Respiration

The process of respiration in plants involves using the sugars produced during photosynthesis plus oxygen to produce energy for plant growth. In many ways, **respiration is the opposite of photosynthesis**. In the natural environment, plants produce their own food to survive.

They use the carbon dioxide (CO_2) from the environment to produce sugars and oxygen (O_2), which can later be utilized as a source of energy. While photosynthesis takes place in the leaves and stems only, respiration occurs in the leaves, stems and roots of the plant. The process of respiration is represented as follows:

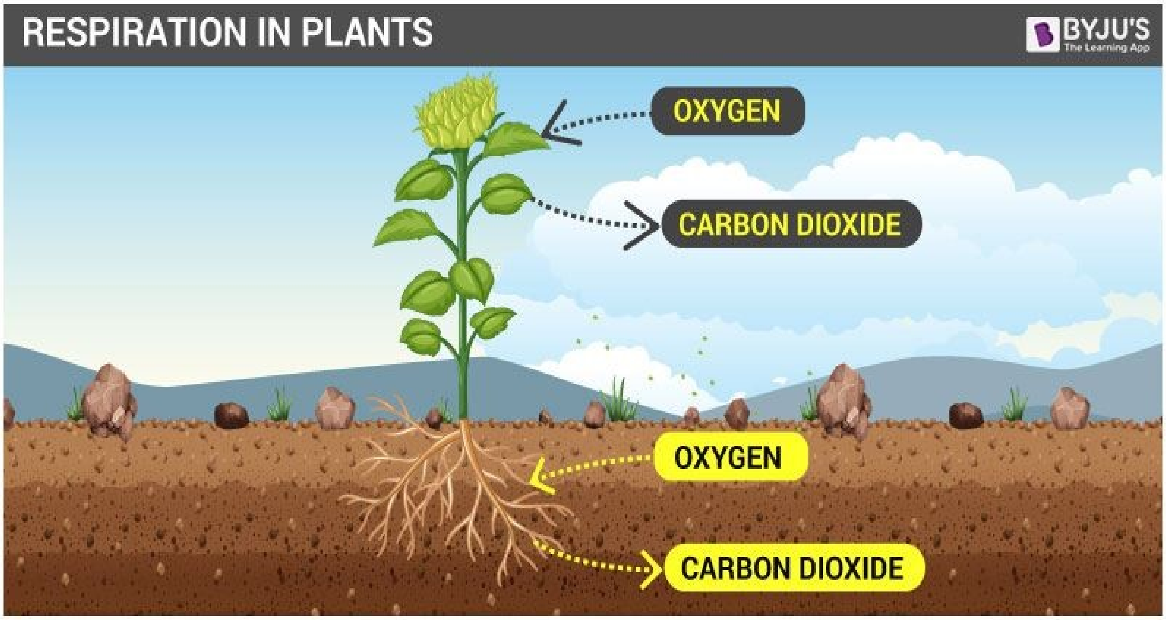
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + 32 ATP (*energy*)

As with photosynthesis, plants get oxygen from the air through the stomata. Respiration takes place in the mitochondria of the cell in the presence of oxygen, which is called "aerobic respiration". In plants, there are two types of respiration: dark respiration and photo respiration. The first kind occurs in the presence or absence of light, while the second occurs exclusively in the presence of light.

The Process of Respiration in Plants:

During respiration, very little amount of gas exchanges takes place within the different parts of the plants. Therefore, each part takes care of its own energy requirements.

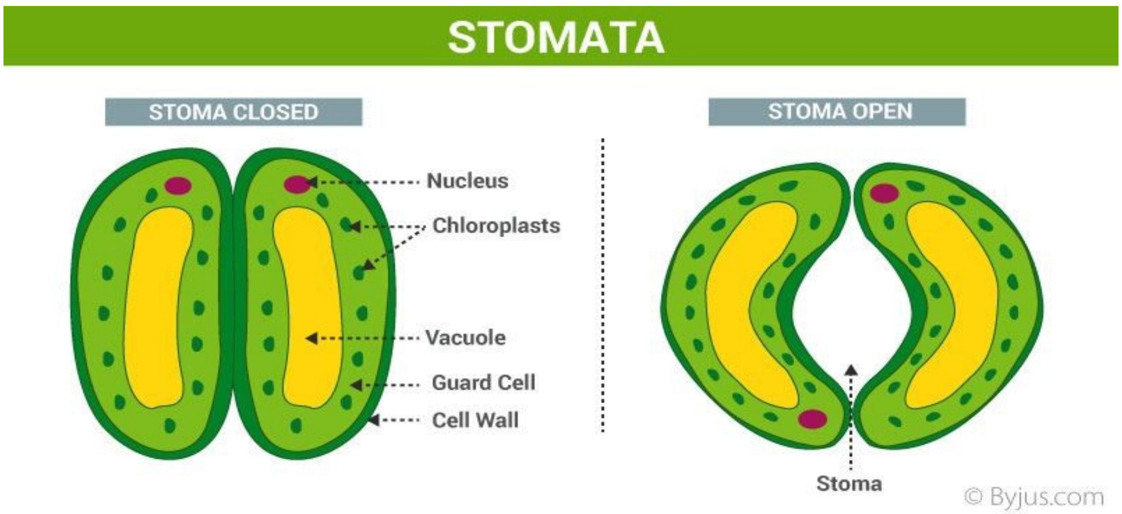
Roots, stems, and leaves of plants exchange gases for respiration separately. As we all know, leaves have tiny pores called stomata, which is used for the exchange of gases. The oxygen, taken in through stomata is used by cells in the leaves to break down glucose into carbon dioxide and water.



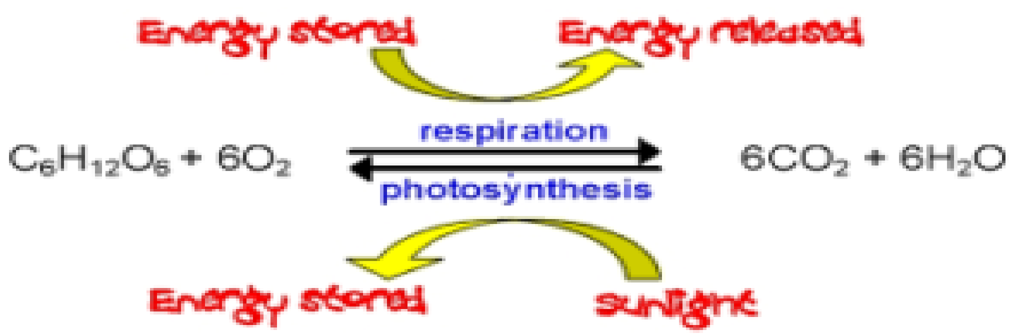
Respiration in Leaves:

The leaves of plants have tiny pores on their surface which are called stomata. The exchange of gases in the leaves during respiration takes place through stomata.

