Cell Biology: Carbon Fixation and Photosynthesis

AI-Generated Study Guide

(Based on [lectures delivered by Dr. Ty C.M. Hoffman])

I. Overview of Photosynthesis

- **Definition:** The process by which certain organisms convert light energy into chemical energy, creating organic compounds from inorganic sources.
- **Producers vs. Consumers:** Photosynthetic organisms are producers, meaning they make their own food. Consumers rely on producers for organic molecules.
- **Historical Context:** Photosynthesis evolved at least 2 billion years ago, long before plants (which are only about 500 million years old) and even before eukaryotes.
- **Diversity of Photosynthetic Organisms:Plants:** Major photosynthesizers on land.
- **Bacteria:** Photosynthetic bacteria existed before eukaryotes and are still globally important.
- **Algae:** Major photosynthetic organisms in oceans, older than plants. All algae are protists.
- **Protists:** A catch-all term for any eukaryote that is not an animal, plant, or fungus. Photosynthetic protists are called algae.
- **Chemosynthesis:** An alternative production method using chemical energy instead of light, but most production is photosynthetic.
- **Reciprocal Relationship with Cellular Respiration:** Photosynthesis and the complete oxidation of glucose are reciprocal processes. The starting materials of one are the ending products of the other, and vice-versa. However, they are not simply reverse reactions; they are complex, multi-step pathways.

II. Anatomy of Photosynthesis in Plants

- **Leaves:** The primary organs of photosynthesis in typical plants due to their specialized structure and green color (indicating chlorophyll presence).
- **Exceptions:** Cacti photosynthesize in their stems.
- **Leaf Structure (Cross-section):Waxy Epidermal Layers:** Waterproof outer layers.

- **Stomata (singular: stoma):** Openings on the leaf surface for gas exchange (CO_2 intake, O_2 release, water vapor release).
- **Mesophyll Cells:** Middle section of the leaf, containing numerous chloroplasts.
- **Chloroplasts:** The organelles of eukaryotic photosynthesis.
- **Structure:Double Membrane:** Outer and inner membranes.
- **Thylakoid Membrane:** Elaborately folded inner membrane, forming coin-like structures called thylakoids. This is where the light-dependent reactions occur.
- **Thylakoids:** Individual coin-like structures.
- **Grana (singular: granum):** Stacks of thylakoids.
- **Intermembrane Space:** Compartment between the outer and inner membranes.
- **Stroma:** The fluid-filled space inside the inner membrane but outside the thylakoids. This is where the light-independent reactions (Calvin Cycle) occur.
- **Thylakoid Space (Lumen):** The interior compartment of the thylakoids.
- **Function:** Analogous to mitochondria in respiration; increased membrane surface area (thylakoids) allows for more photosynthetic machinery.

III. Summary Reaction of Photosynthesis

- **Overall Equation:** $6CO_2 + 12H_2O$ + Light Energy → $C_6H_{12}O_6 + 6O_2 + 6H_2O$
- **Simplified Equation:** $6CO_2 + 6H_2O$ + Light Energy → $C_6H_{12}O_6 + 6O_2$
- **Source of Oxygen:** The oxygen released as a byproduct of photosynthesis comes *exclusively* from the splitting of water (H_2O), not from carbon dioxide. This is reciprocal to cellular respiration, where oxygen accepts electrons and protons to form water.

IV. The Two Major Parts of Photosynthesis

Photosynthesis is divided into two main sets of reactions:

A. Light-Dependent Reactions (Light Reactions)

- **Location:** Thylakoid membrane within the chloroplast.
- **Purpose:** To convert light energy into chemical energy in the form of ATP and NADPH, which will power the Calvin Cycle.
- **Inputs:** Light energy, Water (H_2O), ADP, $NADP^+$
- **Outputs:** Oxygen (O_2 – waste product), ATP, NADPH
- **Key Processes:Light Absorption by Pigments:Light as Energy:** Electromagnetic radiation, described as waves (wavelength, frequency) and particles (photons).
- **Electromagnetic Spectrum:** Photosynthesis primarily uses the visible light portion (approx. 400-750 nm), coincidentally the same range humans see.
- **Pigments:** Substances that absorb certain wavelengths of visible light and reflect others.
- **Chlorophyll:** The chief photosynthetic pigment (chlorophyll a and chlorophyll b). Appears green because it absorbs red and blue light well, but reflects green light.

