CHAPTER 16

Respiration

INTRODUCTION

ALL living organisms whether plants or animals require energy to drive live activities. Solar energy trapped by green plants during photosynthesis is the ultimate source of energy available to living organisms for the purpose. To keep the life process in motion, the energy is obtained by the oxidation of various photosynthetic products by the process called *respiration*.

Respiration is a vital process which occurs in all living cells of the plant but the most actively respiring regions are growing regions like floral and vegetative buds, germinating seedlings, stem and root apices. Roughly respiration may be called a process which includes the intake of oxygen and chemically brings about the oxidation and decomposition of organic compounds with the release of energy. During normal conditions the process involves the liberation of carbon dioxide, absorption of oxygen and conversion of potential energy into kinetic energy. The overall respiration process may be represented as

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 686 \text{ kcal.}$$

However, oxygen gas does not react directly with glucose. Water molecules are required which are added to intermediate products to glucose degradation and hydrogen atoms in the intermediate products are transferred to oxygen. In that case, overall summary of the process would be

$$C_6H_{12}O_6 + 6H_2O + 6O_2 \longrightarrow 6CO_2 + 12H_2O + \text{Energy}$$

The utilization of water molecules at various steps are explained under heading *mechanism of respiration.*

Respiration is a complex process which includes
(i) absorption of oxygen,
(ii) conversion of carbohydrate (complex) to carbon dioxide and water (simpler substances), i.e. oxidation of food,
(iii) release of energy–a part of which is utilised in various vital processes and rest may be lost in the form of heat,
(iv) formation of intermediate products playing different roles in metabolism,
(v) liberation of carbon dioxide and water, and
(vi) loss in weight in plants as a result of oxidation.

Respiration is, therefore, a reverse process of photosynthesis. The table 16.1 summarises the points of differences between the two processes.

Table 16.1. Differences between respiration and photosynthesis

Respiration	*Photosynthesis*
1. Oxygen is absorbed in the process.	1. Oxygen is liberated in the process.
2. Carbon dioxide is evolved as a result of oxidation of carbon containing compounds.	2. Carbon dioxide is absorbed and is fixed inside to form carbon containing compounds.
3. The process occurs day and night.	3. Process occurs only in presence of light.
4. Light is not essential for the process.	4. Light is essential for the process.
5. During the process, potential energy is converted into kinetic energy.	5. During the process, radiant energy (light energy) is converted into potential energy.
6. Raw materials used are glucose and oxygen.	6. Raw materials used are CO_2 and water.
7. The presence of chlorophyll is not necessary.	7. Presence of chlorophyll is necessary for the photosynthesis.
8. Energy is released during the process hence it is an exothermic process.	8. Energy is stored during process hence it is endothermic process.
9. Due to respiration the plant suffers with the loss of weight.	9. By the process, the weight is gained.
10. It is a catabolic process and includes the destruction of stored food.	10. It is an anabolic process and includes the manufacture of food.
11. The process includes dehydrolysis and decarboxylation.	11. It includes the processes like hydrolysis and carboxylation.
12. During the breakdown of one glucose molecule, 38 ATP molecules are formed.	12. During the synthesis of one glucose molecule, 18 ATP molecules are utilised.

Significance of Respiration

The respiration is an important process because

(i) It releases energy which is comsumed in various metabolic processes essential for plant life and activates cell division.

(ii) It brings about the formation of other necessary compounds participating as important cell constituents.

(iii) It converts insoluble food into soluble form.

(iv) It liberates carbon dioxide and plays a part actively in maintaining the balance of carbon cycle in nature.

(v) It converts stored energy (potential energy) into usable form (kinetic energy).