This happens as follows: Oxygen from the air enters into a leaf through stomata and reaches all the cells by the process of diffusion. This oxygen is used in respiration in cells of the leaf. The carbon dioxide produced during diffuses out from the leaf into the air through same stomata.



The photosynthesis reaction makes glucose and the respiration reaction break it down. In photosynthesis, the energy which goes into the reaction is light energy. In respiration, the energy which comes out is chemical energy.

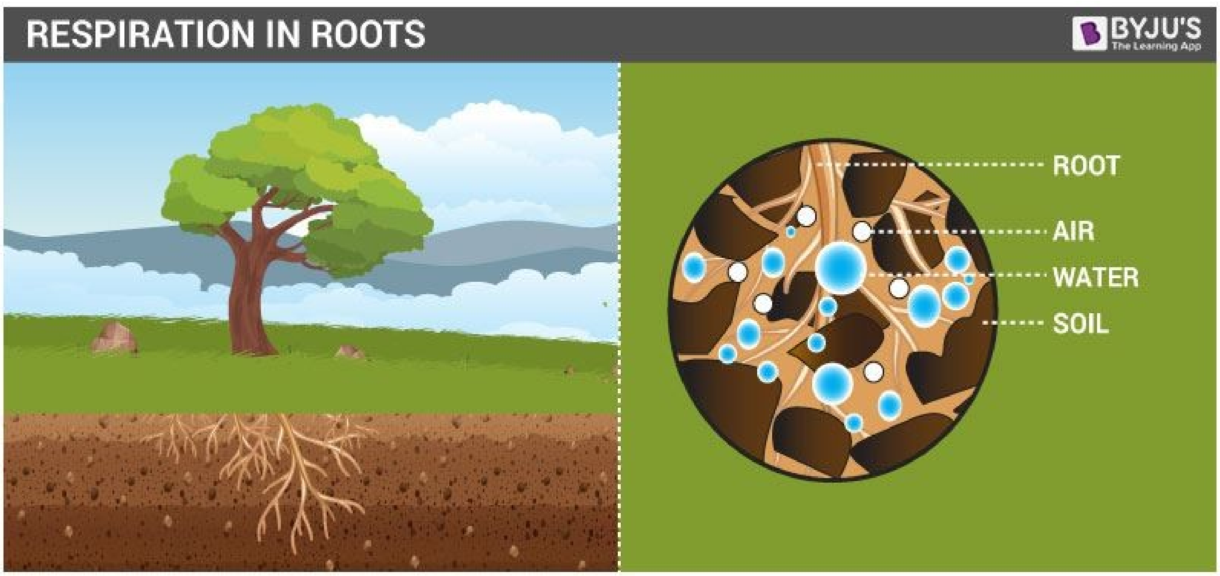


Respiration in Roots:

The roots of plants are under the ground but root cells also need oxygen to carry out respiration and release energy for their own use.

How Does Respiration Occur in Roots?

The roots of a plant take up air from the spaces between the soil particles. Root hairs are in contact with the air in the soil particles. Oxygen from the air in soil particles diffuse into root hair and reach all the cells of the root



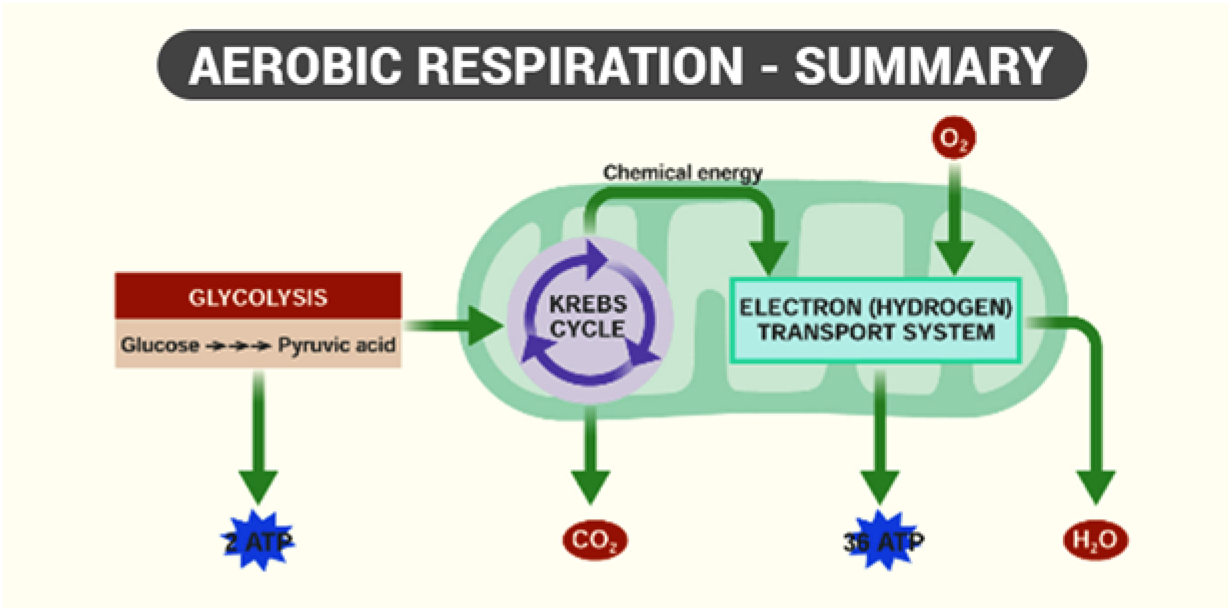
Carbon dioxide produced in the cells of the root during respiration goes out through the same root hair by the process of diffusion. The roots of a plant take up air from the spaces between the soil particles. Root hairs are in contact with the air in the soil particles. Oxygen from the air in soil particles diffuse into root hair and reach all the cells of the root where it is utilized in respiration. Carbon dioxide produced in the cells of the root during respiration goes out through the same root hair by the process of diffusion

If a potted plant is over watered for a long time, then the plant may ultimately die. This is because too much water expels all the air from in between the soil particles. Due to this, oxygen is not available to the roots for aerobic respiration. In this condition, the roots of plant respire anaerobically producing alcohol. This may kill the plant. Germinating seeds during early stage respire anaerobically because they have seed coat which does not allow the oxygen to enter through it.

Respiration in Stems:

In the case of the stem, the air gets diffused in the stomata and passes through various parts of the cell for respiration. The carbon dioxide produced during this stage also diffuses through the stomata. In higher plants or woody plants, the gaseous exchange is carried out by lenticels.

