

Lecture Outline: Carbon Fixation and Photosynthesis

I. Introduction to Photosynthesis

- A. Photosynthesis is an ancient process, predating plants and eukaryotes.
- B. Photosynthetic organisms are ecological **producers**, making their own food.

- 1. Most producers are photosynthetic; some are chemosynthetic.
- 2. Consumers rely entirely on producers for food.

C. Examples of Photosynthetic Organisms

- 1. **Plants**: Major photosynthesizers on land.
- 2. **Algae**: Major photosynthesizers in oceans, older than plants.
 - a. Algae are classified as **protists**, a catch-all term for eukaryotes that are not animals, plants, or fungi.
- 3. Photosynthetic bacteria exist and are globally important.

D. Overall Process of Photosynthesis

- 1. **Anabolic** process: Builds larger, more complex organic molecules (sugars) from smaller inorganic molecules (carbon dioxide).
- 2. **Endergonic** process: Requires energy input, supplied by sunlight.
- 3. Summary Reaction (simplified): $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$

4. Reciprocal relationship with complete oxidation of glucose (cellular respiration).
 - a. Starting point of photosynthesis is ending point of glucose oxidation, and vice versa.
 - b. Unlike cellular respiration, photosynthesis occurs entirely within the **chloroplast**.

II. Plant Structures for Photosynthesis

A. **Leaves:** Primary organs of photosynthesis in typical plants.

1. Any green part of a plant can photosynthesize, but leaves are specialized.

B. Leaf Anatomy

1. Waxy epidermal layers: Waterproofing.
2. **Stomata** (singular: stoma): Openings on leaf surface.
 - a. Allow **gas exchange**: CO₂ enters for photosynthesis, O₂ (byproduct) is released.
 - b. Water vapor also exits through stomata.
3. **Mesophyll cells**: Middle section of the leaf, where most photosynthesis takes place.

C. Chloroplasts

1. Organelles of eukaryotic photosynthesis, typically 50 per mesophyll cell.
2. **Doubly membrane-bounded**: outer and inner membranes.
3. Inner membrane folds extensively to form **thylakoid membranes**.
 - a. Individual coin-like structures are **thylakoids**.
 - b. Stacks of thylakoids are **grana** (singular: granum).
 - c. Increased membrane surface area analogous to cristae in mitochondria, enhancing efficiency.

d. Site where light-dependent reactions occur.

4. **Three compartments within chloroplasts:**

a. Intermembrane space (between outer and inner membranes).

b. **Stroma:** Inside the inner membrane but outside the thylakoids.

(1) Site where the Calvin cycle (light-independent reactions) takes place.

d. **Thylakoid space** (lumen): Interior of the thylakoids.

III. **Light: The Energy Source**

A. Light is a form of **electromagnetic radiation**.

1. Can be described as waves (wavelength, frequency, amplitude) and particles (**photons**).

2. **Wavelength:** Distance between two corresponding points on a wave.

3. **Frequency:** Number of wave crests passing a point per unit time.

4. Relationship: Longer wavelength = lower frequency = lower energy. Shorter wavelength = higher frequency = higher energy.

B. **Electromagnetic Spectrum**

1. Visible light is a small portion (approx. 400-750 nanometers).

2. Plants use the same range of visible light as humans see.

3. Blue/violet end: high energy, shorter wavelength.

4. Red end: lower energy, longer wavelength.

C. **Pigments and Light Absorption**

1. A **pigment** is any substance that absorbs specific wavelengths of visible light.

2. **Chlorophyll**: The chief photosynthetic pigment ("green leaf").
 - a. Why plants look green: Chlorophyll absorbs red and blue light for photosynthesis but reflects green light, which is then seen by our eyes. Green light is largely useless for photosynthesis.
3. Types of photosynthetic pigments in plants:
 - a. **Chlorophyll A** and **Chlorophyll B**: Have slightly different chemical structures (CH₃ vs. CHO group) leading to different absorption spectra.
 - b. **Carotenoids**: Accessory pigments that broaden the range of light absorbed.
4. **Absorption Spectrum**: Graph showing how well a pigment absorbs different wavelengths of light.
5. **Action Spectrum**: Graph showing the rate of photosynthesis (e.g., O₂ release) at different wavelengths, demonstrating which wavelengths are most effective.

