BIOL 1020 – CHAPTER 10 LECTURE NOTES

Chapter 10: Photosynthesis

1. List and differentiate the 4 possible groups of organisms based on how they obtain energy and useful carbon.

2. Define the following:
- **electromagnetic radiation**
- **photons**
- **wavelength**
- **ionization**
- **fluorescence**
- **ground state**

3. Rank major types of EM radiation from the highest energy content per photon to lowest; do the same for the major colors of visible light (also note the wavelengths for the extremes of visible light).

4. Draw a chloroplast cross-section and:
- **label: stroma, thylakoid membrane, thylakoid lumen, granum**
- **label location of: chlorophyll, accessory pigments**

5. Differentiate between absorption spectrum and action spectrum, and:
- **draw the typical absorption spectra for chl a, chl b, and carotenoids**
- **draw the typical action spectrum for photosynthesis**

6. Write the overall chemical equation for photosynthesis and note what gets oxidized and what gets reduced.

7. Go back to your chloroplast diagram and label where:
- **light energy is captured**
- **photolysis occurs**
- **ATP and NADPH are produced**
- **carbohydrates are produced**

8. Describe a photosystem (include terms antenna complex, reaction center)

9. Diagram noncyclic electron transport, noting:
- **photosytems I (P700) and II (P680)**
- **where photons are absorbed**
- **electron transport chains**
- **ferredoxin**
- **NADPH production**
- **plastocyanin**
- **ATP production**
- **photolysis**

10. Diagram cyclic electron transport, noting relevant items from the list given for the noncyclic diagram.

11. Diagram the C_3 cycle (whole class activity).

12. Define photorespiration.

13. Explain the extra cost of C_4 and CAM pathways and what benefit they can provide.

14. Diagram the C_4/CAM pathway, noting where and how the two differ.

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Chapter 10: Photosynthesis

I. Organisms can be classified based on how they obtain energy and how they obtain carbon

A. energy source

1. **chemotrophs** can only get energy directly from chemical compounds
2. **phototrophs** can get energy directly from light (these organisms can use chemical compounds as energy sources as well)

B. carbon source

1. **autotrophs** can fix carbon dioxide, thus they can use CO_2 as a carbon source
2. **heterotrophs** cannot fix CO_2; they use organic molecules from other organisms as a carbon source

C. combined, these lead to 4 possible groups:

1. **photoautotrophs** – carry out **photosynthesis** (use light energy to fix CO_2, storing energy in chemical bonds of organic molecules); includes green plants, algae, and some bacteria
2. **photoheterotrophs** – use light energy but cannot fix CO_2; only nonsulfur purple bacteria
3. **chemoautotrophs** – obtain energy from reduced inorganic molecules and use some of it to fix CO_2; some bacteria
4. **chemoheterotrophs** – use organic molecules as both carbon and energy sources; dependent completely on other organisms for energy capture and carbon fixation; includes all animals, all fungi, most protests, and most bacteria

II. The **electromagnetic spectrum** and visible light

A. visible light is a form of **electromagnetic radiation**

B. electromagnetic radiation consists of particles or packets of energy (**photons**) that travel as waves

1. amount of energy carried is inversely proportional to **wavelength** (distance from one wave peak to another)
2. spectrum ranges from short wavelength/high energy gamma rays to long wavelength/low energy radio waves

C. the portion of the spectrum visible to humans (thus what we call visible light) ranges from higher-energy violet at 380 nm to lower-energy red at 760 nm; between lie all the colors of the rainbow

D. molecules can absorb photons, thus becoming energized; typically, an electron absorbs the energy

1. high energy: electron can be freed from the atom it was bound to (**ionization**)
2. moderate energy (of correct amount): electron moves to a higher-energy orbital
   - electron can then be removed from the atom, going to an acceptor molecule
   - electron can return to a lower energy level, emitting a photon (**fluorescence**) or a series of photons (mostly infrared, experienced as heat)
   - **ground state** – when all electrons in a atom fill only the lowest possible energy levels