- **Carotenoids:** Accessory pigments that widen the range of light absorbed.
- **Absorption Spectrum:** Graphs showing how well different wavelengths of light are absorbed by specific pigments.
- **Action Spectrum:** Graphs showing the rate of photosynthesis (e.g., O2 release) at different wavelengths of light, indicating which wavelengths are most effective.
- **Chlorophyll Molecule:** Consists of a light-absorbing "head" (pigment part) and a hydrophobic hydrocarbon "tail" that anchors it in the thylakoid membrane.
- **Photosystems:** Protein complexes embedded in the thylakoid membrane that capture light energy.
- **Structure:** Consist of light-harvesting complexes (containing pigment molecules) surrounding a reaction-center complex (containing a special pair of chlorophyll a molecules and a primary electron acceptor).
- **Function:** Prevent wasteful fluorescence by funneling excitation energy (via resonance energy transfer) to the reaction center.
- **Excitation and Electron Transfer:** When a photon strikes a pigment, an electron is excited to a higher energy level. This excitation energy is passed among pigments until it reaches the reaction center, where an electron is completely stripped from the special chlorophyll pair and transferred to the primary electron acceptor (oxidation of chlorophyll, reduction of acceptor). This is the initial conversion of light energy to chemical energy.
- **Electron Transport Chains (ETCs):Photosystem II (PSII):** Functions first.
- **Electron Source:** Water is split (photolysis) to replace the lost electron in PSII's reaction center, releasing O2 as a byproduct. Water also provides protons.
- **Electron Destination:** Electrons are passed from PSII to the first ETC.
- **First Electron Transport Chain:** Transfers electrons, pumping protons from the stroma into the thylakoid space, creating a proton gradient.
- **ATP Synthesis (Chemiosmosis):** Protons diffuse back into the stroma through ATP synthase, generating ATP from ADP and inorganic phosphate.
- **Photosystem I (PSI):** Functions second.
- **Electron Source:** Receives electrons from the first ETC.
- **Excitation:** Absorbs another photon, re-exciting the electron.
- **Electron Destination:** Passes the excited electron to a shorter second ETC.
- **Second Electron Transport Chain:** Transfers electrons to NADP+, reducing it to NADPH (and H+). This chain does not pump protons.
- **Types of Electron Flow:Non-Cyclic Electron Flow (Linear):** The primary pathway, involving both PSII and PSI, producing both ATP and NADPH. Electrons move in one direction from water to NADPH.
- **Cyclic Electron Flow:** Involves only PSI. Electrons from PSI are recycled back to the first ETC (between PSII and PSI), leading to *only* ATP production. No NADPH is made, and no water is split.
- **Regulation:** Plants switch between non-cyclic and cyclic flow to adjust the ATP:NADPH ratio. The Calvin Cycle requires more ATP (3:2 ATP to NADPH ratio), so cyclic flow helps meet the higher ATP demand. When NADP+ taxis are full (all are NADPH), electrons are shunted to cyclic flow.

