Photosynthesis: Using Light to Make Food

Why Photosynthesis Matters

If you want to reduce the rate of global climate change, plant a tree.

Nearly all life on Earth—including you—can trace its source of energy back to the sun.

Protecting yourself from short wavelengths of light can be lifesaving.
A Greasy Crime Wave

In September 2013, police in Ocala, Florida, arrested two men and charged them with organized fraud and grand theft. Their crime? The men were caught red handed with more than 700 gallons of stolen used cooking oil pilfered from a variety of local eateries. Why would anyone steal that nasty stuff? The reason is simple: Remnants of restaurant deep fryers, sometimes called "liquid gold," fetch about $2 per pound when sold to recyclers. That makes the burglars' haul worth more than $5,000. Why is grease so valuable?

As fossil fuel supplies dwindle and prices rise, the need for reliable, renewable sources of energy increases. In response, scientists are researching better ways to harness biofuels, energy obtained from living material. Some researchers focus on burning plant matter directly (wood pellet boilers, for example), and others focus on using plant material to produce biofuels that can be burned.

There are several types of biofuels. Bioethanol is a type of alcohol (the same kind found in alcoholic drinks) that is made from wheat, corn, sugar beets, and other food crops. Starch made naturally by plants is converted to glucose and then fermented to ethanol by microorganisms such as single-celled algae. Bioethanol can be used directly as a fuel source in specially designed vehicles, but it is more commonly used as a gasoline additive that can increase fuel efficiency while decreasing vehicle emissions. You may have noticed a sticker on a gas pump that declares the percentage of ethanol in that gasoline. Most cars today run on a blend of 85% gasoline and 15% ethanol. Many car manufacturers are producing "flexible fuel" vehicles that can run on any combination of gasoline and bioethanol. Although bioethanol does reduce carbon emissions and is a renewable resource, its production raises the prices of food crops (which become more expensive as acreage is diverted to biofuel production).

Cellulosic ethanol is a form of bioethanol made from cellulose found in nonedible plant material such as wood, grass, or scraps from crops. Biodiesel, the most common biofuel in Europe, is made from plant oils such as recycled frying oil. Like bioethanol, it can be used on its own or as an emissions-reducing additive to standard diesel. In a strange twist, rising values for diesel have sparked a greasy crime wave as thieves tap into this new and largely unguarded source of raw material. Today, only about 2.7% of the world's fuel used for driving is provided by biofuels, but the International Energy Agency has set a goal of 25% by 2050.

When we derive energy from biofuels, we are actually tapping into the energy of the sun, which drives photosynthesis in plants. Photosynthesis is the process by which plants use light to make sugars from carbon dioxide—sugars that are food for the plant and the starting point for most of our own food. In this chapter, we'll first examine some basic concepts of photosynthesis; then we'll look at the specific mechanisms involved in this process.
The Basics of Photosynthesis

The process of photosynthesis is the ultimate source of energy for nearly every ecosystem on Earth.

Photosynthesis is a process whereby plants, algae (which are protists), and certain bacteria transform light energy into chemical energy, using carbon dioxide and water as starting materials and releasing oxygen gas as a by-product. The chemical energy produced via photosynthesis is stored in the bonds of sugar molecules.

Organisms that generate their own organic matter from inorganic ingredients are called autotrophs (see Chapter 6). Plants and other organisms that do this by photosynthesis—photoautotrophs—are the producers for most ecosystems (Figure 7.1). Not only do photoautotrophs feed us, they also clothe us (as the source of cotton fibers), house us (wood), and provide energy for warmth, light, and transportation (biofuels).

Chloroplasts: Sites of Photosynthesis

Photosynthesis in plants and algae occurs within light-absorbing organelles called chloroplasts (see Chapter 4, especially Figure 4.17). All green parts of a plant have chloroplasts and thus can carry out photosynthesis. In most plants, however, the leaves have the most chloroplasts (about 500,000 per square millimeter of leaf surface—that's equivalent to about 300 million chloroplasts in a leaf the size of a standard postage stamp). Their green color is from chlorophyll, a pigment (light-absorbing molecule) in the chloroplasts that plays a central role in converting solar energy to chemical energy.

