Chapter 8
BIOENERGETICS

After studying this chapter, students will be able to:

- Describe the importance of oxidation-reduction reactions.
- Explain ATP as a molecule that is the chief energy currency of all cells.
- Describe photosynthesis.
- State the role of chlorophyll found in chloroplast.
- State the equation (in words or symbols) for photosynthesis.
- Describe respiration.
- Describe anaerobic respiration and state its importance.
- State the equation (in words or symbols) for aerobic respiration.
- Compare aerobic and anaerobic respiration with reference to the amount of energy released.
- List ways in which respiratory energy is used in the body.
- Compare respiration and photosynthesis.

Bioenergetics is the study of how living organisms acquire, convert, store, and utilize energy to fuel their life processes. Organisms obtain energy primarily from their surroundings. Plants capture sunlight through photosynthesis, while animals and other organisms consume food. This energy is then converted into usable chemical energy, stored in molecules like ATP (adenosine triphosphate). ATP acts as a ready source of energy. Cells can use ATP whenever they need energy for processes such as growth, movement, repair, and reproduction.

Oxidation-reduction (redox) reactions are fundamental to the metabolism of organisms. In these reactions, electrons are transferred between molecules. In oxidation, molecule loses electrons and in reduction, it gains electrons. This electron flow is essential for generating energy in the form of ATP during

processes like cellular respiration and photosynthesis. **Bioenergetics** is the study of energy transformations in living organisms.

8.1- ATP: THE CELL'S ENERGY CURRENCY

Cells use a special energy currency for their reactions. This currency is a **nucleotide** called **adenosine triphosphate (ATP)**. When cells store energy, they make ATP. When cells need energy, they break ATP. ATP molecule has three subunits i.e. **adenine**, (a nitrogen containing base); **ribose** (a five-carbon sugar) and three **phosphate** groups.

In 1941, the Nobel prize winner, Fritz Lipmann proposed that ATP is the main energy-transfer molecule in the cell.

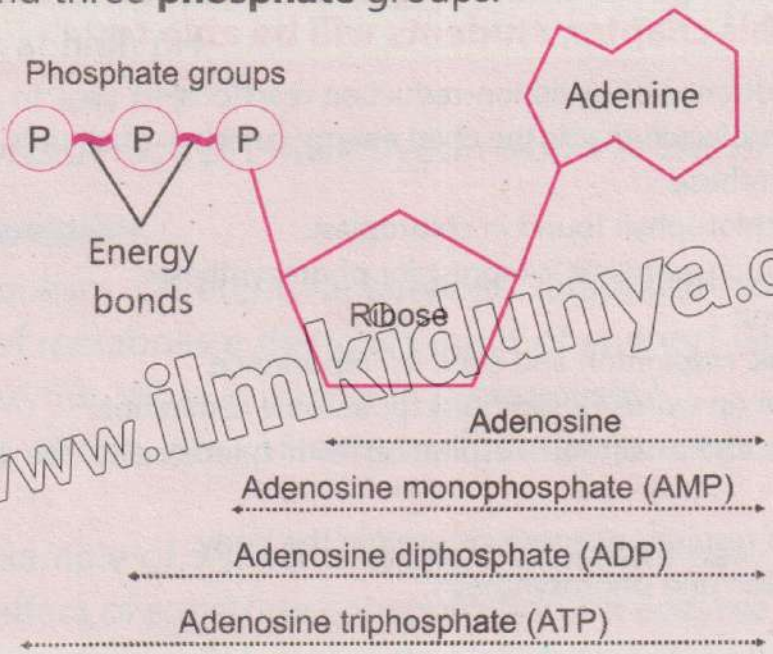

FIGURE 8.1: Molecular structure of ATP

In the molecule of ATP, the covalent bonds between **two phosphates** are high-energy bonds. When one of these bonds is broken, inorganic phosphate (Pi) separates and energy is released.

