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Chapter 10: Photosynthesis

1. What are autotrophs and heterotrophs?

Autotrophs are "self-feeders"; they sustain themselves without eating anything derived from other living beings. Heterotrophs obtain their organic material by living on compounds produced by other organisms.

3. Write out the formula for photosynthesis.

carbon dioxide ($6CO_2$) + water ($6H_2O$) + light energy → glucose ($C_6H_{12}O_6$) + oxygen gas ($6O_2$)

4. Using ^{18}O as the basis for your discussion, explain how we know that the oxygen released in photosynthesis comes from water.

Scientists tested this hypothesis by using oxygen-18, a heavy isotope, as a tracer to follow the fate of oxygen atoms during photosynthesis. The experiments showed that the O_2 from plants was labeled with ^{18}O *only* if water was the source of the tracer. If the ^{18}O was introduced to the plant in the form of CO_2, the label did not turn up in the released O_2.

5. Explain what occurs in the light reactions stage of photosynthesis. Explain the Calvin cycle.

The light reactions are the steps of photosynthesis that convert solar energy to chemical energy. Water is split, providing a source of electrons and protons and giving off O_2 as a byproduct. Light absorbed by chlorophyll drives a transfer of the electrons and hydrogen ions from water to an electron acceptor called $NADP^+$, where they are stored temporarily. The light reactions use solar power to reduce $NADP^+$ to NADPH by adding a pair of electrons along with a hydrogen ion. The light reactions also generate ATP, using chemiosmosis to power the addition of a phosphate group to ADP, a process called phosphorylation. Thus, light energy is initially converted to chemical energy in the form of two compounds: NADPH, and ATP.

The Calvin cycle begins by incorporating CO_2 from the air into organic molecules already present in the chloroplast, a process known as carbon fixation. The cycle then reduces the fixed carbon to carbohydrate by the addition of electrons. The reducing power is provided by NADPH, which acquired its cargo of electrons in the light reactions. To convert CO_2 to carbohydrate, the cycle also requires chemical energy in the form of ATP, which is also generated by the light reactions.

6. What items are cycled between the light reactions and the Calvin cycle? ✐

While the Calvin cycle makes sugars, it can only do so with the NADPH and ATP produced by the light reactions.

7. What are the colors of the visible spectrum?

The colors of the visible spectrum, 380 nm to 750 nm in wavelength, are red, orange, yellow, green, blue, indigo, and violet.

8. Explain the correlation between an absorption spectra and an action spectrum.

An absorption spectrum is a graph plotting a pigment's light absorption versus wavelength, which can be used to determine how well a particular pigment absorbs different wavelengths of visible light. An action spectrum profiles the relative effectiveness of different wavelengths of radiation in driving photosynthesis.

9. Describe how Engelmann was able to form an action spectrum long before the invention of a spectrophotometer.

In 1883, Theodor W. Engelmann illuminated a filamentous alga with light that had been passed through a prism, exposing different segments of the alga to different wavelengths. He used aerobic bacteria, which concentrate near an oxygen source, to determine which segments of the alga were releasing the most O_2 and thus photosynthesizing most. Bacteria congregated in greatest numbers around the parts of the alga illuminated with violet-blue or red light.

10. A photosystem is composed of a…

…protein complex called a reaction-center complex surrounded by several light-harvesting complexes.

11. Explain the role of the components of the photosystem. ✏

The reaction-center complex is an organized association of proteins holding a special pair of chlorophyll *a* molecules. Each light-harvesting complex consists of various pigment molecules bound to proteins. Together, these light-harvesting complexes act as an antenna for the reaction-center complex. When a pigment molecule absorbs a photon, the energy is transferred from pigment molecule to pigment molecule within a light-harvesting complex, until it is passed into the reaction-center complex. The reaction-center complex also contains a molecule capable of accepting electrons and becoming reduced; this is called the primary electron acceptor. The solar-powered transfer of an electron from the reaction-center chlorophyll *a* pair to the primary electron acceptor is the first step of the light reactions.

12. Photosystem I is referred to by the wavelength at which its reaction center best absorbs light, P700.

Photosystem II is also known by this characteristic as P680.

