Photosynthesis

How do light-dependent and light-independent reactions provide food for a plant?

Why?

Plants are the original solar panels. Through photosynthesis a plant is able to convert electromagnetic (light) energy into chemical energy. This energy is used not only to keep the plant alive, but also to sustain all creatures that rely on the plant for food and shelter. Plants and photosynthetic algae are also the source of all oxygen on Earth, allowing the inhabitants of Earth to benefit from our most plentiful renewable energy resource.

Model 1 – Chloroplast

\[6 \text{CO}_2 + 12 \text{H}_2 \text{O} + \text{sunlight energy} \rightarrow \text{C}_6 \text{H}_{12} \text{O}_6 + 6 \text{O}_2 + 6 \text{H}_2 \text{O}\]

1. Consider the organelle illustrated in Model 1.
   a. What is the name of this organelle?
      A chloroplast.
   b. Is this organelle more likely to be found in animal cells or plant cells?
      Chloroplasts are found in plant cells.

2. The structures inside the organelle in Model 1 are called thylakoids. What compound necessary for photosynthesis is contained in the thylakoids?
   Chlorophyll.
3. Consider the chemical reaction in Model 1. This represents photosynthesis.
   a. What substances are the reactants in photosynthesis? Include the name and chemical formula of each substance in your answer.
      *Carbon dioxide (CO₂) and water (H₂O).*
   b. Where in the organelle are these molecules stored before they are used in photosynthesis?
      *The stroma.*
   c. Is photosynthesis an endergonic or exergonic reaction? Support your answer with evidence from Model 1.
      *Endergonic—the reaction has sunlight on the left side, meaning it must be absorbed.*
   d. What is the energy source for photosynthesis?
      *Sunlight.*

4. Photosynthesis occurs in two parts—the **light-dependent reactions** and the **light-independent reactions**.
   a. What is another name for the light-independent reactions?
      *The Calvin cycle.*
   b. In what part of the chloroplast do the light-dependent reactions occur?
      *Thylakoid.*
   c. In what part of the chloroplast do the light-independent reactions occur?
      *In the stroma.*

5. Considering your answers to Question 4, what compound is best able to absorb the light energy from the Sun and convert it into chemical energy?
   *Chlorophyll.*

6. What substances are produced during photosynthesis? Include the name and chemical formula of each substance in your answer.
   *Glucose (C₆H₁₂O₆) and oxygen (O₂).*

7. Why is it necessary to have six CO₂ entering the chloroplast?
   *The photosynthesis reaction must be balanced. Six carbons are needed to make glucose, so six CO₂ molecules are needed.*
8. In Model 2, what shape or symbol represents a single electron?

Small black dot.

9. In the light-dependent reactions electrons are released from molecules in two ways.

a. Find two places in Model 2 where electrons are released from chlorophyll by a photon of light coming from the Sun.

   On the stroma side of photosystem I and photosystem II.

b. Find one place in Model 2 where electrons are released from water molecules.

   On the inner thylakoid side of photosystem II.

c. When the electrons are released from water molecules, what other products are formed?

   Oxygen ($O_2$) and hydrogen ions ($H^+$).
Read This!

The light-dependent reactions of photosynthesis include three major processes:

A. Excited electrons leave chlorophyll and reduce NADP⁺ into NADPH.

B. Excited electrons moving through the electron transport chain provide the free energy needed to pump hydrogen ions into the inner thylakoid.

C. Hydrogen ions flowing out of the thylakoid via a protein channel provide the free energy needed to convert ADP to ATP.

10. In Model 2, label the diagram with “A,” “B,” and “C” to indicate where the three steps in the Read This! box are occurring.

See Model 2.

11. The light-dependent reactions include an electron transport chain system that works in a very similar fashion to the electron transport chain in respiration. Briefly describe how this system works and what job it performs in the light-dependent reactions. (Your answer should include a discussion about concentration gradient.)

*The electron transport chain uses the energy from excited electrons to move hydrogen ions (H⁺) across the thylakoid membrane in a direction that is against the concentration gradient. This produces a high concentration of H⁺ inside the thylakoid membrane.*

12. Refer to Model 2.

   a. Name the embedded protein complex found in the thylakoid membrane that uses excited electrons to reduce NADP⁺ into NADPH.

      *Photosystem I.*

   b. Name the embedded protein complex found in the thylakoid membrane that provides excited electrons to the electron transport chain.

      *Photosystem II.*

   c. Name the embedded protein complex found in the thylakoid membrane that converts ADP to ATP using free energy from a flow of hydrogen ions.

      *ATP synthase.*
13. Once a chlorophyll molecule has released electrons it is no longer useful until those electrons are replaced.

   a. According to Model 2, what is the source of replacement electrons for those released from photosystem I?
      
      *Electrons that have completed the electron transport chain.*
   
   b. According to Model 2, what is the source of replacement electrons for those released from photosystem II?
      