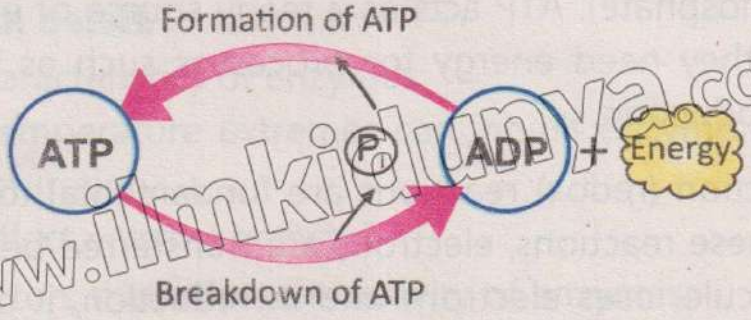

FIGURE 8.2: ATP-ADP Cycle

The breaking of one phosphate bond releases about 7.3 kcal (7,300 calories) per mole of ATP.

$$ATP + H_2O \rightarrow ADP + P_i + energy\ (7.3\ kcal/mole)$$

In common energy reactions only the outer P-P high-energy bond breaks. When this happens, ATP becomes **ADP (adenosine diphosphate)** and one Pi is released. In some cases, ADP is further broken down to **AMP (adenosine monophosphate)** and Pi:

$$ADP + H_2O \rightarrow AMP + Pi + energy\ (7.3\ kcal/mole)$$

Cells get energy from the oxidation of food. They store this energy by combining ADP with Pi to form ATP. So, we can summarize that ATP is made during energy-releasing processes and is broken down during energy-consuming processes. In this way ATP transfers energy between metabolic reactions.

8.2- PHOTOSYNTHESIS

Autotrophic organisms (plants, algae, some bacteria) use inorganic raw materials to prepare their organic food. The organic food is in the form of carbohydrates. The carbohydrates are used for getting energy and are also converted to other molecules like proteins, lipids etc.

Photosynthesis is the synthesis of glucose from carbon dioxide and water in the presence of sunlight (and chlorophyll), with oxygen as a by-product. It is the most important metabolic reaction and all life depends on it. A simple general equation for photosynthesis is as follows;

$$6\ CO_2 + 12\ H_2O + photons \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

carbon dioxide + water + light energy → glucose + oxygen + water

Mechanism of Photosynthesis

Photosynthesis occurs in two phases i.e. light reactions and dark reactions. Light reactions take place on the thylakoid membranes of chloroplasts. Dark reactions take place in the stroma of the chloroplasts.

1- Light Reactions

During light reaction, light energy is used to make high-energy molecules (ATP and NADPH). Following are the key events of light reactions:

Nicotinamide adenine dinucleotide (NAD):
It is a coenzyme. One form of this coenzyme also carries phosphate. It is called NADP.

- When chlorophyll absorbs light, two of its electrons become high-energy electrons. These high energy electrons are released from **chlorophyll**.
- The high energy electrons are passed to an **electron transport chain**. In this chain, when electrons pass from higher to lower energy level, they release energy which is used to produce **ATP.**
- Light also breaks water molecule. **Oxygen** is released while hydrogen atoms give electrons to chlorophyll and become hydrogen ions.
- The electrons of chlorophyll, after the production of ATP, and the hydrogen ions of water are used to reduce a NADP into **NADPH** (Nicotinamide Adenine Dinucleotide Phosphate – reduced)..

