# 13. Respiration and Energy Transfer

**Can you recall?**

1. Which nutrients are used for energy production?
2. Which is most preferred nutrient among carbohydrate, protein and fat for energy production? Why?
3. Why do organisms take up oxygen and release carbondioxide?
4. What is aerobic and anaerobic respiration?
5. Which steps are involved in aerobic respiration?

**Always Remember**

1. Maintenance of life requires continuous supply of energy.
2. Respiration fulfills the continuous need of energy.

## 13.1 Formation of ATP :

Formation of ATP is called as phosphorylation. In nature, phosphorylation occurs in three different ways as - **photophosphorylation, substrate-level phosphorylation** and **oxidative phosphorylation**. You have already learnt the photophosphorylation in the photosynthesis.

Substrate-level phosphorylation is a direct phosphorylation of ADP by transfer of a phosphate group from any suitable substrate. It occurs in cytoplasm of the cells and matrix of mitochondria.

Oxidative phosphorylation is phosphorylation of ADP at the cost of energy released during oxidation of substrates like $NADH+H^+$ and $FADH_2$. This occurs on the inner mitochondrial membrane only.

When energy is required for any metabolic process, ATP is hydrolysed. ATP hydrolysis releases the energy which is used for the metabolic activities.

Respiration is a catabolic process wherein complex organic substrate is oxidized to simple components to generate biological energy. Cellular respiration occurs in two different ways as anaerobic and aerobic respiration.

## 13.2 Anaerobic respiration :

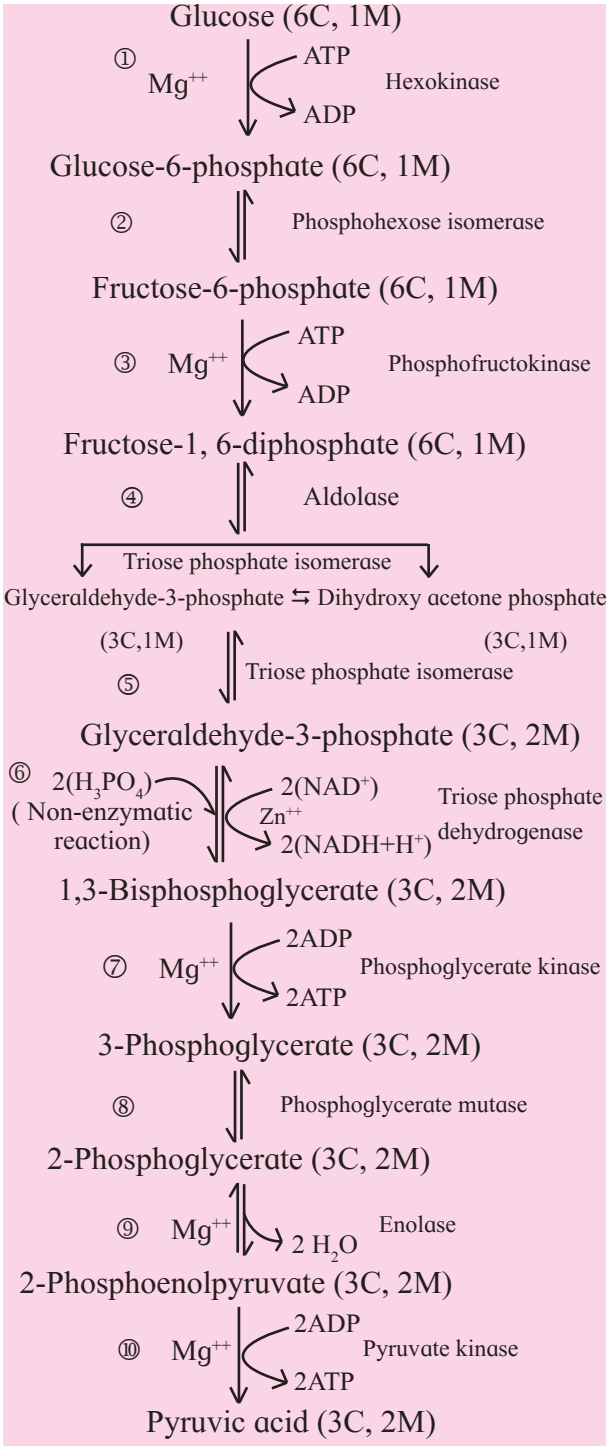
Anaerobic respiration is the cellular respiration that does not involve the atmospheric oxygen. It is also called fermentation. It is completed through steps viz. glycolysis and incomplete conversion of glycolytic products into lactic acid/ ethanol.

