Chapter 7: Capturing Solar Energy: Photosynthesis

OVERVIEW

You will learn about photosynthesis in this chapter. The authors outline the light-dependent and light-independent steps of photosynthesis, and present the two major ways that plants trap carbon dioxide. About 65 million years ago, a 6-mile in diameter meteorite crashed into the Earth near the Yucatan Peninsula, creating a hole one mile deep and 120 miles across. Trillions of tons of debris were thrown up into the stratosphere, and heat from the impact caused massive fires. Ashes, smoke and dust blocked sunlight from reaching Earth for months, causing the demise of the dinosaurs.

1) What Is Photosynthesis?

Around 2 billion years ago, mutations caused some cells to gain the ability to combine simple molecules into glucose by harvesting solar energy, a process called **photosynthesis**. Other mutations caused cells to use oxygen to break down glucose more efficiently, a process called cellular respiration.

Starting with carbon dioxide and water, photosynthesis converts sunlight energy into chemical energy stored in the bonds of glucose and oxygen ($6\ CO_2 + 6\ H_2O$ + light energy $\rightarrow C_6H_{12}O_6 + 6\ O_2$). It occurs in plants, algae, and some bacteria. Photosynthetic organisms are called autotrophs ("self- feeders"). In plants, leaves and chloroplasts are adaptations for photosynthesis. Leaves obtain CO_2 from the air through adjustable pores (called **stomata**; singular is **stoma**) in the outer transparent cells of the epidermis. **Mesophyll** ("middle of the leaf") cells within leaves contain most of the chloroplasts. Vascular bundles (veins) carry water and minerals to the mesophyll cells and carry sugars to other plant parts.

Chloroplast organelles consist of a double outer membrane enclosing a semifluid medium, the **stroma,** which contains disk-shaped membranous sacs called **thylakoids**. Thylakoids tend to be stacked atop each other in stacks called **grana** (singular is **granum**).

The dozens of reactions in photosynthesis can be grouped into two series of reactions. In the **light-dependent** reactions, chlorophyll and other molecules in the thylakoids capture sunlight energy and convert it into chemical energy stored in ATP and NADPH (nicotinamide adenine dinucleotide phosphate) energy-carriers. Oxygen gas is released. In the **light-independent** reactions, enzymes in the stroma use the chemical energy from ATP and NADPH to make glucose or other organic molecules.

2) Light-Dependent Reactions: How Is Light Energy Converted to Chemical Energy?

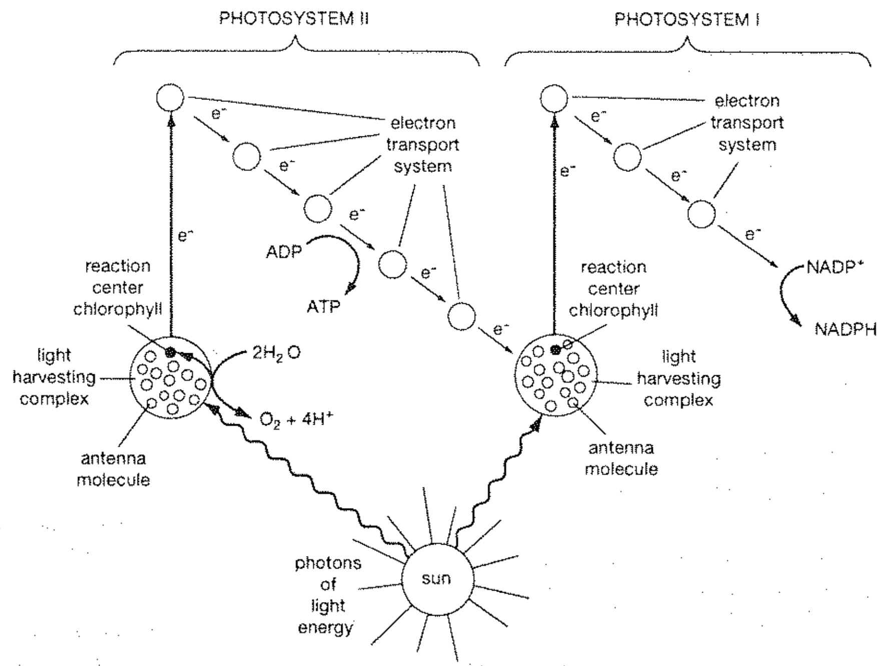
Light is first captured by pigments in chloroplasts. Wavelengths of light are composed of **photons** (individual packets of energy). Short wavelength photons are very energetic, whereas long wavelength photons have lower energies. Visible light is energetic enough to alter the shape of certain pigment molecules but not strong enough to cause mutations in DNA. When light strikes a leaf, it is either absorbed, reflected (bounced back again), or transmitted (passed through). Reflected and transmitted light reaches our eyes, and gives an object its color.