Chloroplasts are concentrated in the interior cells of leaves (Figure 7.2), with a typical cell containing 30–40 chloroplasts. Carbon dioxide (CO₂) enters a leaf, and oxygen (O₂) exits, by way of tiny pores called stomata (singular: stoma, meaning "mouth"). The carbon dioxide that enters the leaf is the source of carbon for much of the body of the plant, including the sugars and starches that we eat. So the bulk of the body of a plant derives from the air, not the soil. As proof of this idea, consider hydroponics, a means of growing plants using only air and water, no soil whatsoever is involved. In addition to carbon dioxide, photosynthesis requires water, which is absorbed by the plant's roots and transported to the leaves, where veins carry it to the photosynthetic cells.

Membranes within the chloroplast form the framework where many of the reactions of photosynthesis occur. Like a mitochondrion, a chloroplast has a double-membrane envelope. The chloroplast's inner membrane encloses a compartment filled with stroma, a thick fluid. It's easy to confuse two terms associated with photosynthesis: stroma are pores through which gases are...
exchanged, and stroma is the fluid within the chloroplast.) Suspended in the stroma are interconnected membranous sacs called thylakoids. The thylakoids are concentrated in stacks called grana (singular, granum). The chlorophyll molecules that capture light energy are built into the thylakoid membranes. The structure of a chloroplast—with its stacks of disks—aids its function by providing a large surface area for the reactions of photosynthesis.

Figure 7.2 Journey into a leaf. This series of blowups takes you into a leaf’s interior, then into a plant cell, and finally into a chloroplast, the site of photosynthesis.

CHECKPOINT
Photosynthesis takes place within organelles called using gases that are exchanged via pores called called _____________.

An Overview of Photosynthesis

The following chemical equation, simplified to highlight the relationship between photosynthesis and cellular respiration, provides a summary of the reactants and products of photosynthesis:

\[ 6 \text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_12\text{O}_6 + 6\text{O}_2 \]

Notice that the reactants of photosynthesis—carbon dioxide (CO₂) and water (H₂O)—are the same as the waste products of cellular respiration (see Figure 6.2). Also notice that photosynthesis produces what respiration uses—glucose (C₆H₁₂O₆) and oxygen (O₂). In other words, photosynthesis recycles the “exhaust” of cellular respiration and rearranges its atoms to produce food and oxygen. Photosynthesis is a chemical transformation that requires a lot of energy and sunlight absorbed by chlorophyll provides that energy.

Recall that cellular respiration is a process of electron transfer (see Chapter 6). A “fall” of electrons from food molecules to oxygen to form water releases the energy that mitochondria can use to make ATP (see Figure 6.9). The opposite occurs in photosynthesis: Electrons are boosted “uphill” and added to carbon dioxide to produce sugar. Hydrogen is moved along with the electrons being transferred from water to carbon dioxide. This transfer of hydrogen requires the chloroplast to split water molecules into hydrogen and oxygen. The hydrogen is transferred along with electrons to carbon dioxide to form sugar. The oxygen escapes through stomata in leaves into the atmosphere as O₂, a waste product of photosynthesis.

The overall equation for photosynthesis is a simple summary of a complex process. Like many energy-producing processes within cells, photosynthesis is a multistep chemical pathway, with each step in the path producing products that are used as reactants in the next step. This is a clear example of one of biology’s major themes: the use of metabolic pathways to obtain, process, and store energy. To help get a better overview, let’s take a look at the two stages of photosynthesis: the light reactions and the Calvin cycle (Figure 7.3).
In the **light reactions**, chlorophyll in the thylakoid membranes absorbs solar energy (the “photo” part of photosynthesis), which is then converted to the chemical energy of ATP (the molecule that drives most cellular work) and NADPH (an electron carrier). During the light reactions, water is split, providing a source of electrons and giving off O₂ gas as a by-product.

The **Calvin cycle** uses the products of the light reactions to power the production of sugar from carbon dioxide (the “synthesis” part of photosynthesis). The enzymes that drive the Calvin cycle are dissolved in the stroma. ATP generated by the light reactions provides the energy for sugar synthesis. And the NADPH produced by the light reactions provides the high-energy electrons that drive the synthesis of glucose from carbon dioxide. Thus, the Calvin cycle indirectly depends on light to produce sugar because it requires the supply of ATP and NADPH produced by the light reactions.