### Glycolysis :

Glycolysis involves the breakdown of glucose molecule into two pyruvic acid molecules. Hence known as glycolysis. This is a common step in anaerobic as well as aerobic respiration. It occurs in cytoplasm of cell. It is completed in two phases as **preparatory phase** and **pay-off phase**.

Overall process of glycolysis is completed through ten steps. First five steps constitute the preparatory phase through which glucose is phosphorylated twice at the cost of two ATP molecules and a molecule of fructose 1, 6-bisphosphate is formed. This molecule is then split to form a molecule of glyceraldehyde 3-phosphate and a molecule of dihydroxyacetone phosphate. Both of these molecules are 3-carbon carbohydrates (trioses) and are isomers of each other. Dihydroxy acetone phosphate is isomerised to second molecule of glyceraldehyde-3-phosphate. Thus, two molecules of glyceraldehyde-3-phosphate are formed and here, first phase i.e. preparatory phase of glycolysis ends.

In the pay-off phase, both the molecules of glyceraldehyde-3-phosphate are converted to two molecules of 1, 3-bis phosphoglycerate by oxidation and phosphorylation. Here, phosphorylation is brought about with the help of inorganic phosphate and not ATP.




**Overall reaction of glycolysis:**

**Glucose+2 ATP+2 iP + 4 ADP +2 $NAD^+$ ⟶**

**2 Pyruvate+2ADP+4ATP+2NADH+$H^+$+2$H_2O$**

Both molecules of 1, 3-bisphosphoglycerate are converted into two molecules of pyruvic acid through series of reactions accompanied with release of energy. This released energy is used to produce ATP (4 molecules) by substrate-level phosphorylation.

Glycolysis is under tight control. Its rate depends upon the requirement of ATP and many other factors. Glycolytic rate control is achieved by complex interplay between ATP consumption, $NADH_2$ regeneration and regulation of various glycolytic enzymes like hexokinase, PFK-1, pyruvate kinase, etc. Besides, it is also controlled by hormones like glucagon, epinephrine and insulin.

**Use your brain power**

1. What is role of $Mg^{++}$, $Zn^{++}$ in various steps of glycolysis?
2. Why some reactions of glycolysis are reversible and some irreversible?
3. Why is glycolysis considered as biochemical proof of evolution?
4. Why do athletes like sprinters have higher proportion of white muscle fibers?

**Do you know?**

1. Glycolysis is only source of energy production in erythrocytes, renal medulla, brain and sperm.
2. Some plant tissues which are modified to store starch (like potato) mainly depend upon glycolysis for energy production.
3. In chapter 3, Biomolecules, you have read about the oxygen storing and transporting pigment myoglobin of skeletal muscles. Red (dark) muscles are richer in myoglobin than the white (pale) muscles. Therefore, red fibers can utilize the oxygen stored in myoglobin to continue energy production over prolonged period by aerobic oxidation of glucose. This enables them to perform sustained work over a long period. On the contrary, white fibers produce the energy needed for very fast and severe work by glycolysis as sufficient oxygen is not immediately available to them for such work. But white muscles accumulate lactic acid and get fatigued in a short time. Thus athletes with a higher proportion of red fibers in their muscles are physiologically better adapted for sustained events like marathon or swimming over long distances.

$$C_6H_{12}O_6 \xrightarrow{\text{Glycolysis}} 2CH_3COCOOH + 2NADH+H^+ \longrightarrow 2CH_3CHOHCOOH + 2NAD^+$$