Chloroplasts contain several pigments that absorb different wavelengths of light: **chlorophyll** absorbs violet, blue, and red light and reflects green (this is why leaves are green) and **accessory pigments** (**carotenoids** absorb blue and green and reflect yellow, orange, and red, and **phycocyanins** absorb green and yellow and reflect blue and purple) absorb light energy and transfer it to chlorophyll.

Light-dependent reactions occur in clusters of molecules called **photosystems** (proteins including chlorophyll, accessory pigments, and electron-carrying molecules) within the thylakoid membranes. Each thylakoid contains thousands of copies of two types of photosystems, named photosystem I and

photosystem II. Each photosystem has two major parts: (1) a **light-harvesting complex** (300 pigment molecules that absorb light and pass the energy to a specific chlorophyll called the **reaction center**); and (2) an **electron transport system** (ETS). The ETS is a series of electron carrier molecules embedded in the thylakoid membranes. Photosystem II generates ATP, and photosystem I generates NADPH. When the reaction center chlorophyll receives energy, one of its electrons enters the ETS and moves from one carrier to the next, releasing energy that allows ADP to form ATP (through a hydrogen ion gradient called **chemiosmosis** in photosystem II) and $NADP^+$ to form NADPH (in photosystem I). Electrons from the ETS of photosystem II replenish those lost by the reaction center chlorophyll of photosystem I.

Splitting water maintains the flow of electrons through the photosystems. Electrons flow one way: from splitting water through reaction center of system II through ETS of system II to reaction center of system I through ETS of system I to NADPH.



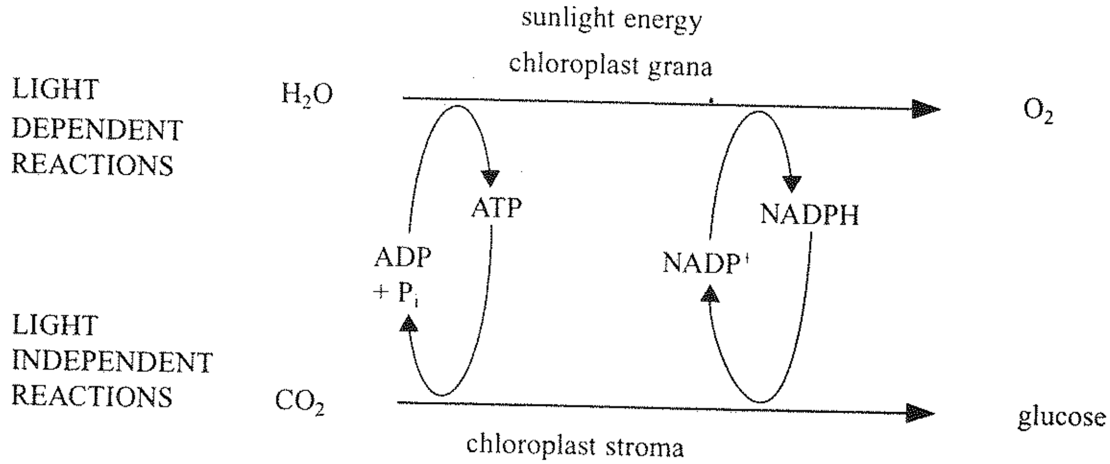
3) Light Independent Reactions: How Is Chemical Energy Stored in Glucose Molecules?

As long as sufficient ATP and NADPH are available, the light-independent reactions do not require sunlight. The **C_3 cycle** (three-carbon or **Calvin-Benson cycle**) captures carbon dioxide. It requires (1) CO_2 from the air; (2) CO_2-capturing sugar, ribulose bisphosphate (RuBP); (3) stroma enzymes; and (4) energy from ATP and NADPH (from light-dependent reactions).

The three steps of the C_3 cycle are **carbon fixation** (CO_2 attaches to RuBP), using PGA to make G3P intermediate molecules using energy from ATP and NADPH, and regeneration of RuBP. Carbon fixed during the C_3 cycle is used to make glucose.