III. Chloroplasts

A. in photosynthetic eukaryotes (plants and algae), photosynthesis occurs in **chloroplasts**

B. **chloroplasts** have both an inner and outer membrane

1. **stroma** – fluid-filled region inside the inner membrane
2. **thylakoids** – disklike membranous sacs found in stroma (interconnected with each other and inner membrane)
3. **thylakoid lumen** – fluid-filled region inside a thylakoid
4. **granum** – stack of thylakoids (plural: grana)

C. **chlorophyll**, the main light-harvesting molecule, is found in the **thylakoid membrane**

1. chlorophyll has a porphyrin ring and hydrocarbon side chain
2. light energy is absorbed by the ring
3. chlorophyll-binding proteins associate with chlorophyll in the membrane
4. chlorophyll has several forms; in plants, typically **chlorophyll a** (***chl a***) initiates photosynthesis

D. **accessory pigments** are also found in the thylakoid membrane

1. pigments are compounds that absorb light; we see them as the main color of light that they do not absorb well (thus they scatter those colors or reflect them back)
2. all pigments have an **absorption spectrum**
3. *chl a*, a green pigment, absorbs violet-blue and red light
4. several accessory pigments, with absorption spectra that differ from *chl a*, aid in photosynthesis
   - ***chl b*** is the main accessory pigment; a slight difference in the ring shifts its absorption spectrum
   - **carotenoids** are important yellow and orange accessory pigments
   - accessory pigments can transfer captured energy to *chl a*
   - they also help protect *chl a* and other compounds from excess light energy (high light intensity can cause damage)

E. the relative rate of photosynthesis for a given radiation wavelength is an **action spectrum**

1. the action spectrum looks similar to the absorption spectrum of *chl a*, but is augmented by the absorption spectrum of the accessory pigments
2. blue and red light are most effective for photosynthesis
3. action spectra can vary depending on species

F. photosynthetic prokaryotes have plasma membrane folds that act like thylakoid membranes

IV. Photosynthesis overview

A. **photosynthesis** converts energy from light into stored energy in chemical bonds

B. in the process, CO_2 is fixed and used in synthesizing carbohydrates

C. overall reaction: $6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$

1. water is on both sides because it is consumed in some steps and produced in others; overall, there is a net use of water
2. hydrogen atoms are transferred from water to carbon dioxide; yet another **redox reaction**

D. usually divided into light reactions and the C_3 cycle; more details on these later, but in summary:

1. light reactions occur in the thylakoids; they capture light energy and consume water, producing O_2; energy is placed in ATP and NADPH in the stroma
2. the C_3 cycle occurs in the stroma; it consumes CO_2 and energy (proved by ATP and NADPH), producing carbohydrates

E. in many ways this is the reverse of aerobic respiration

V. The light reactions of photosynthesis

A. overall:

$$12\ H_2O + 12\ NADP^+ + 18\ ADP + 18\ P_i + \text{light energy} \rightarrow 6\ O_2 + 12\ NADPH + 12\ H^+ + 18\ ATP + 18\ H_2O$$

B. the overall equation takes into account the amount of NADPH and ATP needed to create one molecule of glucose

C. light is captured in **photosystems** that contain **antenna complexes** and a **reaction center**

1. there are two types, **Photosystem I** and **Photosystem II**
2. **antenna complexes** are highly organized arrangements of pigments, proteins, and other molecules that capture light energy
3. energy is transferred to a **reaction center** where electrons are actually moved into electron transport chains
   - **Photosystem I** reaction center has a *chl a* absorption peak at 700 nm (**P700**)
   - **Photosystem II** reaction center has a *chl a* absorption peak at 680 nm (**P680**)
4. chlorophyll molecule + light energy → an excited electron in the chlorophyll
5. the excited electron is captured by a carrier in the photosynthetic electron transport chain, thus reducing the carrier and oxidizing the chlorophyll molecule (a redox reaction)
6. the electron can then be transferred down the electron transport chain, with energy harvest possible