The initial incorporation of carbon from CO₂ into organic compounds is called **carbon fixation**. This process has important implications for global climate, because the removal of carbon from the air and its incorporation into plant material can help reduce the concentration of carbon dioxide in the atmosphere. Deforestation, which removes a lot of photosynthetic plant life, thereby reduces the ability of the biosphere to absorb carbon. Planting new forests can have the opposite effect of fixing carbon from the atmosphere, potentially reducing the effect of the gases that contribute to global climate change.

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**The Light Reactions: Converting Solar Energy to Chemical Energy**

Chloroplasts are solar-powered sugar factories. Let's look at how they convert sunlight to chemical energy.

**The Nature of Sunlight**

Sunlight is a type of energy called radiation or electromagnetic energy. Electromagnetic energy travels through space as rhythmic waves, like the ripples made by a pebble dropped into a pond. The distance between the crests of two adjacent waves is called a **wavelength**. The full range of radiation, from the very short wavelengths of gamma rays to the very long wavelengths of radio signals, is called the **electromagnetic spectrum** (Figure 7.4). Visible light is the fraction of the spectrum that our eyes see as different colors.

When sunlight shines on a pigmented material, certain wavelengths (colors) of the visible light are absorbed and disappear from the light that is reflected by the material. For example, we see a pair of jeans as blue because pigments in the fabric absorb the other colors, leaving only light in the blue part of the spectrum to be reflected from the fabric to our eyes. In the 1800s, botanists (biologists who study plants) discovered that only certain wavelengths of light are used by plants, as we'll see next.
What Colors of Light Drive Photosynthesis?

In 1883, German biologist Theodor Engelmann made the observation that certain bacteria living in water tend to cluster in areas with higher oxygen concentrations. He already knew that light passed through a prism would separate into the different wavelengths (colors). Engelmann soon began to question whether he could use this information to determine which wavelengths of light work best for photosynthesis.

Engelmann's hypothesis was that oxygen-seeking bacteria would congregate near regions of algae performing the most photosynthesis (and hence producing the most oxygen). Engelmann began his experiment by laying a string of freshwater algal cells within a drop of water on a microscope slide. He then added oxygen-sensitive bacteria to the drop. Next, using a prism, he created a spectrum of light and shined it on the slide. His results, summarized in Figure 7.5, showed that most bacteria congregated around algae exposed to red-orange and blue-violet light, with very few bacteria moving to the area of green light. Other experiments have since verified that chloroplasts absorb light mainly in the blue-violet and red-orange part of the spectrum and that those wavelengths of light are the ones mainly responsible for photosynthesis.

Chloroplast Pigments

The selective absorption of light by leaves explains why they appear green to us: light of that color is poorly absorbed by chloroplasts and is thus reflected or transmitted toward the observer (Figure 7.6). Energy cannot be destroyed, so the absorbed energy must be converted to other forms. Chloroplasts contain several different pigments that absorb light of different wavelengths.

- Figure 7.5 Investigating how light wavelength affects photosynthesis.
  When algal cells are placed on a microscope slide, oxygen-seeking bacteria migrate toward algae exposed to certain colors of light. These results suggest that blue-violet and orange-red wavelengths best drive photosynthesis, while green wavelengths do so only a little bit.

- Figure 7.6 Why are leaves green?
  Chlorophyll and other pigments in chloroplasts reflect or transmit green light while absorbing other colors.
Chlorophyll *a*, the pigment that participates directly in the light reactions, absorbs mainly blue-violet and red light. A very similar molecule, chlorophyll *b*, absorbs mainly blue and orange light. Chlorophyll *b* does not participate directly in the light reactions, but it conveys absorbed energy to chlorophyll *a*, which then puts the energy to work in the light reactions.

Chloroplasts also contain a family of yellow-orange pigments called carotenoids, which absorb mainly blue-green light. Some carotenoids have a protective function. They dissipate excess light energy that would otherwise damage chlorophyll. Some carotenoids are human nutrients: beta-carotene (a bright orange/red pigment found in pumpkins, sweet potatoes, and carrots) is converted to vitamin A in the body, and lycopene (a bright red pigment found in tomatoes, watermelons, and red peppers) is an antioxidant that is being studied for potential anti-cancer properties. Additionally, the spectacular colors of fall foliage in some parts of the world are due partly to the yellow-orange light reflected from carotenoids (Figure 7.7). The decreasing temperatures in autumn cause a decrease in the levels of chlorophyll, allowing the colors of the longer-lasting carotenoids to be seen in all their fall glory.

