15.2: Photosynthesis

Learning Objectives

1. Define the following:
   - photoautotrophenic a. oxyg
   - photoautotroph anoxygenicb.
   - c. photon
2. Name the two stages of photosynthesis.
3. State how all radiations in the electromagnetic spectrum travel.
4. State what constitutes visible light.
5. Define photon and describe what happens when photons of visible light energy strike certain atoms of pigments during photosynthesis and how this can lead to the generation of ATP.
6. Describe the structure of a chloroplast and list the pigments it may contain.
7. Give the overall reaction for photosynthesis.
8. State the reactants and the products for photosynthesis and indicate which are oxidized and which are reduced.

1. Briefly describe the overall function of the light-dependent reactions in photosynthesis and state where in the chloroplast they occur.

- 2. State the reactants and the products for the light-dependent reactions.
- 3. Describe an antenna complex and state the function of the reaction center.
- 4. Briefly describe the overall function of Photosystem II in the light-dependent reactions of photosynthesis.
- 5. Briefly describe how ATP is generated by chemiosmosis during the light-dependent reactions of photosynthesis.
- 6. Briefly describe the overall function of Photosystem I in the light-dependent reactions of photosynthesis.
- 7. Compare noncyclic photophosphorylation and cyclic photophosphorylation in terms of Photosystems involved and products produced.

1. Briefly describe the overall function of the light-independent reactions in photosynthesis and state where in the chloroplast they occur.

1. State how the light-dependent and light-independent reactions are linked during photosynthesis.
2. State the reactants and the products for the light-independent reactions.
3. Briefly describe the following stages of the Calvin cycle:
   - CO2 fixation
   - production of G3P
   - regeneration of RuBP
4. State the significance of glyceraldehyde-3-phosphate (G3P) in the Calvin cycle.

Autotrophs are organisms that are able to synthesize organic molecules from inorganic materials. Photoautotrophs absorb and convert light energy into the stored energy of chemical bonds in organic molecules through a process called photosynthesis. Plants, algae, and bacteria known as cyanobacteria are known as oxygenic photoautotrophs because they synthesize organic molecules from inorganic materials, convert light energy into chemical energy, use water as an electron source, and generate oxygen as an end product of photosynthesis. Some bacteria, such as the green and purple bacteria, are known as anoxygenic phototrophs. Unlike the oxygenic plants, algae, and cyanobacteria, anoxygenic phototrophs do not use water as an electron source and, therefore, do not evolve oxygen during photosynthesis. The electrons come from compounds such as hydrogen gas, hydrogen sulfide, and reduced organic molecules. In this section on photosynthesis, we be concerned with the oxygenic phototrophs.

Photosynthesis is composed of two stages: the light-dependent reactions and the light-independent reactions. The light-dependent reactions convert light energy into chemical energy, producing ATP and NADPH. The light-independent reactions use the ATP and NADPH from the light-dependent reactions to reduce carbon dioxide and convert the energy to the chemical bond energy in carbohydrates such as glucose. Before we get to these photosynthetic reactions however, we need to understand a little about the electromagnetic spectrum and chloroplasts.

The Electromagnetic Spectrum

Visible light constitutes a very small portion of a spectrum of radiation known as the **electromagnetic spectrum**. All radiations in the electromagnetic spectrum travel in **waves** and different portions of the spectrum are catagorized by their wavelength. A **wavelength** is the distance from the peak of one wave to that of the next. At one end of the spectrum are television and radio waves with longer wavelengths and low energy. At the other end of the spectrum are gamma rays with a very short wavelength and a great deal of energy. **Visible light** is the range of wavelengths of the electromagnetic spectrum that humans can see, a mixture of wavelengths ranging from 380 nanometers to 760 nanometers. It is this light that is used in photosynthesis.