Glucose — Pyruvic acid — Lactic acid

**Lactic acid fermentation**

$$C_6H_{12}O_6 \xrightarrow{\text{Glycolysis}} 2CH_3COCOOH \longrightarrow CO_2\uparrow + 2CH_3CHO + 2NADH+H^+ \longrightarrow 2C_2H_5OH$$

Glucose — Pyruvic acid — Acetaldehyde — Ethanol

**Alcoholic fermentation**

In muscles, the $NADH+H^+$ produced during glycolysis is reoxidized to $NAD^+$ by donating one proton and two electrons to pyruvic acid which yields lactic acid. Skeletal muscles usually derive their energy by anaerobic respiration. After vigorous exercise lactic acid accumulates, leading to muscle fatigue. During rest, however, the lactic acid is reconverted to pyruvic acid and is channeled back into the aerobic respiration pathway.

In yeast, the pyruvate is decarboxylated to acetaldehyde. The acetaldehyde is then reduced by $NADH+H^+$ to ethanol. Carbon dioxide is also produced in this process. This type of anaerobic respiration is termed alcoholic fermentation. Accumulation of ethanol by fermentation in a culture of yeast may stop further multiplication and lead to the death of cells. In the presence of oxygen however, yeast can respire aerobically.

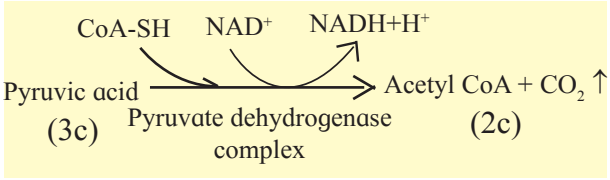
## 13.3 Aerobic Respiration :

Aerobic respiration involves molecular oxygen during oxidation of glucose. Glucose is completely oxidized in this process which is operated through steps viz. glycolysis, production of acetyl CoA (connecting link reaction), Krebs cycle, electron transfer chain reaction and terminal oxidation.

First step of aerobic respiration i.e. glycolysis has been already studied in detail. In case of aerobic respiration, glycolytic product i.e. pyruvic acid is converted into actyl CoA. This process occurs in cytoplasm in case of prokaryotes and in mitochondria in case of eukaryotes. (For structure of mitochondria, refer Chapter 5, Cell Sturcture and Organization)

### Conversion of pyruvic acid to Acetyl CoA :

This is an oxidative decarboxylation reaction. It is catalyzed by a multienzyme complex - pyruvate dehydrogenase complex (PDH). This enzyme is present in mitochondria of eukaryotes and cytosol of prokaryotes.




This reaction is called as 'connecting link' reaction between glycolysis and Krebs cycle.

**Do you know?**

Pyruvate dehydrogenase complex needs thiamin (vitamin $B_1$) as a co-enzyme. It can not function in absence of vitamin $B_1$. Hence, thiamin deficiency causes pyruvic acidosis and lactic acidosis, the life threatening conditions.

Hence balanced diet is very important in the maintenance of health.

### Krebs Cycle ( TCA cycle/ Citric Acid Cycle):

Pyruvic Acid produced by glycolysis undergoes aerobic oxidation in the mitochondrial matrix through the TCA cycle. This cycle serves a common oxidative pathway for carbohydrates fats and proteins. Moreover, some intermediates of the TCA cycle are used in synthesizing important biomolecules such as glutamate and aspartate.

Before participating in the TCA cycle pyruvic acid (3c) enters the mitochondrion. Here it is decarboxylated and the remaining 2-carbon fragment is combined with a molecule of coenzyme A to form acetyl-CoA (2c).

