9.2 Oxidation and Reduction

Definitions

Oxidation: A reaction in which atoms or molecules gain oxygen, or lose hydrogen or electrons.

Reduction: A reaction in which atoms or molecules either lose oxygen, or gain hydrogen or electrons.

Terminal electron acceptor: A molecule that accepts electrons from an oxidized compound.

Aerobic respiration: A form of respiration in the presence of oxygen, in which the terminal electron acceptor is oxygen, leading to the formation of water. This process yields maximum energy.

Anaerobic respiration: A form of respiration in the absence of oxygen, in which the terminal electron acceptors may be nitrate or sulfate ions or other substances. This process yields less energy than aerobic respiration.

Concepts

Oxidation and reduction of matter are intimately linked with energy transformations. Oxidation refers to reactions in which atoms or molecules gain oxygen, or lose hydrogen or electrons. The opposite reaction is called reduction, in which atoms or molecules either lose oxygen, or gain hydrogen or electrons. Oxidation/reductions are coupled so that as one compound is oxidized, the other is reduced. Oxidation reactions result in gains of energy, while reduction reactions require energy. Oxidation and reduction reactions play an important part in cell metabolism and impact the composition of soil air and the atmosphere above the soil.

The process of photosynthesis is an example of the reduction of carbon dioxide into simple sugars. It requires solar energy and occurs in plants which have chlorophyll:

$$6\ CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + O_2 \qquad \text{(Eq. 9.1)}$$

The above reaction produces simple sugars and organic compounds, which support food webs on Earth. Heterotrophic organisms oxidize sugars and other organic compounds in the presence of oxygen to generate carbon dioxide and energy:

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + 6\ H_2O + \text{energy} \qquad \text{(Eq. 9.2)}$$

In the absence of oxygen, bacteria use anaerobic respiration in which bacteria use ions, such as nitrate, as terminal electron acceptors. The overall reaction involves dissimilatory reduction of nitrogen oxides to nitrogen gases:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad \text{(Eq. 9.3)}$$

In order to identify whether an atom or molecule is oxidized or reduced, it is necessary to determine the oxidation state of the elements in reaction as per the following rules (Sylvia et al., 1998):

1. Any element in a free state is assigned an oxidation number of zero; e.g. elemental sulfur (S) has an oxidation state of zero (S^0); each oxygen atom in O_2 has an oxidation state of zero.

2. Elements present as monoatomic ions have an oxidation state equal to the ionic charge: e.g. calcium in Ca^{2+} has an oxidation of +2.

3. When combined with other elements, hydrogen typically has an oxidation state of +1 and oxygen typically has an oxidation state of -2.

4. The sum of oxidation states of the atoms comprising a compound or polyatomic ion must be equal to the overall net charge of the substance; e.g. the N in NH_3 has an oxidation state of -3 while the N in NO_3^- has an oxidation state of +5. Similarly, the C in CH_4 has an oxidation state of -4 while the C in CO_2 has on oxidation state of +4. Both the reduced and oxidized forms of C and N are part of the C and N cycles.

Applications

Table 9.2. Changes in oxidation status of materials being oxidized and reduced in important ecological processes.

Equation	Material being oxidized	Change of oxidation status	Material being reduced	Change in oxidation status
$2S + 3O_2 + 2H_2O = H_2SO_4$	S	0 to +6	O_2	0 to -2
$2 NH_4^+ + 3O_2 = NO_2^- + 4H^+ + 2H_2O$	N	-3 to +5	O_2	0 to -2
$CO_2 + 4H_2 = CH_4 + 2H_2O$	H	0 to +1	C	+4 to -4
$2H_2 + O_2 = 2H_2O$	H	0 to +1	O_2	0 to -2
$C_6H_{12}O_6 + O_2 = 6 CO_2 + 6 H_2O$	C	0 to +4	O_2	0 to -2
$6 CO_2 + 6 H_2O = C_6H_{12}O_6 + O_2$	O_2	-2 to 0	C	+4 to 0
$2NO + O_2 = 2NO_2$	N	+2 to +4	O_2	0 to -2

Oxidation and reduction reactions in cells are coupled. Thus, an organism can generate energy through one reaction and use it to drive another reaction which requires energy. For example, S oxidizing bacteria are chem-autotrophic organisms which oxidize elemental sulfur (S) in the presence of oxygen. The energy from this reaction is used to reduce the C in CO_2 to glucose, which is used in cell synthesis and metabolism.