Types of Respiration:



There are two types of respiration which we classify on the basis of the presence or absence of oxygen:

Aerobic respiration:

The respiration that takes place in the presence of oxygen is called ***aerobic respiration*** because it uses 'air' which contains oxygen. The aerobic respiration involves utilization of oxygen for the breakdown of chemical bonds in glucose to release energy in high amounts. It is the chief source of energy for plants and animals. Animals and plants that use oxygen for respiration are **aerobes**. Majority of animals have aerobic respiration.

$$C6H12O6+6O2 \longrightarrow 6CO2+6H2O+Energy$$

All the organisms that obtain energy by aerobic respiration cannot live without the oxygen. This is because if there is no oxygen, they cannot get energy from the food which they eat. Aerobic respiration produces more energy because a ***complete breakdown*** of glucose occurs during respiration by the use of oxygen.

Anaerobic Respiration:

The respiration that takes place in the absence of oxygen is ***anaerobic respiration.*** In this process, incomplete oxidation of food material is being and produces carbon dioxide and alcohol. Beside this other organic matter like citric acid, oxalic acid, lactic acid, etc are also produced.

This process is also known as **intramolecular Respiration**. The anaerobic respiration takes place in organisms like yeast, some bacteria, and parasitic worms. The animals and plants that can survive and obtain energy even in the absence of oxygen are called Anaerobic.

$$\text{Glucose} \longrightarrow \text{Alcohol} + CO2 + \text{Energy}$$

Yeast is a single-celled fungus. In yeast, a single cell represents the whole organism. Very low amount of energy is realised in this process. Yeast respires anaerobically and during this process, yeast converts glucose into alcohol. Therefore, it is used to make alcohol bread, etc.

Anaerobic respiration produces much less energy because the only partial breakdown of glucose occurs in anaerobic respiration in the absence of oxygen. All the organisms which obtain energy by anaerobic respiration can live without the oxygen.

For example, yeast is an organism which can live without the oxygen of air because it obtains energy by the process of anaerobic respiration. Yeast can survive in the absence of oxygen.

Anaerobic Respiration in Muscles

Human beings normally obtain energy by aerobic respiration. But when we need extra energy, anaerobic respiration can take place in our muscles for a short time. When we do a heavy physical exercise, our muscles need more oxygen. But the supply of oxygen through blood is limited and hence insufficient.

During heavy exercise, some of our muscles respire anaerobically. The anaerobic respiration by muscles brings about the partial breakdown of glucose to form lactic acid. This lactic acid accumulates in the muscles. The accumulation of lactic acid in the muscles causes muscles cramps.

$$\underset{\text{glucose}}{C_6H_{12}O_6} \xrightarrow{\text{enzymes}} \underset{\text{ethanol}}{2C_2H_5OH} + 2CO_2$$

Yeast are single-celled organisms. They respire anaerobically and yield ethyl alcohol and are used to make wine and beer. They are also used in baking industry.

Aerobic vs Anaerobic Respiration

S.No	**Aerobic respiration**	**Anaerobic respiration**
1.	It occurs in the presence of oxygen.	It occurs in the absence of oxygen.
2	Food materials are completely oxidised to release carbon dioxide, water and energy.	Food materials are incompletely oxidised to release alcohol, carbon dioxide and energy.
3.	Sufficient amount of energy is	A small amount of energy is released.

	released.	
4.	It takes places in all organisms.	It Takes place in very few organisms like yeast and in muscles of the human beings.
5.	Enzymes responsible for this process are found in mitochondria.	Enzymes responsible for this process are found in protoplasm.

Similarities Between Aerobic and Anaerobic Respiration

	Aerobic respiration	**Anaerobic respiration**
1	In aerobic respiration, energy is produced by the breakdown of food(like glucose).	In anaerobic respiration, energy is also produced by the breakdown of food (like glucose).
2	Aerobic respiration takes place in the cells of the organism.	Anaerobic respiration also takes place in the cells of the organism

Differences between Respiration and Photosynthesis

Photosynthesis	**Respiration**
This process is common to all green plants containing chlorophyll pigments.	This process is common to all living things including plants, animals, birds,

	etc.
It synthesizes foods.	It oxidizes foods.
It stores energy.	It releases energy.
Photosynthesis is an anabolic process.	Respiration is a catabolic process.
It requires cytochrome.	It also requires cytochrome.
It is Endothermal process.	It is Exothermal process.
It comprises products like sugar, oxygen, and water as products.	It comprises products like hydrogen and carbon dioxide.
During Photosynthesis, radiant energy is converted into potential energy.	During Respiration, potential energy is converted into kinetic energy.
It takes place only in the presence of sunlight.	It takes place continuously throughout the life process from birth to death.

Aerobic respiration It has three steps-

1. Glycolysis
2. Kreb's cycle/ tricarboxylic acid (TCA) cycle,
3. Electron transport chain (ETC)

Glycolysis

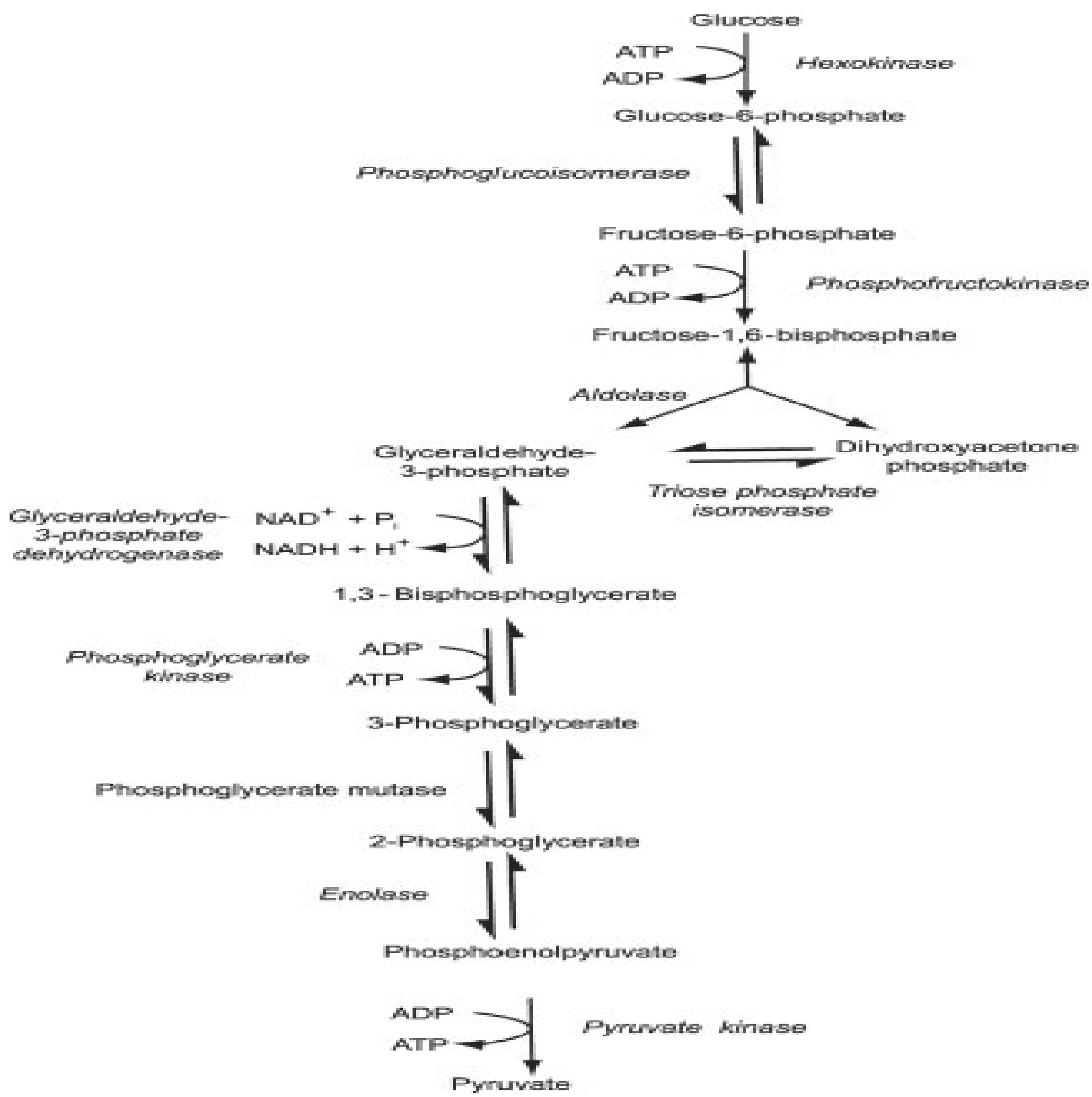
- **Glycolysis** is the process of breaking down glucose.
- Glycolysis can take place with or without oxygen.