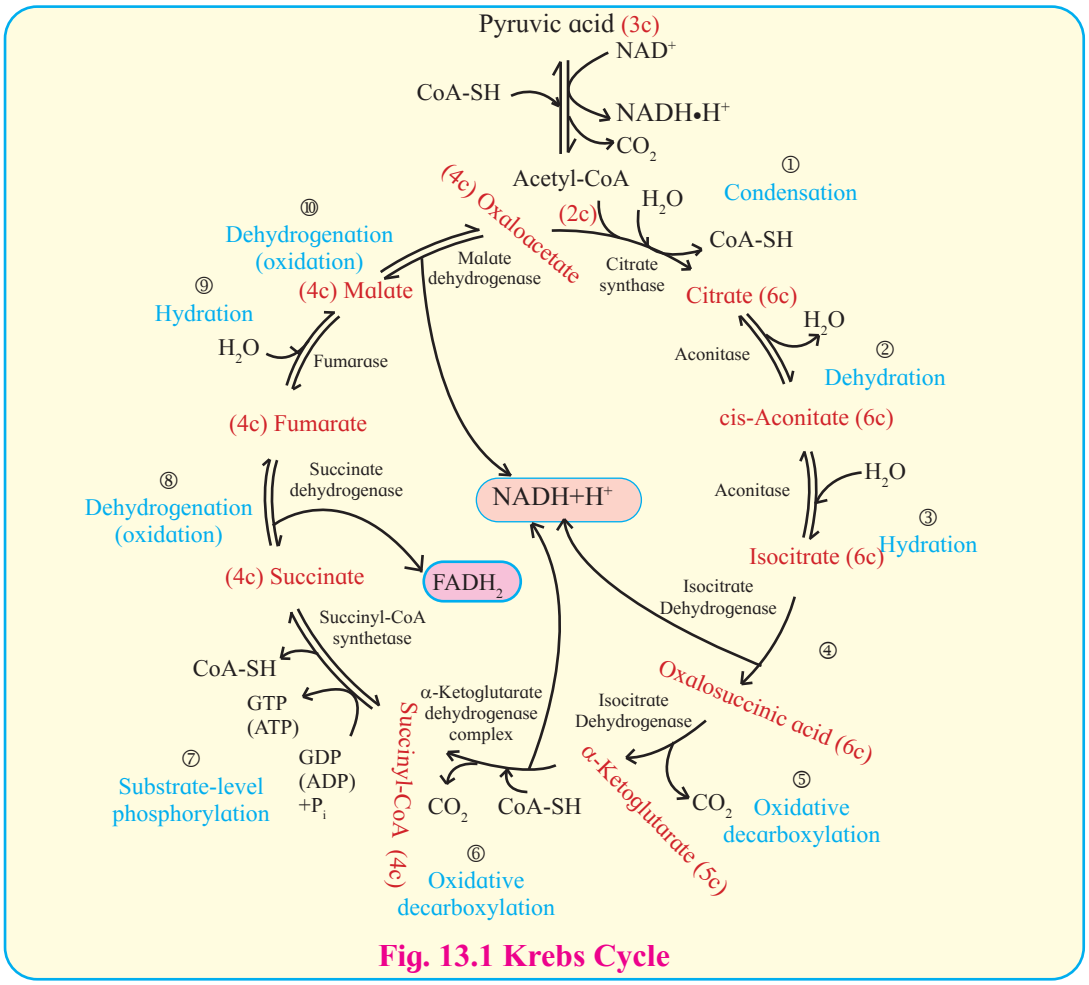



**Fig. 13.1 Krebs Cycle**

This reaction is an oxidative decarboxylation process and produces $H^+$ ions and electrons along with carbon dioxide. During the process $NAD^+$ is reduced to $NADH+H^+$. β-oxidation of fatty acids also produces acetyl-CoA as the end product. Acetyl-CoA from both sources is condensed with oxaloacetic acid (4c) to form citric acid (5c). Citric acid is oxidized step-wise by mitochondrial enzymes, releasing carbon dioxide. This finally regenerates oxaloacetic acid to complete the cycle. There are four steps of oxidation in this cycle, catalyzed by dehydrogenases (oxidoreductases) using $NAD^+$ or $FAD^+$ as the coenzyme. The coenzymes are consequently reduced to $NADH+H^+$ and $FADH_2$ respectively. These transfer their electrons to the mitochondrial respiratory chain to get reoxidised. One molecule of GTP (ATP) is also generated for every molecule of citric acid oxidized.

