

## **Fermentation enables some cells to produce ATP without the help of oxygen**

- Oxidation refers to the loss of electrons to any electron acceptor, not just to oxygen.
  - In glycolysis, glucose is oxidized to two pyruvate molecules *with NAD<sup>+</sup> as the oxidizing agent*, not O<sub>2</sub>.
  - Some of the energy from this oxidation produces 2 ATP (net).
  - If oxygen is present, additional ATP can be generated from the pyruvate when NADH delivers its electrons to the *electron transport chain (LOTS of ATP)*.
- But glycolysis generates 2 ATP (and two pyruvate) whether oxygen is present (**aerobic**) or not (**anaerobic**).

*So what happens to these 2 pyruvate if oxygen is NOT present????*

- Anaerobic catabolism of sugars can occur by fermentation.
- Fermentation can generate ATP from glucose by substrate-level phosphorylation as long as there is a supply of NAD<sup>+</sup> to accept electrons.
  - If the NAD<sup>+</sup> pool is exhausted, glycolysis shuts down.
  - Under aerobic conditions, NADH transfers its electrons to the electron transport chain, recycling NAD<sup>+</sup>.
- Under anaerobic conditions, various fermentation pathways generate ATP by glycolysis and recycle NAD<sup>+</sup> by transferring electrons from NADH to pyruvate or derivatives of pyruvate.
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps.
  - First, pyruvate is converted to a two-carbon compound, acetaldehyde by the removal of CO<sub>2</sub>.
  - Second, acetaldehyde is reduced by NADH to ethanol.
  - Alcohol fermentation by yeast is used in brewing and winemaking.

- During **lactic acid fermentation**, pyruvate is reduced directly by NADH to form lactate (ionized form of lactic acid).
  - Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt.
  - Muscle cells switch from aerobic respiration to lactic acid fermentation to generate ATP when O<sub>2</sub> is scarce.
    - The waste product, lactate, may cause muscle fatigue, but ultimately it is converted back to pyruvate in the liver.
- Fermentation and cellular respiration ***BOTH*** produce ATP from sugars:
- Fermentation is anaerobic (does NOT need oxygen)
- Cellular respiration is aerobic (needs oxygen)
  - Both use glycolysis to oxidize sugars to pyruvate with a net production of 2 ATP by substrate-level phosphorylation.
  - Both use NAD<sup>+</sup> as an electron acceptor.
- In fermentation, the electrons of NADH are passed to an organic molecule, regenerating NAD<sup>+</sup>.
- In respiration, the electrons of NADH are ultimately passed to O<sub>2</sub>, generating ATP by oxidative phosphorylation.
  - In addition, even more ATP is generated from the oxidation of pyruvate in the Krebs cycle.
- Without oxygen, the energy that is still stored in pyruvate is ***unavailable to the cell.***
- Under aerobic respiration, a molecule of glucose yields 38 ATP, but the same molecule of glucose yields only 2 ATP under anaerobic respiration.

- Some organisms (**facultative anaerobes**), including yeast and many bacteria, can survive using either fermentation or respiration.
- At a cellular level, human muscle cells can behave as facultative anaerobes, but nerve cells cannot.
- For facultative anaerobes, pyruvate is a fork in the metabolic road that leads to two alternative routes.
- The oldest bacterial fossils are over 3.5 billion years old, appearing long before appreciable quantities of O<sub>2</sub> accumulated in the atmosphere.
- Therefore, the first prokaryotes may have generated ATP exclusively from glycolysis.
- The fact that glycolysis is also the most widespread metabolic pathway and occurs in the cytosol without membrane-enclosed organelles, suggests that glycolysis evolved early in the history of life.