RESPIRATORY QUOTIENT

Respiratoy Quotient (RQ) may be defined as *"the ratio between the volume of carbon dioxide given out and oxygen taken in simultaneously by a given weight of the tissue in a given period of time at standard temperature and pressure."*

$$\text{Respiratory Quotient} = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ absorbed}}$$

production of CO_2. *At night*, when stomata are open in succulent plants, oxygen is absorbed and intermediate compounds are formed due to partial oxidation on account of which there is no evolution of CO_2 and the RQ value is found to be less than one, mostly zero. In *day time*, when complete oxidation of intermediate acids occurs the CO_2 produced is used up in photosynthesis with the result that there is no evolution of CO_2 and RQ falls to zero.

$$2C_6H_{12}O_6+3O_2 \longrightarrow 3C_4H_6O_5+3H_2O \text{ (malic acid)}$$

$$2C_6H_{12}O_6+3O_2 \longrightarrow 2C_6H_8O_7+4H_2O \text{ (citric acid)}$$

$$RQ = \frac{CO_2}{O_2} = \frac{0}{3} = \text{Zero}$$

(5) Respiratory Quotient of Organic Acids

Organic acids are rich in oxygen and the proportion of oxygen to carbon is very high. When organic acids are used as respiratory substrate lesser oxygen is needed to be absorbed and more CO_2 is evolved with the result that RQ value is found to be more than unity.

$$2C_4H_6O_6+5O_2 \longrightarrow 8CO_2+6H_2O \text{ (Tartaric acid)}$$

$$RQ = \frac{CO_2}{O_2} = \frac{8CO_2}{5O_2} = 1.6$$

$$2(COOH)_2+O_2 \longrightarrow 4CO_2+2H_2O \text{ (oxalic acid)}$$

$$RQ = \frac{CO_2}{O_2} = \frac{4CO_2}{1O_2} = 4$$

$$2C_6H_8O_7+9O_2 \longrightarrow 12CO_2+8H_2O \text{ (citric acid)}$$

$$RQ = \frac{CO_2}{O_2} = \frac{12CO_2}{9O_2} = 1.33$$

$$C_4H_6O_5+3O_2 \longrightarrow 4CO_2+3H_2O \text{ (malic acid)}$$

$$RQ = \frac{CO_2}{O_2} = \frac{4CO_2}{3O_2} = 1.33$$

Malic acid may also convert into hexose, with following intermediate stages. These reactions are popularly known as *Wood-Werkman reaction.*

$$2COOH.\ CH_2CHOH.COOH \longrightarrow 2COOH.CH_2CO.COOH+4\ (H)$$

$$2COOH.CH_2CO.COOH \longrightarrow 2CH_3CO.COOH+2CO_2$$

$$2CH_3.CO.COOH+4(H) \longrightarrow C_6H_{12}O_6 \text{ (hexose)}$$

If this hexose is partly respired, the RQ may increase to 1.33 or more. Some times RQ value is found to be 0.2 to 0.3 when the reaction gets associated with a combination of hexose respiration and organic acid synthesis at the expense of CO_2 i.e.

$$C_6H_{12}O_6 + 2CO_2 \longrightarrow 2C_4H_6O_5 \text{ (malic acid)}$$

(6) Respiratory Quotient when Oxygen is Utilised for Other Metabolic Processes

Apart from respiration some other metabolic processes such as synthesis of anthocyanins and conversion of fats to carbohydrates also require oxygen. In such cases amount of CO_2 evolved does not correspond to the amount of oxygen absorbed and, therefore, the value of RQ falls below unity. In *Bryophyllum*, leaves are capable of utilising CO_2 (liberated during respiration) for the synthetizing organic acids in the dark so the RQ value falls below unity.

(7) Respiratory Quotient of Maturing Fatty Seeds

During the maturation of fatty seeds simple carbohydrates are converted into fats. In the process oxygen is released but it is used up in respiration. As a result CO_2 is released during respiration but oxygen is not absorbed from outside. In such cases the value of RQ is found to be more than unity. But in germinating fatty seeds, RQ value falls below unity because of combined effect of the seed using fat substrate for respiration and also synthetizing carbohydrates from fats.

(8) Respiratory Quotient of Tissue Respiring in Absence of Oxygen

In absence of oxygen (anaerobic respiration) in which CO_2 is evolved without O_2 being absorbed, the RQ value is found to be more than unity.

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH+2CO_2$$

$$RQ=CO_2/O_2=2/0=\text{infinity.}$$

The following table enumerates RQ values in different plant parts and substrates.