**Amphibolic Pathway :** Through we describe the aerobic respiration as catabolic (oxidative) pathway; it is not entirely correct; especially in case of Krebs cycle. Various reactions of Krebs cycle are mainly responsible for step-wise oxidation of acetyl part of acetyl CoA leading to the release of energy and $CO_2$. However, as per need, acetyl CoA or some other intermediates like α-ketoglutarate, oxaloacetate are used as precursors for synthesis of fatty acids, glutamic acid and aspartic acid respectively. Hence, Krebs cycle can be correctly refered to as a 'Amphibolic pathway' i.e. involving catabolism as well as anabolism.

## Electron Transport chain (Electron transfer system) :

Wherever the $NADH_2$ ($NADH+H^+$) and $FADH_2$ are produced during glycolysis, connecting link reaction and Krebs cycle, they are oxidised with the help of various electron carriers and enzymes.

These carriers and enzymes are arranged on inner mitochondrial membrane in the form of various complexes as complex I, II, III, IV and V. $NADH+H^+$ is oxidised by NADH dehydrogenase (complex I) and it's electrons are transferred to ubiquinone (coenzyme Q i.e. CoQ) present on inner membrane of mitochondria. Reduced ubiquinone is called as ubiqunol. $FADH_2$ is oxidised by complex II (Succinate dehydrogenase) and these electrons are also transferred to CoQ. During oxidation of $NADH+H^+$ and $FADH_2$, electrons and protons are released but only electrons are carried forward whereas protons are released into outer chamber of mitochondria.

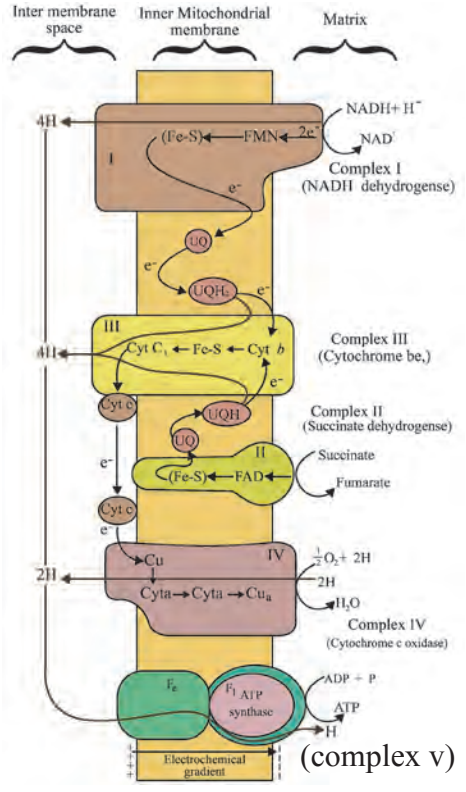



**Fig. 13.2 Electron Transport system (ETS)**

Ubiquinol is oxidised by complex-III (Cytochrome $bc_1$, complex) and it's electrons are transferred to cytochrome C. Cytochrome C is a small, iron-containing protein, loosely associated with inner membrane. It acts as a mobile electron carrier, transferring the electrons between complex III and IV.

Cytochrome C is oxidised by complex IV or cytochrome C oxidase consisting of cytochrome a and $a_3$. Electrons are transferred by this complex to the molecular oxygen. This is terminal oxidation. Reduced molecular oxygen reacts with protons to form water molecule.

Protons necessary for this are channeled from outer chamber of mitochondria into inner chamber by $F_0$ part of oxysome (complex V) embeded in inner mitochondrial membrane. This proton channeling by $F_0$ is coupled to catalytic site of $F_1$ which catalyses the synthesis of ATP from ADP and inorganic phosphate. This is **oxidative phosphorylation**. As transfer of protons is accompanied with synthesis of ATP, this process is named as 'Chemiosmosis' by Peter Mitchell.