Light and other types of radiation are composed of individual packets of energy called **photons**. The shorter the wavelength of the radiation, the greater the energy per photon. As will be seen shortly, when photons of visible light energy strike certain atoms of pigments during photosynthesis, that energy may push an electron from that atom to a higher energy level where it can be picked up by an electron acceptor in an electron transport chain (see Fig. 15.2.1). ATP can then be generated by chemiosmosis.

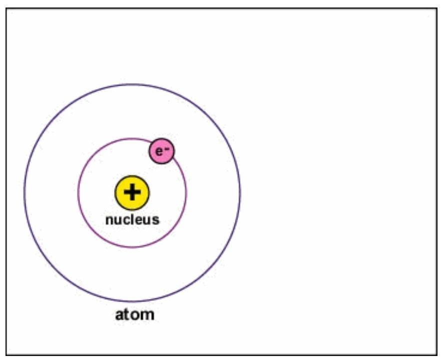

***Fig. 15.2.1**: Interaction Between a Photon and an Atom. When photons of visible light energy strike certain atoms of pigments during photosynthesis, that energy may push an electron from that atom to a higher energy level where it can be picked up by an electron acceptor in an electron transport chain.*

Chloroplasts

In eukaryotic cells, photosynthesis takes place in organelles called **chloroplasts**.

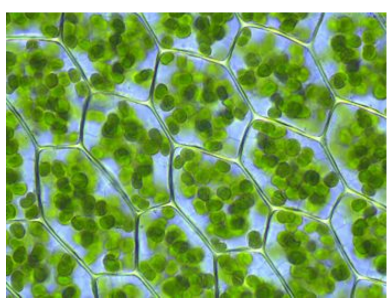

Figure: Chloroplasts visible in the cells of Plagiomnium affine, the many-fruited thyme moss. (GFDL , credit: Kristian Peters)

Like mitochondria, chloroplasts are surrounded by an inner and an outer membrane. The **inner membrane** encloses a fluid-filled region called the **stroma** that contains enzymes for the light-independent reactions of photosynthesis. Infolding of this inner membrane forms interconnected stacks of disk-like sacs called **thylakoids**, often arranged in stacks called **grana**. The thylakoid membrane, which encloses a fluid-filled thylakoid interior space, contains chlorophyll and other photosynthetic pigments as well as electron transport chains. The light-dependent reactions of photosynthesis occur in the thylakoids. The outer membrane of the chloroplast encloses the intermembrane space between the inner and outer chloroplast membranes (see Fig. 2).

The thylakoid membranes contain several pigments capable of absorbing visible light. **Chlorophyll** is the primary pigment of photosynthesis. Chlorophyll absorbs light in the blue and red region of the visible light spectrum and reflects green light. There are two major types of chlorophyll, chlorophyll *a* that initiates the light-dependent reactions of photosynthesis, and chlorophyll *b*, an accessory pigment that also participates in photosynthesis. The thylakoid membranes also contain other accessory pigments. **Carotenoids** are pigments that absorb blue and green light and reflect yellow, orange, or red. **Phycocyanins** absorb green and yellow light and reflect blue or purple. These accessory pigments absorb light energy and transfer it to chlorophyll.

Photosynthetic prokaryotic cells do not possess chloroplasts. Instead, thylakoid membranes are usually arranged around the periphery of the bacterium as infoldings of the cytoplasmic membrane.

Photosynthesis

As mentioned above, photoautotrophs use sunlight as a source of energy and through the process of photosynthesis, reduce carbon dioxide to form carbohydrates such as glucose. The radient energy is converted to the chemical bond energy within glucose and other organic molecules. The **overall reaction for photosynthesis** is as follows:

$$6CO_2 + 12H_2O \text{in the presence of light and chlorophyll yields} C_6H_{12}O_6 + 6O_2 + 6H2O \tag{15.2.1}$$

Note that carbon dioxide (CO_2) is reduced to produce glucose ($C_6H_{12}O_6$), while water (H_2O) is oxidized to produce oxygen (O_2). Photosynthesis is composed of two stages: the light-dependent reactions and the light independent reactions. We will now look at the role of each in the next two sections.