All of these plastid pigments are built into the thylakoid membranes (see Figure 7.2). There the pigments are organized into light-harvesting complexes called photosystems. Our next topic is... How Photosystems Harvest Light Energy

Thinking about light as waves explains most of light's properties. However, light also behaves as discrete packets of energy called photons. A photon is a fixed quantity of light energy. The shorter the wavelength of light, the greater the energy of a photon. A photon of violet light, for example, packs nearly twice as much energy as a photon of red light. This is why short-wavelength light—such as ultraviolet light and X-rays—can be damaging photons at these wavelengths carry enough energy to damage proteins and DNA, potentially leading to cancerous mutations.

When a pigment molecule absorbs a photon, one of the pigment's electrons gains energy. This electron is now said to be "excited"; that is, the electron has been raised from its starting state (called the ground state) to an excited state. The excited state is highly unstable, so an excited electron usually loses its excess energy and falls back to its ground state almost immediately (Figure 7.8a). Most pigments release heat energy as their light-excited electrons fall back to their ground state. (That's why a surface with a lot of pigment, such as a black driveway, gets so hot on a sunny day.) But some pigments emit light as well as heat after absorbing...
photos. The fluorescent light emitted by a glow stick is caused by a chemical reaction that excites electrons of a fluorescent dye (Figure 7.8b). The excited electrons quickly fall back down to their ground state, releasing energy in the form of fluorescent light.

In the thylakoid membrane, chlorophyll molecules are organized with other molecules into photosystems. Each photosystem has a cluster of a few hundred pigment molecules, including chlorophylls a and b and some carotenoids (Figure 7.9). This cluster of pigment molecules functions as a light-gathering antenna. When a photon strikes one of the pigment molecules, the energy jumps from molecule to molecule until it arrives at the reaction center of the photosystem. The reaction center consists of chlorophyll a molecules that sit next to another molecule called a primary electron acceptor. This primary electron acceptor traps the light-excited electron (\( e^- \)) from the chlorophyll a in the reaction center. Another team of molecules built into the thylakoid membrane then uses that trapped energy to make ATP and NADPH.

**How the Light Reactions Generate ATP and NADPH**

Two photosystems cooperate in the light reactions (Figure 7.10). 1. Photons excite electrons in the chlorophyll of the first photosystem. These photons are then trapped by the primary electron acceptor. This photosystem then replaces the lost electrons by extracting new ones from water. This is the step that releases \( O_2 \) during photosynthesis. 2. Energized electrons from the first photosystem pass down an electron transport chain to the second photosystem. The chloroplast uses the energy released by this electron “fall” to make ATP. 3. The second photosystem transfers its light-excited electrons to NADP\(^+\), reducing it to NADPH.

**Figure 7.10** The light reactions of photosynthesis. The orange arrows trace a light-driven flow of electrons from \( H_2O \) to NADPH. These electrons also produce ATP.
Figure 7.11 shows the location of the light reactions in the thylakoid membrane. The two photosystems and the electron transport chain that connects them transfer electrons from \( H_2O \) to \( NADP^+ \), producing NADPH. Notice that the mechanism of ATP production during the light reactions is very similar to the mechanism we saw in cellular respiration (see Figure 6.10). In both cases, an electron transport chain pumps hydrogen ions (\( H^+ \)) across a membrane—the inner mitochondrial membrane in the case of respiration and the thylakoid membrane in photosynthesis. And in both cases, ATP synthases use the energy stored by the \( H^+ \) gradient to make ATP. The main difference is that food provides the high-energy electrons in cellular respiration, whereas light-excited electrons flow down the transport chain during photosynthesis. The traffic of electrons shown in Figures 7.10 and 7.11 is analogous to the cartoon in Figure 7.12.