      *Electrons from the splitting of water.*

14. Is carbon dioxide involved in the light-dependent reaction?

   *No, carbon dioxide is not involved.*

15. Refer to Model 2.

   a. Write a chemical reaction that summarizes all of the chemical reactions in the light-dependent reactions of photosynthesis starting with two water molecules.
      
      \[ 2H_2O + 2NADP^+ + 3ADP + 3P_i \rightarrow O_2 + 2NADPH + 3ATP \]

   b. In the photosynthesis reaction in Model 1, twelve water molecules are shown as reactants, but six water molecules are shown as products. Are any of the twelve water molecules products of the light-dependent reactions?
      
      *No, water molecules are not products in the light-dependent reactions of photosynthesis.*

   c. Calculate the total number of oxygen, NADPH, and ATP molecules that are produced when twelve water molecules complete the light-dependent reactions.
      
      \[ 6O_2 + 12NADPH + 18ATP \]

16. Where do the ATP and NADPH produced during the light-dependent reactions go when the process is complete?

   *To the Calvin cycle (light-independent cycle).*
17. According to Model 3, what are the three phases of the Calvin cycle?

*Carbon fixation, reduction, and regeneration.*

18. Find the compound ribulose biphosphate (RuBP) in Model 3.

   a. How many RuBP molecules are used in one turn of the Calvin cycle?

   *Three RuBP molecules are used.*

   b. How many carbon atoms are in each RuBP molecule?

   *Each RuBP molecule has five carbon atoms.*

   c. Calculate the total number of carbon atoms represented in all of the RuBP molecules used in one turn of the Calvin cycle.

   *3 molecules × 5 atoms each = 15 carbon atoms*
19. Ribulose biphosphate (RuBP) combines with carbon dioxide \( (\text{CO}_2) \) to form phosphoglycerate (PGA) during the carbon fixation phase of the Calvin cycle.

   a. How many \( \text{CO}_2 \) molecules are used in one turn of the Calvin cycle?

      *Three \( \text{CO}_2 \) molecules are used each time.*

   b. How many PGA molecules are made in one turn of the Calvin cycle?

      *Six PGA molecules are made.*

   c. How many carbon atoms are in each PGA molecule?

      *There are three carbons atoms in each PGA molecule.*

   d. Calculate the total number of carbon atoms represented in all of the PGA molecules used in one turn of the Calvin cycle.

      \[ 6 \text{ molecules} \times 3 \text{ atoms each} = 18 \text{ carbon atoms} \]

20. Explain what happened to the carbon atom from the carbon dioxide molecule that entered the Calvin cycle.

    *The carbon atom from the \( \text{CO}_2 \) was incorporated into the PGA molecules.*

21. Consider the term “carbon fixation.” Think individually for a moment what this term might mean, then share ideas among the group. Record the group’s consensus definition for carbon fixation here.

    *Answers may vary. Students should understand that during the process of photosynthesis, carbon atoms are removed from the atmosphere and incorporated (fixed) into larger molecules within the plant.*

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**Read This!**

Model 3 is a simplified version of the Calvin cycle. Each of the three phases in the cycle consist of multiple reactions that are catalyzed by enzymes specific to that reaction. These enzymes have names like RuBisCo, phosphoglycerate kinase, and PGAL hydrogenase.

22. Refer to the reduction phase of the Calvin cycle in Model 3.

   a. What molecule does the PGA molecule turn into during this phase of the Calvin cycle?

      *The PGA molecule turns into PGAL.*

   b. Describe specifically how the structures of the two molecules in part a are different.

      *The PGA molecule loses an oxygen atom as it turns into PGAL.*

   c. Identify the types and numbers of molecules that provide the free energy necessary for the reduction of the PGA molecules.

      *Six ATP and six NADPH are used in the reduction phase as a source of energy.*

   d. Is the total number of carbon atoms present in the Calvin cycle changed during the reduction phase? Support your answer with evidence from Model 3.

      *No, the six PGAL molecules have a total of 18 carbon atoms—equal to the six PGA molecules.*
23. Water is a product of the reduction phase of the Calvin cycle.
   a. How many water molecules are produced?
      \textit{Six water molecules are formed.}
   b. Explain where the hydrogen and oxygen atoms in these water molecules originated.
      \textit{The oxygen for the water molecule was removed from PGA as it turned into PGAL. The hydrogen atoms came from the conversion of NADPH to NADP+}.