- Glycolysis produces two molecules of **pyruvate**, two molecules of **ATP**, two molecules of **NADH**, and two molecules of **water**.
- Glycolysis takes place in the **cytoplasm**.
- There are 10 enzymes involved in breaking down sugar. The 10 steps of glycolysis are organized by the order in which specific enzymes act upon the system.

Glycolysis can occur with or without oxygen. In the presence of oxygen, glycolysis is the first stage of cellular respiration. In the absence of oxygen, glycolysis allows cells to make small amounts of ATP through a process of fermentation. Glycolysis takes place in the cytosol of the cell's cytoplasm. A net of two ATP molecules are produced through glycolysis (two are used during the process and four are produced.) Learn more about the 10 steps of glycolysis below.

Step 1

The enzyme **hexokinase** phosphorylates or adds a phosphate group to glucose in a cell's cytoplasm. In the process, a phosphate group from ATP is transferred to glucose producing glucose 6-phosphate or G6P. One molecule of ATP is consumed during this phase.



Step 2

The enzyme **phosphoglucomutase** isomerizes G6P into its isomer fructose 6-phosphate or F6P. Isomers have the same molecular formula as each other but different atomic arrangements.

Step 3

The kinase **phosphofructokinase** uses another ATP molecule to transfer a phosphate group to F6P in order to form fructose 1,6-bisphosphate or FBP. Two ATP molecules have been used so far.

Step 4

The enzyme **aldolase** splits fructose 1,6-bisphosphate into a ketone and an aldehyde molecule. These sugars, dihydroxyacetone phosphate (DHAP) and glyceraldehyde 3-phosphate (GAP), are isomers of each other.

Step 5

The enzyme **triose-phosphate isomerase** rapidly converts DHAP into GAP (these isomers can inter-convert). GAP is the substrate needed for the next step of glycolysis.

Step 6

The enzyme **glyceraldehyde 3-phosphate dehydrogenase** (GAPDH) serves two functions in this reaction. First, it dehydrogenates GAP by transferring one of its hydrogen (H^+) molecules to the oxidizing agent nicotinamide adenine dinucleotide (NAD^+) to form NADH + H^+.

Next, GAPDH adds a phosphate from the cytosol to the oxidized GAP to form 1,3-bisphosphoglycerate (BPG). Both molecules of GAP produced in the previous step undergo this process of dehydrogenation and phosphorylation.

Step 7

The enzyme **phosphoglycerokinase** transfers a phosphate from BPG to a molecule of ADP to form ATP. This happens to each molecule of BPG. This reaction yields two 3-phosphoglycerate (3 PGA) molecules and two ATP molecules.

Step 8

The enzyme **phosphoglyceromutase** relocates the P of the two 3 PGA molecules from the third to the second carbon to form two 2-phosphoglycerate (2 PGA) molecules.

Step 9

The enzyme **enolase** removes a molecule of water from 2-phosphoglycerate to form phosphoenolpyruvate (PEP). This happens for each molecule of 2 PGA from Step 8.

Step 10

The enzyme **pyruvate kinase** transfers a P from PEP to ADP to form pyruvate and ATP. This happens for each molecule of PEP. This reaction yields two molecules of pyruvate and two ATP molecules.

Oxidative Decarboxylation & Krebs Cycle:

Oxidative Decarboxylation

Once Glycolysis takes place in the cells cytoplasm it produces pyruvate, which continues on and into the matrix of the mitochondria. The Krebs cycle is the next step of cellular respiration, but before the Krebs cycle takes place we need another step called **Oxidative Decarboxylation** which has to convert pyruvate into acetyl-CoA.

The following steps occur:

1. A carboxyl group is removed as CO_2. This is the decarboxylation part.

2. Then the remaining 2-carbon part is oxidized by NAD^+. The NAD^+ gains two hydrogen's and the remaining two-carbon compound becomes an acetic acid.

3. Then a coenzyme A (CoA) attaches to the acetic acid part forming acetyl-CoA. This is the molecule that is needed to continue in the Krebs Cycle.

The overall equation: 2 pyruvate + 2 NAD^+ + 2 CoA à 2 acetyl-CoA + 2NADH + 2H^+ + 2CO_2

Krebs Cycle/ Tricarboxylic acid (TCA) cycle:

The citric acid cycle, also known as the Krebs cycle or tricarboxylic acid (TCA) cycle, is the second stage of cellular respiration. This cycle is catalyzed by several enzymes and is named in honor of the British scientist Hans Krebs who identified the series of steps involved in the citric acid cycle. The usable energy found in the carbohydrates, proteins, and fats we eat is released mainly through the citric acid cycle. Although the citric acid cycle does not use oxygen directly, it works only when oxygen is present.
Acetyl CoA which is formed in **Oxidative Decarboxylation** is then used in the first step of the citric acid cycle. Each step in the cycle is catalyzed by a specific enzyme.