14. Describe the components of the linear electron flow.

Light is the source of energy that is required to boost one of PS II's electrons to a higher energy level. Water is the source of electrons for linear electron flow, and also the source of oxygen in the atmosphere. As electrons fall between PS I and PS II, the cytochrome complex uses the energy to pump H^+ ions. This builds a proton gradient that is used in chemiosmosis to produce ATP. In PS II, the excited electron is eventually used by $NADP^+$ reductase to join $NADP^+$ and a H^+ to form NADPH.

15. Cyclic electron flow is thought to be similar to the first forms of photosynthesis to evolve.

In cyclic electron flow no water is split, there is no production of NADPH and no release of oxygen.

16. Use four examples to compare how chemiosmosis is similar in photosynthesis and cellular respiration.

Some of the electron carriers, including the iron-containing proteins called cytochromes, are very similar in chloroplasts and mitochondria. The ATP synthase complexes of the two molecules are also very much alike. The inner membrane of the mitochondrion pumps protons from the mitochondrial matrix out to the intermembrane space, which then serves as a reservoir of hydrogen ions. The thylakoid membrane of the chloroplast pumps protons from the stroma into the thylakoid space, which functions as the H^+ reservoir. In the mitochondrion, protons diffuse down their concentration gradient from the intermembrane space through ATP synthase to the matrix, driving ATP synthesis. In the chloroplast, ATP is synthesized as the hydrogen ions diffuse from the thylakoid space back to the stroma through ATP synthase complexes, whose catalytic knobs are on the stroma side of the membrane, where it is used to help drive sugar synthesis during the Calvin cycle.

17. Use two key differences to contrast chemiosmosis in photosynthesis and cellular respiration.

In mitochondria, the high-energy electrons dropped down the transport chain are extracted from organic molecules (which are thus oxidized), while in chloroplasts, the source of electrons is water. Chloroplasts do not need molecules from food to make ATP; their photosystems capture light energy and use it to drive their electrons from water to the top of the transport chain. Mitochondria use chemiosmosis to transfer chemical energy from food molecules to ATP, while chloroplasts transform light energy into chemical energy in the form of ATP.

19. List the three places in the light reactions where a proton-motive force is generated.

Proton-motive forces are generated when H^+ is split from H_2O, when H^+ is pumped across the membrane by the cytochrome complex, and when H^+ is removed from the stroma when it is taken up by $NADP^+$, reducing it to NADPH.

20. The light reactions store chemical energy in…

…the form of ATP and NADPH, which shuttle the energy to the carbohydrate-producing Calvin cycle.

21. The carbohydrate produced directly from the Calvin cycle is not glucose, but the three-carbon compound G3P.

Each turn of the Calvin cycle fixes one molecule of CO_2; therefore, it will take three turns of the Calvin cycle to net one G3P.

22. Explain the important events that occur in the carbon fixation stage of the Calvin cycle.

The Calvin cycle incorporates each CO_2 molecule, one at a time, by attaching it to a five-carbon sugar named ribulose bisphosphate (RuBP). The enzyme that catalyzes this first step is RuBP carboxylase, or rubisco. The product of the reaction is a six-carbon intermediate so unstable that it immediately splits in half, forming 2 molecules of 3-phosphoglycerate per CO_2 fixed.

23. The enzyme responsible for carbon fixation in the Calvin cycle is…

…rubisco, the most abundant protein in chloroplasts and possibly the most abundant protein on Earth.

24. In phase two, the reduction stage, the reducing power of…

…NADPH will donate electrons to the low-energy acid 1,3-bisphosphoglycerate to form the three-carbon sugar G3P (glyceraldehyde 3-phosphate).

25. To allow the production of one net G3P, the Calvin cycle must be turned three times.

Each turn will require a starting molecule of ribulose biphosphate, a five-carbon compound. This means we start with 15 carbons distributed in three RuBPs. After fixing three carbon dioxides using the enzyme rubisco, the Calvin cycle forms 6 G3Ps with a total of 18 carbons. At this point the net gain of carbons is 3, or one net G3P molecule.

26. Three turns of the Calvin cycle nets one G3P because the other five must be recycled to RuBP. Explain how the regeneration of RuBP is accomplished.

In the last step of the Calvin cycle, the carbon skeletons of five molecules of G3P are rearranged to form three molecules of RuBP, a process that uses up three molecules of ATP.

27. The net production of one G3P requires…

…nine molecules of ATP and six molecules of NADPH.