4.5A Cellular Respiration in Detail
Glycolysis and the Krebs Cycle

KEY CONCEPT Cellular respiration is an aerobic process with two main stages.

MAIN IDEAS

- Glycolysis is needed for cellular respiration.
- The Krebs cycle is the first main part of cellular respiration.
- The electron transport chain is the second main part of cellular respiration.

Review
glycolysis, Krebs cycle, electron transport chain, cellular respiration, aerobic respiration

Connect If chloroplasts are like tiny factories that make products, mitochondria are like power plants that burn fuel to produce electricity. In a power plant, a processed fuel is burned in the presence of oxygen and energy is released as useful electricity. During cellular respiration, oxygen and digested molecules from food are used to produce useful energy in the form of ATP.

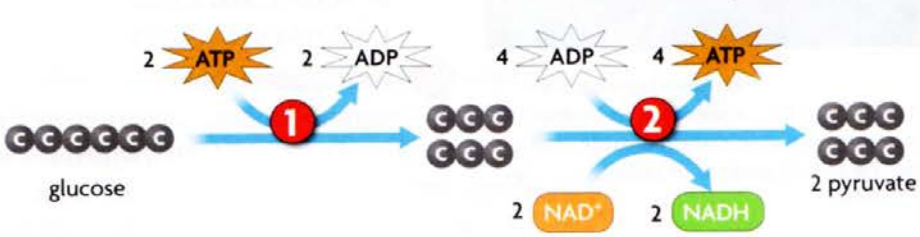
MAIN IDEA

Glycolysis is needed for cellular respiration.

In Section 4.4 you read a summary of how cellular respiration produces ATP molecules. But cellular respiration, like photosynthesis, is a very complex process. For example, glucose and oxygen do not react directly with one another, and many chemical reactions, such as glycolysis, must take place.

Glycolysis is an ongoing process in all cells, including yours. It takes place in the cytoplasm before cellular respiration, and it does not require oxygen. Glycolysis makes a small number of ATP molecules, but its other products are much more important. If oxygen is available, the products of glycolysis are used to produce many more ATP molecules through cellular respiration. The process of glycolysis can be summarized as follows.

1. Two ATP molecules are used to energize a glucose molecule. The glucose molecule is split into two three-carbon molecules. A series of enzymes and chemical reactions rearranges the three-carbon molecules.
2. Energized electrons from the three-carbon molecules are transferred to molecules of NAD^+. Molecules of NADH are formed. A series of reactions converts the three-carbon molecules to pyruvate (py-ROO-vayt), which enters cellular respiration. Four ATP molecules are made.



Connecting CONCEPTS

Fermentation When cells do not have a supply of oxygen for the aerobic processes of cellular respiration, the anaerobic processes of fermentation take place. You will learn about fermentation in Section 4.6.

Although glycolysis makes four ATP molecules, recall that two ATP molecules are used to first split the glucose molecule. So the breakdown of one glucose molecule by glycolysis gives a net gain of two ATP molecules. The pyruvate and NADH produced by glycolysis are used for cellular respiration when oxygen is present. NADH is an electron carrier like NADPH, the electron carrier in photosynthesis.

Summarize How does glycolysis result in a net gain of two ATP molecules?

MAIN IDEA

The Krebs cycle is the first main part of cellular respiration.

