Photosynthesis

Light reactions

Solar energy

H₂O

NADP⁺

ATP

thylakoid membrane

Calvin Cycle reactions

CO₂

ADP + Pi

NADPH

O₂

CH₂O

stroma

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Outline

- Photosynthetic Organisms
- Photosynthetic Process
- Plants as Solar Energy Converters
- Photosynthesis
  - Light Reactions
    - Noncyclic
    - Cyclic
  - Calvin Cycle Reactions
    - Fixation of Carbon Dioxide
    - C4
    - CAM
Photosynthetic Organisms

- All life on Earth depends on a star 93 million miles away (solar energy)
- Photosynthetic organisms (algae, plants, and cyanobacteria) transform solar energy into carbohydrates
  - Called **autotrophs** because they produce their own food.
- Photosynthesis:
  - A process that captures solar energy
  - Transforms solar energy into chemical energy
  - Energy ends up stored in a carbohydrate
- Photosynthesizers produce all food energy
  - Only 42% of sun’s energy directed towards Earth reaches surface
  - Of this, only 2% is captured by photosynthesizers
  - Of this, only a tiny portion results in biomass
Photosynthetic Organisms

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Photosynthesis

- Photosynthesis takes place in the green portions of plants
  - Leaf of flowering plant contains mesophyll tissue
  - Cells containing chloroplasts
  - Specialized to carry on photosynthesis
- Raw materials for photosynthesis are carbon dioxide and water
  - Roots absorb water that moves up vascular tissue
  - Carbon dioxide enters a leaf through small openings called **stomata**
  - Diffuses into chloroplasts in mesophyll cells
  - In stroma, CO\textsubscript{2} combined with H\textsubscript{2}O to form C\textsubscript{6}H\textsubscript{12}O\textsubscript{6} (sugar)
  - Energy supplied by light
    - **Chlorophyll** and other pigments absorbs solar energy and energize electrons prior to reduction of CO\textsubscript{2} to a carbohydrate
Leaves and Photosynthesis

- Leaves
- Photosynthesis
- Leaf cross section
- Granum
- Chloroplast
- Stroma
- Thylakoid space
- Thylakoid membrane
- Independent thylakoid in a granum
- Overlapping thylakoid in a granum

CO₂ → O₂ → Stoma → Stroma

Cuticle
Upper epidermis
Mesophyll
Lower epidermis

37,000×

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Photosynthetic Pigments

- Pigments:
  - Chemicals that absorb some colors in rainbow more than others
  - Colors least absorbed reflected/transmitted most

- Absorption Spectra
  - Pigments found in chlorophyll absorb various portions of visible light
  - Graph showing relative absorption of the various colors of the rainbow
  - Chlorophyll is green because it absorbs much of the reds and blues of white light
Photosynthetic Pigments

a. The electromagnetic spectrum includes visible light.

b. Absorption spectrum of photosynthetic pigments.
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Photosynthetic Reactions: Two Sets of Reaction

- **Light Reaction** – takes place only in the presence of light
  - They are the energy-capturing reactions
  - Chlorophyll absorbs solar energy
  - This energizes electrons
  - Electrons move down electron transport chain
    - Pumps H\(^+\) into thylakoids
    - Used to make ATP out of ADP and NADPH out of NADP

- **Calvin Cycle Reaction** takes place in stroma
  - CO\(_2\) is reduced to a carbohydrate
  - Use ATP and NADPH produced carbohydrate
  - They are synthetic reactions
Photosynthesis Overview

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Photosynthetic Reactions: The Light Reactions

- Light reactions consist of two alternate electron pathways:
  - Noncyclic electron pathway
  - Cyclic electron pathway

- Capture light energy with photosystems
  - Pigment complex helps collect solar energy like an antenna
  - Occur in the thylakoid membranes

- Both pathways produce ATP
- The noncyclic pathway also produces NADPH
Light Reactions:
The Noncyclic Electron Pathway

