4.1

Introduction to Cellular Respiration and Fermentation

Forest fires release an enormous amount of energy. The major component of the wood that burns is cellulose. Cellulose molecules, the main component of plant cell walls, are complex carbohydrates made of glucose. When cellulose burns, it combines with oxygen gas in the atmosphere and releases a tremendous amount of potentially life-threatening energy. When animals eat plants, what happens to all of this stored energy? What pathways allow them to extract energy from their food without literally burning up? In this chapter, you will examine the fundamental biological processes that enable organisms to extract energy from molecules such as glucose.

Most of the energy that enters the biosphere is solar radiation. The process of photosynthesis (which you will study in Chapter 5) transforms this light energy into chemical potential energy, which is then available to plants and other organisms in food webs. Photosynthesis captures light energy and uses it to convert carbon dioxide and water into organic molecules, such as sugars, that contain an abundance of free energy (**Figure 1**).

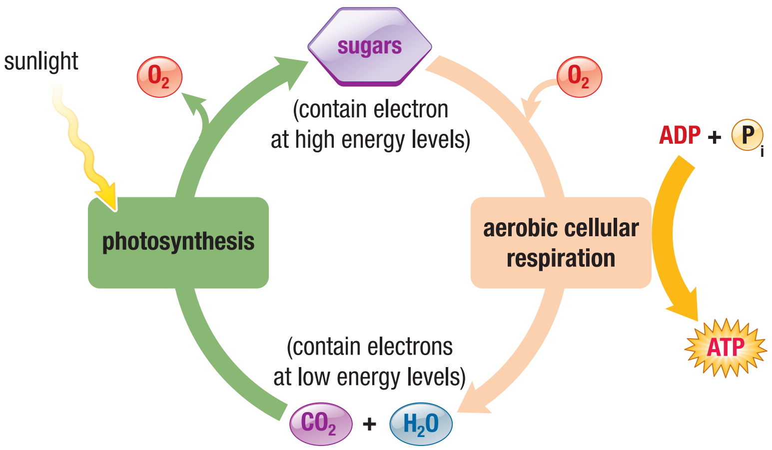


Figure 1 The flow of energy from sunlight to ATP

The immediate products of photosynthesis, sugars and O_2, are used in energy-releasing reactions in aerobic cells. Potential energy is extracted from these food molecules through oxidation and is used to synthesize adenosine triphosphate (ATP). The chemical energy, which is now stored in ATP, can readily be released and used by the cell for most of the activities that require energy. When O_2 is unavailable, anaerobic cells have alternative ways to release energy from food molecules.

Aerobic Cellular Respiration

aerobic cellular respiration a process that uses oxygen to harvest energy from organic compounds

Aerobic cellular respiration (or, simply, aerobic respiration) is the process that extracts energy from food in the presence of oxygen (Figure 1). The energy is used to synthesize ATP from ADP and P_i. The ATP molecules are then used to supply energy directly to the cells for their energy-demanding activities. As shown in the following equation, carbon dioxide and water are released as waste products in the reaction. Gibbs free energy is also released and is used to make ATP.

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \qquad \Delta G = -2870\ \text{kJ/mol}$$

obligate aerobe an organism that cannot live without oxygen

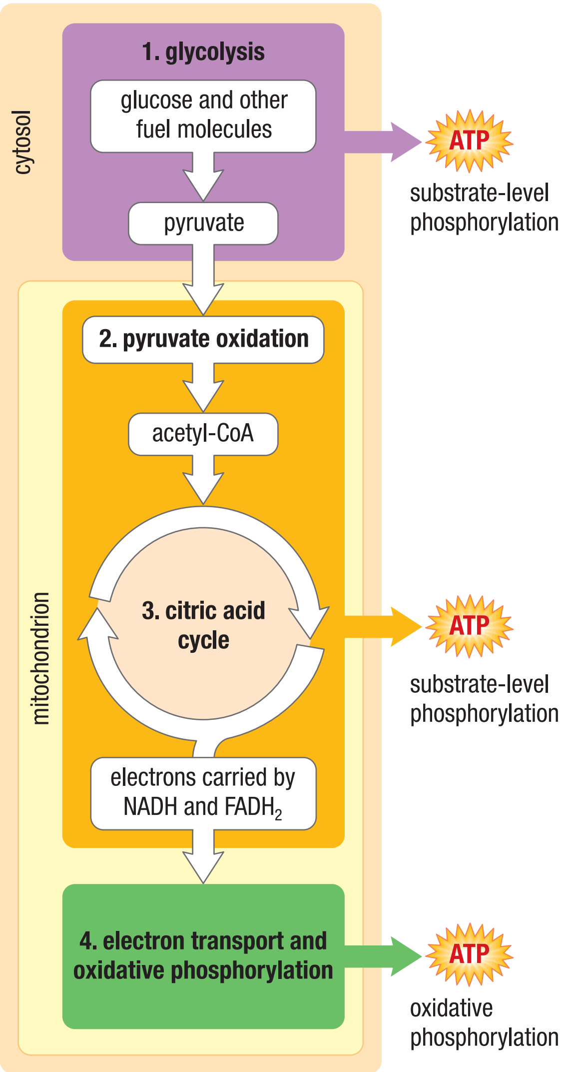
Aerobic cellular respiration takes place in most eukaryotes and some prokaryotes. Most eukaryotes, including all plants and animals, are **obligate aerobes**: they cannot live without oxygen, and they use aerobic cellular respiration exclusively or most of the time.

