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**Unit 3, Part 3 Notes – Exceptions to Normal Photosynthesis and**

**Comparing Photosynthesis & Cellular Respiration**

AP Biology, 2018-2019

***Section A: Exceptions to Normal Photosynthesis***

**1. Is photosynthesis a perfect process? Why or why not?**

1. No, photosynthesis is not a perfect process. One enzyme involved in the Calvin Cycle—rubisco—has an active site which can accept oxygen gas (O2) or carbon dioxide (CO2). If oxygen binds to the active site of rubisco, the enzyme cannot do its job of “fixing” carbon dioxide to RuBP, which is the first step of the Calvin Cycle.
2. Remember, the normal product of “carbon fixation” is two three-carbon molecules called 3-PGA. Later in the Calvin Cycle, 3-PGA is converted to 1,3-bisphospoglycerate, which can then be converted to PGAL. PGAL can later be converted into glucose.

1. When oxygen (instead of carbon dioxide) binds to Rubisco, this is known as **photorespiration.**
2. Photorespiration tends to occur frequently when plants close their stomata to prevent water loss through transpiration. This often happens on hot, dry days. With their stomata closed, the plants will be unable to take in CO2 but will be making O2 during the light reactions. Because of this, Rubisco will be more likely to bind to O2 than CO2
3. Most plants have no special mechanisms to prevent photorespiration. They conduct both the light reactions and the Calvin cycle (aka the Calvin-Benson Cycle) in the **mesophyll cells** of the leaf.



1. Because carbon fixation in these plants begins with the creation of the three-carbon molecule 3-PGA, they known as **C3 plants.** About 85% of all plant species are C3 plants. They include rice, wheat, soybeans, and all trees.
2. Some plants have evolved ways to prevent O2 from binding to Rubisco’s active site, thus making photosynthesis more efficient. The two commonly-known strategies are called **C4 photosynthesis** and **CAM (crassulacean acid metabolism) photosynthesis.**

**2. How does C4 photosynthesis work?**

1. For C4 plants, noncyclic photophosphorylation (i.e., normal light reactions that involve both photosystem II and photosystem I) occurs within the mesophyll cells. Remember, it is the splitting of water that regenerations electrons lost from chlorophyll in photosystem II. This splitting of water releases oxygen gas. As such, oxygen gas tends to accumulate in the mesophyll cells, particularly when the stomata are closed.
2. Rubisco, however, is not found in the mesophyll cells of C4 plants. Instead, it is found in the **bundle sheath cells** that surround the veins of the leaf. These cells are unable to perform noncyclic photophosphorylation. Instead, they can only perform cyclic photophosphorylation, which only uses photosystem I. (Cyclic photophosphorylation produces ATP only, rather than both ATP and NADPH). No splitting of water is required during cyclic photophosphorylation, so no oxygen gas is released. Therefore, these cells are (somewhat) protected from the oxygen gas produced in the mesophyll cells.



***Another Image of Cyclic Electron Flow***

*Note: Everything in black is the path of non-cyclic electron flow, but the shaded gray boxes represent cyclic electron flow.*



1. As carbon dioxide enters the mesophyll cells after coming into the leaf via the stomata, it is fixed to (joined to) a three-carbon molecule called **PEP** by the enzyme **PEP carboxylase**. The product of this reaction is a four-carbon molecule called **oxaloacetate**. This molecule may be more generally referred to as a **four-carbon organic acid**. Plants that use this method are called **C4 plants** because their first step of carbon fixation involves creating a four-carbon molecule.
2. Oxaloacetate can then be converted to another four-carbon molecule called **malate** (aka **malic acid**). Malate can be transported from the mesophyll cells to the bundle sheath cells through **plasmodesmata** (small holes connecting the cell walls of adjacent plant cells).
3. Once in the bundle sheath cells, malate can be converted back into CO2 and **pyruvate** (a molecule we learned about in our cellular respiration notes). CO2 can then be fixed to RuBP by Rubisco to begin the Calvin Cycle. Remember, this cycle ultimately creates PGAL, which can be converted into glucose.
4. Pyruvate is then transported back to the mesophyll cells, where it can be converted into PEP using energy from ATP created during cyclic electron flow in the bundle sheath cells. Once PEP is regenerated, the process can begin again. Because energy from ATP is required, C4 photosynthesis is more energetically costly than C3 photosynthesis. **The C4 photosynthesis diagram 🡪on the next page.**



1. However, the extra energy required by C4 photosynthesis is worth the cost for plants that live in hot, very sunny conditions. These plants must partially close their stomata during the day. Without a high input of CO2 from the stomata, these plants would be vulnerable to high rates of photorespiration (and therefore fewer sugars created) if they did not have a method for isolating Rubisco from O2.
2. Only 3% of vascular plants are C4 plants. (Vascular plants contain tubes called xylem and phloem that transport water, minerals, and sugars around the plant.) C4 plants include crabgrass, sugarcane, and corn.
3. In C4 plants, the first step of carbon fixation (involving the enzyme PEP carboxylase) is spatially/structurally separated from the Calvin Cycle. This means that these two processes happen in different cells. For the same reason, the light reactions (with the exception of cyclic electron flow) are also considered **spatially separated** from the Calvin Cycle.