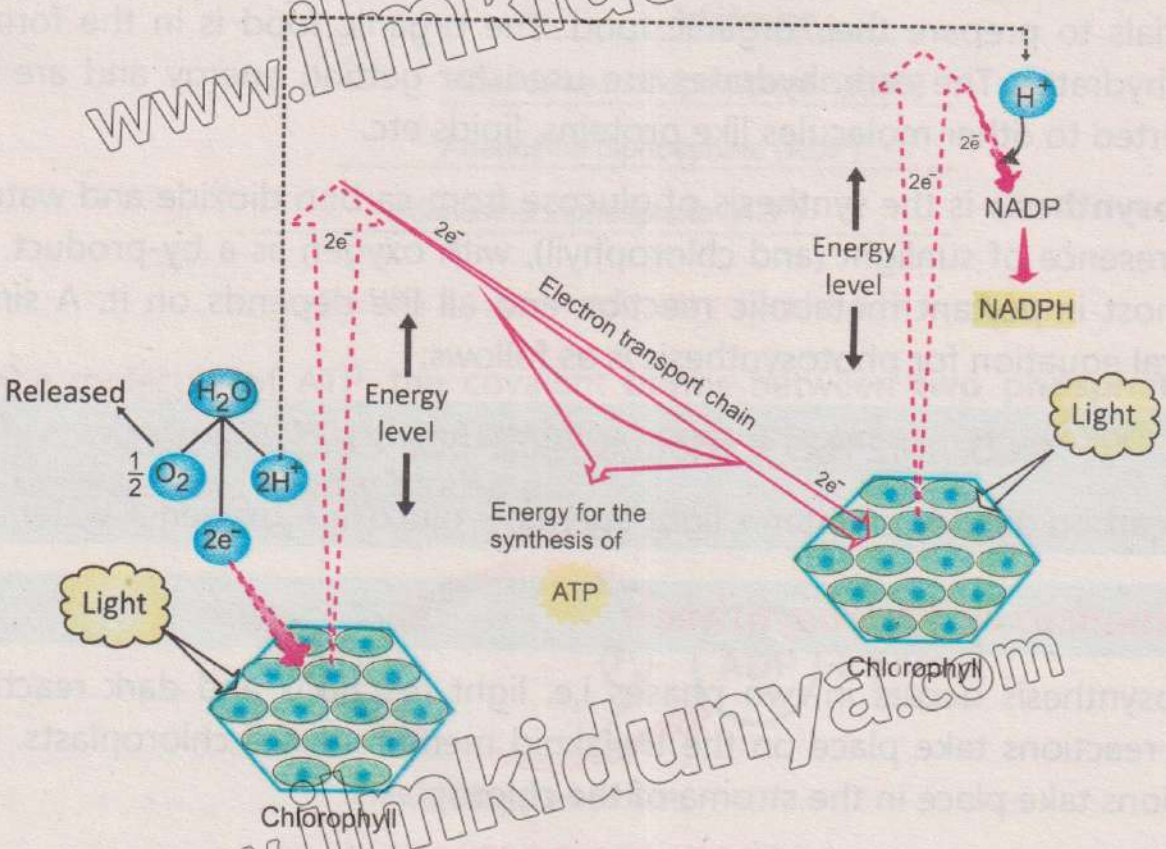

FIGURE 8.3: Light reactions of photosynthesis

2- Dark Reactions (Calvin Cycle)

During this phase, carbon dioxide is reduced to make glucose. The details of dark reactions were discovered by Melvin Calvin. Following is the summary of dark reactions:

- CO_2 molecules combine with 5-carbon compounds to form 6-carbon compounds. This 6-carbon compound is unstable and splits into two 3-carbon compounds.
- The 3-carbon compounds are reduced to 3-carbon carbohydrates by using ATP and hydrogen from NADPH (produced during light reactions). The 3-carbon carbohydrates are used to make glucose.
- The 3-carbon carbohydrates are also used to regenerate the original 5-carbon compounds. This step also utilizes ATP.