Plants	*RQ*
1. Leaves rich in carbohydrate.	1
2. Darkened shoots of *Opuntia.*	0.03
3. Germinating starchy seed.	1
4. Germinating linseed (high fat).	0.64
5. Germinating buckwheat (high protein).	0.5
6. Germinating Peas.	1.54-2.4

TYPES OF RESPIRATION

On the basis of availability of oxygen, respiration has been divided into two categories.

(A) **Aerobic respiration.** It takes place in presence of oxygen and the stored food (respiratory substrate) gets completely oxidised into carbon dioxide and water, i.e.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 686 \text{ kcal.}$$

This type of respiration is of common occurrence and is found in all plants.

(B) **Anaerobic respiration.** It takes place in absence of oxygen or when oxygen concentration is less than one per cent. The stored food is incompletely oxidised and instead of carbon dioxide and water certain other compounds are also formed. This type of respiration is of rare occurrence but common among micro-organisms like yeasts and can be represented by

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + 56 \text{ kcal.}$$

cytochromes.

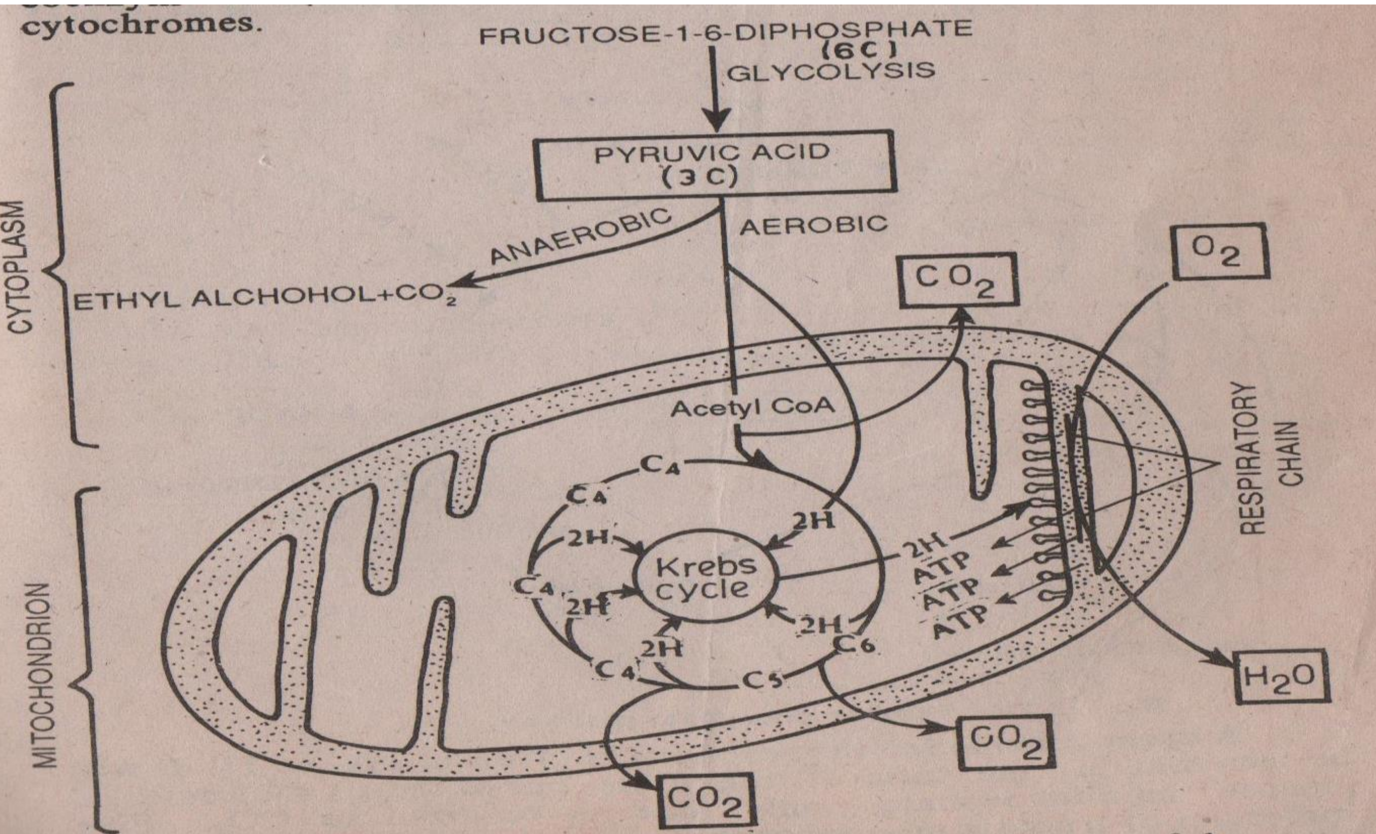


Fig. 15·10. Schematic representation of the localisation of the mechanism of respiration in a plant cell.

cytosol = Cytoplasm

Table 16.2. Distinction between aerobic and anaerobic respiration

Aerobic respiration	*Anaerobic respiration*
1. It is common to all plants.	1. It is of rare occurrence.
2. It goes on throughout the life.	2. It occurs for a temporary phase of life.
3. Energy is liberated in larger quantity. In total, 38 ATP molecules are formed.	3. Energy is liberated in lesser quantity. Only 2 ATP molecules are formed.
4. The process is not toxic to plants.	4. It is toxic to plants.
5. Oxygen is utilized during the process.	5. It occurs in absence of oxygen.
6. The carbohydrates are oxidised completely and are broken down into CO_2 and water.	6. The carbohydrates are oxidised incompletely and ethyl alcohol and carbon dioxide are formed.
7. The end-products are carbon dioxide and water.	7. The end-products are ethyl alcohol and carbon dioxide.
8. Process takes place partly (*glycolysis*) in cytosol and partly (*Krebs cycle*) inside mitochondria.	8. The process occurs only in the cytosol. (Cytoplasm)