Later in the chapter, you will learn that proteins and lipids can also be oxidized by cells as a source of potential energy. However, because the oxidation of glucose is the most widely used pathway, it is the focus of our discussion.

Aerobic cellular respiration can be divided into four stages (**Figure 2**). Each stage involves the transfer of free energy, producing ATP in one of two ways: substrate-level phosphorylation and oxidative phosphorylation. **Substrate-level phosphorylation** forms ATP directly in an enzyme-catalyzed reaction through the transfer of a phosphate group from one molecule to an adenosine diphosphate (ADP) molecule. **Oxidative phosphorylation** forms ATP indirectly through a series of redox reactions involving a final electron acceptor. In aerobic respiration, oxygen is the final electron acceptor. You will learn about aerobic cellular respiration in Sections 4.2 and 4.3.

substrate-level phosphorylation the formation of ATP by the direct transfer of a phosphate group from a substrate to ADP

oxidative phosphorylation a process that forms ATP using energy transferred indirectly from a series of redox reactions



1. Glycolysis (in cytosol). Enzymes break down one molecule of glucose into two molecules of pyruvate. Some high-energy ATP (via substrate-level phosphorylation) and NADH is synthesized.

2. Pyruvate oxidation (in mitochondria). Each of the two molecules of pyruvate produced in glycolysis is transported to mitochondria and is oxidized, resulting in the production of CO_2 (a waste molecule), NADH, and an acetyl group that is initially attached to coenzyme A (acetyl-CoA).

3. Citric acid cycle (in mitochondria). Acetyl-CoA molecules from pyruvate oxidation enter a metabolic cycle, where the acetyl group is completely oxidized to CO_2. In the process, ATP (via substrate-level phosphorylation) and the electron carriers NADH and $FADH_2$ are synthesized.

4. Electron transport and oxidative phosphorylation (in mitochondria). The NADH and $FADH_2$ (synthesized during glycolysis, pyruvate oxidation, and the citric acid cycle) are oxidized. Their high-energy electrons and hydrogens are passed from one oxidizing agent to the next until they are transferred to O_2, producing water. The free energy released during electron transport is indirectly used to synthesize a large amount of ATP by oxidative phosphorylation.

glycolysis a series of reactions in which a glucose molecule is broken into two pyruvate molecules and energy is released

pyruvate oxidation a reaction in which pyruvate is oxidized by NAD^+, and CO_2 is removed, forming an acetyl group and releasing NADH

citric acid cycle a cyclic series of reactions that transfers energy from organic molecules to ATP, NADH, and $FADH_2$ and releases carbon atoms as CO_2

Figure 2 This greatly simplified flow diagram shows the four stages of cellular respiration.

The Mitochondrion

In eukaryotic cells, glycolysis occurs in the cytosol, whereas pyruvate oxidation, the citric acid cycle, and electron transport occur in the mitochondrion. This membrane-bound organelle is often referred to as the powerhouse of the cell because, as the location of the citric acid cycle and electron transport, it generates most of the ATP that is used by the cell. The mitochondrion is composed of two membranes, the outer membrane and the inner membrane, which together define two compartments (**Figure 3**). The intermembrane space is between the outer and inner membranes, and the matrix is the interior aqueous environment of the organelle.

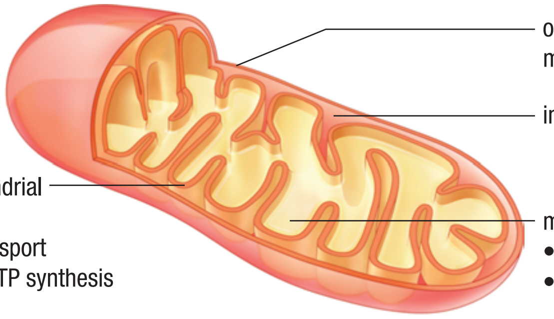


Figure 3 The membranes and compartments of the mitochondrion

Some prokaryotes undergo aerobic cellular respiration without mitochondria. In prokaryotes, the process of glycolysis, pyruvate oxidation, and the citric acid cycle occur in the cytosol of the cell, whereas electron transport occurs on internal membranes that are derived from the plasma membrane. These prokaryotes possess the full complement of reactions that make up aerobic cellular respiration—from glycolysis through electron transport and oxidative phosphorylation.