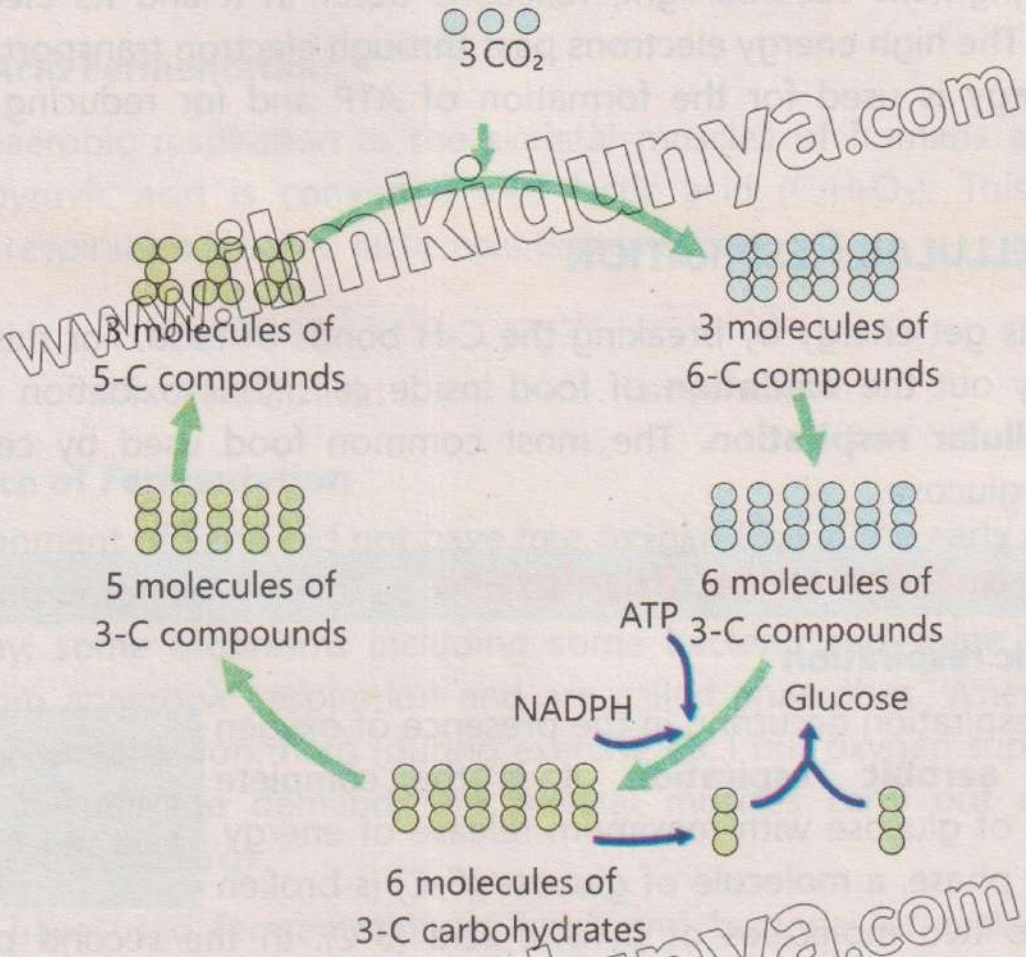

FIGURE 8.4: Dark reactions of photosynthesis

Role of Chlorophyll in Photosynthesis

The thylakoid membranes of chloroplasts contain pigments. **Chlorophyll-a** is the main pigment. Others are called **accessory pigments** and include chlorophyll-b and carotenoids.

Pigments absorb sunlight and convert it into chemical energy for photosynthesis. Only about 01% of the light falling on the leaf surface is absorbed, the rest is reflected or transmitted. The blue and red lights carry out more photosynthesis. Different pigments absorb different wavelengths of light. Chlorophyll-a absorbs light of **blue and red** wavelengths. The wavelengths which are not absorbed by chlorophyll-a are absorbed by accessory pigments.

Pigments are the substances that absorb visible light. Different pigments absorb light of different wavelengths (colours).

When a pigment absorbs light, reactions occur in it and its electrons are released. The high energy electrons pass through electron transport chain and their energy is used for the formation of ATP and for reducing NADP to NADPH.

8.3- Cellular Respiration

Organisms get energy by breaking the C-H bonds of food. For this purpose, they carry out the **oxidation** of food inside cells. This oxidation of food is called **cellular respiration.** The most common food used by cells to get energy is glucose.

Aerobic and Anaerobic Respiration

1- Aerobic respiration

Cellular respiration occurring in the presence of oxygen is called **aerobic respiration**. It is the complete oxidation of glucose with maximum release of energy. In its first phase, a molecule of glucose (6-C) is broken down into two molecules of pyruvic acid (3-C). In the second phase, the molecules of pyruvic acid are completely oxidized (all C-H bonds are broken) and all energy is released.

In anaerobic process, many C-H bonds of food are left unbroken.

2- Anaerobic Respiration (Fermentation)

Cellular respiration that occurs in the absence of oxygen is called **anaerobic respiration**. In anaerobic respiration, glucose is incompletely oxidized with less amount of energy released. Its first phase is exactly similar to that of aerobic respiration. A molecule of glucose is broken down into two molecules of pyruvic acid. In the second phase, pyruvic acid may be treated in two ways:

A. Alcoholic Fermentation:

During anaerobic respiration in bacteria and yeast etc. pyruvic acid is further broken down into alcohol (C_2H_5OH) and CO_2. This type of anaerobic respiration is called alcoholic fermentation.