Light-Dependent Reactions

The exergonic light-dependent reactions of photosynthesis convert light energy into chemical energy, producing ATP and NADPH. These reactions occur in the thylakoids of the chloroplasts. The products of the light-dependent reactions, ATP and NADPH, are both required for the endergonic light-independent reactions.

The light-dependent reactions can be summarized as follows:

12 H_2O + 12 $NADP^+$ + 18 ADP + 18 P_i + light and chlorophyll yields 6 O_2 + 12 NADPH + 18 ATP

The light-dependent reactions involve two photosystems called **Photosystem I and Photosystem II**. These photosystems include units called **antenna complexes** composed of chlorophyll molecules and accessory pigments located in the thylakoid membrane. **Photosystem I contain chlorophyll *a* molecules called P700** because they have an absorption peak of 700 nanometers. **Photosystem II contains chlorophyll *a* molecules referred to as P680** because they have an absorption peak of 680 nanometers.

Each antenna complex is able to trap light and transfer energy to a complex of chlorophyll molecules and proteins called the **reaction center** (see Fig. 3). As photons are absorbed by chlorophyll and accessory pigments, that energy is eventually transfered to the reaction center where, when absorbed by an excitable electron, moves it to a higher energy level. Here the electron may be accepted by an electron acceptor molecule of an electron transport chain (see Fig. 3) where the light energy is converted to chemical energy by chemiosmosis.

The most common light-dependent reaction in photosynthesis is called noncyclic photophosphorylation. Noncyclic photophosphorylation involves both Photosystem I and Photosystem II and produces ATP and $NADPH$. During noncyclic photophosphorylation, the generation of ATP is coupled to a one-way flow of electrons from H_2O to $NADP^+$. We will now look at Photosystems I and II and their roles in noncyclic photophosphorylation.

1. **As photons are absorbed by pigment molecules in the antenna complexes of Photosystem II, excited electrons from the reaction center are picked up by the primary electron acceptor of the Photosystem II electron transport chain. During this process, Photosystem II splits molecules of H_2O into 1/2 O_2, $2H^+$, and 2 electrons**. These electrons continuously replace the electrons being lost by the P680 chlorophyll *a* molecules in the reaction centers of the Photosystem II antenna complexes (see Fig. 4).

During this process, ATP is generated by the Photosystem II electron transport chain and chemiosmosis. According to the **chemiosmosis theory**, as the electrons are transported down the electron transport chain, some of the energy released is used to pump protons across the thylakoid membrane from the stroma of the chloroplast to the thylakoid interior space **producing a proton gradient or proton motive force**. As the accumulating protons in the thylakoid interior space pass back across the thylakoid membrane to the stroma through **ATP synthetase** complexes, this proton motive force is used to **generate ATP** from ADP and P*i* (see Fig. 4 and Fig. 5).

Flash animation illustrating the development of proton motive force as a result of chemiosmosis and ATP production by ATPsynthase.

2. Meanwhile, **photons are also being absorbed by pigment molecules in the antenna complex of Photosystem I and excited electrons from the reaction center are picked up by the primary electron acceptor of the Photosystem I electron transport chain.** The electrons being lost by the P700 chlorophyll *a* molecules in the reaction centers of Photosystem I are replaced by the electrons traveling down the Photosystem II electron transport chain. **The electrons transported down the Photosystem I electron transport chain combine with 2H$^+$ from the surrounding medium and NADP$^+$ to produce NADPH + H$^+$** (see Fig. 4).

McGraw-Hill Flash animation illustrating photosynthetic electran transport and ATP production by ATPsynthase.