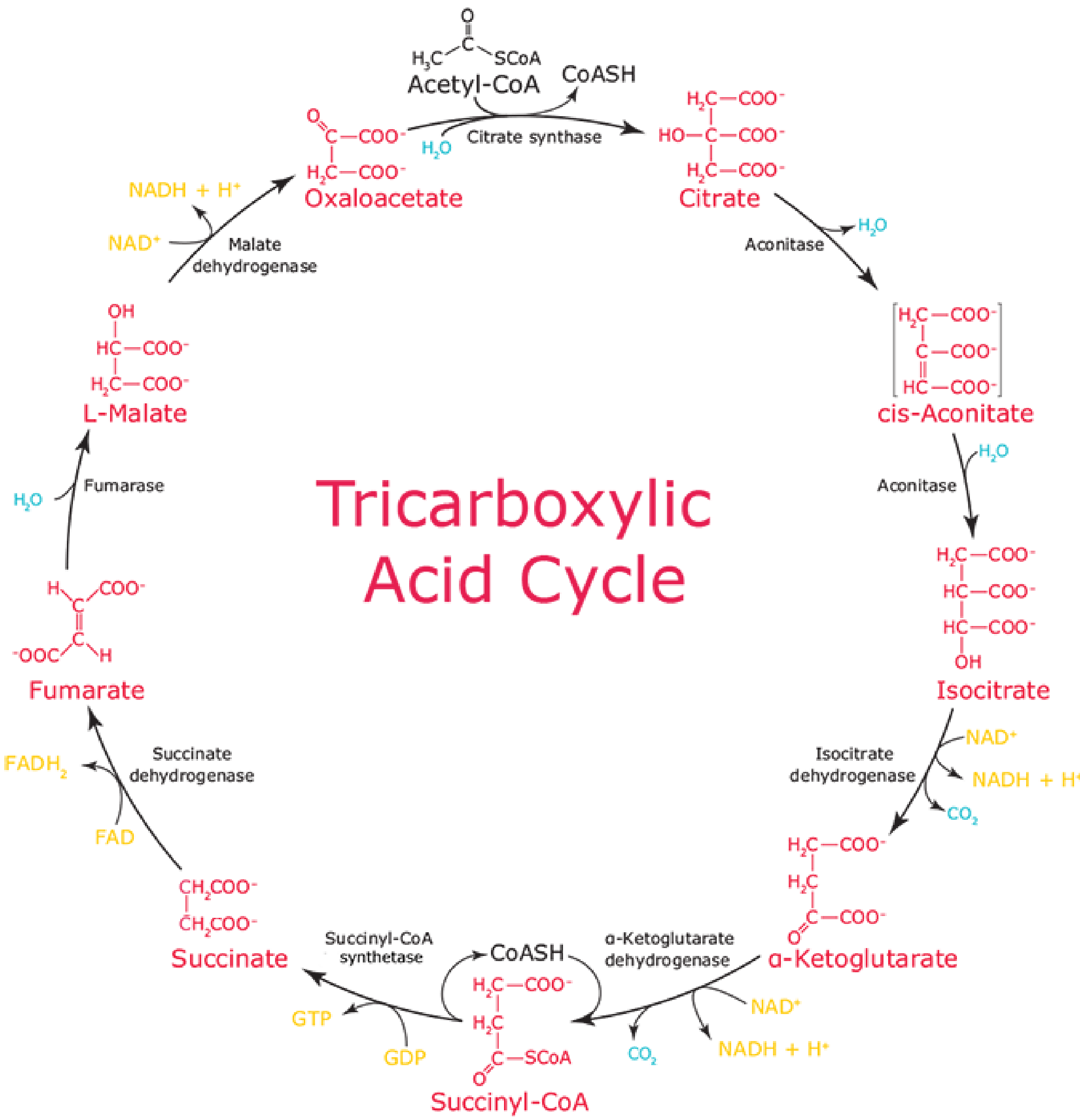
The following steps are important out of the 8.

1. There is a hydrolysis reaction which converts Critic Acid into Isocitric Acid.

3. Isocitric is oxidized by NAD^+, at the same time the NAD^+ is reduced from NADH. CO_2 is released forming alpha-ketoglutarate

4. CoA oxidizes alpha-ketoglutarate, NAD^+ is reduced to form NADH, CO_2 is released again. The molecule Succinyl CoA is formed

5. A water gives its hydrogen atoms to CoA, then a phosphate group forms a bond with Succinyl. The phosphate is transferred to GDP to produce an energy molecule of GTP. ATP is also formed in this step.



6. Sucinate is oxidized by **FAD^+** forming $FADH_2$. This forms Fumaric Acid

8. Malic Acid is oxidized by NAD^+ which forms NADH in the final step of the Krebs Cycle Oxaloacetic acid is formed.

Overall in the Krebs cycle you should understand that free energy is released, hence cellular respiration. For simplicity: Steps 3,4,8 NAD^+ is reduced to NADH

ATP is formed

Step 6, FAD^+ is reduced to $FADH_2$

Steps 3, 4 CO_2 Is released

A total gain of 3NADH, 1ATP, 1$FADH_2$, CO_2. The cycle happens twice, so do not forget to multiply by 2.

Electron Transport Chain:

- The electron transport chain is a series of protein complexes and electron carrier molecules within the inner membrane of **mitochondria** that generate ATP for energy.

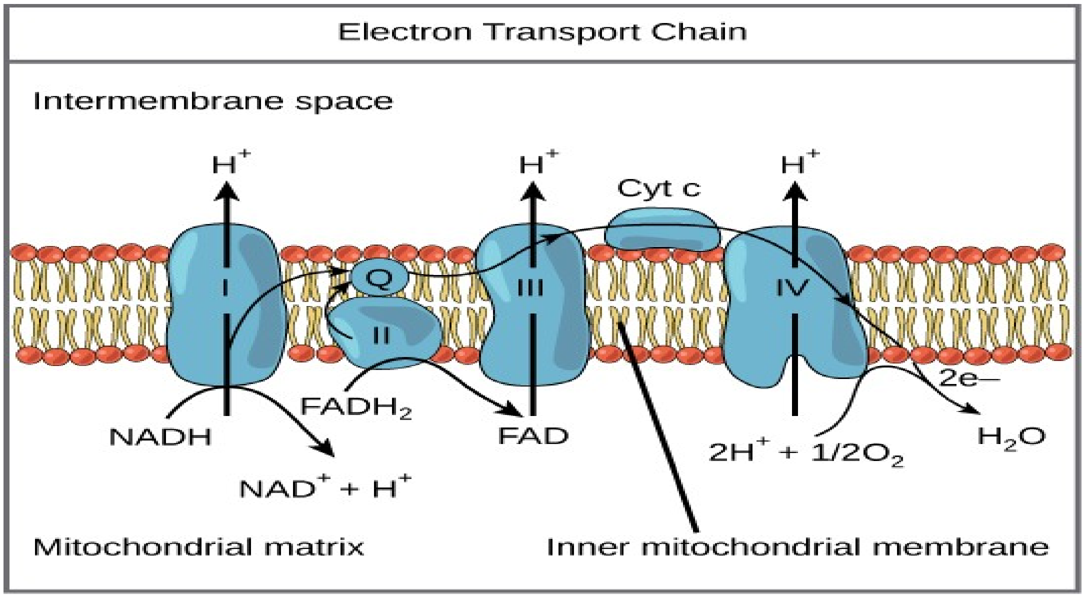
- Electrons are passed along the chain from protein complex to protein complex until they are donated to oxygen. During the passage of electrons, protons are pumped out of the **mitochondrial matrix** across the inner membrane and into the intermembrane space.