> Yeast and bacteria can ferment sugars of berries to alcohol. Birds eating these berries can become quite drunk, as is obvious from their flight pattern.

$$2(C_3H_4O_3) \longrightarrow 2(C_2H_5OH) + 2CO_2$$

Pyruvic acid — Ethyl Alcohol

B. Lactic Acid Fermentation:

During anaerobic respiration in the skeletal muscles of humans and other animals, pyruvic acid is converted into lactic acid ($C_2H_6O_3$). This type of anaerobic respiration is called lactic acid fermentation.

$$2(C_3H_4O_3) + 4H \longrightarrow 2(C_3H_6O_3)$$

Pyruvic acid — Lactic acid

Importance of Fermentation

The environment of Earth did not have free oxygen (O_2) in the early phases of life. The early organisms respired anaerobically and got energy for their life. Even today, some organisms including some bacteria and some fungi get energy from anaerobic respiration and are called anaerobes. When skeletal muscles of humans work hard (during exercise etc.) but oxygen supply is not sufficient to fulfil the demand, the skeletal muscles carry out anaerobic respiration to get energy.

Scientists have used fermentation in fungi and bacteria for making useful products for mankind. For examples, the fermentation in bacteria is used for making cheese and yogurt. Fermentation in yeasts is used in brewing and

baking industries. Similarly, the soy sauce is made through the fermentation by a fungus.

Mechanism of Cellular Respiration

For the study of all the reactions of cellular respiration, we will go into the mechanism of aerobic respiration. There are three main steps of aerobic respiration.

1- Glycolysis

In the first step, the glucose (6C) molecule is broken. It results in two molecules of pyruvic acid (3C), with two ATPs and two NADH. This process is called **glycolysis** and it occurs in cytoplasm. Oxygen is not required for glycolysis. That is why, it also occurs in anaerobic respiration.

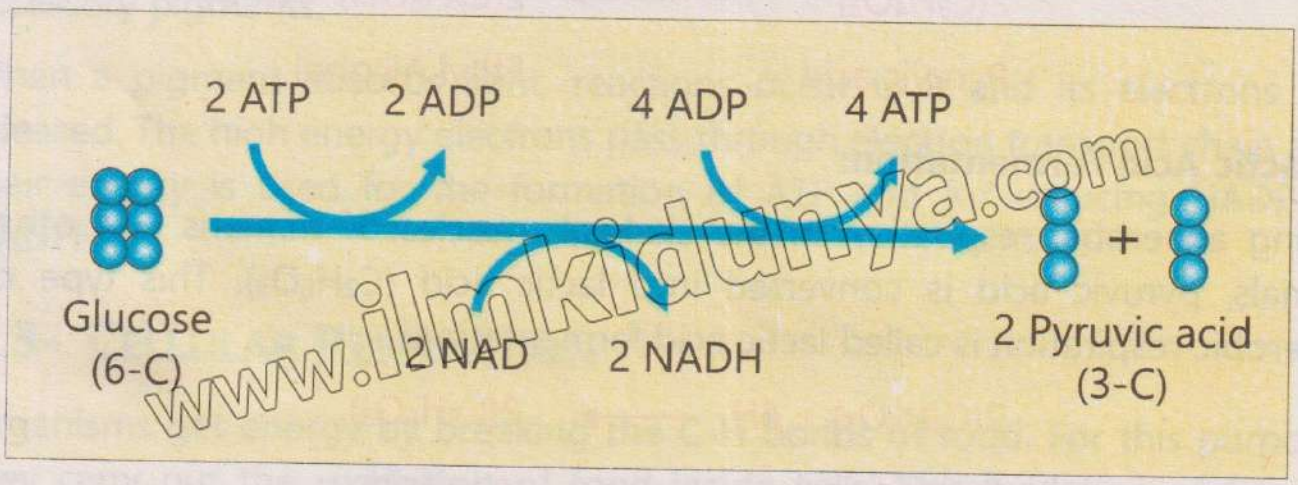

FIGURE 8.5: Summary of Glycolysis

2- Krebs Cycle

When oxygen is available, the molecules of pyruvic acid move from cytoplasm to the matrix of mitochondria. Here, a series of reaction called Krebs cycle (discovered by a British scientist Sir Hans Krebs) occurs. Before Krebs cycle, each pyruvic acid is converted into **acetyl coenzyme-A**, carbon dioxide and NADH.

In Krebs cycle, the acetyl coenzyme-A is completely oxidized to carbon dioxide. It results in the formation of ATP and energy-rich compounds i.e. NADH and $FADH_2$ (Flavin Adenine Dinucleotide – reduced).

