Fermentation and anaerobic respiration

How cells extract energy from glucose without oxygen. In yeast, the anaerobic reactions make alcohol, while in your muscles, they make lactic acid.

Introduction

Ever wonder how yeast ferment barley malt into beer? Or how your muscles keep working when you're exercising so hard that they're very low on oxygen?

Both of these processes can happen thanks to alternative glucose breakdown pathways that occur when normal, oxygen-using (aerobic) cellular respiration is not possible—that is, when oxygen isn't around to act as an acceptor at the end of the electron transport chain. These **fermentation** pathways consist of glycolysis with some extra reactions tacked on at the end. In yeast, the extra reactions make alcohol, while in your muscles, they make lactic acid.

Fermentation is a widespread pathway, but it is not the only way to get energy from fuels **anaerobically** (in the absence of oxygen). Some living systems instead use an inorganic molecule other than O_2, such as sulphate, as a final electron acceptor for an electron transport chain. This process, called **anaerobic cellular respiration**, is performed by some bacteria and Achaea.

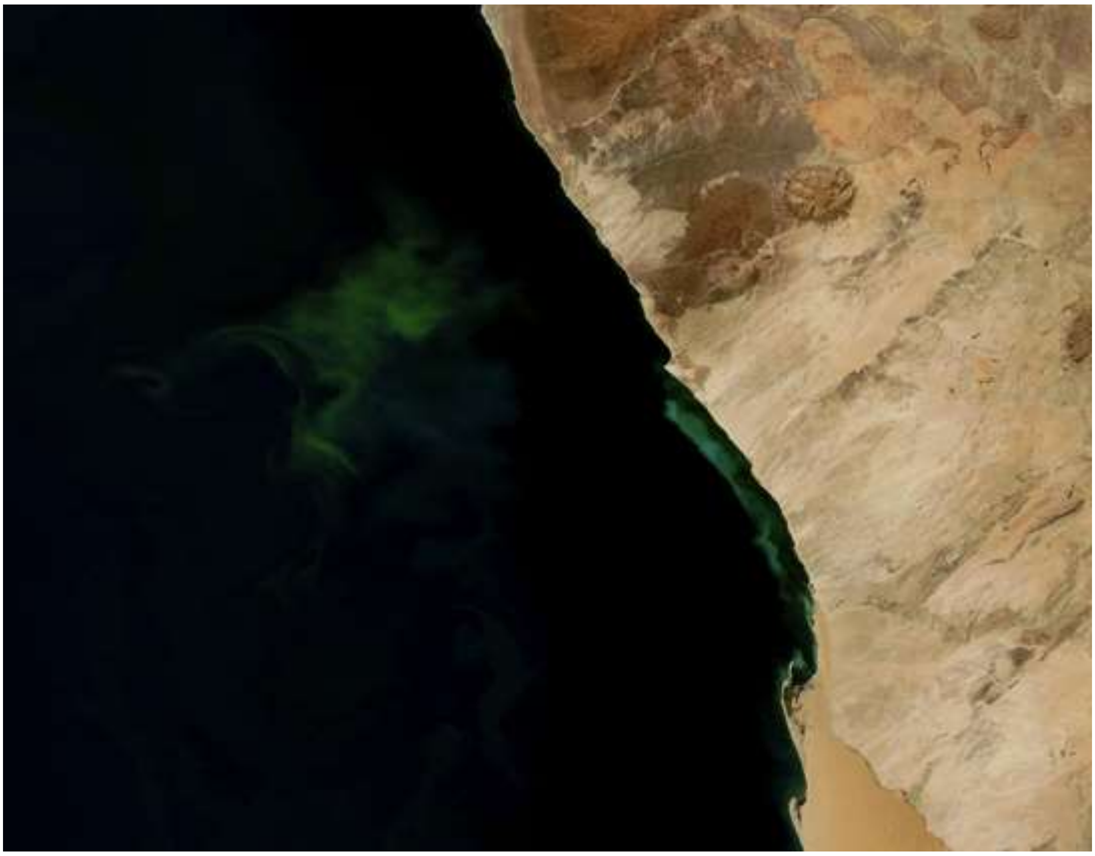
In this article, we'll take a closer look at anaerobic cellular respiration and at the different types of fermentation.