MECHANISM OF RESPIRATION

Respiratory substrate. The substrates which are broken down in respiration for the release of energy may be carbohydrates, fats or proteins. Proteins are used up as respiratory substrate only when carbohydrates and fats are not available. Blackman proposed that respiration in which carbohydrates are used as respiratory substrate are called *floating respiration* and if proteins are used, *protoplasmic respiration.*

Fats are used as respiratory substrates after their hydrolysis to fatty acids and glycerol by lipase and their subsequent conversion to hexose sugars. Proteins serve as respiratory substrates after their breakdown to amino acids by proteolytic enzymes. As regards carbohydrates, not only simple hexose sugars like glucose and fructose but complex disaccharides particularly sucrose and polysaccharides such as starch, inulin and hemicelluloses are also used as respiratory substrates.

During respiration, the complex substrates are broken down into simpler ones and finally CO_2 is liberated and water is formed. During oxidation of respiratory substrate, certain amount of energy is released. Part of this energy is trapped in the form of energy rich compounds such as ATP while remaining part is lost in the form of heat. The energy trapped in ATP molecules can be used in various ways (both for physical and chemical requirements). Here, the typical example of respiratory substrate, i.e. carbohydrate has been discussed. Oxidation of fats and proteins are given separately.

All complex carbohydrates are firstly converted into hexoses (glucose or fructose) before actually entering into respiratory process (fig. 16.1). The oxidation of glucose to CO_2 and water consists of two distinguishable phases: (*i*) Glycolysis and (*ii*) Krebs cycle.

In glycolysis glucose is converted into pyruvic acid. Steps of glycolytic pathway are common to all kinds of respiration, hence may be called common

respiratory metabolism. The fate of pyruvic acid, however, depends on the presence or the absence of oxygen. In presence of oxygen, the final degradation products are carbon dioxide and water (Krebs cycle) while in absence of oxygen ethyl alcohol and carbon dioxide in fermentation and lactic acid in lactic acid formation are formed.