D. **noncyclic electron transport** produces ATP and NADPH

1. P700 absorbs energy and sends an electron to an electron transport chain
2. eventually, the electron winds up on **ferredoxin**
3. when 2 electrons have reached ferredoxin, they can be used to make **NADPH** from $NADP^+ + H^+$; the NADPH is released in the stroma
4. the electrons are passed down one at a time, and are replaced in P700 by electrons donated from P680

5. P680 absorbs energy and sends an electron to an electron transport chain
    - this chain differs from the one that P700 uses
    - eventually, the electron winds up on **plastocyanin**
    - the ultimate electron acceptor for this chain is P700
6. $P680^+$ can accept electrons from water in the thylakoid lumen; thus:
    - $2\ P680^+ + H_2O \rightarrow 2\ P680 + ½\ O_2 + 2\ H^+$
    - this is a big deal, nothing else in living systems can readily take electrons from water
    - this consumes water and releases O_2
7. a proton gradient is established, with high $[H^+]$ in the thylakoid lumen
    - H^+ produced in the lumen when water is split
    - H^+ consumed in stroma when NADPH is made
    - H^+ pumped into lumen using energy released as electrons move along the electron transport chain between P680 and P700
    - the overall gradient winds up being about a 1000-fold difference in $[H^+]$
        - gradient provides an energy source for making ATP using **ATP synthase** (**chemiosmosis**)
        - compare this process (**photophosphorylation**) to **oxidative phosphorylation**

E. **cyclic electron transport** is possible for P700; all it can accomplish is to enhance the proton gradient that can be used to make ATP

F. overall ATP generation is variable, depending on how much cyclic electron transport occurs

1. for every 2 electrons moved through the whole P680 – P700 noncyclic electron transport system, one NADPH is produced and the proton gradient is enhanced enough for ~1 or more ATP
    - the net amount of ATP needed for the rest of photosynthesis comes out to 1.5 ATP per molecule of NADPH; thus the numbers in the equation at the start of this section
    - cyclic electron transport can be used to make up the difference in ATP needed for the rest of photosynthesis, as well as to produce extra ATP
    - all of the ATP that is made is released in the stroma

VI. carbon fixation by the **C_3 cycle** (AKA the Calvin-Benson cycle or Calvin cycle)

A. overall:

$$12\ NADPH + 12\ H^+ + 18\ ATP + 18\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 12\ NADP^+ + 18\ ADP + 18\ P_i + 6\ H_2O$$

B. note that this consumes all of the products of the light reactions except O_2, and regenerates much of the reactants for the light reactions, thus generating the overall result for photosynthesis:

$$12\ H_2O + 6\ CO_2 + \text{light energy} \rightarrow 6\ O_2 + C_6H_{12}O_6 + 6\ H_2O$$

C. the details of the 13 reactions involved in this process were described by Calvin and Benson in the 1950s

D. all 13 enzymes are in the stroma; 10 of them are also enzymes that work in aerobic respiration

1. enzymes can usually catalyze reactions in both directions – the intermediate ES complex looks the same in both cases
2. the direction of the reaction depends on thermodynamics, which is influenced by concentrations of all substances involved in the reaction

E. the C_3 cycle is broken into three phases: carbon fixation, carbon reduction, and RuBP regeneration

F. **carbon fixation** (AKA CO_2 uptake):

1. CO_2 combines with the 5-carbon compound ribulose 1,5-bisphosphate (**RuBP**)
   - catalyzed by the enzyme ribulose bisphosphate carboxylase/oxygenase (abbreviated **rubisco**)
   - **rubisco** is one of the most abundant proteins on earth
   - the carboxylase function is used here
2. the resulting 6-carbon compound is unstable and immediately splits into 2 molecules of 3-phosphoglycerate (**3-PGA**)
3. the overall reaction is: RuBP + $CO_2 \rightarrow$ 2 (3-PGA)
4. to assimilate 6 CO_2: 6 RuBP + 6 $CO_2 \rightarrow$ 12 (3-PGA)