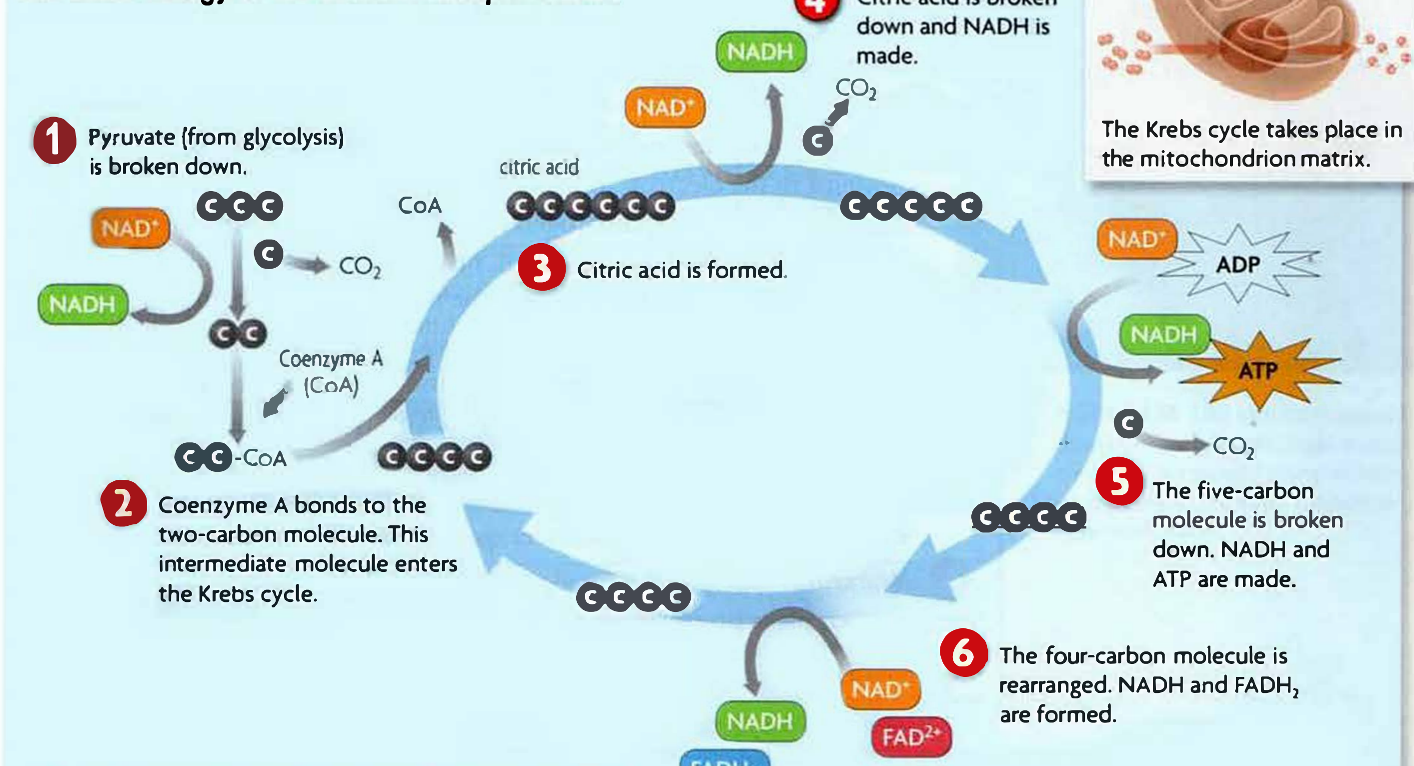
Cellular respiration makes many more ATP molecules than does glycolysis. It begins with the breakdown of pyruvate in steps 1 and 2 below. The process continues with the Krebs cycle, shown in **FIGURE 4.14.** Notice that steps 1, 4, and 5 below are very similar. In those steps, a carbon-based molecule is split, a molecule of carbon dioxide is formed, and energy-carrying NADH molecules are made. In fact, the main function of the Krebs cycle is to transfer high-energy electrons to molecules that carry them to the electron transport chain. The Krebs cycle is also sometimes called the citric acid cycle because citric acid is the first molecule formed, as you can see in step 3 below.

FIGURE 4.13 Gasoline engines burn carbon-based molecules in the presence of oxygen, and they release water, carbon dioxide, and energy. The overall process of cellular respiration is similar.

1. **Pyruvate broken down** A pyruvate molecule is split into a two-carbon molecule and a molecule of carbon dioxide, which is given off as a waste product. High-energy electrons are transferred from the two-carbon molecule to NAD^+, forming a molecule of NADH. The NADH moves to the electron transport chain.
2. **Coenzyme A** A molecule called coenzyme A bonds to the two-carbon molecule made from the breakdown of pyruvate. This intermediate molecule goes to the Krebs cycle.
3. **Citric acid formed** The two-carbon part of the intermediate molecule is added to a four-carbon molecule to form a six-carbon molecule called citric acid. Coenzyme A goes back to step 2.
4. **Citric acid broken down** The citric acid molecule is broken down by an enzyme and a five-carbon molecule is formed. A molecule of NADH is made and moves out of the Krebs cycle. A molecule of carbon dioxide is given off as a waste product.
5. **Five-carbon molecule broken down** The five-carbon molecule is broken down by an enzyme. A four-carbon molecule, a molecule of NADH, and a molecule of ATP are formed. The NADH leaves the Krebs cycle. Carbon dioxide is given off as a waste product.
6. **Four-carbon molecule rearranged** Enzymes rearrange the four-carbon molecule. High-energy electrons are released. Molecules of NADH and $FADH_2$, which is another electron carrier, are made. They leave the Krebs cycle and the four-carbon molecule remains.

Figure 4.14 The Krebs Cycle

The Krebs cycle breaks down citric acid and transfers energy to the elctron transport chain.



Infer: Does glycolysis directly produce as much ATP as the Krebs cycle? Indirectly? Explain your answer.

The products from the breakdown of one molecule of pyruvate are

- three molecules of carbon dioxide that are given off as a waste product
- one molecule of ATP
- four molecules of NADH to the electron transport chain
- one molecule of $FADH_2$ to the electron transport chain

Remember, glycolysis produces two pyruvate molecules. Therefore, the products above are half of what comes from one glucose molecule. The totals are six carbon dioxide, two ATP, eight NADH, and two $FADH_2$ molecules.

In what two ways is the Krebs cycle important for making ATP?