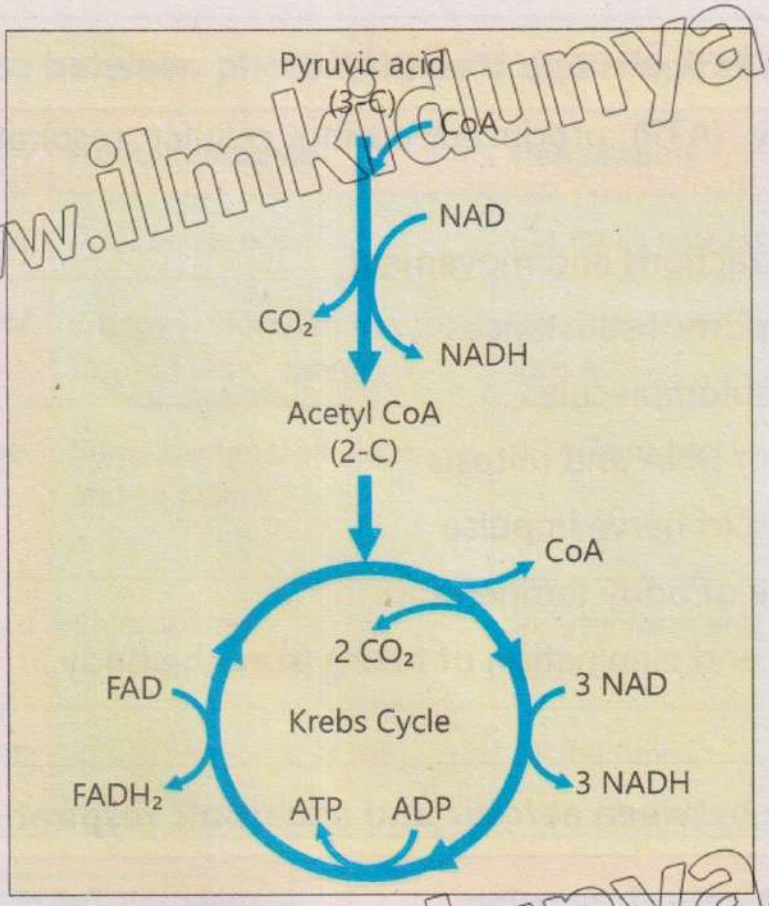

FIGURE 8.6: Summary of Krebs cycle

3- Electron Transport Chain

This step occurs on the inner membranes of mitochondria. During it, NADH and $FADH_2$ change back to NAD and FAD by releasing electrons and hydrogen ions. The released electrons pass through an electron transport chain and release energy. This energy is used to make ATP. At the end of chain, electrons and hydrogen ions combine with oxygen and form water.

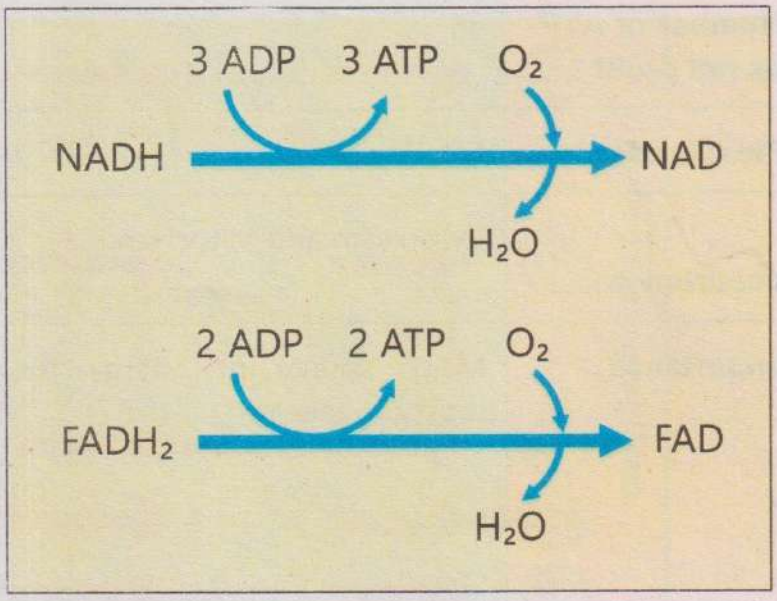

FIGURE 8.7: Electron transport chain

Use of Respiratory Energy in Body

Respiratory energy (ATP) produced during cellular respiration is used in various ways:

1. Muscle contractions and movement
2. Active transport of substances
3. Synthesis of biomolecules
4. Replication of DNA and mitosis
5. Transmission of nerve impulse
6. Maintenance of body temperature
7. Break down and elimination of toxins from the body.