B. Light-Independent Reactions (Calvin Cycle)

- **Location:** Stroma of the chloroplast.
- **Purpose:** To use the ATP and NADPH generated in the light-dependent reactions to fix inorganic carbon (CO_2) into organic compounds (sugars). This is an anabolic and endergonic process.
- **Inputs:** CO_2, ATP, NADPH
- **Outputs:** Glyceraldehyde-3-phosphate (G3P) – a 3-carbon sugar (the direct output of photosynthesis). ADP, NADP+ (recycled back to light reactions).
- **Key Processes:Carbon Fixation (Phase 1):Definition:** The process of incorporating inorganic carbon (CO_2) into an organic molecule. This is the ecologically most important part of photosynthesis.
- **Enzyme:** RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) – the most abundant enzyme on Earth.
- **Substrates:** Ribulose-1,5-bisphosphate (RuBP, a 5-carbon sugar) and CO_2.
- **Reaction:** RuBisCO adds CO_2 to RuBP, forming an unstable 6-carbon intermediate that immediately splits into two 3-carbon compounds called 3-phosphoglycerate.
- **Photorespiration:** A problem where RuBisCO can bind O_2 instead of CO_2, leading to a wasteful process that consumes ATP and doesn't produce sugar. Oxygen has a higher affinity for RuBisCO than CO_2.
- **Reduction (Phase 2):**3-phosphoglycerate molecules are converted into Glyceraldehyde-3-phosphate (G3P).
- This phase consumes ATP and NADPH.
- **Regeneration of CO_2 Acceptor (Phase 3):**Most G3P molecules are used to regenerate RuBP (the CO_2 acceptor), which requires additional ATP.
- **Output (G3P):**G3P is the direct product of the Calvin Cycle.
- Two G3P molecules can combine to form a 6-carbon sugar like glucose.
- G3P can also be used to synthesize other organic molecules (amino acids, lipids, etc.).
- Plants often export sugar (e.g., sucrose) from leaves to other parts of the plant (e.g., roots) for fuel.

V. Adaptations to Minimize Photorespiration

- **C3 Plants:** Most plants; they perform carbon fixation and the Calvin cycle in mesophyll cells, experiencing photorespiration when O_2 levels are high.
- **C4 Plants:** Have evolved anatomical and biochemical adaptations to minimize photorespiration.
- **Spatial Separation:** Carbon fixation occurs in mesophyll cells, and the Calvin cycle occurs in deeper bundle-sheath cells.
- **PEP Carboxylase:** In mesophyll cells, CO_2 is initially fixed by PEP carboxylase (which has no affinity for O_2) into a 4-carbon compound (e.g., malate).

- **CO_2 Delivery:** This 4-carbon compound is transported to bundle-sheath cells, where CO_2 is released and enters the Calvin cycle. This creates a high CO_2 concentration around RuBisCO, minimizing photorespiration.
- **CAM Plants (Crassulacean Acid Metabolism):** Adaptations for arid environments.
- **Temporal Separation:** Carbon fixation and the Calvin cycle occur in the same cells but at different times.
- **Night:** Stomata open to take in CO_2, which is fixed into organic acids (e.g., malate) and stored. This minimizes water loss in hot daytime conditions.
- **Day:** Stomata close. The stored organic acids release CO_2, which then enters the Calvin cycle. This provides CO_2 when light is available for ATP/NADPH production, without the risk of high daytime water loss or excessive photorespiration.

Photosynthesis Quiz

Instructions: Answer each question in 2-3 sentences.

1. Describe the primary function of photosynthetic organisms in an ecosystem.
2. Explain why plants appear green to the human eye, even though chlorophyll is crucial for absorbing light.
3. Name the two major parts of photosynthesis and state where each occurs within the chloroplast.
4. What is the direct source of the oxygen gas (O_2) released during photosynthesis? How does this relate to cellular respiration?
5. What are the two high-energy molecules produced by the light-dependent reactions that are essential for the Calvin Cycle?
6. Explain the difference between non-cyclic and cyclic electron flow in the light-dependent reactions. Why would a plant switch between these two modes?
7. Define carbon fixation. What is the name of the most abundant enzyme responsible for this process, and what is its unfortunate dual function?
8. What is photorespiration, and why is it considered problematic for C3 plants?
9. Briefly describe how C4 plants minimize photorespiration.
10. How do CAM plants spatially and temporally separate their photosynthetic processes to adapt to arid conditions?