We have seen how the light reactions absorb solar energy and convert it to the chemical energy of ATP and NADPH. Notice again, however, that the light reactions did not produce any sugar. That’s the job of the Calvin cycle, as we’ll see next.
The Calvin Cycle: Making Sugar from Carbon Dioxide

If chloroplasts are solar-powered sugar factories, then the Calvin cycle is the actual sugar-manufacturing machinery. This process is called a cycle because its starting material is regenerated. With each turn of the cycle, there are chemical inputs and outputs. The inputs are CO₂ from the air as well as ATP and NADPH produced by the light reactions. Using carbon from CO₂, energy from ATP, and high-energy electrons from NADPH, the Calvin cycle constructs an energy-rich sugar molecule called glyceraldehyde 3-phosphate (G3P). The plant cell can then use G3P as the raw material to make the glucose and other organic compounds (such as cellulose and starch) that it needs. Figure 7.13 presents the basics of the Calvin cycle, emphasizing inputs and outputs. Each ◦ symbol represents a carbon atom, and each ◆ symbol represents a phosphate group.

Biofuels  EVOLUTION CONNECTION

Creating a Better Biofuel Factory

Throughout this chapter, we’ve studied how plants convert solar energy to chemical energy via photosynthesis. Such transformations are vital to our welfare and to Earth’s ecosystems. As discussed in the Biology and Society section, scientists are attempting to tap into the “green energy” of photosynthesis to produce biofuels. But the production of biofuels is highly inefficient. In fact, it is usually far more costly to produce biofuels than to extract the equivalent amount of fossil fuels.

Biomechanical engineers are working to solve this dilemma by turning to an obvious example: evolution by natural selection. In nature, organisms with genes that make them better suited to their local environment will, on average, more often survive and pass those genes on to the next generation. Repeated over many generations, genes that enhance survival within that environment will become more common, and the species evolves.

When trying to solve an engineering problem, scientists can impose their own desired outcomes using a process called directed evolution (see the Process of Science section in Chapter 5 for another example).
During this process, scientists in the laboratory (instead of the natural environment) determine which organisms are the fittest. Directed evolution of biofuel production often involves microscopic algae (Figure 7.14) rather than plants because algae are easier to manipulate and maintain within the laboratory. Furthermore, some algae produce nearly half their own body weight in hydrocarbons that are only a few chemical steps away from useful biofuels.

In a typical directed evolution experiment, the researcher starts with a large collection of individual alga—sometimes naturally occurring species and sometimes transgenic algae that have been engineered to carry useful genes, such as fungal genes for enzymes that break down cellulose. The algae are exposed to mutation-promoting chemicals. This produces a highly varied collection of algae that can be screened for the desired outcome: the ability to produce the most useful biofuel in the largest quantity. The tiny fraction of total algae that can best perform this task is grown and subjected to another round of mutation and selection. After many repetitions, the algae may slowly improve their ability to efficiently produce biofuels. Many research laboratories—some within major petroleum companies—are using such methods and may someday produce an alga that can provide the ultimate source of green energy, an achievement that would highlight how lessons from natural evolution can be applied to improve our lives.

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**Chapter Review**

### SUMMARY OF KEY CONCEPTS

#### The Basics of Photosynthesis

Photosynthesis is a process whereby light energy is transformed into chemical energy stored as bonds in sugars made from carbon dioxide and water.

#### Chloroplasts: Sites of Photosynthesis

Chloroplasts contain a thick fluid called stroma surrounding a network of membranes called thylakoids.

### Energy Transformation: An Overview of Photosynthesis

Light energy

\[ 6 \text{CO}_2 + 6 \text{H}_2\text{O} \xrightarrow{\text{Photosynthesis}} \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \]

- Carbon dioxide
- Water
- Glucose
- Oxygen gas
The overall process of photosynthesis can be divided into two stages connected by energy- and electron-carrying molecules:

**The Light Reactions: Converting Solar Energy to Chemical Energy**

**The Nature of Sunlight**
Visible light is part of the spectrum of electromagnetic energy. It travels through space as waves. Different wavelengths of light appear as different colors; shorter wavelengths carry more energy.

**Chloroplast Pigments**
Pigment molecules absorb light energy of certain wavelengths and reflect other wavelengths. We see the reflected wavelengths as the color of the pigment. Several chloroplast pigments absorb light of various wavelengths and convey it to other pigments, but it is the green pigment chlorophyll that participates directly in the light reactions.