4) How Are the Light-Dependent and Light-Independent Reactions Related?

The "photo" part of photosynthesis is the capture of light energy by the light-dependent reactions, using chlorophyll in the thylakoids to "charge up" ADP and $NADP^+$ to form ATP and NADPH. The "synthesis" part refers to the making of glucose that occurs in the light-independent reactions using enzymes in the stroma and energy from ATP and NADPH captured by the light-dependent reactions.



5) Water, CO_2, and the C_4 Pathway.

For land plants, having leaves porous to CO_2 also allows water to evaporate. Large waterproof leaves with adjustable pores (stomata) help compensate for this. When stomata close to reduce water loss, however, less CO_2 enters and less O_2 leaves.

When stomata are closed to conserve water, wasteful **photorespiration** occurs. During photorespiration, oxygen combines with RuBP and no useful cellular energy results, preventing the C_3 pathway from making glucose. During hot dry weather, plants may die due to lack of sufficient glucose.

C_4 plants (plants that have chloroplasts in mesophyll cells and in **bundle-sheath cells** around their leaf veins) reduce photorespiration using a two-stage carbon fixation process called the **C_4 pathway**. In C_4 plants, CO_2 reacts with PEP (phosphoenolpyruvate) instead of RuBP in the mesophyll, making oxaloacetate (a 4-carbon molecule). This reaction is highly specific for CO_2 and is not hindered by high O_2 concentrations. Oxaloacetate travels to bundle sheath cells where it breaks down to release CO_2 there, where the regular C_3 cycle occurs. The remnant molecule returns to the mesophyll where ATP energy is used to regenerate PEP.

C_3 and C_4 plants are each adapted to different environmental conditions. C_4 plants use more energy to make glucose than do C_3 plants. Thus, C_4 plants (crabgrass, for instance) thrive in deserts and in midsummer (much light energy, scarce water) but C_3 plants (Kentucky bluegrass, for instance) thrive in cool, wet, cloudy climates.

Case study revisited. Did dinosaurs die from lack of sunlight? About 70% of all species became extinct around 65 million years ago (the end of the Cretaceous period). Clay deposited at that time contains soot, and has 30 times the normal level of a rare element called iridium, often found in some meteorites. The Yucatan meteorite could have led to the extinction of the dinosaurs, but increased volcanic activity, spewing iridium from deep within the Earth, also could be to blame. Either a meteorite impact or increased volcanic activity could have significantly reduced the amount of sunlight and impacted the rate of photosynthesis. Less vegetation for large herbivorous dinosaurs could have reduced their numbers and had an impact on the predatory dinosaurs as well, leading to the extinction of both.

KEY TERMS AND CONCEPTS

Fill-In: From the following list of key terms, fill in the blanks in the sentences below.

ATP	glucose	photosynthesis
bundle-sheath cells	light-dependent	photosystems
chemical	light-harvesting complex	photosystem I
chlorophyll	light-independent	photosystem II
chemiosmosis	oxygen	reaction center
C_3	oxaloacetic acid	stroma
C_4	phosphoenolpyruvate (PEP)	sunlight
electron transport system	photorespiration	thylakoids

1. Starting with carbon dioxide and water, ________________ converts ________________ energy into ________________ energy stored in the bonds of glucose and oxygen.

2. During the ____________________ reactions of photosynthesis, ____________________ in the thylakoid membranes captures sunlight energy to split water and make ____________________ gas and some ________________ and NADPH energy-carriers.

3. During the ______________________ reactions, ____________________ enzymes use chemical energy in ATP and NADPH to make ____________________ from CO_2.

4. Light-dependent reactions occur in clusters of molecules called ______________________ consisting of proteins including chlorophyll, accessory pigments, and electron-carrying molecules in the ________________.

5. Each photosystem has two major parts. The ____________________ has 300 pigment molecules that absorb light and pass the energy to a specific chlorophyll called the ____________________. The ____________________ is a series of electron carrier molecules embedded in the thylakoid membrane.

6. In ________________________, ADP becomes ATP through a hydrogen ion gradient called ________________. In ____________________, $NADP^+$ becomes NADPH. Electrons from the electron transport system leave ______________________ and replenish those lost by the reaction center chlorophyll of ____________________.