Quiz Answer Key

1. Photosynthetic organisms are producers, meaning they convert inorganic carbon (CO_2) into organic compounds (food) using light energy. This process, known as carbon fixation, forms the base of most food webs, upon which consumers depend for their organic molecules.

2. Plants appear green because their primary photosynthetic pigment, chlorophyll, absorbs red and blue wavelengths of light very effectively for photosynthesis. However, it poorly absorbs green light, which is instead reflected off the leaf and perceived by our eyes as green.
3. The two major parts of photosynthesis are the **light-dependent reactions**, which occur in the **thylakoid membrane**, and the **light-independent reactions (Calvin Cycle)**, which occur in the **stroma** of the chloroplast.
4. The direct source of O2 released during photosynthesis is the splitting of water (H2O) molecules. This is reciprocal to cellular respiration, where oxygen acts as the final electron acceptor, combining with electrons and protons to form water.
5. The two high-energy molecules produced by the light-dependent reactions that are essential for the Calvin Cycle are **ATP (adenosine triphosphate)** and **NADPH (nicotinamide adenine dinucleotide phosphate, reduced form)**.
6. Non-cyclic electron flow involves both Photosystem II and I, producing both ATP and NADPH. Cyclic electron flow involves only Photosystem I and produces only ATP. A plant switches between them to balance the ATP and NADPH production, as the Calvin Cycle requires more ATP than NADPH (a 3:2 ratio).
7. Carbon fixation is the process of incorporating inorganic carbon (carbon dioxide) into an organic molecule. The most abundant enzyme responsible for this is RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase), which unfortunately can also bind oxygen as a substrate (oxygenase function), leading to photorespiration.
8. Photorespiration is a wasteful process in C3 plants where RuBisCO binds O2 instead of CO2, leading to the consumption of ATP and a lack of sugar production. It costs the plant energy to undo the products of photorespiration, reducing photosynthetic efficiency.
9. C4 plants minimize photorespiration by spatially separating carbon fixation and the Calvin Cycle into different cell types: mesophyll cells and bundle-sheath cells. PEP carboxylase in mesophyll cells efficiently fixes CO2 even in low concentrations, and the CO2 is then concentrated in bundle-sheath cells where the Calvin Cycle occurs, minimizing RuBisCO's exposure to oxygen.
10. CAM plants minimize photorespiration and water loss by temporally separating carbon fixation and the Calvin Cycle. They open stomata and fix CO2 into organic acids at night when temperatures are cooler and humidity is higher. During the day, stomata close, and the stored CO2 is released for use in the Calvin Cycle.

Essay Format Questions

1. Compare and contrast the structure and function of mitochondria and chloroplasts, highlighting their reciprocal roles in energy metabolism and how their internal compartmentalization facilitates their respective processes.
2. Discuss the evolutionary significance of photosynthesis, explaining how it transformed Earth's atmosphere and enabled the development of complex life forms. Include a

discussion of the major types of photosynthetic organisms and their relative historical emergence.
3. Explain the journey of energy from sunlight to the formation of a 3-carbon sugar molecule (G3P) in a typical C3 plant. Detail the roles of pigments, photosystems, electron transport chains, and the Calvin Cycle, identifying the key inputs and outputs at each stage.
4. Analyze the problem of photorespiration for C3 plants. Then, describe two distinct evolutionary adaptations (C4 and CAM pathways) that different plant groups have developed to mitigate this problem, comparing their mechanisms of spatial and/or temporal separation.
5. Photosynthesis is an anabolic and endergonic process. Elaborate on what these terms mean in the context of photosynthesis, and explain how the light-dependent reactions provide the necessary energy currency (ATP and NADPH) to drive the anabolic and endergonic reactions of the Calvin Cycle.