Anaerobic cellular respiration

Anaerobic cellular respiration is similar to aerobic cellular respiration in that electrons extracted from a fuel molecule are passed through an electron transport chain, driving ATP synthesis. Some organisms use sulphate (SO_4^{3-}) as the final electron acceptor at the end of the transport chain, while others use nitrate (NO_3^-), sulphur, or one of a variety of other molecules[1].

What kinds of organisms use anaerobic cellular respiration? Some prokaryotes—bacteria and archaea—that live in low-oxygen environments rely on anaerobic respiration to break down fuels. For example, some archaea called methanogens can use carbon dioxide as a terminal electron acceptor, producing methane as a by-product. Methanogens are found in soil and in the digestive systems of ruminants, a group of animals including cows and sheep.

Similarly, sulphate-reducing bacteria and Archaea use sulphate as a terminal electron acceptor, producing hydrogen sulphide (H_2S) as a by-product. The image below is an aerial photograph of coastal waters, and the green patches indicate an overgrowth of sulphate-reducing bacteria.



Aerial photograph of coastal waters with blooms of sulfate-reducing bacteria appearing as large patches of green in the water.

Image credit: "Metabolism without oxygen: Figure 1," OpenStax College, Biology, CC BY 3.0; Modification of work by NASA/Jeff Schmaltz, MODIS Land Rapid Response Team at NASA GSFC, Visible Earth Catalog of NASA images.

Fermentation

Fermentation is another anaerobic (non-oxygen-requiring) pathway for breaking down glucose, one that's performed by many types of organisms and cells. In **fermentation**, the only energy extraction pathway is glycolysis, with one or two extra reactions tacked on at the end.

Fermentation and cellular respiration begin the same way, with glycolysis. In fermentation, however, the pyruvate made in glycolysis does not continue through oxidation and the citric acid cycle, and the electron transport chain does not run. Because the electron transport chain isn't functional, the $NADH$ made in glycolysis cannot drop its electrons off there to turn back into NAD^+.

The purpose of the extra reactions in fermentation, then, is to regenerate the electron carrier NAD^+ from the $NADH$ produced in glycolysis. The extra reactions accomplish this by letting $NADH$ drop its electrons off with an organic molecule (such as pyruvate, the end product of glycolysis). This drop-off allows glycolysis to keep running by ensuring a steady supply of NAD^+ start superscript, plus, end superscript.

Lactic acid fermentation

In **lactic acid fermentation**, NADH transfers its electrons directly to pyruvate, generating lactate as a by-product. Lactate, which is just the deprotonated form of lactic acid, gives the process its name. The bacteria that make yogurt carry out lactic acid fermentation, as do the red blood cells in your body, which don't have mitochondria and thus can't perform cellular respiration.