7. Plants with chloroplasts in both mesophyll and ____________________ around the leaf veins reduce ________________ using a two-stage carbon fixation process called the ________________ pathway.

8. In these plants, CO_2 reacts with __________________ instead of RuBP in the mesophyll, making ________________ (4-carbon molecule) which travels to the __________________ cells where it breaks down to release CO_2.

9. In the bundle sheath cells, the regular __________________ cycle occurs. The remnant molecule returns to the mesophyll where __________________ energy is used to regenerate __________________.

Key Terms and Definitions

accessory pigments: colored molecules other than chlorophyll that absorb light energy and pass it to chlorophyll.

bundle-sheath cell: one of a group of cells that surround the veins of plants; in C_4 (but not in C_3) plants, bundle-sheath cells contain chloroplasts.

C_3 cycle: the cyclic series of reactions whereby carbon dioxide is fixed into carbohydrates during the light-independent reactions of photosynthesis; also called *Calvin-Benson cycle.*

C_4 pathway: the series of reactions in certain plants that fixes carbon dioxide into oxaloacetic acid, which is later broken down for use in the C_3 cycle of photosynthesis.

Calvin-Benson cycle: see *C_3 cycle*.

carbon fixation: the initial steps in the C_3 cycle, in which carbon dioxide reacts with ribulose bisphosphate to form a stable organic molecule.

carotenoid (ka-rot´-en-oid): a red, orange, or yellow pigment, found in chloroplasts, that serves as an accessory light-gathering molecule in thylakoid photosystems.

chemiosmosis (ke-mē-oz-mō´-sis): a process of ATP generation in chloroplasts and mitochondria. The movement of electrons down an electron transport system is used to pump hydrogen ions across a membrane, thereby building up a concentration gradient of hydrogen ions across the membrane; the hydrogen ions diffuse back across the membrane through the pores of ATP-synthesizing enzymes; the energy of their movement down their concentration gradient drives ATP synthesis.

chlorophyll (klor´-ō-fil): a pigment found in chloroplasts that captures light energy during photosynthesis; absorbs violet, blue, and red light but reflects green light.

electron transport system: a series of electron carrier molecules, found in the thylakoid membranes of chloroplasts and the inner membrane of mitochondria, that extract energy from electrons and generate ATP or other energetic molecules.

granum (gra´-num; pl., grana): a stack of thylakoids in chloroplasts.

light-dependent reactions: the first stage of photosynthesis, in which the energy of light is captured as ATP and NADPH; occurs in thylakoids of chloroplasts.

light-harvesting complex: in photosystems, the assembly of pigment molecules (chlorophyll and accessory pigments) that absorb light energy and transfer that energy to electrons.

light-independent reactions: the second stage of photosynthesis, in which the energy obtained by the light-dependent reactions is used to fix carbon dioxide into carbohydrates; occurs in the stroma of chloroplasts.

mesophyll (mez´-ō-fil): loosely packed parenchyma cells beneath the epidermis of a leaf.

photon (fō´-ton): the smallest unit of light energy.

photorespiration: a series of reactions in plants in which O_2 replaces CO_2 during the C_3 cycle, preventing carbon fixation; this wasteful process dominates when C_3 plants are forced to close their stomata to prevent water loss.

photosynthesis: the complete series of chemical reactions in which the energy of light is used to synthesize high-energy organic molecules, normally carbohydrates, from low-energy inorganic molecules, normally carbon dioxide and water.

photosystem: in thylakoid membranes, a light-harvesting complex and its associated electron transport system.

phycocyanin (fī-kō-sī´-uh-nin): a blue or purple pigment that is located in the membranes of chloroplasts and is used as an accessory light-gathering molecule in thylakoid photosystems.

reaction center: in the light-harvesting complex of a photosystem, the chlorophyll molecule to which light energy is transferred by the antenna molecules (light-absorbing pigments); the captured energy ejects an electron from the reaction center chlorophyll, and the electron is transferred to the electron transport system.

stoma (stō´-muh; pl., stomata): an adjustable opening in the epidermis of a leaf, surrounded by a pair of guard cells, that regulates the diffusion of carbon dioxide and water into and out of the leaf.

stroma (strō´-muh): the semi-fluid material inside chloroplasts in which the grana are embedded.

thylakoid (thī´-luh-koid): a disk-shaped, membranous sac found in chloroplasts, the membranes of which contain the photosystems and ATP-synthesizing enzymes used in the light-dependent reactions of photosynthesis.