- The accumulation of protons in the intermembrane space creates an electrochemical gradient that causes protons to flow down the gradient and back into the matrix through ATP synthase. This movement of protons provides the energy for the production of ATP.

- The electron transport chain is the third step of **aerobic cellular respiration**. Glycolysis and the Krebs cycle are the first two steps of cellular respiration.

Protein Complexes in the Chain

There are four protein complexes that are part of the electron transport chain that functions to pass electrons down the chain. A fifth protein complex serves to transport hydrogen ions back into the matrix. These complexes are embedded within the inner mitochondrial membrane.



Complex I

NADH transfers two electrons to Complex I resulting in four H^+ ions being pumped across the inner membrane. NADH is oxidized to NAD^+, which is recycled back into the Krebs cycle. Electrons are transferred from Complex I to a carrier molecule ubiquinone (Q), which is reduced to ubiquinol (QH2). Ubiquinol carries the electrons to Complex III.

Complex II

$FADH_2$ transfers electrons to Complex II and the electrons are passed along to ubiquinone (Q). Q is reduced to ubiquinol (QH2), which carries the electrons to Complex III. No H^+ ions are transported to the intermembrane space in this process.

Complex III

The passage of electrons to Complex III drives the transport of four more H^+ ions across the inner membrane. QH2 is oxidized and electrons are passed to another electron carrier protein cytochrome C.

Complex IV

Cytochrome C passes electrons to the final protein complex in the chain, Complex IV. Two H^+ ions are pumped across the inner membrane. The electrons are then passed from Complex IV to an oxygen (O_2) molecule, causing the molecule to split. The resulting oxygen atoms quickly grab H^+ ions to form two molecules of water.

ATP Synthase

ATP synthase moves H^+ ions that were pumped out of the matrix by the electron transport chain back into the matrix. The energy from the influx of protons into the matrix is used to generate ATP by the phosphorylation (addition of a phosphate) of ADP. The movement of ions across the selectively permeable mitochondrial membrane and down their electrochemical gradient is called chemiosmosis.

NADH generates more ATP than $FADH_2$. For every NADH molecule that is oxidized, 10 H^+ ions are pumped into the intermembrane space. This yields about three ATP molecules. Because $FADH_2$ enters the chain at a later stage (Complex II), only six H^+ ions are transferred to the intermembrane space. This accounts for about two ATP molecules. A total of 32 ATP molecules are generated in electron transport and oxidative phosphorylation.

Glyoxylate Cycle:

It had been observed by many plant physiologists that during the germination of fatty seeds, the fat content decreased with a simultaneous increase in sucrose (i.e., carbohydrates). This apparent conversion of fats into sucrose remained a mystery till 1957 when Kornberg and Krebs discovered that a strain of bacterium Pseudomonas could readily convert ^{14}C-labelled acetic acid into labelled malic acid and citric acid (these are intermediates of Krebs' Cycle) which involved the following reactions:

(1) Acetyl-CoA combined with Oxaloacetic acid to form Citric Acid.

Acetyl-CoA + Oxaloacetic acid → Citric Acid + CoA

(Acetic acid first reacted with Coenzyme-A to form Acetyl CoA).

(2) Acetyl CoA reacted with glyoxylic acid in the presence of the enzyme malate syn-thetase to produce Malic acid.

Acetyl CoA + Glyoxylic Acid → Malic Acid + CoA

The glyoxylic acid was obtained through the breakdown of Iso-Citric Acid (an inter-mediate of Krebs' Cycle) by the enzyme Isocitratase

Isocitric acid → glyoxylic acid + succinic acid

On the bases of the above reactions Kornberg and Krebs (1957) framed a cycle which is called as Glyoxylic acid cycle or Glyoxylate Cycle through which the fats could be converted into sucrose (i.e., carbohydrate) during the germination of fatty seeds in plants.

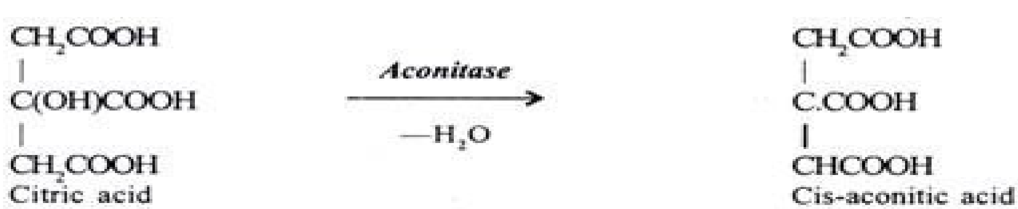
The glyoxylate cycle (which is intimately associated with Krebs' Cycle) is now known to occur in many other bacteria, yeasts, molds, and higher plants and is completed in glyoxysomes, mitochondria and cytosol.

Steps Involved in Glyoxylate Cycle:

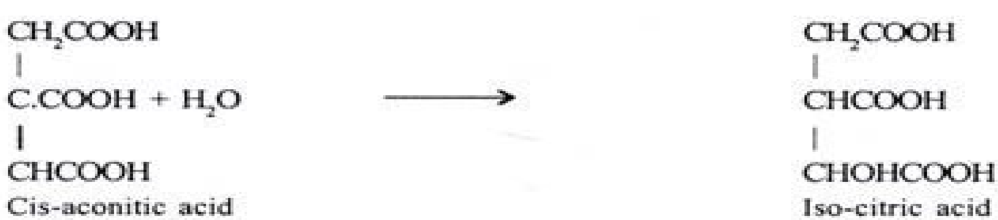
a) Reactions in Glyoxysome:

(i) Acetyl-CoA produced after the β-oxidation of fatty acids (in glyoxysomes) condenses with oxaloacetic acid to form Citric Acid.