D. Chlorophyll Molecule Structure

1. **Pigment part** (porphyrin ring with Magnesium): The "business end" that absorbs photons and captures energy.
2. **Hydrocarbon tail**: Hydrophobic, anchors the chlorophyll molecule within the thylakoid membrane.

E. Excitation and Energy Transfer

1. When a photon strikes a pigment molecule, its energy excites an electron, bumping it to a higher energy level. The photon ceases to exist.
2. In isolated chlorophyll, this excitation energy is lost as light (**fluorescence**) and heat, which is wasteful.
3. In a plant, chlorophyll is organized into **photosystems** to prevent wasteful fluorescence.

IV. Photosystems and Light-Dependent Reactions

A. Photosystem Structure

1. Embedded in the **thylakoid membrane**.
2. Composed of:
 - a. **Light-harvesting complexes**: Protein complexes holding various pigment molecules (chlorophyll A, B, carotenoids).
 - b. **Reaction-center complex**: A core containing a special pair of chlorophyll 'a' molecules and a primary electron acceptor.
3. Prevents fluorescence by efficiently transferring excitation energy.

B. Mechanism of Energy Capture

1. A photon strikes a pigment in a light-harvesting complex, exciting an electron.
2. Excitation energy is passed from pigment to pigment via **resonance energy transfer** until it reaches the special chlorophyll 'a' pair in the reaction center.
3. The special chlorophyll 'a' becomes highly excited and loses an electron completely.
4. This electron is immediately accepted by the **primary electron acceptor** within the reaction center.
 - a. This is an **oxidation-reduction** (redox) reaction, converting light energy into chemical energy.

C. Two Types of Photosystems

1. **Photosystem II (PSII)**: Operates first.
 - a. Loses an electron from its reaction center.
 - b. Replacement electrons come from the **splitting of water** (**photolysis**).

- (1) H₂O is broken down into electrons, protons (H⁺), and **oxygen gas (O₂)**.
- (2) O₂ is a waste product of photosynthesis but essential for cellular respiration.
- (3) This is why water is a required input for photosynthesis.

2. **Photosystem I (PSI)**: Operates second.

- a. Loses an electron from its reaction center.
- b. Replacement electrons come from the **electron transport chain** linking PSII and PSI.

D. **Electron Transport Chain (ETC) and ATP Synthesis**

1. Electrons from the primary electron acceptor of PSII are passed down an ETC between PSII and PSI.
2. As electrons move down the chain, they release energy used to **pump protons (H⁺)** from the stroma into the thylakoid space.
3. This creates a **proton gradient** (stored energy) across the thylakoid membrane.
4. Protons flow back out of the thylakoid space into the stroma through **ATP synthase** molecules (**chemiosmosis**).
5. This flow drives the phosphorylation of ADP to produce **ATP**.

E. **NADPH Production**

1. Electrons from PSI are passed down a shorter second ETC.
2. These electrons are then used to reduce **NADP⁺** (oxidized form) to **NADPH** (reduced form).
 - a. NADPH is a phosphorylated version of NADH, acting as an electron carrier specialized for photosynthesis.

F. **Purpose of Light-Dependent Reactions**: To convert light

energy into chemical energy stored in **ATP and NADPH**.

1. Both ATP and NADPH are then supplied to the Calvin cycle.

G. **Non-cyclic vs. Cyclic Electron Flow**

1. **Non-cyclic electron flow:** The usual process described above, producing both ATP and NADPH (and O₂ from water).
2. **Cyclic electron flow:**
 - a. Electrons from PSI are recycled back to the first ETC between PSII and PSI.
 - b. Only produces **ATP**; no NADPH is made.
 - c. Occurs when the Calvin cycle requires more ATP than NADPH (e.g., a 3:2 ratio of ATP to NADPH).
 - d. Regulated by the availability of NADP⁺ (if all NADP⁺ is reduced to NADPH, electrons are forced into cyclic flow).