24. Refer to the regeneration phase of the Calvin cycle in Model 3.
   a. How many PGAL molecules continue on to the regeneration phase of the Calvin cycle?
      \textit{Only five PGAL molecules continue on in the Calvin cycle.}
   b. Identify the types and numbers of molecules that provide the free energy necessary for the regeneration of these molecules.
      \textit{Three ATP molecules provide the free energy for regeneration.}
   c. How many total carbon atoms remain in the Calvin cycle at this point?
      \textit{Only 15 carbon atoms are in the five PGAL molecules that remain in the cycle.}
   d. What molecule(s) are "regenerated" in this phase of the cycle?
      \textit{The three RuBP molecules at the "start" of the cycle are regenerated.}
   e. How many total carbon atoms leave the Calvin cycle before the regeneration phase?
      \textit{Three carbon atoms leave the Calvin cycle as one molecule of PGAL.}
   f. What happens to the PGAL molecule that does not continue on in the Calvin cycle?
      \textit{It is used by the cell to make glucose and other biomolecules.}

\textbf{Read This!}

As you have learned from your careful study of the Calvin cycle illustrated in Model 3, three atoms of carbon enter the cycle as carbon dioxide and three carbon atoms leave the cycle as PGAL. It is easy to assume that the three atoms that leave are one and the same with the three that entered, but that is incorrect. It may be that none of the carbon atoms from the carbon dioxide become incorporated into a molecule of PGAL that leaves the cycle. Alternatively, it is also possible that one of the carbon atoms from the carbon dioxide will become part of a PGAL molecule that leaves the cycle. Eventually all of the carbon atoms that enter the cycle will leave as part of a PGAL molecule, but they must wait their turn.
25. The reaction in Model 1 shows glucose ($C_{6}H_{12}O_{6}$) as a product of photosynthesis.

   a. How many PGAL molecules will it take to make one molecule of glucose? Justify your answer with a discussion of numbers of carbon atoms.

      *Two PGAL molecules will be needed. Each PGAL molecule contains three carbon atoms, but a glucose molecule contains six carbon atoms.*

   b. How many turns of the Calvin cycle will it take to make one molecule of glucose?

      *It will require two turns of the Calvin cycle to make one molecule of glucose.*

   c. Calculate the total number of ATP and NADPH molecules used in the production of one molecule of glucose.

      *2 turns (9 ATP + 6 NADPH) = 18 ATP and 12 NADPH molecules required.*

26. Where do the ADP and NADP+ go after they are used in the Calvin cycle?

      *They travel back to the thylakoid to be recycled in the light-dependent reaction.*

27. Explain in detail, using complete sentences, how the two reactions (light-dependent and light-independent) depend on each other.

      *Students should be able to articulate that the 18 ATP molecules and the 12 NADPH molecules produced during the light-dependent cycle are needed to power the light-independent cycle, and that the 18 ADP molecules and 12 NADP+ molecules from the light-independent cycle are returned to the light-dependent cycle.*

28. Under each molecule in the equation below, indicate whether it is involved (either used or produced) in the light-dependent reactions or the Calvin cycle.

   $$6CO_{2} + 12H_{2}O \rightarrow C_{6}H_{12}O_{6} + 6O_{2} + 6H_{2}O$$

      *Used in the Calvin cycle*  *Produced in the Calvin cycle*  *Produced in the light-dependent reaction*  *Produced in the light-dependent reaction*  *Produced in the Calvin cycle*

29. Throughout photosynthesis, energy is transferred from light to several molecules with increasingly higher potential energy. Use the words below to summarize the order in which the energy flow occurs.

      *electrons*  *ATP*  *glucose*  *sunlight*  *sunlight*  *electrons*  *ATP*  *glucose*

30. Although photosynthesis does produce some ATP, these molecules are not used to do the work of the plant cells. What other process occurs in the cells that provides the ATP necessary to do cellular work such as make proteins, divide cells, and move substances across membranes?

      *Cellular respiration uses the glucose that was made in photosynthesis.*
Extension Questions

Model 4 – The Study of Photosynthesis

31. When algae are undergoing photosynthesis, the concentrations of various molecules change within the cells. These concentrations can be monitored and graphed. In complete sentences, explain the shape of each line on the graph in Model 4.

- Carbon dioxide — The concentration of CO₂ starts high because it is a reactant in photosynthesis. As it is used, the concentration steadily decreases.
- Oxygen — The concentration of O₂ starts low because it is a product of photosynthesis and has not been produced yet. As it is produced, the concentration steadily increases.
- RuBP — RuBP is constantly recycled during the Calvin cycle, so after an initial fall (from a resting state of no Calvin cycle activity), the RuBP concentration will remain fairly constant.

32. Photosynthesis is typically represented by a simple equation.

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]

a. Compare and contrast this simplified equation with the one presented in Model 1.

The equation above only has water as a reactant. It shows the net change in water not the input and output shown by the equation in Model 1.

b. Using the information from this activity explain why the equation above is a vastly oversimplified representation of the actual process.

Photosynthesis is a complex series of reactions. They are separated both spatially and temporally, whereas the equation indicates that in only one step water and CO₂ can combine with a sufficient source of energy to produce glucose and oxygen.