18.5: Fermentation

Skills to Develop

1. Define fermentation.
2. State the mechanism for ATP generation during fermentation.
3. Briefly describe the function of glycolysis during fermentation and indicate the reactants and products.
4. Compare the maximum yield of ATP from one molecule of glucose for aerobic respiration and for fermentation.

Fermentation is an anaerobic breakdown of carbohydrates in which an organic molecule is the final electron acceptor. It does not involve an electron transport system. Furthermore:

a. Fermentation is a partial breakdown of glucose producing only 2 net ATP's per glucose by way of substrate-level phosphorylation;
b. Fermentation involves only glycolysis; and
c. Fermentation is found in bacteria that are obligate anaerobes and facultative anaerobes.

Glycolysis during Fermentation

Function: As during aerobic respiration, glycolysis is a partial breakdown of a six-carbon glucose molecule into two, three-carbon molecules of pyruvate, 2NADH +2H+, and 2 net ATP as a result of substrate-level phosphorylation, as shown in (see Figure 1 and Figure 2).
Figures 1 and 2: A Summary of Glycolysis. 1. A phosphate from the hydrolysis of a molecule of ATP is added to glucose, a 6-carbon sugar, to form glucose 6-phosphate. 2. The glucose 6-phosphate molecule is rearranged into an isomer called fructose 6-phosphate. 3. A second phosphate provided by the hydrolysis of a second molecule of ATP is added to the fructose 6-phosphate to form fructose 1,6-diphosphate. 4. The 6-carbon fructose 1,6-biphosphate is split into two molecules of glyceraldehyde 3-phosphate, a 3-carbon molecule. 4. Oxidation and phosphorylation of each glyceraldehyde 3-phosphate produces 1,3-biphosphoglycerate with a high-energy phosphate bond (wavy red line) and NADH. 5. Through substrate-level phosphorylation, the high-energy phosphate is removed from each 1,3-biphosphoglycerate and transferred to ADP forming ATP and 3-phosphoglycerate. 6. Each 3-phosphoglycerate is oxidized to form a molecule of phosphoenolpyruvate with a high-energy phosphate bond. 7. Through substrate-level phosphorylation, the high-energy phosphate is removed from each phosphoenolpyruvate and transferred to ADP forming ATP and pyruvate.

Glycolysis occurs in the cytoplasm of the cell. As mentioned above, the overall reaction is:

\[
glucose (6C) + 2 NAD^+ + 2 ADP + 2 \text{inorganic phosphates (P}_i\text{)} \rightarrow 2 \text{pyruvate (3C)} + 2 \text{NADH} + 2 H^+ + 2 \text{net ATP}
\]

Glycolysis also produces a number of key precursor metabolites, as shown in Figure 3.

Figure 3: Integration of Metabolism - Precursor Metabolites. Carbohydrates, proteins, and lipids can be used as energy sources; metabolites involved in energy production can be used to synthesize carbohydrates, proteins, lipids, nucleic acids, and cellular structures.

Since there is no electron transport system, the protons and electrons donated by certain intermediate precursor
molecules during glycolysis generate no additional molecules of ATP. Instead, they combine with the coenzyme NAD\(^+\), the organic molecule which serves as the final electron and proton acceptor, reducing it to NADH + H\(^+\) (see Figure 1 and Figure 2).

Animation: Glycolysis

Glycolysis is the partial breakdown of one molecule of glucose into two molecules of pyruvic acid, two net molecules of ATP, two molecules of NADH, and 2H\(^+\).

Glycolysis is a partial breakdown of a six-carbon glucose molecule into two, three-carbon molecules of pyruvate, 2NADH +2H\(^+\), and 2 net ATP as a result of substrate-level phosphorylation. Glycolysis occurs in the cytoplasm of the cell.

The 2 pyruvic acids are then converted into one of many different fermentation end products in several non-energy-producing steps.

### Fermentation end products

Some fermentation end products produced by microorganisms are very beneficial to humans and are the basis of a number of industries (brewing industry, dairy industry, etc.). Fermentation is used in the production of many food products including bread, alcohol, yogurt, sour cream, cheeses, vinegar, sauerkraut, pickles, olives, soy sauce, poi, and kimchi. Examples of microbial fermentation end products include:

- **Saccharomyces**: ethyl alcohol and CO\(_2\)
- **Streptococcus** and **Lactobacillus**: lactic acid
- **Propionibacterium**: propionic acid, acetic acid, and CO\(_2\)
- **Escherichia coli**: acetic acid, lactic acid, succinic acid, ethyl alcohol, CO\(_2\), and H\(_2\)
- **Enterobacter**: formic acid, ethyl alcohol, 2,3-butanediol, lactic acid, CO\(_2\), and H\(_2\)
- **Clostridium**: butyric acid, butyl alcohol, acetone, isopropyl alcohol, CO\(_2\), and H\(_2\)

### Summary

1. Fermentation is an anaerobic breakdown of carbohydrates in which an organic molecules the final electron acceptor
and does not involve an electron transport system.

2. Fermentation is a partial breakdown of glucose producing only 2 net ATP's per glucose by way of substrate-level phosphorylation, involves only glycolysis, and is found in anaerobic and facultative anaerobic bacteria.

3. The overall reaction is glucose (6C) + 2 NAD$^+$ + 2 ADP +2 inorganic phosphates (Pi) yields 2 pyruvate (3C) + 2 NADH + 2 H$^+$ + 2 net ATP.

4. Glycolysis also produces a number of key precursor metabolites.

5. Some fermentation end products produced by microorganisms are very beneficial to humans and are the basis of a number of industries (brewing industry, dairy industry, etc.).

Contributors

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