**How Photosystems Harvest Light Energy and How the Light Reactions Generate ATP and NADPH**

**The Calvin Cycle: Making Sugar from Carbon Dioxide**
Within the stroma (fluid) of the chloroplast, carbon dioxide from the air and ATP and NADPH produced during the light reactions are used to produce G3P, an energy-rich sugar molecule that can be used to make glucose and other organic molecules.

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**SELF-QUIZ**
1. The light reactions take place in the structures of the chloroplast called the ________, while the Calvin cycle takes place in the ________.
2. In terms of the spatial organization of photosynthesis within the chloroplast, what is the advantage of the light reactions producing NADPH and ATP on the stroma side of the thylakoid membrane?
3. Which of the following are inputs to photosynthesis? Choose all that apply. Which are outputs? Choose all that apply.
   a. CO₂
   b. O₂
   c. sugar
   d. H₂O
   e. light
4. Explain how the name “photosynthesis” describes what this process accomplishes.
5. What color of light is the least effective in driving photosynthesis? Why?
CHAPTER 7
PHOTOSYNTHESIS: USING LIGHT TO MAKE FOOD

6. When light strikes chlorophyll molecules, they lose electrons, which are ultimately replaced by splitting molecules of ______.

7. Which of the following are produced by reactions that take place in the thylakoids and are consumed by reactions in the stroma?
   a. CO₂ and H₂O
   b. NADP⁺ and ADP
   c. ATP and NADPH
   d. glucose and O₂

8. The reactions of the Calvin cycle are not directly dependent on light, and yet they usually do not occur at night. Why?

9. Of the following metabolic processes, which one is common to photosynthesis and cellular respiration?
   a. reactions that convert light energy to chemical energy
   b. reactions that split H₂O molecules and release O₂
   c. reactions that store energy by pumping H⁺ across membranes
   d. reactions that convert CO₂ to sugar

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

10. Tropical rain forests cover only about 3% of Earth’s surface, but they are estimated to be responsible for more than 20% of global photosynthesis. For this reason, rain forests are often referred to as the “lungs” of the planet, providing O₂ for life all over Earth. However, most experts believe that rain forests make little or no net contribution to global O₂ production. From your knowledge of photosynthesis and cellular respiration, can you explain why they might think this? (Hint: What happens to the energy stored as sugars in the body of a plant when that plant dies or parts of it are eaten by animals?)

11. Suppose you wanted to discover whether the oxygen atoms in the glucose produced by photosynthesis come from H₂O or CO₂. Explain how you could use a radioactive isotope to find out.

12. Interpreting Data The graph above right is called an absorption spectrum. Each line on the graph is made by shining light of varying wavelengths through a sample. For each wavelength, the amount of that light absorbed by the sample is recorded. This graph combines three such measurements, one each for the pigments chlorophyll a, chlorophyll b, and the carotenoids. Notice that the graphs for the chlorophyll pigments match the data presented in Figure 7.5. Imagine a plant that lacks chlorophyll and relies only on carotenoids for photosynthesis. What colors of light would work best for this plant? How would this plant appear to your eye?

13. There is strong evidence that Earth is getting warmer because of an intensified greenhouse effect resulting from increased CO₂ emissions from industry, vehicles, and the burning of forests. Global climate change could influence agriculture, melt polar ice, and flood coastal regions. In response to these threats, 192 parties have accepted the Kyoto Protocol, which calls for mandatory reductions of greenhouse gas emissions in 30 industrialized nations by 2012. The United States has signed but not ratified (put into effect) the agreement, instead proposing a more modest set of voluntary goals allowing businesses to decide whether they wish to participate and providing tax incentives to encourage them to do so. The reasons given for rejecting the agreement are that it might hurt the American economy and that some less industrialized countries (such as India) are exempted from it, even though they produce a lot of pollution. Do you agree with this decision? In what ways might efforts to reduce greenhouse gases hurt the economy? How can those costs be weighed against the costs of global climate change? Should poorer nations carry an equal burden to reduce their emissions?

14. Burning biomass to produce electricity avoids many of the problems associated with gathering, refining, transporting, and burning fossil fuels. Yet the use of biomass as fuel is not without its own set of problems. What challenges might arise from a large-scale conversion to biomass energy? How do these challenges compare with those encountered with fossil fuels? Which set of challenges do you think is more likely to be overcome? Does one energy source have more benefits and fewer costs than the others? Explain.