Glossary of Key Terms

- **Absorption Spectrum:** A graph plotting the amount of light absorbed by a pigment versus its wavelength.
- **Accessory Pigments:** Pigments (like carotenoids) that absorb light wavelengths not effectively absorbed by chlorophyll, widening the range of light usable for photosynthesis.
- **Action Spectrum:** A graph plotting the effectiveness of different wavelengths of light in driving a specific process, such as photosynthesis, often measured by O2 release.
- **Algae (singular: alga):** Photosynthetic protists; can be unicellular or multicellular.
- **Anabolic:** A metabolic process that builds complex molecules from simpler ones, requiring energy.
- **ATP (Adenosine Triphosphate):** A high-energy molecule that serves as the main energy currency of the cell.
- **ATP Synthase:** An enzyme complex that catalyzes the synthesis of ATP from ADP and inorganic phosphate, driven by the flow of protons across a membrane.
- **Bundle-Sheath Cells:** Specialized cells surrounding the vascular bundles in C4 plants, where the Calvin cycle takes place.
- **CAM Plants (Crassulacean Acid Metabolism):** Plants that fix CO2 at night and use it during the day, a temporal separation adaptation to arid environments.
- **Carbon Fixation:** The initial incorporation of inorganic carbon (CO2) from the atmosphere into an organic molecule.
- **Carotenoids:** Yellow and orange accessory pigments in plants that broaden the spectrum of colors that can drive photosynthesis and provide photoprotection.
- **C3 Plants:** Plants that use only the Calvin cycle for carbon fixation, forming a three-carbon compound as the first stable intermediate. Most common plant type.

- **C4 Plants:** Plants that have adapted to hot, dry climates by spatially separating carbon fixation (in mesophyll cells) from the Calvin cycle (in bundle-sheath cells).
- **Calvin Cycle (Light-Independent Reactions):** The set of metabolic reactions that occur in the stroma of the chloroplast, using ATP and NADPH to fix CO_2 into sugars.
- **Chemiosmosis:** The process of using the energy of a proton (H^+) gradient across a membrane to drive cellular work, such as ATP synthesis.
- **Chemosynthetic Organisms:** Organisms that produce organic compounds using chemical energy from the oxidation of inorganic substances, rather than light energy.
- **Chlorophyll:** The main photosynthetic pigment in plants, absorbing red and blue light and reflecting green light.
- **Chloroplast:** The organelle found in plant and algal cells where photosynthesis takes place.
- **Consumers:** Organisms that obtain energy by feeding on other organisms or their organic remains.
- **Cyclic Electron Flow:** A pathway in the light-dependent reactions that involves only Photosystem I, producing only ATP, without the production of NADPH or the splitting of water.
- **Electron Transport Chain (ETC):** A series of protein complexes that transfer electrons, releasing energy to pump protons and create an electrochemical gradient.
- **Endergonic:** A chemical reaction that requires an input of energy to proceed (non-spontaneous).
- **Excitation:** The process of an electron moving to a higher energy level, often by absorbing a photon.
- **Fluorescence:** The emission of light by a substance that has absorbed light, typically at a longer wavelength than the absorbed light, occurring almost immediately after absorption.
- **G3P (Glyceraldehyde-3-Phosphate):** A three-carbon sugar molecule that is the direct product of the Calvin Cycle and a precursor for glucose and other organic compounds.
- **Grana (singular: Granum):** Stacks of thylakoids within the chloroplast.
- **Hydrocarbon Tail:** A nonpolar, hydrophobic chain composed of hydrogen and carbon atoms, found in molecules like chlorophyll and fatty acids, which helps anchor them in membranes.
- **Intermembrane Space (Chloroplast):** The narrow space between the outer and inner membranes of the chloroplast.
- **Light-Dependent Reactions:** The first stage of photosynthesis, occurring on the thylakoid membranes, where light energy is converted into chemical energy (ATP and NADPH).
- **Light-Harvesting Complex:** A protein complex containing pigment molecules that gathers light energy and transfers it to the reaction-center complex of a photosystem.
- **Light-Independent Reactions:** See Calvin Cycle.
- **Malate:** A four-carbon organic acid that transports carbon dioxide from mesophyll cells to bundle-sheath cells in C4 plants.

