Lab-wide Learning Outcomes for Photosynthesis Explored

Knowledge-Based Outcomes

Upon completion of *Photosynthesis Explored*, students should be able to:

1. Describe photosynthesis as a process whereby plants use light energy to convert water and carbon dioxide into carbohydrates and oxygen.
2. Explain that during photosynthesis, the energy in sunlight is converted into chemical potential energy stored in molecules like glucose.
3. Identify the locations where the two main stages of photosynthesis occur: light-dependent reactions (thylakoid membrane) and the Calvin cycle (chloroplast stroma).
4. Summarize the overall inputs and outputs of the light-dependent reactions: H_2O + ADP + Pi + $NADP^+$ + light → ATP + NADPH + O_2.
5. Explain how ATP and NADPH shuttle energy from the light-dependent reactions to the Calvin cycle.
6. Summarize the overall inputs and outputs of the Calvin cycle: CO_2 + ATP + NADPH → G3P + ADP + $NADP^+$.

Photosynthesis Explored, Part 1: Plants, Photosynthesis, and Energy

Knowledge-Based Outcomes

Upon completion of *Part 1: Plants, Photosynthesis, and Energy*, students should be able to:

1. Describe the role of plants in capturing and storing energy that supports most life on Earth.
2. Explain that most of a terrestrial plant's dry mass comes from CO_2 in the air, not from the soil.
3. Identify where photosynthesis occurs in plants (chloroplasts) and distinguish the roles of chloroplasts and mitochondria.
4. Describe how stomata enable gas exchange for photosynthesis.
5. Identify and compare different forms of energy storage in the photosynthetic pathway.
6. Define key terms: photosynthesis, chloroplast, mitochondria, potential energy, thylakoid, thylakoid membrane, stroma.

Skills-Based Outcomes

Upon completion of *Part 1: Plants, Photosynthesis, and Energy*, students should be able to:

1. Interpret data from simulations to infer that most dry plant mass comes from carbon dioxide in the air, and not the soil.
2. In a diagram of a chloroplast, label the thylakoids and stroma, and indicate on the diagram which part of photosynthesis occurs in each location.
3. Use energy diagrams (seesaw or spring representations) to reason about energy transfer among molecules during photosynthesis.
4. Sort molecules involved in photosynthesis (e.g. CO_2, H_2O, ATP, etc.) into higher- and lower-energy molecules and indicate whether they are inputs or outputs of the light-dependent reactions or Calvin cycle.

Photosynthesis Explored, Part 2: Mechanism of Light-Dependent Reactions

Knowledge-Based Outcomes

Upon completion of *Part 2: Mechanism of Light-Dependent Reactions*, students should be able to:

1. Describe the relationship between wavelength and color of light.
2. Explain the role of chlorophyll in absorbing specific wavelengths of light and why most plants appear green.
3. Describe how antenna complexes increase light capture.
4. Explain how photosystem II splits water and transfers energy to electrons.
5. Describe how energy from electrons is used to pump protons into the thylakoid lumen, generating a proton gradient that stores energy.
6. Explain that photosystem I uses light energy to transfer electrons to proteins, eventually reaching $NADP^+$ in order to make NADPH.
7. Illustrate how a proton gradient stores energy and how ATP synthase uses it to make ATP.
8. Explain oxidation and reduction in the context of electron flow through the light-dependent reactions.
9. Define pigment, chlorophyll, ATP, NADPH, reduction, oxidation.

Skills-Based Outcomes

Upon completion of *Part 2: Mechanism of Light-Dependent Reactions*, students should be able to:

- Predict the color of a pigment given its absorption spectrum.
- Given a redox reaction involved in photosynthesis, show the movement of electrons between molecules.
- Predict how perturbations to the light-dependent reactions will alter ATP production and H_2O consumption.
- Predict what could happen to a cell or whole plant based on perturbations to the light-dependent reactions.

Photosynthesis Explored, Part 3: Mechanism of the Calvin Cycle

Knowledge-Based Outcomes

Upon completion of *Part 3: Mechanism of the Calvin Cycle*, students should be able to:

1. Explain how replacing C-O bonds with C-H bonds (i.e., reducing carbon) increases the energy stored in a molecule.
2. Explain how we know that carbon dioxide is not incorporated directly into glucose during the Calvin cycle.
3. Describe the three phases of the Calvin cycle and what happens during each phase in terms of function, reactants, and products.
4. Define carbon fixation and explain that RuBisCO incorporates CO_2 into RuBP to make two PGA molecules.
5. Explain why energy from NADPH and ATP is required for reducing PGA to G3P.
6. Explain why RuBP needs to be regenerated, and why most of the G3P produced by reduction is used in this step.
7. Track the flow and conservation of carbon atoms through the Calvin cycle, and explain why three CO_2 molecules are fixed per each G3P molecule produced.
8. Distinguish between molecules that enter or exit the Calvin cycle and those that are used as intermediates.

Skills-Based Outcomes

Upon completion of *Part 3: Mechanism of the Calvin Cycle*, students should be able to:

- Based on the Calvin-Benson experiment, predict where radioactive carbon dioxide would first be observed if carbon dioxide were incorporated directly into glucose.
- Predict how blocking parts of the Calvin cycle will affect carbon fixation, G3P production, and RuBP regeneration.

Photosynthesis Explored, Part 4: C3, C4, and CAM Photosynthesis

Knowledge-Based Outcomes

Upon completion of *Part 4:* C_3*,* C_4*, and CAM Photosynthesis*, students should be able to:

1. Describe the conditions under which photorespiration is most likely to occur, and explain why it is problematic for a plant.
2. Explain why the terms "C_3" and "C_4" are used to describe different forms of photosynthesis.
3. Describe the anatomical and functional differences between leaf tissue in C_3 plants and that in C_4 plants.
4. Explain how and why C_4 plants concentrate CO_2.
5. Explain the fundamental challenges faced by plants in tropical and arid environments, and discuss how C_4 and CAM photosynthesis help some plants to overcome these challenges.
6. Explain the trade-offs between having stomata open vs. closed in environments that differ in humidity and temperature.
7. Explain how and why CAM plants store CO_2.
8. Explain why most plant species in the world use C_3 photosynthesis.

Skills-Based Outcomes

Upon completion of *Part 4:* C_3*,* C_4*, and CAM Photosynthesis*, students should be able to:

1. Given a change to temperature, humidity, or CO_2 level, predict the effect on photosynthesis, in terms of carbohydrate production, photorespiration risk, and water loss, in a C_3 plant with stomata open versus closed.
2. Given environmental characteristics of a location (temperature, humidity), assess whether the location would be likely to have species of plants that perform C_4 or CAM photosynthesis.
3. Label a diagram of the interior structure of a leaf from a C_3 plant and a C_4 plant, focusing on the arrangement of mesophyll and bundle sheath cells.