Heterotrophic CO_2 fixation can be an important factor in culturing microbes. When a culture is initiated at low density (i.e., few cells per unit volume) with little accumulation of intracellular CO_2, or when a gas sparge rate into a fermentation tank is high, then growth may be limited by the rate of CO_2 fixation to maintain the TCA cycle.

5.4. RESPIRATION

The respiration reaction sequence is also known as the electron transport chain. The process of forming ATP from the electron transport chain is known as *oxidative phosphorylation*. Electrons carried by $NADH + H^+$ and $FADH_2$ are transferred to oxygen via a series of electron carriers, and ATPs are formed. Three ATPs are formed from each $NADH + H^+$ and two ATPs for each $FADH_2$ in eucaryotes. The details of the respiratory (cytochrome) chain are depicted in Fig. 5.6. The major role of the electron transport chain is to regenerate NADs for glycolysis and ATPs for biosynthesis. The term P/O ratio is used to indicate the number of phosphate bonds made ($ADP + Pi \rightarrow ATP$) for each oxygen atom used as an electron acceptor (e.g., $\frac{1}{2}O_2 + NADH + H^+ \rightarrow H_2O + NAD^+$).

Formation of $NADH + H^+$, $FADH_2$, and ATP at different stages of the aerobic catabolism of glucose are summarized in Table 5.1. The overall reaction (assuming 3 ATP/NADH) of aerobic glucose catabolism in eucaryotes[†]

$$\text{glucose} + 36\ Pi + 36\ ADP + 6\ O_2 \longrightarrow 6\ CO_2 + 6\ H_2O + 36\ ATP \tag{5.7}$$

The energy deposited in 36 mol of ATP is 263 kcal/mol glucose. The free-energy change in the direct oxidation of glucose is 686 kcal/mol glucose. Therefore, the energy efficiency of glycolysis is 38% under standard conditions. With the correction for nonstandard conditions, this efficiency is estimated to be greater than 60%, which is significantly higher than the efficiency of man-made machines. The remaining energy stored in glucose is dissipated as heat. However, in procaryotes the conversion of the reducing power to ATP is less efficient. The number of ATP generated from $NADH + H^+$ is usually ≤ 2, and only one ATP may be generated from $FADH_2$. Thus, in procaryotes a single glucose molecule will yield less than 24 ATP, and the P/O ratio is generally between 1 and 2.

TABLE 5.1 Summary of NADH, $FADH_2$, and ATP Formation during Aerobic Catabolism of Glucose (Based on Consumption of 1 Mole of Glucose)

	NADH	$FADH_2$	ATP	Total ATP[a]
Glycolysis	2	–	2	6[b]
Oxidative decarboxylation of pyruvate	2	–	–	6
TCA cycle	6	2	2	24
Total	10	2	4	36 mol ATP

[a]Assumes a P/O ratio of 3 (i.e., 3 ATP phosphates made for each proton transported by the electron transport chain) for NADH and a P/O ratio of 2 for each $FADH_2$.

[b]The yield is 6 ATP rather than 8 because 2 NADH are converted to 2 $FADH_2$ for the transfer of acetyl CoA into mitochondria.

[†]The yield is about 30 ATP if we assume 2.5 ATP/NADH.