Oxidation of one $NADH+H^+$ leads to production of 3 ATP molecules where as oxidation of $FADH_2$ leads to production of 2 ATP molecules. However the number of ATP produced depends upon the physiological conditions and source of respiratory substrate.

**Internet my friend**

What is effect of carbon monoxide poisoning on cytochromes?

| Step of Respiration | Consumption | Production | | | | Total | Net benefit |
|---|---|---|---|---|---|---|---|
| | | Substrate level phosphorylation | Oxidative Phosphorylation | | | | |
| | | | $NADH+H^+$ | $FADH_2$ | Total | | |
| Glycolysis | 2 | 4 | 2 x 3 =6 | ----- | 6 | 10 | 8 |
| Pyruvate → AcetylCoA | ----- | ----- | 2 x 3 =6 | ----- | 6 | 6 | 6 |
| Krebs cycle | ----- | 1 x 2 = 2 | 6 x 3=18 | 2 x 2 = 4 | 22 | 24 | 24 |
| Total | 2 | [6] | 30 + 4 = [34] | | | [40] | 38 |

**Table 13.3 Balance sheet for ATP by aerobic oxidation of 1 glucose molecule**

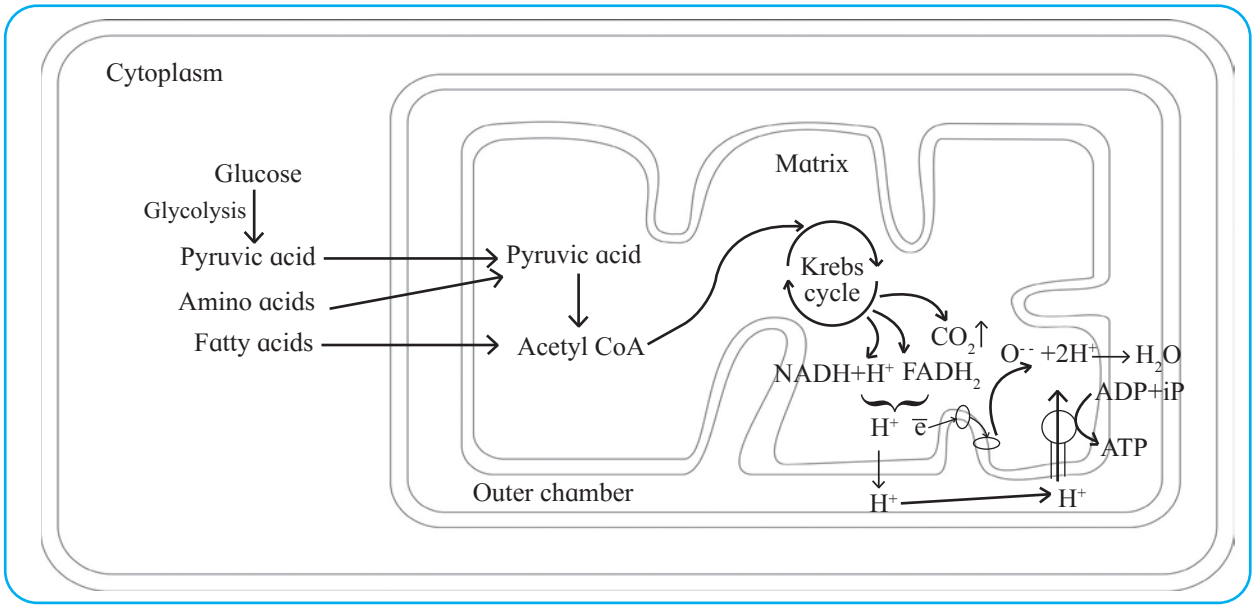



**Fig. 13.4 Summary of Aerobic Respiration**

**Significance of ETS :**

- The electron transport system (ETS) or terminal oxidation generates major amount of energy in the form of ATP molecules, 34 ATP molecules out of total 38 ATP molecules are produced through ETS.
- It regenerates oxidized coenzymes such as $NAD^+$ and $FAD^+$ from their reduced forms ($NADH+H^+$ and $FADH_2$) for recycling.
- It also produces water molecules.
- It releases energy in a stepwise manner to prevent damage of cells.