Table: Difference between aerobic and anaerobic respiration

	Aerobic Respiration	Anaerobic Respiration
Presence of Oxygen	Yes	No
Number of ATP as net profit	36	02
Final products	CO_2, H_2O	Lactic acid or Ethanol + CO_2
occurrence	Cytoplasm and Mitochondria	Cytoplasm
Importance	Major source of energy for most organisms	• Source of energy for anaerobic organisms • Source of energy for aerobic organisms in short supply of O_2 • Source of useful products (ethanol, cheese etc.)

Table: Difference between photosynthesis and respiration

Characteristics	Photosynthesis	Respiration
Type of metabolism	Anabolic process	Catabolic process
Energy investment / production	Energy is stored in the form of bond energy	Bond energy of food is transformed into ATP
Organisms capable of performing this process	Some bacteria, all algae, and all plants	All organisms
Site of occurrence	Chloroplasts In green parts only	In cytoplasm and mitochondria In all cells
Time of occurrence	In daytime only, in the presence of light	All the time

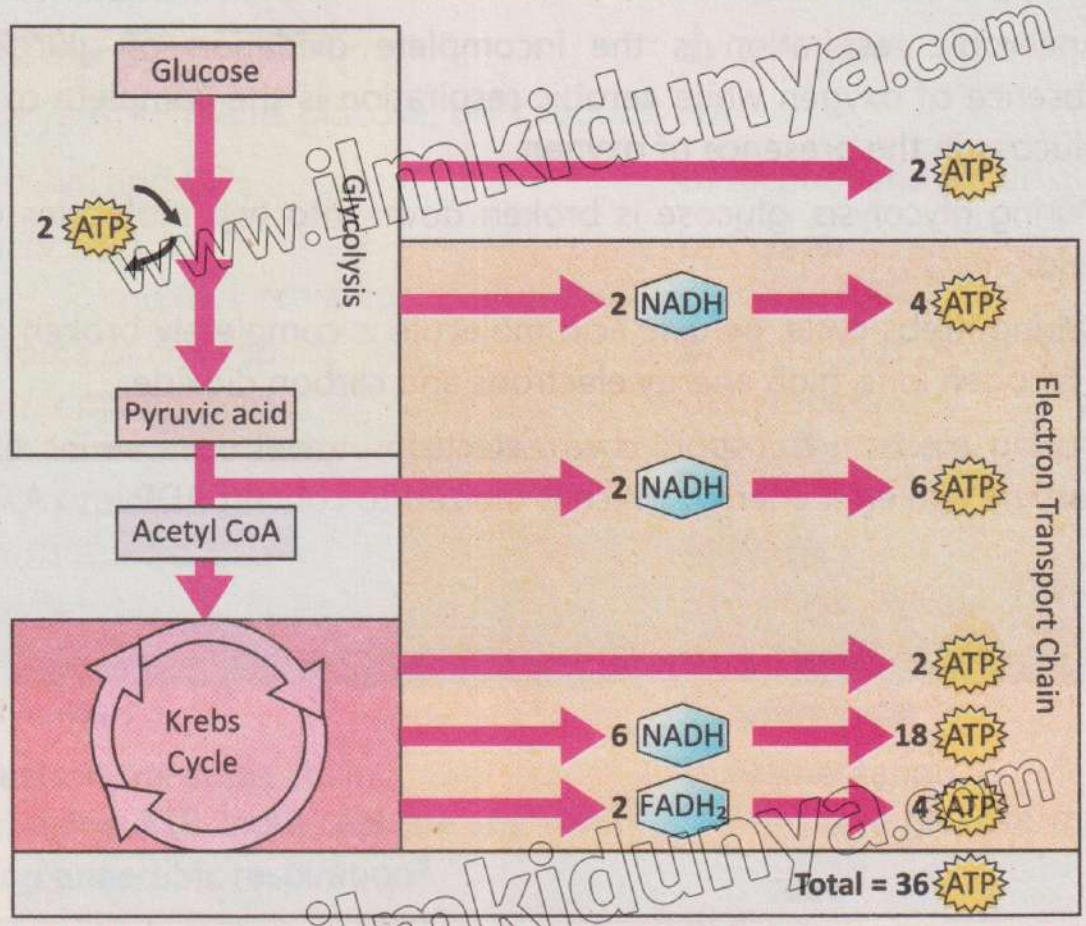

FIGURE 8.8: An overview of number of ATPs reduced by the aerobic oxidation of glucose