G. carbon reduction

1. 3-PGA is reduced to glyceraldehyde 3-phosphate (G3P) in two steps; in the process, ATP and NADPH are used
2. from 6 CO_2 you get 12 G3P
3. 2 G3P are removed and used to make glucose or fructose (thus 6 carbons leave to make $C_6H_{12}O_6$)
4. the remaining 10 G3P are used to regenerate RuBP

H. RuBP regeneration

1. a series of ten reactions rearrange the 10 G3P to make 6 ribulose phosphate molecules, to which a phosphate is added to make 6 RuBP
2. ATP is consumed for each RuBP formed (it is the source of the phosphate)

VII. **photorespiration**

A. sometimes, rubisco adds O_2 to RuBP rather than a CO_2 (the oxygenase function of RUBISCO)

B. this is most likely under conditions of conditions of low [CO_2] and high [O_2]

C. the product cannot be used in the C_3 cycle, and photorespiration is a drain on the overall efficiency of photosynthesis

D. some byproducts are broken down in part into CO_2 and H_2O; organic material is lost from the system, and no energy is captured (no ATP are produced; in fact, some are consumed)

E. called photorespiration because it occurs in the light and consumes O_2, while producing CO_2 and H_2O

F. for C_3 plants (plants with only the C_3 pathway), photorespiration rate increases as the rate of photosynthesis increases, especially if stomata are closed – thus, bright, hot, dry days are inefficient days for C_3 plants

G. the effect of photorespiration is minimal in C_4 and CAM plants because they keep $[CO_2]$ high for RUBISCO

VIII. supplemental carbon fixation pathways: C_4 and CAM pathways

A. while the C_3 pathway is used by all plants, some plants have supplemental pathways that increase the efficiency of photosynthesis in either intense light or arid conditions

B. intense light – $[CO_2]$ becomes limiting; C_4 pathway gets around this by increasing $[CO_2]$ for the C_3 pathway

C. arid conditions – $[H_2O]$ is most limiting during the day; CAM pathway gets around this by allowing initial carbon fixation to occur at night

D. **C_4 pathway** (AKA Hatch-Slack pathway)

1. in mesophyll cells:
   - pyruvate + ATP + H_2O → phosphoenolpyruvate (PEP) + AMP + P_i
   - **PEP carboxylase** binds CO_2 even at very low $[CO_2]$ (binds it much better than RUBISCO binds CO_2); PEP carboxylase catalyzes: PEP + CO_2 → oxaloacetate
   - oxaloacetate + NADPH + H^+ → $NADP^+$ + malate (usually)
2. malate is then sent to bundle sheath cells
3. in bundle sheath cells:
   - malate + $NADP^+$ → CO_2 + pyruvate + NADPH + H^+
   - greatly increases $[CO_2]$ in bundle sheath cells (10-60x), allowing the C_3 pathway to proceed in those cells
   - pyruvate is sent back to the mesophyll cells
4. overall, invests 12 more ATP per glucose or fructose than C_3 alone; only worthwhile under intense light, but then it is very worthwhile
5. examples of plants with a C_4 pathway include corn, sugar cane, crabgrass

E. **CAM pathway** (crassulacean acid metabolism)

1. at night, when stomata are open and gas exchange can occur, cells perform reactions like the "mesophyll cell C_4 reactions"; malate (or a similar organic acid) is stored in vacuoles

2. during the day, the malate is released and cells perform reactions like the "bundle sheath cell C_4 reactions"; this allows the C_3 pathway to proceed during the day (when stomata are closed to prevent excessive water loss, and thus gas exchange is not possible)

3. CAM plants include many desert plants such as cactuses

F. C_4 works by altering the ***location*** of initial CO_2 fixation, while CAM works by altering the ***time*** of initial CO_2 fixation; all of the plants still use the C_3 cycle