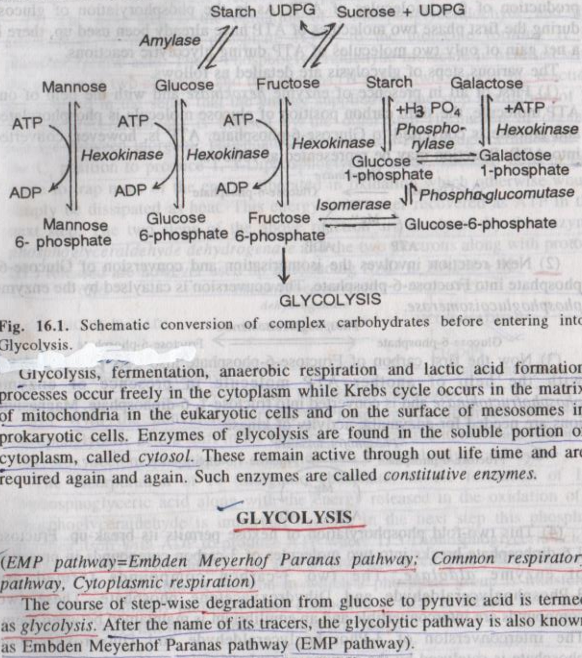


Fig. 16.1. Schematic conversion of complex carbohydrates before entering into Glycolysis.

Glycolysis, fermentation, anaerobic respiration and lactic acid formation processes occur freely in the cytoplasm while Krebs cycle occurs in the matrix of mitochondria in the eukaryotic cells and on the surface of mesosomes in prokaryotic cells. Enzymes of glycolysis are found in the soluble portion of cytoplasm, called *cytosol.* These remain active through out life time and are required again and again. Such enzymes are called *constitutive enzymes.*

GLYCOLYSIS

(*EMP pathway=Embden Meyerhof Paranas pathway; Common respiratory pathway, Cytoplasmic respiration*)

The course of step-wise degradation from glucose to pyruvic acid is termed as *glycolysis.* After the name of its tracers, the glycolytic pathway is also known as Embden Meyerhof Paranas pathway (EMP pathway).

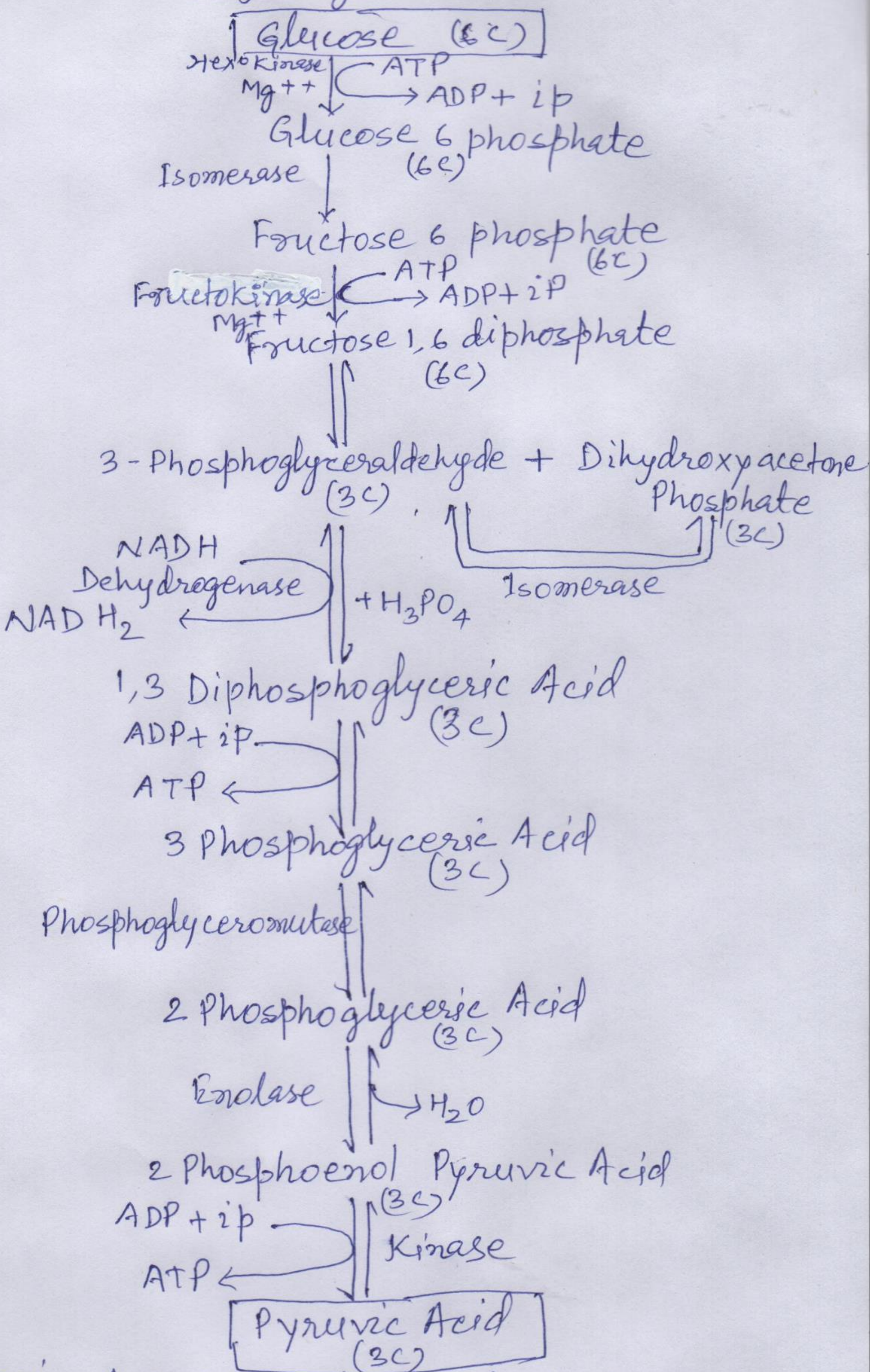
Glycolysis can be broadly represented as follows:

$$\underset{\text{(Hexose)}}{C_6H_{12}O_6} \longrightarrow \underset{\text{(Pyruvate)}}{2C_3H_4O_3 + 4H}$$

It thus states that a molecule of glucose which is a 6-carbon compound is broken down into two molecules of pyruvic acid which is a 3-carbon compound through a large number of step-wise closely integrated reactions. It occurs in following three important phases.

In the **first phase** of glycolysis, the glucose molecule is phosphorylated with the introduction of two phosphate groups into its structure. For this phase two molecules of ATP are needed.

Glycolysis



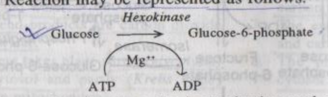
Net gain of ATP through Glycolysis is 8ATP.

The **second phase** involves the breaking up of 6-carbon compound Fructose 1,6-diphosphate into two molecules of 3-carbon compounds, i.e. 3-Phosphoglyceraldehyde and Dihydroxyacetone phosphate. These two 3-carbon compounds are interconvertible.

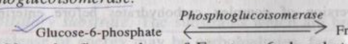
The **third phase** involves degradation of 3-PGAld into pyruvic acid with the production of four molecules of ATP. As in the phosphorylation of glucose during the first phase two molecules of ATP have already been used up, there is a net gain of only two molecules of ATP during glycolytic reactions.

The various steps of glycolysis are detailed as follows.

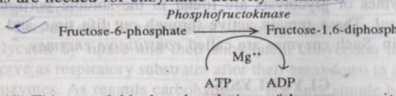
(1) First of all in presence of enzyme *hexokinase* and with the help of one ATP molecule, the sixth carbon position of glucose molecule is phosphorylated and glucose is converted to Glucose-6-phosphate. ATP is, however, converted into ADP. Reaction may be represented as follows.



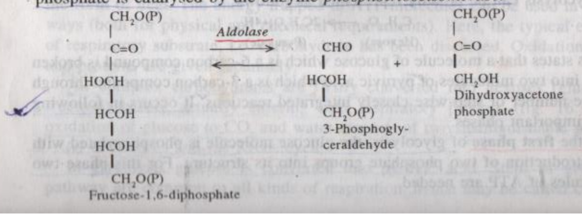
(2) Next reaction involves the isomerisation and conversion of Glucose-6-phosphate into Fructose-6-phosphate. The conversion is cataylsed by the enzyme *phosphoglucoisomerase*.

