sunlight to make organic molecules
- Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes
- These organisms feed not only themselves but also most of the living world
- **Heterotrophs** obtain their organic material from other organisms
- Heterotrophs are the consumers of the biosphere
- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O₂
- The Earth's supply of fossil fuels was formed from the remains of organisms that died hundreds of millions of years ago
- In a sense, fossil fuels represent stores of solar energy from the distant past

Concept 10.1: Photosynthesis converts light energy to the chemical energy of food

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria
- The structural organization of these cells allows for the chemical reactions of photosynthesis

Chloroplasts: The Sites of Photosynthesis in Plants

- Leaves are the major locations of photosynthesis
- Their green color is from **chlorophyll**, the green pigment within chloroplasts
- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- Each mesophyll cell contains 30–40 chloroplasts
- CO₂ enters and O₂ exits the leaf through microscopic pores called **stomata**
- The chlorophyll is in the membranes of **thylakoids** (connected sacs in the chloroplast); thylakoids may be stacked in columns called grana
- Chloroplasts also contain **stroma**, a dense interior fluid

Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis is a complex series of reactions that can be summarized as the following equation:

The Splitting of Water

- Chloroplasts split H₂O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules and releasing oxygen as a by-product

Photosynthesis as a Redox Process

- Photosynthesis reverses the direction of electron flow compared to respiration

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- Photosynthesis is a redox process in which H₂O is oxidized and CO₂ is reduced
- Photosynthesis is an endergonic process; the energy boost is provided by light

The Two Stages of Photosynthesis: A Preview

- Photosynthesis consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
- The light reactions (in the thylakoids)
 - Split H₂O
 - Release O₂
 - Reduce **NADP⁺** to NADPH
 - Generate ATP from ADP by **photophosphorylation**
- The Calvin cycle (in the stroma) forms sugar from CO₂, using ATP and NADPH
- The Calvin cycle begins with **carbon fixation**, incorporating CO₂ into organic molecules

Concept 10.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is a form of electromagnetic energy, also called electromagnetic radiation
- Like other electromagnetic energy, light travels in rhythmic waves
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy
- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (including those that drive photosynthesis) that produce colors we can see
- Light also behaves as though it consists of discrete particles, called **photons**

Photosynthetic Pigments: The Light Receptors

- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll reflects and transmits green light
- A **spectrophotometer** measures a pigment's ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength
- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll a** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of

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- radiation in driving a process
- The action spectrum of photosynthesis was first demonstrated in 1883 by Theodor W. Engelmann
- In his experiment, he exposed different segments of a filamentous alga to different wavelengths
- Areas receiving wavelengths favorable to photosynthesis produced excess O₂
- He used the growth of aerobic bacteria clustered along the alga as a measure of O₂ production
- Chlorophyll *a* is the main photosynthetic pigment
- Accessory pigments, such as **chlorophyll *b***, broaden the spectrum used for photosynthesis
- Accessory pigments called **carotenoids** absorb excessive light that would damage chlorophyll

Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state, which is unstable
- When excited electrons fall back to the ground state, photons are given off, an afterglow called fluorescence
- If illuminated, an isolated solution of chlorophyll will fluoresce, giving off light and heat

A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) transfer the energy of photons to the reaction center
- A **primary electron acceptor** in the reaction center accepts excited electrons and is reduced as a result
- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions
- There are two types of photosystems in the thylakoid membrane
- **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of 680 nm
- The reaction-center chlorophyll *a* of PS II is called P680
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

Linear Electron Flow

- During the light reactions, there are two possible routes for electron flow: cyclic and linear
- **Linear electron flow**, the primary pathway, involves both photosystems and produces ATP and NADPH using light energy
- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680