**Always Remember**

Not only glucose but amino acids from protein metabolism and fatty acids from lipid metabolism also participate in Kreb's cycle through acetyl CoA.

**Try this**

**Aerobic respiration can be demonstrated by two simple experiments.**

**A.** A pinch of dry bakers yeast suspended in water or a few ml of yeast suspension used in a bakery is added to about 10ml of 10 percent glucose solution in a test tube (Tube A).

The surface of the liquid is carefully covered with oil to prevent contact with air. The test tube is closed tightly with rubber stopper. One end of a short bent glass tube is inserted through it to reach the air inside the tube. Other end of the glass tube is connected by a polyethylene or rubber tubing to another bent glass tube fitted into a stopper. The open end of the glass tube (delivery tube) is dipped into lime water containing in a test tube (Tube B). Stoppers of both the tubes are fitted tightly to prevent leakage of gases. First test tube is placed in warm water ($37^0$C-$38^0$C) in a beaker. Lime water gradually turns milky, indicating the evolution of carbon dioxide from the yeast preparation.

Level of the lime water in the delivery tube does not rise, showing that there is no decline in volume of gas in test tube A and consequently no utilization of oxygen by yeast. Preparation is stored for a day or two. When you open the stopper of tube A. You will notice a smell of alcohol indicating the formation of ethanol. From this activity it may be inferred that yeast respires anaerobically to ferment glucose to ethanol and carbon dioxide.

**B.** Seed coats of a few germinating seeds (peas, beans or gram) are removed. Dehulled seeds are then put in a test tube filled with mercury. After closing the test tube with the thumb, it is vertically inverted in a trough of mercury and the thumb is carefully removed. Being lighter than mercury, the seeds rise to the closed upper end of the test tube. No gas is seen at first in the test tube. As germination proceeds, a gas begins to collect at the top of the mercury in the test tube. On introducing a pellet of potassium hydroxide into the tube, it rises to the top and absorbs the gas. The mercury again fills the tube. The potassium hydroxide reacts with carbon dioxide gas to produce potassium carbonate and water.

**Use your brain power**

Do the plants breath like animals? If yes, how and why?

The gas therefore disappears. Evidently germinating seeds produce carbon dioxide by anaerobic respiration in the absence of oxygen in the mercury column.

## 13.4 Utility of stepwise oxidation :

You have noted that both anaerobic and aerobic respiration are conducted in many steps. You may wonder what could be the utility of a metabolic pathway with so many steps? Such stepwise metabolism serves several purposes.

i. A stepwise release of the chemical bond energy facilitates the utilization of a relatively higher proportion of that energy in ATP synthesis.

ii. Activities of enzymes for the different steps may be enhanced or inhibited by specific compounds. This provides a means of controlling the rate of the pathway and the energy output according to need of the cell.

iii. The same pathway may be utilized for forming intermediates used in the synthesis of other biomolecules like amino acids.

**Always Remember**

Removal of Hydrogen from respiratory materials is the primary process in respiration : The fact that during respiration oxygen is taken in and carbon dioxide is given out may give a false impression that respiratory materials directly unite with oxygen. It must be remembered that oxygen does not play such a primary role in the process of respiration. The primary process in respiration consists in removal of hydrogen from the respiratory materials. The reactions in which hydrogen is removed are catalyzed by enzymes called dehydrogenases as free hydrogen cannot exist in the cell. As soon as it is removed from respiratory material it is picked up by substances known as acceptors. In aerobic respiration this hydrogen is ultimately handed over to oxygen. These two combine with each other and form water.

**Think and Compare**

Comparison of overall equations of photosynthesis and respiration show that to some extent, two processes are reverse of each other. Photosynthesis involves reduction of $CO_2$ to glucose and respiration involves oxidation of glucose.