- **Mesophyll Cells:** The internal cells of a leaf, between the upper and lower epidermis, where most photosynthesis occurs in C3 plants and initial carbon fixation occurs in C4 plants.
- **NADPH (Nicotinamide Adenine Dinucleotide Phosphate, Reduced Form):** A high-energy electron carrier molecule used in anabolic reactions, particularly in the Calvin cycle of photosynthesis.
- **NADP+ (Nicotinamide Adenine Dinucleotide Phosphate, Oxidized Form):** The oxidized form of NADPH, an "empty taxi" ready to accept electrons.
- **Non-Cyclic Electron Flow:** The main pathway of electron flow in the light-dependent reactions, involving both Photosystem II and Photosystem I, producing both ATP and NADPH. Also called linear electron flow.
- **Oxidation:** The loss of electrons from a substance.
- **PEP Carboxylase:** An enzyme found in C4 and CAM plants that catalyzes the initial fixation of CO2 into a four-carbon compound; has no affinity for O2.
- **Phosphorescence:** A type of luminescence where light is emitted after an excitation, but the emission continues for a longer period after the light source is removed (like "glow-in-the-dark" materials).
- **Photolysis:** The splitting of water molecules during the light-dependent reactions of photosynthesis, which provides electrons to Photosystem II and releases oxygen as a byproduct.
- **Photon:** A discrete packet of light energy.
- **Photorespiration:** A metabolic pathway that consumes oxygen, releases carbon dioxide, and decreases photosynthetic output; generally occurs on hot, dry days when stomata close, and RuBisCO binds O2 instead of CO2.
- **Photosynthesis:** The process by which green plants and some other organisms use sunlight to synthesize foods from carbon dioxide and water.
- **Photosystem:** A light-capturing unit in the thylakoid membrane, consisting of a reaction-center complex surrounded by light-harvesting complexes.
- **Primary Electron Acceptor:** A molecule in the reaction center of a photosystem that accepts excited electrons from the special pair of chlorophyll a molecules, becoming reduced.
- **Producers:** Organisms that produce their own food, typically through photosynthesis or chemosynthesis, forming the base of a food chain.
- **Protists:** A diverse group of eukaryotic organisms that are not animals, plants, or fungi.
- **Reaction-Center Complex:** The core of a photosystem, containing a special pair of chlorophyll a molecules that can lose an excited electron to a primary electron acceptor.
- **Reduction:** The gain of electrons by a substance.
- **Resonance Energy Transfer:** The non-radiative transfer of excitation energy from one pigment molecule to an adjacent one within a light-harvesting complex.
- **Ribulose-1,5-bisphosphate (RuBP):** A five-carbon sugar that is the initial CO2 acceptor in the Calvin Cycle.
- **RuBisCO (Ribulose-1,5-bisphosphate Carboxylase/Oxygenase):** The enzyme that catalyzes the first step of carbon fixation in the Calvin Cycle, attaching CO2 to RuBP; can also bind O2.

- **Stoma (plural: Stomata):** Pores on the leaf surface, regulated by guard cells, that allow for gas exchange (CO_2 intake, O_2 and water vapor release).
- **Stroma:** The dense fluid within the chloroplast, outside the thylakoid membranes, where the Calvin Cycle takes place.
- **Thylakoid:** A flattened sac or disc-like membrane found within the chloroplasts, where the light-dependent reactions occur.
- **Thylakoid Membrane:** The internal membrane system of chloroplasts, extensively folded to form thylakoids and grana, providing a large surface area for photosynthetic reactions.
- **Thylakoid Space (Lumen):** The interior compartment of the thylakoids, where protons accumulate during the light-dependent reactions.
- **Wavelength:** The distance between successive crests of a wave, a characteristic property of electromagnetic radiation.