- Takes place in thylakoid membrane
- Uses two photosystems, PS-I and PS-II
- PS II captures light energy
- Causes an electron to be ejected from the reaction center (chlorophyll \( a \))
  - Electron travels down electron transport chain to PS-I
  - Replaced with an electron from water
  - Which causes H\(^+\) to concentrate in thylakoid chambers
  - Which causes ATP production
- PS-I captures light energy and ejects an electron
  - Transferred \textit{permanently} to a molecule of NADP\(^+\)
  - Causes NADPH production
Light Reactions: Noncyclic Electron Pathway

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Light Reactions: The Cyclic Electron Pathway

- Uses only photosystem I (PS-I)
- Begins when PS I complex absorbs solar energy
- Electron ejected from reaction center
  - Travels down electron transport chain
  - Causes H\(^+\) to concentrate in thylakoid chambers
  - Which causes ATP production
  - Electron returns to PS-I (cyclic)
- Pathway only results in ATP production
Organization of the Thylakoid Membrane

- **PS II:**
  - Consists of a pigment complex and electron-acceptors
  - Adjacent to an enzyme that oxidizes water
  - Oxygen is released as a gas
- **Electron transport chain:**
  - Consists of cytochrome complexes
  - Carries electrons between PS II and PS I
  - Also pump H\(^+\) from the stroma into thylakoid space
- **PS I:**
  - Has a pigment complex and electron acceptors
  - Adjacent to enzyme that reduces NADP\(^+\) to NADPH
- **ATP synthase complex:**
  - Has a channel for H\(^+\) flow
  - Which drives ATP synthase to join ADP and P\(_i\)
Organization of a Thylakoid

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In plants, photosynthesis occurs in specialized organelles called chloroplasts. The internal membranes of chloroplasts are organized into sacs called thylakoids.
ATP Production

- Thylakoid space acts as a reservoir for hydrogen ions (H⁺)
- Each time water is oxidized, two H⁺ remain in the thylakoid space
- Electrons yield energy
  - Used to pump H⁺ across thylakoid membrane
  - Move from stroma into the thylakoid space
- Flow of H⁺ back across thylakoid membrane
  - Energizes ATP synthase
  - Enzymatically produces ATP from ADP + Pᵢ
- This method of producing ATP is called chemiosmosis
Ecology Focus: Tropical Rain Forests

- Equatorial; Temp>$26^\circ$C; Rainfall>200cm & uniform
- Most plants woody; many vines and epiphytes; little or no undergrowth
- Contribute greatly to CO$_2$ uptake, slowing global warming
  - Development has reduced them from 14% to 6% of Earth’s surface
  - Deforestation adds 20-30% of atmospheric CO$_2$, but also removes CO$_2$ sink
  - Increasing temps also reduce productivity
Ecology Focus: Global Warming and Tropical Rain Forests

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Calvin Cycle Reactions: Overview of C3 Photosynthesis

- A cyclical series of reactions
- Utilizes atmospheric carbon dioxide to produce carbohydrates
- Known as C3 photosynthesis
- Involves three stages:
  - Carbon dioxide fixation
  - Carbon dioxide reduction
  - RuBP regeneration
Calvin Cycle Reactions: Carbon Dioxide Fixation

- CO$_2$ is attached to 5-carbon RuBP molecule
  - Result in a 6-carbon molecule
  - This splits into two 3-carbon molecules (3PG)
  - Reaction accelerated by RuBP Carboxylase (Rubisco)
- CO$_2$ now “fixed” because it is part of a carbohydrate
The Calvin Cycle: Fixation of CO$_2$

The Calvin Cycle is a series of chemical reactions that occurs in the stroma of chloroplasts. These reactions use the energy from light to convert CO$_2$ into organic molecules such as glucose. The cycle involves the fixation of CO$_2$ into a six-carbon molecule, known as RuBP, which is then split into two three-carbon molecules. These three-carbon molecules can be reduced to form organic compounds, and the cycle continues until six molecules of ATP and six molecules of NADPH are produced. These molecules are then used by the plant to produce glucose and other organic molecules.