KEY POINTS

- In oxidation-reduction (redox) reactions, electrons are transferred between molecules.
- In oxidation, molecule loses electrons.
- In reduction, it gains electrons.
- Electron flow (oxidation-reduction) is essential for generating energy.
- ATP is the energy currency of the cells.
- In photosynthesis, water and carbon dioxide combine in the presence of light and chlorophyll and carbohydrates and oxygen are produced.
- During light reactions of photosynthesis chlorophyll captures sunlight and makes ATP.
- During dark reactions carbon dioxide is reduced to make glucose.
- Anaerobic respiration is the incomplete oxidation of glucose in the absence of oxygen while aerobic respiration is the complete oxidation of glucose in the presence of oxygen.
- During glycolysis, glucose is broken down into two molecules of pyruvic acid.
- During Krebs cycle, pyruvic acid molecule is completely broken down into hydrogen ions, high energy electrons and carbon dioxide.
- During electron transport chain, electrons travel on a series of electron carriers and emit energy, which is utilized to convert ADP into ATP.

EXERCISE

A. Select the correct answers for the following questions.

1. When we get energy from ATP, which bonds are broken?
   a) P-P bonds
   b) C-H bonds
   c) C-N bonds
   d) C-O bonds
2. Light reactions of photosynthesis occur in;
   a) Plasma membrane of cell
   b) Cytoplasm of cell
   c) Stroma of chloroplasts
   d) Thylakoids of chloroplasts
3. Which type of chlorophyll is most common in plants?
   a) Chlorophyll a
   b) Chlorophyll b
   c) Chlorophyll c
   d) Chlorophyll d
4. Which wavelengths of light are absorbed to maximum by chlorophylls?
   a) Green and blue
   b) Green and red
   c) Red and blue
   d) Only green
5. When yeast ferments glucose, the products are;
   a) Alcohol and CO_2
   b) Alcohol and water
   c) Lactic acid
   d) CO_2 and H_2O
6. Where do the dark reactions of photosynthesis occur?
   a) Stroma of chloroplast
   b) Thylakoids of chloroplast
   c) Outer membrane
   d) Cytoplasm
7. Which molecule donates electrons in the light-dependent reactions of photosynthesis?
   a) NADPH
   b) Water
   c) Oxygen
   d) Carbon dioxide
8. Which process in aerobic respiration produces the most ATP?
   a) Glycolysis
   b) Krebs cycle
   c) Electron transport chain
   d) Fermentation
9. How many ATP molecules are the net profit from one glucose molecule during anaerobic respiration?
   a) 2
   b) 4
   c) 12
   d) 36

10. What is a common byproduct of anaerobic respiration in animal cells?

a) Oxygen
b) Water
c) Lactic acid
d) Carbon dioxide

B. Write short answers.

1. Write the importance of oxidation-reduction reactions.
2. What do ATP and ADP mean? What are the roles of these molecules for the cellular metabolism?
3. Write down the word equation for photosynthesis.
4. Why is chlorophyll important for photosynthesis?
5. How is oxygen produced during photosynthesis?
6. Which organisms carry out photosynthesis? Which cell organelle is responsible for the absorption of light for photosynthesis?
7. State the main purpose of cellular respiration?
8. State the equation (in words or symbols) for aerobic respiration.
9. Write a brief note on the role of oxygen in aerobic respiration.
10. Define anaerobic and aerobic respiration.
11. What are the end products of anaerobic respiration in animals and yeast?
12. How do muscles respond to oxygen deficiency during intense exercise?
13. List ways in which respiratory energy is used in the body.

C. Write answers in detail.

1. Explain ATP as a molecule that is the chief energy currency of all cells.
2. Outline the processes involved in photosynthesis?
3. Write a note on the intake of carbon dioxide and water by plants
4. Explain the types and importance of anaerobic respiration.
5. Outline the mechanism of aerobic respiration.
6. Compare the processes of respiration and photosynthesis.

D. Inquisitive questions.

1. How does the structure of ATP enable it to store and release energy efficiently?