**3. How does CAM photosynthesis work?**

1. An adaptation to very hot, arid (dry) conditions is **CAM photosynthesis**. CAM stands for **crassulacean acid metabolism**. It is named after the family of plants in which this photosynthetic pathway evolved, the Crassulaceae.
2. **CAM plants** include many succulent (water-storing) plants including cacti and pineapples. They are very common in desert ecosystems.
3. Like the C4 pathway, the CAM pathway helps to minimize photorespiration. Instead of spatially separating the first step of carbon fixation from the Calvin cycle, these two processes occur at different times in CAM plants. This is called **temporal separation** (separation in time). The light reactions are also temporally separated from the Calvin Cycle in CAM plants.
	1. *Memory Trick: I remember that CAM plants deal with doing the different parts of photosynthesis at different* ***times*** *because C****AM*** *has A.M. in it, which reminds me of morning (A.M.) vs. night (P.M.).*
4. CAM plants keep their stomata fully closed during the day to minimize water loss through transpiration. At night, they open their stomata, which allows CO2 to diffuse into the mesophyll cells in their leaves. (Note: C3 and C4 plants do not open their stomata at night.) **See diagram for CAM photosynthesis on the next page.**
5. During the day, this CO2 is fixed to (joined to) PEP by the enzyme PEP carboxylase to create oxaloacetate. Oxaloacetate is then converted to malate. Malate is stored in the **vacuole** of the mesophyll cell until the next day.
6. On the next day, malate is transported out of the vacuole into the cytoplasm, where it is converted to CO2. The CO2 can diffuse into the stroma of the chloroplast, where Rubisco is located. Then, the Calvin Cycle can take place
7. The Calvin cycle only takes place during the day because it requires ATP and NADPH from the light reactions (which can only occur during the day when there is light). Remember, the light reactions also produce O2. By fixing CO2 to store as malate at night, the mesophyll cells build up their supply of CO2.  By pumping CO2 into the space surrounding Rubisco during the day, these cells minimize the risk that O2 will bind to Rubisco and photorespiration will occur.
8. The CAM pathway does require energy from ATP at multiple steps (which is not shown in the diagram to the right). As such, it is more energetically costly than C3 photosynthesis. However, this is an acceptable trade-off for plants that are vulnerable to water loss by transpiration due to hot, arid conditions.

**Section B: Comparing Photosynthesis and Cellular Respiration**

**1. How is photosynthesis related to cellular respiration?**

1. The glucose and oxygen produced in photosynthesis are used as the **reactants** (starting molecules) of cellular respiration
2. The water and carbon dioxide produced in cellular respiration are used as the r**eactants** (starting molecules) of photosynthesis

**2. What types of organisms use photosynthesis and cellular respiration?**

1. **Autotrophs** are organisms that can make their own glucose / food. (Note: autotroph literally means “self feeder.”) Some autotrophs make glucose using photosynthesis (using the energy from sunlight to make glucose). Examples of photosynthetic autotrophs include plants, algae, and some types of bacteria.
2. In contrast, some autotrophs use energy from simple chemicals (ex: hydrogen gas, hydrogen sulfide, or methane) instead of sunlight to make glucose. These autotrophs are called **chemoautotrophs** (Note: “chemo” stands for “chemical”). Chemoautotrophs are typically bacteria.
3. **Heterotrophs**, in contrast, are organisms that cannot make their own food and have to obtain glucose by eating other organisms. Animals and fungi are examples of multicellular heterotrophs. Animals digest their food inside their bodies, whereas fungi secrete (release) enzymes to break down their food source outside their bodies and absorb the nutrients using finger-like projections called hyphae. The fungus that causes athlete’s foot actually secretes enzymes to digest the outer layer of your foot skin. GROSS!!! Single-celled (unicellular) organisms can also be heterotrophic. Certain types of bacteria are heterotrophs and certain protists (ex: amoebas) are heterotrophs are as well.
4. No matter how organisms obtain glucose, they must convert the energy in glucose to the energy in ATP through cellular respiration.
5. In summary, ***ALL organisms use cellular respiration, but only certain types of autotrophs (i.e. photoautotrophs) use photosynthesis***

**3. How is the electron transport chain different in chloroplasts (photosynthesis) vs. mitochondria (cellular respiration)?**

|  |  |
| --- | --- |
| **Photophosphorylation in Chloroplasts** | **Oxidative Phosphorylation in Mitochondria** |
| -Light energy is transformed into the chemical energy of ATP-H+ ions are pumped from the stroma into the thylakoid space (aka thylakoid lumen)-H+ ions then flow back down their electrochemical / concentration gradient from the thylakoid space across the thylakoid membrane to the stroma through ATP synthase | -Energy from electrons carried by NADH and FADH2 (Note: the electrons are originally from food molecules like glucose) is converted to energy in ATP.-H+ ions are pumped from the matrix out to the intermembrane space.-H+ ions then flow back down their electrochemical / concentration gradient form the intermembrane space across the mitochondrial inner membrane to the matrix through ATP synthase.  |
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**Notes Questions**

1) What is photorespiration? (Use the term Rubisco in your response.)

2) How do C4 plants prevent Rubisco from fixing oxygen gas instead of carbon dioxide?

3) How do CAM plants prevent Rubisco from fixing oxygen gas instead of carbon dioxide?

4) Why do CAM plants tend to survive well in hot, dry environments?

5) Describe the difference between spatial and temporal separation.

6) What is the difference between autotrophs and heterotrophs? Which processes—photosynthesis, cellular respiration, or both—take place in autotrophs vs. heterotrophs?

7) How are chemoautotrophs different from photoautotrophs?

8) List three similarities between the electron transport chains used in photosynthesis and cellular respiration.

9) List three differences between the electron transport chains used in photosynthesis and cellular respiration.