The metabolites of the Calvin Cycle include RuBP, ribulose-1,5-bisphosphate; 3PG, 3-phosphoglycerate; BPG, 1,3-bisphosphoglycerate; G3P, glyceraldehyde-3-phosphate; ATP, adenosine triphosphate; and NADPH, nicotinamide adenine dinucleotide phosphate.

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Calvin Cycle Reactions: Carbon Dioxide Reduction

- 3PG reduced to BPG
- BPG then reduced to G3P
- Utilizes NADPH and some ATP produced in light reactions
The Calvin Cycle: Reduction of $\text{CO}_2$

As 3PG becomes G3P, ATP becomes ADP + P and NADPH becomes NADP$^+$.
Calvin Cycle Reactions: Regeneration of RuBP

- RuBP used in CO$_2$ fixation must be replaced

- Every three turns of Calvin Cycle,
  - Five G3P (a 3-carbon molecule) used
  - To remake three RuBP (a 5-carbon molecule)
  - $5 \times 3 = 3 \times 5$
As five molecules of G3P become three molecules of RuBP, three molecules of ATP become three molecules of ADP + P.
Importance of Calvin Cycle

- G3P (glyceraldehyde-3-phosphate) can be converted to many other molecules
- The hydrocarbon skeleton of G3P can form:
  - Fatty acids and glycerol to make plant oils
  - Glucose phosphate (simple sugar)
  - Fructose (which with glucose = sucrose)
  - Starch and cellulose
  - Amino acids
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Fate of G3P

G3P

- glucose phosphate
- fatty acid synthesis
- amino acid synthesis
- + fructose phosphate
- sucrose
- starch
- cellulose
C₄ Photosynthesis

- In hot, dry climates
  - Stomata must close to avoid wilting
  - CO₂ decreases and O₂ increases
  - O₂ starts combining with RuBP instead of CO₂
  - Photorespiration, a problem solve in C₄ plants

- In C₄ plants
  - Fix CO₂ to PEP a C₃ molecule
  - The result is oxaloacetate, a C₄ molecule
  - In hot & dry climates
    - Avoid photorespiration
    - Net productivity about 2-3 times C₃ plants
  - In cool, moist, can’t compete with C₃
Chloroplast Distribution in $C_4$ vs. $C_3$ Plants

$C_3$ Plant

- bundle sheath cell
- mesophyll cells
- vein
- stoma

$C_4$ Plant

- bundle sheath cell
- mesophyll cells
- vein
- stoma
CO₂ Fixation in C₄ vs. C₃ Plants

a. CO₂ fixation in a C₃ plant, blue columbine, Aquilegia caerulea

b. CO₂ fixation in a C₄ plant, corn, Zea mays

b: © Nigel Cattlin/Photo Researchers, Inc.
Cam Photosynthesis

- **Crassulacean-Acid Metabolism**
  - CAM plants partition carbon fixation by time
    - **During the night**
      - CAM plants fix CO$_2$
      - Forms C$_4$ molecules,
      - Stored in large vacuoles
    - **During daylight**
      - NADPH and ATP are available
      - Stomata closed for water conservation
      - C$_4$ molecules release CO$_2$ to Calvin cycle
CO₂ Fixation in a CAM Plant

CO₂ fixation in a CAM plant, pineapple, Ananas comosus

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Climatic Adaptation: Photosynthesis

- Each method of photosynthesis has advantages and disadvantages.
- Depends on the climate.
- $C_4$ plants most adapted to:
  - High light intensities
  - High temperatures
  - Limited rainfall
- $C_3$ plants better adapted to
  - Cold (below 25°C)
  - High moisture
- CAM plants better adapted to extreme aridity
  - CAM occurs in 23 families of flowering plants
  - Also found among nonflowering plants
Review

- Flowering Plants
- Photosynthetic Pigments
- Photosynthesis
  - Light Reactions
    - Noncyclic
    - Cyclic
  - Carbon Fixation
    - Calvin Cycle Reactions
    - C4
    - CAM
Photosynthesis

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Solar energy

H₂O

CO₂

Calvin Cycle reactions

ADP + P

NADP⁺

NADP⁺

ATP

thylakoid membrane

stroma

thylakoid membrane

O₂

CH₂O