### Respiratory Quotient :

Ratio of volume of $CO_2$ released to the volume of $O_2$ consumed in respiration is called the **respiratory quotient** (RQ) or respiratory ratio. It depends on the type of respiratory substrate.

When carbohydrates are used as respiratory substrate and are completely oxidized, the RQ is 1, because volume of $CO_2$ released is equal to volume of $O_2$ consumed, as shown in the equation.

When fats or proteins are used as a substrate, the RQ is less than 1, as volume of $CO_2$ released is always less than volume of $O_2$ consumed.

Mostly for fats, RQ is about 0.7 and for proteins it is about 0.9

In case of anaerobic respiration RQ is always infinity as $CO_2$ is evolved without taking $O_2$.

**Significance of Respiration**

1. Respiration provides energy for synthesis of biomolecules.
2. It is also a source of energy for cell division, growth, repairs and replacement of worn out parts, movements, locomotion etc.
3. Various intermediates of Krebs cycle are used as building blocks for synthesis of other complex compounds.
4. Coupled with photosynthesis, it helps to maintain the balance between $CO_2$ and $O_2$ in the atmosphere.
5. Anaerobic respiration (fermentation) is used in various industries such as dairies, bakeries, distilleries, leather industries, paper industries etc. It is used in the commercial production of alcohol, organic acids, vitamins, antibiotics etc.


**Internet my friend**

Calculate the RQ for different respiratory substrates using appropriate formula.

## Exercise

### 1. Choose correct option

A. The reactions of the TCA cycle occur in
   a. ribosomes
   b. grana
   c. mitochondria
   d. endoplasmic reticulum

B. In eucaryotes the complete oxidation of a molecule of glucose results in the net gain of
   a. 2 molecules of ATP
   b. 36 molecules of ATP
   c. 4 molecules of ATP
   d. 38 molecules of ATP

C. Which step of Krebs cycle operates substrate-level phosphorylation?
   a. α-ketoglutarate → succinyl CoA.
   b. Succinyl CoA → succinate
   c. Succinate → fumarate
   d. Fumarate → malate

### 2. Fill in the blanks with suitable words

A. Acetyl CoA is formed from ..... and co-enzyme A.

B. In the prokaryotes ..... molecules of ATP are formed per molecule of glucose oxidised.

C. Glycolysis takes place in .....

D. $F_1$- $F_0$ particles participate in the synthesis of .....

E. During glycolysis ..... molecules of $NADH+H^+$ are formed.

### 3. Answer the following questions

A. When and where does anaerobic respiration occur in man and yeast?

B. Why is less energy produced during anaerobic respiration than in aerobic respiration?

C. Which is the site of ETS in mitochondrial respiration?

D. Which is the terminal electron acceptor in aerobic respiration?

E. What is RQ.? What is its value for fats?

F. What are respiratory substrates? Name the most common respiratory substrate.

G. Write explanatory notes on :
   i. Glycolysis
   ii. Fermentation by yeast
   iii. Electron transport chain

H. How are glycolysis, TCA cycle and electron transport chain linked? Explain.

I. How would you demonstrate that yeast can respire both aerobically and anaerobically?

J. What is the advantage of step wise energy release in respiration?

K. Explain ETS.

L. Discuss. "The respiratory pathway is an amphibolic pathway".

M. Why is Krebs cycle reffered as amphibolic pathway?

N. Which of the following step of aerobic respiration would be omitted when fatty acids are used as respiratory substrate?
   a. Glycolysis
   b. Krebs cycle
   c. Electron transfer chain reaction
   d. Terminal oxidation.

### 4. Compare

A. Photosynthesis and Respiration.

B. Anaerobic and Anaerobic respiration.

### 5. Differentiate between

A. Respiration and combustion

B. Glycolysis and Krebs cycle

C. Aerobic respiration and fermentation

**6. Identify the cycle given below. Correct it and fill in the blanks and write discription of it in your own words**

**Practical / Project :**

**Make Power point Presentation on Glycolysis, Kerbs Cycle and Conduct the group discussion on it, in classroom.**