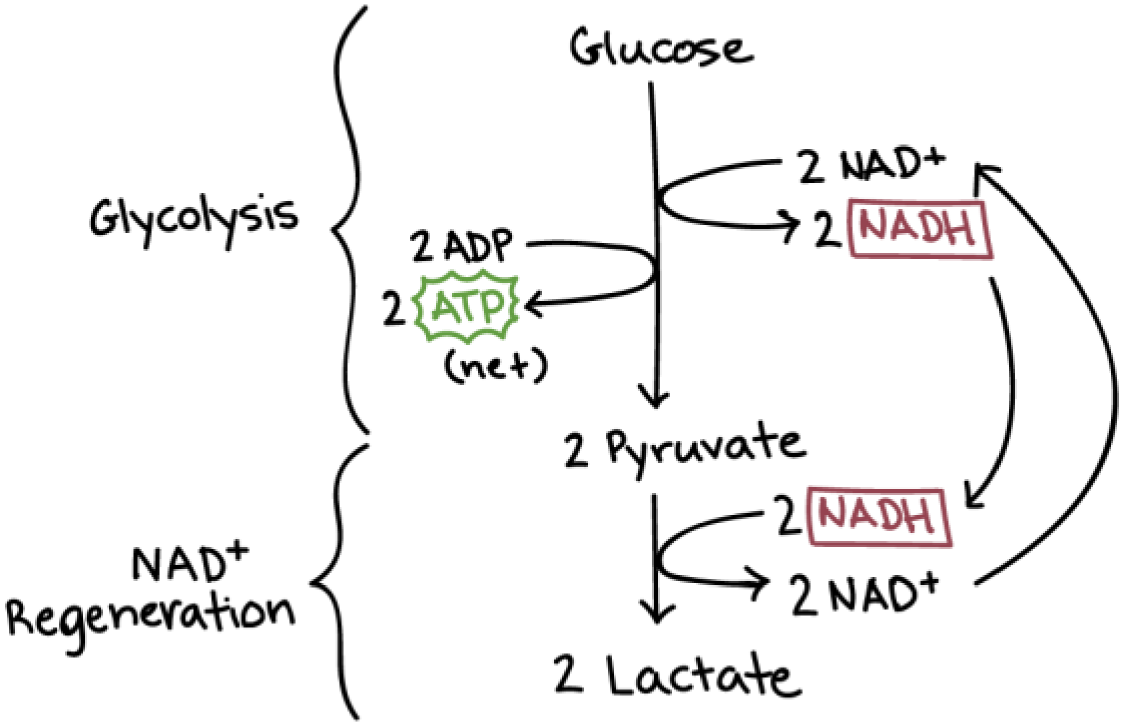


Diagram of lactic acid fermentation. Lactic acid fermentation has two steps: glycolysis and NADH regeneration.

During glycolysis, one glucose molecule is converted to two pyruvate molecules, producing two net ATP and two NADH.

During NADH regeneration, the two NADH donate electrons and hydrogen atoms to the two pyruvate molecules, producing two lactate molecules and regenerating NAD^+.

Muscle cells also carry out lactic acid fermentation, though only when they have too little oxygen for aerobic respiration to continue—for instance, when you've been exercising very hard. It was once thought that the accumulation of lactate in muscles was responsible for soreness caused by exercise, but recent research suggests this is probably not the case.

Lactic acid produced in muscle cells is transported through the bloodstream to the liver, where it's converted back to pyruvate and processed normally in the remaining reactions of cellular respiration.

Alcohol fermentation

Another familiar fermentation process is **alcohol fermentation**, in which NADH donates its electrons to a derivative of pyruvate, producing ethanol.

Going from pyruvate to ethanol is a two-step process. In the first step, a carboxyl group is removed from pyruvate and released in as carbon dioxide, producing a two-carbon molecule called acetaldehyde. In the second step, NADH passes its electrons to acetaldehyde, regenerating NAD^+ and forming ethanol.