Anaerobic Pathways

anaerobic respiration a process that uses a final inorganic oxidizing agent other than oxygen to produce energy

fermentation a process that uses an organic compound as the final oxidizing agent to produce energy

obligate anaerobe an organism that cannot survive in the presence of oxygen

facultative anaerobe an organism that can live with or without oxygen

Energy can be extracted from food molecules through a number of biochemical pathways. As well as using aerobic cellular respiration, which requires the presence of oxygen, many organisms can extract energy from food without using oxygen. There are two general processes by which certain cells can oxidize fuel molecules and generate ATP in the absence of oxygen: anaerobic respiration and fermentation. **Anaerobic respiration** is similar to aerobic cellular respiration in using a series of electron-transferring steps, but it uses an inorganic molecule other than oxygen as the final oxidizing agent. **Fermentation** does not use an electron transport system. It relies on an organic compound to act as the final oxidizing agent. Both anaerobic respiration and fermentation are catabolic (energy-yielding) processes. The following equation shows the overall reaction for one common fermentation pathway. The released free energy is used to make ATP. Notice that the products of this fermentation pathway are ethanol, CH_3CH_2OH, and CO_2:

$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 \qquad \Delta G = -218\ \text{kJ/mol}$$

There is a striking difference between the small amount of free energy that is released by this fermentation pathway and the amount released during aerobic cellular respiration.

Many prokaryotes and some protists live in environments with little or no oxygen. They use anaerobic respiration or fermentation to obtain energy from their food. Examples of these organisms are the bacteria that are responsible for tetanus and botulism poisoning, and the protist *Trichonympha*, which lives within the guts of termites and feeds on ingested cellulose. *Trichonympha* lacks mitochondria and relies on an unusual fermentation pathway to generate ATP. All of these organisms are **obligate anaerobes** and cannot survive in the presence of oxygen. They use inorganic substances such as NO_2, S, and Fe^{3+} as final electron acceptors to obtain energy. Other organisms, such as yeast and the *E. coli* bacteria that live in our gut, survive with or without oxygen. These organisms are called **facultative anaerobes**. You will learn more about the anaerobic respiration and fermentation processes in Section 4.4.

4.1 Review

Summary

- There are three main types of energy pathways: aerobic respiration, anaerobic respiration, and fermentation. They all produce ATP.
- The four stages of aerobic cellular respiration are glycolysis, pyruvate oxidation, the citric acid cycle, and the electron transport chain.
- Mitochondria generate most of the ATP that is used in eukaryotic cells.
- Respiration pathways use electron transport systems to generate ATP by oxidative phosphorylation. Fermentation pathways lack such transport systems.
- Anaerobic respiration uses an inorganic substance other than oxygen as the final oxidizing agent. Fermentation relies on an organic compound.

Questions

1. (a) What is the final energy-rich product of the pathways that extracts energy from food?
   (b) What is this product responsible for in the cell? K/U
2. Explain the main difference between aerobic respiration and anaerobic respiration. K/U
3. Use a Venn diagram to compare and contrast anaerobic respiration with fermentation. K/U
4. Describe the differences between the following:
   - obligate aerobes
   - obligate anaerobes
   - facultative anaerobes K/U
5. (a) What is the overall equation that represents aerobic cellular respiration?
   (b) Describe this equation using simple words that a non-scientist could understand. K/U C
6. How many stages are involved in aerobic cellular respiration? Briefly describe each stage. K/U
7. Some bacteria cells are quite similar in structure to mitochondria. Both contain their own DNA, and both are able to divide on their own (mitochondria divide within eukaryotic cells). However, bacteria cells are able to survive independently, while mitochondria are not. K/U T/I
   (a) What part of the aerobic respiration pathway cannot be performed by mitochondria?
   (b) In terms of energy pathways only, what two chemicals (in addition to ADP and P_i) do mitochondria need to take in to generate ATP?
8. Suggest a commercial application of a fermentation pathway. A
9. Using the Internet and other sources, research commercial ethanol production. How could using bacteria to generate ethanol through cellulosic fermentation lead to a more efficient method of producing ethanol as a biofuel? T/I A
10. What would be the net effect for life on Earth if the aerobic pathway had not developed? T/I A

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