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- An excited electron from P680 is transferred to the primary electron acceptor (we now call it P680⁺)
- P680⁺ is a very strong oxidizing agent
- H₂O is split by enzymes, and the electrons are transferred from the hydrogen atoms to P680⁺, thus reducing it to P680
- O₂ is released as a by-product of this reaction
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of H⁺ (protons) across the membrane drives ATP synthesis
- In PS I (like PS II), transferred light energy excites P700, which loses an electron to an electron acceptor
- P700⁺ (P700 that is missing an electron) accepts an electron passed down from PS II via the electron transport chain
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
- The electrons are then transferred to NADP⁺ and reduce it to NADPH
- The electrons of NADPH are available for the reactions of the Calvin cycle
- This process also removes an H⁺ from the stroma

Cyclic Electron Flow

- **Cyclic electron flow** uses only photosystem I and produces ATP, but not NADPH
- No oxygen is released
- Cyclic electron flow generates surplus ATP, satisfying the higher demand in the Calvin cycle
- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria generate ATP by chemiosmosis, but use different sources of energy
- Mitochondria transfer chemical energy from food to ATP; chloroplasts transform light energy into the chemical energy of ATP
- Spatial organization of chemiosmosis differs between chloroplasts and mitochondria but also shows similarities
- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma
- ATP and NADPH are produced on the side facing the stroma, where the Calvin cycle takes place
- In summary, light reactions generate ATP and increase the potential energy of

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electrons by moving them from H₂O to NADPH

Concept 10.3: The Calvin cycle uses the chemical energy of ATP and NADPH to reduce CO₂ to sugar

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle
- The cycle builds sugar from smaller molecules by using ATP and the reducing power of electrons carried by NADPH
- Carbon enters the cycle as CO₂ and leaves as a sugar named **glyceraldehyde 3-phosphate (G3P)**
- For net synthesis of 1 G3P, the cycle must take place three times, fixing 3 molecules of CO₂
- The Calvin cycle has three phases
 - **Carbon fixation** (catalyzed by **rubisco**)
 - **Reduction**
 - **Regeneration of the CO₂ acceptor (RuBP)**

Concept 10.4: Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- Dehydration is a problem for plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis
- On hot, dry days, plants close stomata, which conserves H₂O but also limits photosynthesis
- The closing of stomata reduces access to CO₂ and causes O₂ to build up
- These conditions favor an apparently wasteful process called **photorespiration**

Photorespiration: An Evolutionary Relic?

- In most plants (**C₃ plants**), initial fixation of CO₂, via rubisco, forms a three-carbon compound (3-phosphoglycerate)
- In photorespiration, rubisco adds O₂ instead of CO₂ in the Calvin cycle, producing a two-carbon compound
- Photorespiration consumes O₂ and organic fuel and releases CO₂ without producing ATP or sugar
- Photorespiration may be an evolutionary relic because rubisco first evolved at a time when the atmosphere had far less O₂ and more CO₂
- Photorespiration limits damaging products of light reactions that build up in the absence of the Calvin cycle
- In many plants, photorespiration is a problem because on a hot, dry day it can drain as much as 50% of the carbon fixed by the Calvin cycle

C₄ Plants

- **C₄ plants** minimize the cost of photorespiration by incorporating CO₂ into four-carbon compounds in mesophyll cells
- This step requires the enzyme **PEP carboxylase**
- PEP carboxylase has a higher affinity for CO₂ than rubisco does; it can fix CO₂ even when CO₂ concentrations are low
- These four-carbon compounds are exported to **bundle-sheath cells**, where they

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- release CO₂ that is then used in the Calvin cycle
- In the last 150 years since the Industrial Revolution, CO₂ levels have risen greatly
- Increasing levels of CO₂ may affect C₃ and C₄ plants differently, perhaps changing the relative abundance of these species
- The effects of such changes are unpredictable and a cause for concern

CAM Plants

- Some plants, including succulents, use **crassulacean acid metabolism (CAM)** to fix carbon
- **CAM plants** open their stomata at night, incorporating CO₂ into organic acids
- Stomata close during the day, and CO₂ is released from organic acids and used in the Calvin cycle

The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
- Plants store excess sugar as starch in structures such as roots, tubers, seeds, and fruits
- In addition to food production, photosynthesis produces the O₂ in our atmosphere