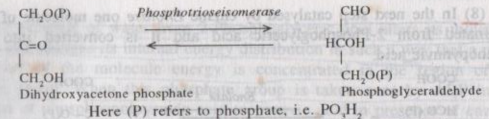


(3) Now the first carbon of Fructose-6-phosphate also gets phosphorylated with the help of another ATP molecule in presence of enzyme *phosphofructokinase* and is converted into fructose-1, 6-diphosphate. Magnesium ions are needed for enzymatic activity of kinase.



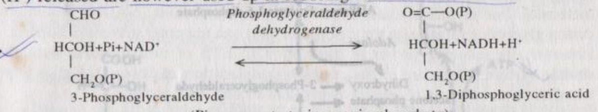
(4) This two-fold phosphorylation of hexose permits its break-up. Fructose 1,6-diphosphate breaks into two molecules of 3-carbon compounds in presence of enzyme *aldolase*. The two 3-carbon compounds formed are 3-Phosphoglyceraldehyde and Dihydroxyacetone phosphate. These two compounds are interconvertible and an equilibrium is maintained between them. The interconversion of 3-Phosphoglyceraldehyde and Dihydroxyacetone phosphate is catalysed by the enzyme *phosphotrioseisomerase*.





Here (P) refers to phosphate, i.e. PO_4H_2

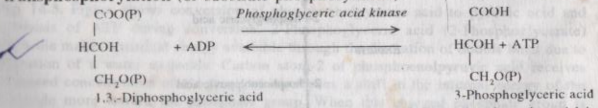
(5) The next step is the oxidation of 3-Phosphoglyceraldehyde and the attachments of inorganic phosphate H_3PO_4 to the molecule forming 1, 3-phosphoglyceric acid. The 3-Phosphoglyceraldehyde molecule is oxidised with the release of two electrons and two protons (H^+). The two steps of the reaction are coupled in the sense that the energy supplied by one step (oxidation of 3-Phosphoglyceraldehyde) is utilised by the other step (formation of organic linkage between inorganic phosphate and oxidised 3-Phosphoglyceraldehyde in the C_1 position to produce 1, 3-Diphosphoglyceric acid). The two steps in fact serve to trap most of the energy liberated in oxidation which otherwise would simply be dissipated as heat. This energy is however recovered as ATP in the next step. The two steps of the above reaction are catalysed by the enzyme *phosphoglyceraldehyde dehydrogenase* and the two electrons along with protons (H^+) released are however used up in reducing NAD to NADH + H^+.



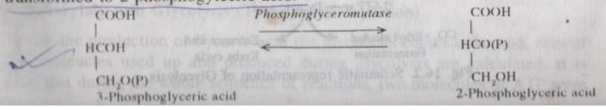
(Pi represents to inorganic phosphate)

(6) With the conversion of the 3-Phosphoglyceraldehyde to 1,3-Diphosphoglyceric acid a shift in the balance is affected and to maintain it more of Dihydroxyacetone phosphate is converted into 3-Phosphoglyceraldehyde.

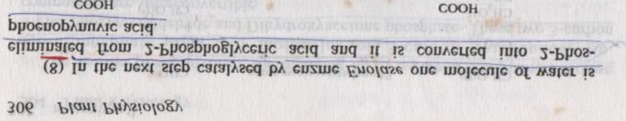
The incorporation of Pi (inorganic phosphate) in the formation of 1,3-Diphosphoglyceric acid along with the energy released in the oxidation of 3-Phosphoglyceraldehyde is important because in the next step this phosphate attaches itself with ADP to produce ATP where 1, 3-Diphosphoglyceric acid is converted into 3-Phosphoglyceric acid in presence of enzyme *phosphoglyceric acid kinase*. This kind of reaction in which a phosphate group is transferred from another already phosphorylated compound to ADP to form ATP is called **transphosphorylation** (or substrate phosphorylation).



(7) In presence of enzyme *phosphoglyceromutase*, 3-Phosphoglyceric acid is transformed to 2-phosphogylceric acid.