Cyclic photophosphorylation occurs less commonly in plants than noncyclic photophosphorylation, most likely occurring when there is too little NADP$^+$ available. It is also seen in certain photosynthetic bacteria. Cyclic photophosphorylation involves only Photosystem I and generates ATP but not NADPH. As the electrons from the reaction center of Photosystem I are picked up by the electron transport chain, they are transported back to the reaction center chlorophyll. As the electrons are transported down the electron transport chain, some of the energy released is used to pump protons across the thylakoid membrane from the stroma of the chloroplast to the thylakoid interior space producing a proton gradient or proton motive force. As the accumulating protons in the thylakoid interior space pass back across the thylakoid membrane to the stroma through ATP synthetase complexes, this energy is used to generate ATP from ADP and P*i* (see Fig. 6).

McGraw-Hill Flash animation illustrating cyclic and non-cyclic photophosphorylation.

Light Independent Reactions

The endergonic light-independent reactions of photosynthesis use the ATP and NADPH synthesized during the exergonic light-dependent reactions to provide the energy for the synthesis of glucose and other organic molecules from inorganic carbon dioxide and water. This is done by "fixing" carbon atoms from CO_2 to the carbon skeletons of existing organic molecules. These reactions occur in the stroma of the chloroplasts.

The *light-independent reactions* can be summarized as follows:

12 NADPH + 18 ATP + 6 CO_2 yields $C_6H_{12}O_6$ (glucose) + 12 NADP$^+$ + 18 ADP + 18 P_i + 6 H_2O

Most plants use the Calvin (C_3) cycle to fix carbon dioxide. C_3 refers to the importance of 3-carbon molecules in the cycle. Some plants, known as C_4 plants and CAM plants, differ in their initial carbon fixation step.

> ### *1. The Calvin (C_3) Cycle*
>
> *There are three stages to the Calvin cycle: 1) CO_2 fixation; 2) production of G3P; and 3) regeneration of RuBP. We will now look at each stage.*
>
> > ### *stage 1: CO_2 fixation*
> >
> > *To begin the Calvin cycle,* ***a molecule of CO_2 reacts with a five-carbon compound called***

ribulose bisphosphate (RuBP) producing an unstable six-carbon intermediate which immediately breaks down into two molecules of the three-carbon compound phosphoglycerate (PGA) *(see Fig. 7). The carbon that was a part of inorganic CO_2 is now part of the carbon skeleton of an organic molecule. The enzyme for this reaction is ribulose bisphosphate carboxylase or Rubisco. A total of six molecules of CO_2 must be fixed this way in order to produce one molecule of the six-carbon sugar glucose.*

stage 2: Production of G3P from PGA

The energy from ATP and the reducing power of NADPH (both produced during the light-dependent reactions) is now used to convert the molecules of PGA to glyceraldehyde-3-phosphate (G3P), another three-carbon compound *(see Fig. 7). For every six molecules of CO_2 that enter the Calvin cycle, two molecules of G3P are produced. Most of the G3P produced during the Calvin cycle - 10 of every 12 G3P produced - are used to regenerate the RuBP in order for the cycle to continue (see Fig. 7).* ***Some of the molecules of G3P, however, are used to synthesize glucose and other organic molecules****. As can be seen in Fig. 7, two molecules of the three-carbon G3P can be used to synthesize one molecule of the six-carbon sugar glucose. The G3P is also used to synthesize the other organic molecules required by photoautotrophs (see Fig. 8).*

stage 3: Regeneration of RuBP from G3P

> *As mentioned in the previous step, most of the G3P produced during the Calvin cycle - 10 of every 12 G3P produced - are used to regenerate the RuBP so that the cycle may continue (see Fig. 7).* ***Ten molecules of the three-carbon compound G3P eventually form six molecules of the four-carbon compound ribulose phosphate (RP)*** *(see Fig. 7).* ***Each molecule of RP then becomes phosphorylated by the hydrolysis of ATP to produce ribulose bisphosphate (RuBP)****, the starting compound for the Calvin cycle (see Fig. 7).*

Contributors and Attributions

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