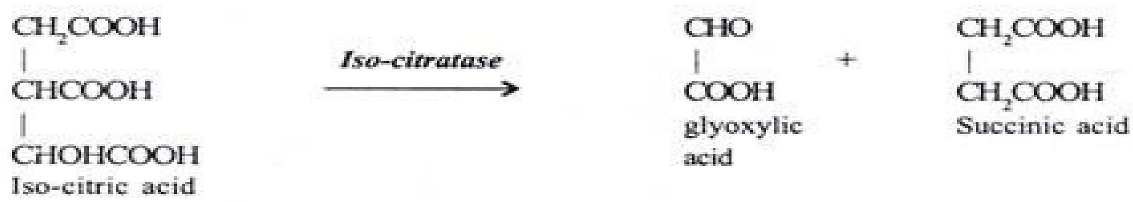
(ii) Citric acid is dehydrated to produce Cis-aconitic Acid in the presence of Aconitase.



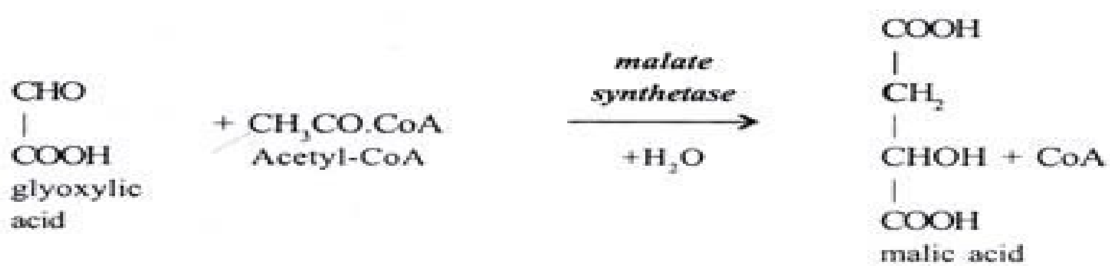
(iii) Cis-aconitic acid reacts with one molecule of H_2O to form Iso-citric acid.



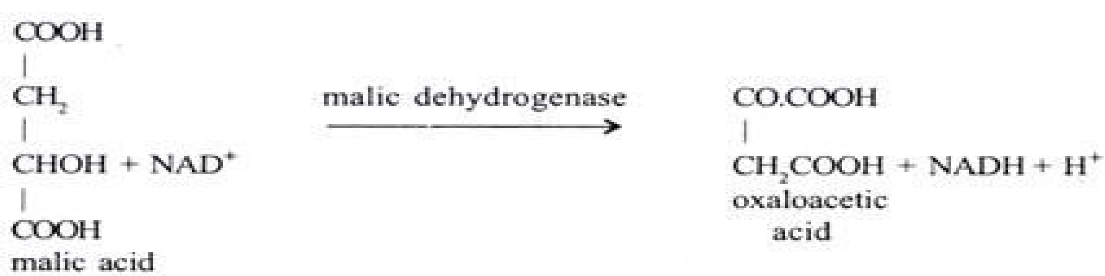
(iv) Iso-citric acid is broken down into glyoxylic acid and succinic acid by the enzyme Isocitratase.



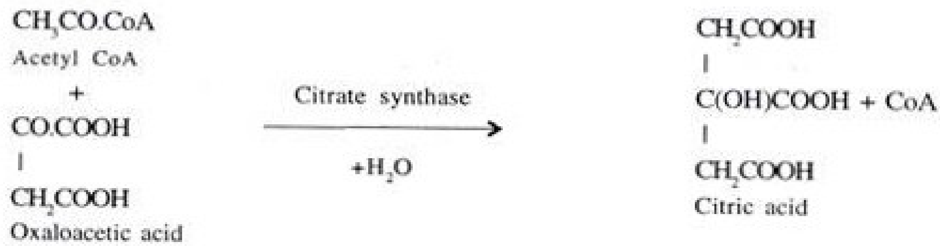
(v) Glyoxylic acid combines with acetyl CoA (produced after the β-oxidation of fatty acids) in the presence of Malate synthetase to produce Malic acid.



(vi) Malic acid is oxidised into oxaloacetic acid in the presence of Malic dehydrogenase and the coenzyme NAD.



Oxaloacetic acid thus produced combines with acetyl-CoA to regenerate citric acid.



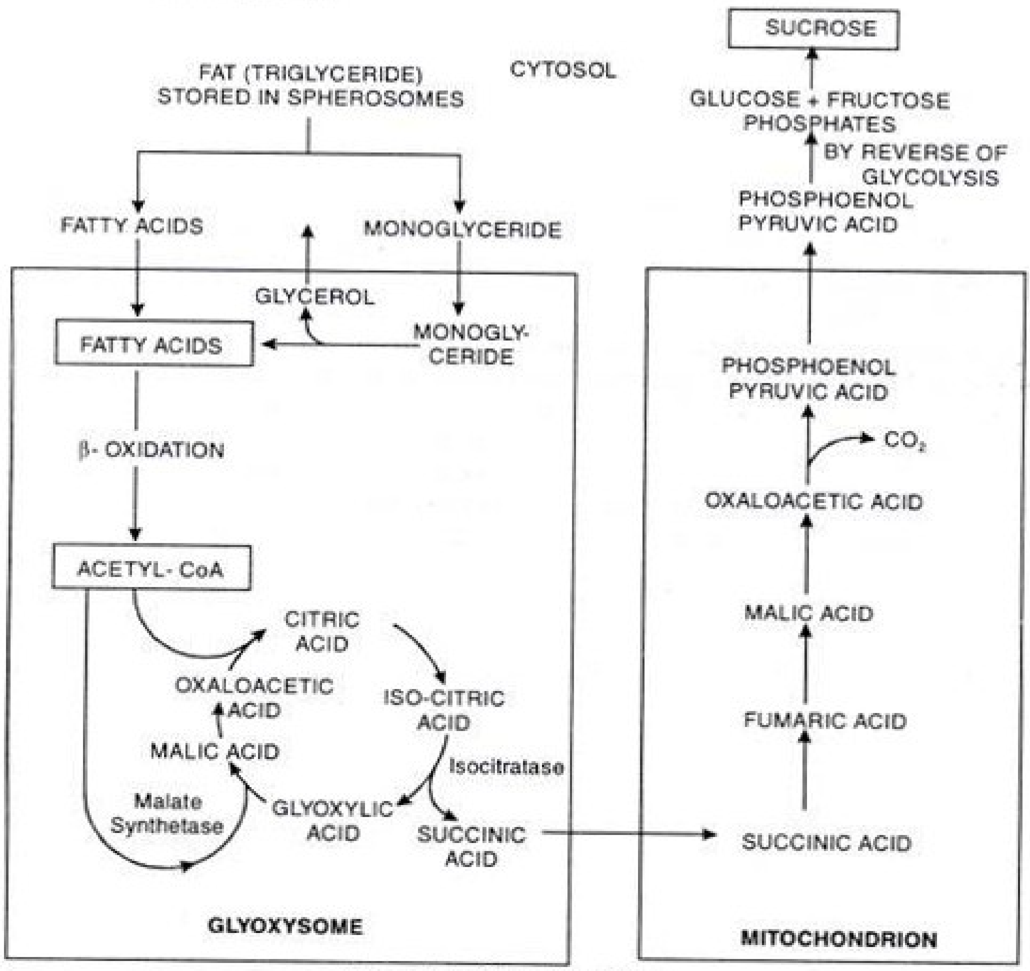
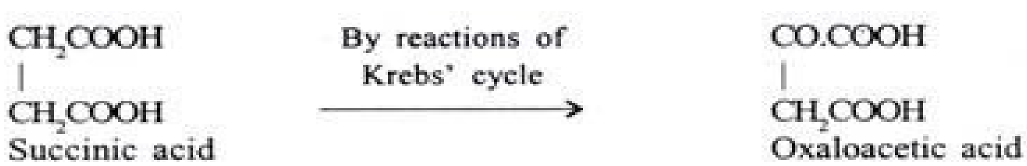