(8) In the next step catalysed by enzyme Enolase one molecule of water is eliminated from 2-Phosphoglyceric acid and it is converted into 2-Phosphoenopyruvic acid.



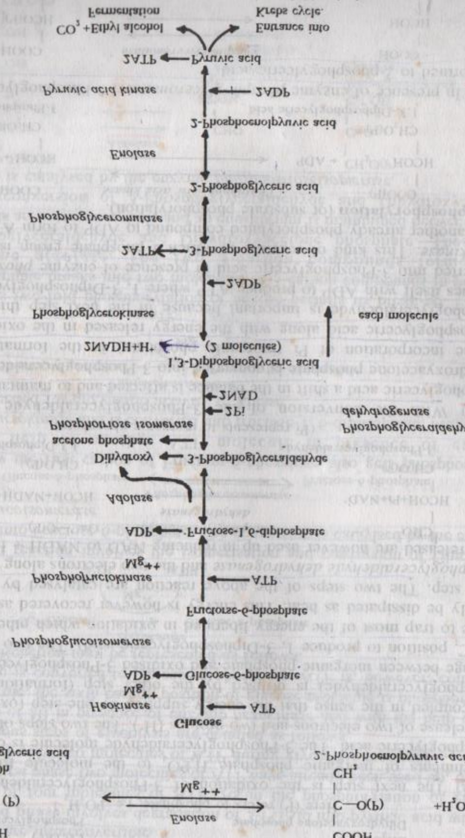
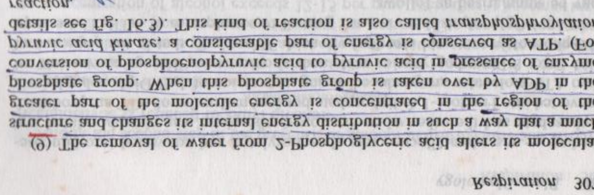


Fig. 16.2. Schematic representation of Glycolysis.

(9) The removal of water from 2-Phosphoglyceric acid alters its molecular structure and changes its internal energy distribution in such a way that a much greater part of the molecule energy is concentrated in the region of the phosphate group. When this phosphate group is taken over by ADP in the conversion of phosphoenolpyruvic acid to pyruvic acid in presence of enzyme pyruvic acid kinase, a considerable part of energy is conserved as ATP. (For details see fig. 16.3). This kind of reaction is also called *transphosphorylation* reaction.



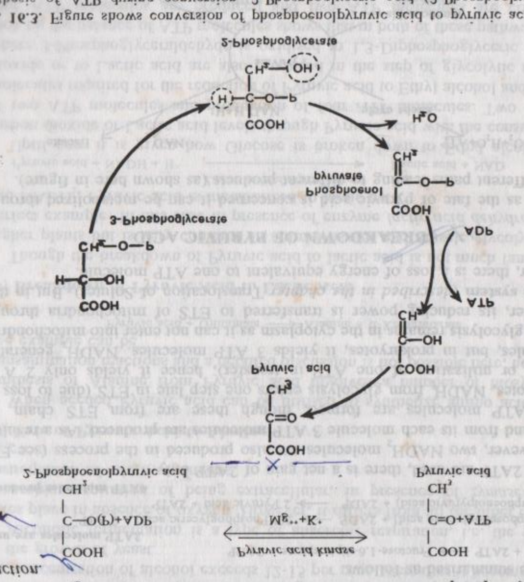


Fig. 16.3. Figure shows conversion of phosphoenolpyruvic acid to pyruvic acid and synthesis of ATP during conversion. 2-Phosphoglyceric acid (2-Phosphoglycerate) molecule makes chemical energy available through the formation of double bond due to liberation of a water molecule. Carbon atom-2 of phosphoenolpyruvic acid receives increased concentration of electrons which causes a shift in the internal energy of the molecule more toward the phosphate group. When this charged phosphate group is donated to ADP it forms ATP.

Phosphorylation in Glycolysis (Transphosphorylation)

With the production of Pyruvic acid the glycolysis comes to an end. Now if ATP molecules used up and produced during glycolysis are calculated, it is found that during the whole sequence of reactions, two molecules of ATP were