V. **Light-Independent Reactions (Calvin Cycle)**

- A. **Location:** Occurs in the **stroma** of the chloroplast.
- B. **Purpose:** To use the ATP and NADPH from the light-dependent reactions to **fix inorganic carbon (CO₂) into organic molecules (sugars)**.
- C. **Carbon Fixation:** The crucial process of incorporating inorganic carbon (from CO₂) into an organic compound. No consumers can perform this.
- D. **Three Phases of the Calvin Cycle:**
 1. **Carbon Fixation**
 - a. CO₂ is combined with **Ribulose biphosphate (RuBP)**, a 5-carbon sugar, forming an unstable 6-carbon intermediate.
 - b. The 6-carbon intermediate immediately breaks into two molecules of **3-phosphoglycerate** (3-carbon

compounds).

c. Enzyme: **RuBisCO** (Ribulose biphosphate carboxylase oxygenase).

(1) Most abundant enzyme on Earth.

(2) **Carboxylase activity**: Binds CO₂ (desired for carbon fixation).

(3) **Oxygenase activity**: Can bind O₂ instead of CO₂ (undesired).

2. Reduction

a. 3-phosphoglycerate molecules are reduced.

b. **ATP and NADPH are consumed** (energy from light reactions).

c. Produces **Glyceraldehyde 3-phosphate (G3P)**, a 3-carbon sugar.

d. G3P is the direct output of photosynthesis.

e. G3P molecules can be combined to form 6-carbon sugars (like glucose) or used to synthesize other organic compounds (e.g., amino acids if nitrogen is available).

3. Regeneration of CO₂ Acceptor

a. Most G3P molecules are used to regenerate **RuBP**.

b. Requires additional **ATP consumption**.

c. Ensures the cycle can continue to accept more CO₂.

E. **Interdependence with Light-Dependent Reactions**: The Calvin cycle is "light-independent" but relies on ATP and NADPH produced by the light-dependent reactions. It will cease in prolonged darkness.

F. Output Utilization:

1. G3P forms various organic compounds for the plant.

2. Glucose produced can be used as fuel in the plant's own mitochondria.
3. Sugars are often exported as **sucrose** (table sugar) to other parts of the plant (e.g., roots) that don't photosynthesize.

VI. Photorespiration and Plant Adaptations

- A. **Photorespiration**: When RuBisCO binds **oxygen** instead of carbon dioxide.
 1. Costly to the plant:
 - a. Does not fix carbon or produce sugar.
 - b. Consumes energy (ATP) to "undo" the problem.
 2. Problem exacerbated by oxygen having a higher affinity for RuBisCO than carbon dioxide.
- B. **C3 Plants**: Most common type of plant, performing photosynthesis as described, and thus susceptible to photorespiration.
- C. **C4 Plants**: Evolved a mechanism to minimize photorespiration through **spatial separation**.
 1. Involves two types of cells: **mesophyll cells** (near surface) and **bundle sheath cells** (deeper).
 2. **Mesophyll cells**: Perform initial carbon fixation using **PEP carboxylase** (only binds CO₂, not O₂). CO₂ is fixed into a 4-carbon compound (e.g., malate).
 3. **Bundle sheath cells**: Malate is transported here and releases CO₂. These cells are deeper and have lower O₂ concentration. The Calvin cycle occurs here with RuBisCO, minimizing photorespiration.
 4. This mechanism is more efficient, especially in hot, dry conditions.
- D. **CAM Plants** (Crassulacean Acid Metabolism): Evolved a

mechanism to minimize photorespiration through **temporal separation**.

1. Adaptation for very hot, arid environments to conserve water.
2. **Nighttime**: Stomata open to allow CO₂ entry. CO₂ is fixed into organic acids using PEP carboxylase and stored. This reduces water loss during the day.
3. **Daytime**: Stomata close (conserving water). Stored organic acids release CO₂, which then enters the Calvin cycle within the same cell. O₂ cannot enter.
4. This strategy ensures CO₂ is available for the Calvin cycle when stomata are closed and photorespiration is minimized.