THINKING THROUGH THE CONCEPTS

True or False: Determine if the statement given is true or false. If it is false, change the underlined word(s) so that the statement reads true.

10. ______ Cellular respiration probably evolved before photosynthesis.
11. ______ The light-dependent reactions occur in the stroma.
12. ______ Glucose is synthesized in the grana.
13. ______ Blue is a more energetic wavelength of light than red.
14. ______ Light energy is first captured in photosystem I.
15. ______ As electrons are transferred from one carrier to another, the electrons gain energy.
16. ______ Photosynthesis uses O_2 and produces CO_2.
17. ______ In the light dependent reactions, chlorophyll captures sunlight energy and uses it to make glucose.
18. ______ The electron transport system is part of the light-dependent process of photosynthesis.

Identify: Determine whether the following statements refer to the light **dependent** reactions or the light **independent** reactions of photosynthesis.

19. ______________ CO_2 is captured and converted into sugars.
20. ______________ Light energy is converted into chemical energy of ATP and NADPH.
21. ______________ Occurs in chloroplast grana.
22. ______________ Uses chemical energy to make glucose.
23. ______________ Uses chlorophyll, carotenoids, and phycocyanins to trap light energy.
24. ______________ Calvin-Benson, or C_3 cycle.
25. ______________ Energy obtained from NADPH and ATP.
26. ______________ Produces oxygen gas.
27. ______________ Thylakoid membranes.
28. ______________ Photosystems I and II.
29. ______________ Carbon fixation occurs.
30. ______________ Involves electron transport.
31. ______________ Occurs in chloroplast stroma.
32. ______________ Water is split into oxygen and hydrogen.

Multiple Choice: Pick the most correct choice for each question.

33. Molecules of chlorophyll are located in the membranes of sacs called
    a. cristae
    b. thylakoids
    c. stroma
    d. grana
    e. chloroplasts

34. A pigment that absorbs red and blue light and reflects green light is
    a. phycocyanin
    b. carotenoid
    c. chlorophyll
    d. melanin
    e. colored orange

35. Light dependent photosynthetic reactions produce
    a. ATP, NADPH, oxygen gas
    b. ATP, NADPH, carbon dioxide gas
    c. glucose, ATP, oxygen gas
    d. glucose, ATP, carbon dioxide gas
    e. ADP, NADP, glucose

36. Where does the oxygen gas produced during photosynthesis come from?
    a. carbon dioxide
    b. water
    c. ATP
    d. glucose
    e. the atmosphere

37. Carbon fixation requires which of the following?
    a. sunlight
    b. products of energy-capturing reactions
    c. high levels of oxygen gas and low levels of carbon dioxide gas
    d. water, ADP, and NADP

38. The immediate source of hydrogen atoms for the production of sugar during photosynthesis comes from
    a. ATP
    b. water
    c. NADPH
    d. glucose
    e. chlorophyll

APPLYING THE CONCEPTS

These practice questions are intended to sharpen your ability to apply critical thinking and analysis to biological concepts covered in this chapter.

39. Suppose you wanted to devise an experiment to determine whether the oxygen gas generated by photosynthesis came from oxygen molecules released from water or from carbon dioxide, each of which are broken down during photosynthesis. Briefly describe an idea you might have for such a study. Hint: perhaps you might want to use a radioactive isotope of oxygen in your study.

40. Suppose you wanted to determine which color of light had the greatest effect on the amount of photosynthesis occurring in plants. How would you set up such an experiment? What variables would you use and what aspects would serve as controls?

41. The leaves of plants contain many types of pigments. One group of pigments present in leaves is the carotenoids, which are yellow or orange in color. Carotenoids function during photosynthesis by absorbing certain wavelengths of light energy. What colors of light do carotenoids absorb and reflect, and why is that useful to the plant?

42. What are the three physical things that could happen to a photon of light when it interacts with a pigment granule, and which of the three is most important in terms of photosynthesis?

43. Crabgrass, a C_4 plant, grows well in the summer but not in the spring. The reverse is true for Kentucky bluegrass, a C_3 plant. Describe the process used by crabgrass to trap carbon dioxide and explain why this process is more advantageous in hot, dry weather.

44. How would humans be different if we had all the enzymes necessary to carry out photosynthesis?

45. Suppose more plants were C_4 rather than C_3. What would be the economic impact of this change?