Fig. 14.3. Glyoxylate Cycle.

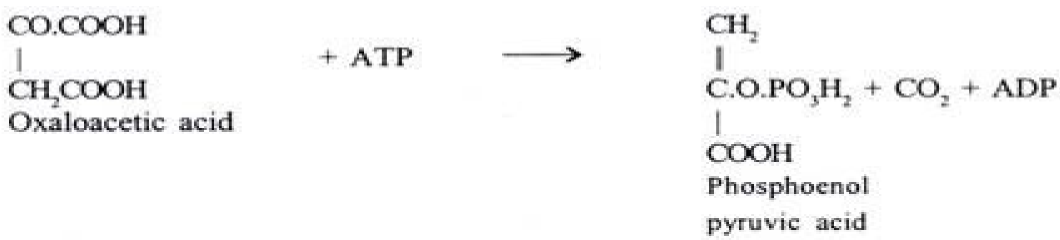
(b) Reactions in Mitochondrion:

(vii) Succinic acid (produced in reaction iv) Moves into mitochondrion and is converted into oxaloacetic acid as in the Krebs' cycle.



The conversion of succinic acid into oxaloacetic acid does not take place in glyoxysomes because of the absence of appropriate enzymes (i.e., succinic dehydrogenase and fumarase) in the latter. It takes place in mitochondria

(viii) Oxaloacetic acid produced in the above step (viii) is decarboxylated in the presence of ATP to form phosphoenol pyruvic acid. This reaction also takes place in mitochondria)



(c) Reactions in Cytosol:

(ix) Phosphoenol pyruvic acid moves into cytosol and by the reverse reactions of glycolysis and with slight modification is converted into the glucose and fructose phosphates.

(x) Finally, glucose and fructose phosphates are converted into sucrose

After the conversion of fats into carbohydrates is completed, the glyoxysomes disappear from the cells.

Significance of Glyoxylate Cycle:

(1) During the germination of fatty seeds, the fats which are insoluble are hydrolysed into fatty acids and glycerol. Fatty acids after P-oxidation produce acetyl-CoA units which synthesize sucrose (which is soluble) through glyoxylate cycle. Soluble sucrose is then supplied to different growing regions of the young germinating seedling till it develops its own photosynthetic system.

(2) Those micro-organisms which can grow on ethyl alcohol or acetate as a sole source of energy and carbon make use of this cycle in synthesizing longer carbon chains.

(3) The glyoxylate cycle is an example of gluconeogenesis.

Cyanide Resistant Respiration and its Significance:

The flow of electrons in the usual mitochondrial electron transport chain (in both animals and plants) during aerobic respiration is blocked by the presence of cyanides which inhibit the activity of cytochrome oxidase. This type of respiration is therefore, known as cyanide sensitive respiration.

Plant mitochondria, however, differ from the animal mitochondria in having an alternate oxidase system pathway through which terminal oxidation of reduced coenzyme continues even in the presence of cyanides. This type of respiration is known as cyanide resistant (or cyanide insensitive) respiration.

In cyanide resistant respiration, the flow of electrons from reduced coenzymes to Ubiquinone is the same as in usual mitochondrial electron transport chain. But after this point (branch point) the electrons pass from UQ to a flavoprotein FPma (with a mid-range E'_0 (= + 0.02 V) and a large absorbance change on redox change), and from there to a cyanide resistant or alternate oxidase (designated as X) and finally to O_2. Usually the reduction of O_2 should result in the formation of H_2O but present evidences indicate the possibility of H_2O_2 being formed instead of H_2O. The H_2O_2 can easily be converted into water arid oxygen then by the enzyme catalase.

P/O ratio (i.e. no. of ADP molecules converted into ATP molecules per O atom) in cyanide resistant respiration is one. As in conventional electron transport chain, the first phosphorylation site is coupled with electron transport chain in cyanide resistant respiration also.

Physiological Significance of Cyanide Resistant Respiration:

The physiological significance of cyanide resistant respiration is not very clear. Following roles are usually attributed to it.

1. Cyanide resistant respiration is believed to be responsible for the climacteric in fruits (i.e., remarkable increase in respiration during and just before ripening). The climacteric is induced by ethylene and the latter may act to implement the cyanide resistant respiration in ripening fruit, (production of H_2O_2 and superoxide increases the oxidation and breakdown of membrane which are necessary activities in the ripening process).
2. Cyanide resistant respiration is known to generate heat in thermogenic tissues. Thermogenecity is observed in the flowers or inflorescences of some plants such as water lily (Victoria), arum lilies, Arum maculatum, Symplocarpus foetidus (skunk cabbage) etc. The excessive heat produced in the inflorescence of Arum etc. is used to volatilize the odiferous compounds such as amines & indoles which are produced in them and which serve to attract pollinating insects. The amount of heat produced in thermogenic tissues may be as high as 51°C with an atm. temp, of 15°C (e.g., in appendix of Arum italicum).

(In cyanide resistant respiration, most of the energy liberated in the oxidation of respiratory substrate is lost as heat and only little of it is consumed in the production of ATPs. For instance the P/O ratio for 1 NADH molecule is only one in cyanide resistant respiration while in cyanide sensitive or usual respiration it is 3).

3. If ATPs generated in usual respiration in mitochondria are not sufficiently drained off, they may inhibit the Krebs' cycle (TCA cycle) via the stoppage of electron flow in electron transport chain. Therefore, cyanide resistant respiration may provide continued oxidation of NADH and operation of TCA cycle though the energy demand is lesser. The operation of TCA cycle is important because TCA cycle intermediates are precursors for cellular components.