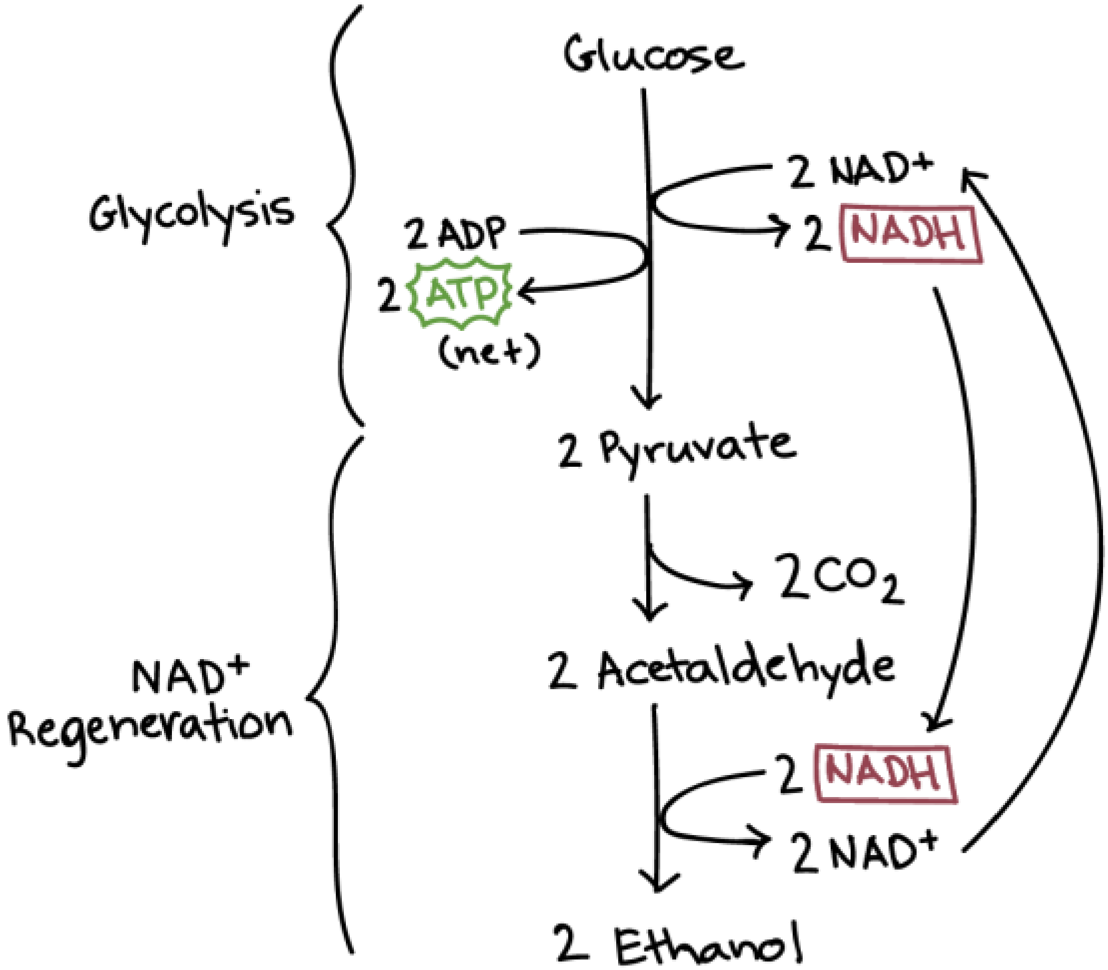


Diagram of alcohol fermentation. Alcohol fermentation has two steps: glycolysis and NADH regeneration.

During glycolysis, one glucose molecule is converted to two pyruvate molecules, producing two net ATP and two NADH.

During NADH regeneration, the two pyruvate molecules are first converted to two acetaldehyde molecules, releasing two carbon dioxide molecules in the process. The two NADH then donate electrons and hydrogen atoms to the two pyruvate molecules, producing two lactate molecules and regenerating NAD^+.

Alcohol fermentation by yeast produces the ethanol found in alcoholic drinks like beer and wine. However, alcohol is toxic to yeasts in large quantities (just as it is to humans), which puts an upper limit on the percentage alcohol in these drinks. Ethanol tolerance of yeast ranges from about 5 percent to 21 percent, depending on the yeast strain and environmental conditions.

Facultative and obligate anaerobes

Many bacteria and Achaea are **facultative anaerobes**, meaning they can switch between aerobic respiration and anaerobic pathways (fermentation or anaerobic respiration) depending on the availability of oxygen. This approach allows lets them get more ATP out of their glucose molecules when oxygen is around—since aerobic cellular respiration makes more ATP than anaerobic pathways—but to keep metabolizing and stay alive when oxygen is scarce.

Other bacteria and Achaea are **obligate anaerobes**, meaning they can live and grow only in the absence of oxygen. Oxygen is toxic to these microorganisms and injures or kills them on exposure. For instance, the *Clostridium* bacteria that are responsible for botulism (a form of food poisoning) are obligate anaerobes[2]. Recently, some multicellular animals have even been discovered in deep-sea sediments that are free of oxygen[3,4].
