Respiration in Plants

CONTENTS

4. RESPIRATION IN PLANTS

4.1 Introduction

- To perform their many tasks, living cells require energy from outside sources.
- Energy enters most ecosystems as sunlight and leaves as heat.
- Light energy is converted into chemical energy that is stored in the bonds of complex organic molecules of carbohydrates like glucose and starch.
- Cells harvest the chemical energy stored in organic molecules and use it to regenerate ATP, the molecule that drives most cellular work.
- Respiration has three key pathways: Glycolysis, the citric acid cycle, and oxidative phosphorylation.
- A more efficient and widespread catabolic process, **cellular respiration,** consumes oxygen as a reactant to complete the breakdown of a variety of organic molecules.
- In eukaryotic cells, mitochondria are the site of most of the processes of cellular respiration.
- Cellular respiration is similar in broad principle to the combustion of gasoline in an automobile engine after oxygen is mixed with hydrocarbon fuel.
- Food is the fuel for respiration. The exhaust is carbon dioxide and water.

4.2 Definition

" Respiration is a process of physiochemical change by which environmental oxygen is taken into, to oxidize the stored food, for release of CO_2, water and energy . The energy released is used for doing various life activities, whereas CO_2 is used by the plants."

or

"Cellular respiration, also known as 'oxidative metabolism', is one of the key ways a cell gains useful energy. It is the set of the metabolic reactions and processes that take place in organisms' cells to convert biochemical energy from nutrients into adenosine triphosphate (ATP), and then release waste products."

The reactions involved in respiration are catabolic reactions that involve the oxidation of one molecule and the reduction of others.

Or

"The phenomenon of release of energy by oxidation of various organic molecules, for cellular use is known as Respiration."

Or

"Respiration may also be defined as an oxidative, catabolic and exothermic process in which large molecules of food materials are broken down into the smaller ones with the release of energy in usable form."

4.3 Difference between Combustion and Respiration

Combustion	Respiration
Does not occur in living things.	Occurs in the cells of the living organisms.
Unlimited energy is liberated once during combustion.	Energy is liberated in small quantities during each step of a series of reactions.
No energy is stored during combustion, so lot of it is wasted.	The liberated energy is stored in ATP molecules.

4.4 Difference between Breathing and Respiration

Breathing	Respiration
It is a biophysical process.	It is a biochemical process.
Oxygen is taken in and CO_2 is given out.	Water , carbon dioxide and energy is released by the oxidation of carbohydrates.

4.5 Importance of Respiration

- During the process of respiration, O_2 and CO_2 H_2O and energy are released as products.
- The whole of energy contained in respiratory substrates is not released all at once. It is released slowly in a stepwise series of reactions controlled by enzymes.
- The energy is utilised in various energy-requiring process of the organisms, and the biochemical intermediate produced during respiration are used as precursors for biosynthesis of other molecules in the cells that take part in growth, repair and metabolism.
- Respiration takes place in all types of living cells, even the photosynthetic ones that trap solar energy and store the same in organic compounds.
- Respiration is represented by following equation-

$$C_6H_{12}O_6 + 6O_2 \rightarrow \underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \underset{\text{Energy}}{\text{Energy}} \text{ (2870 kJ or 686 Kcal)}$$

4.6 Types of Respiration

- On the basis of respiratory substrate, respiration may be-

4.6.1 Protoplasmic Respiration

- Respiration involving proteins as respiratory substrate is Protoplasmic Respiration.
- Protoplasmic Respiration cannot be continued for long as it depletes protein as well as liberates toxic ammonia.

4.6.2 Floating Respiration

- Respiration involving carbohydrate and fats as respiratory substrate is Floating Respiration.
- Depending upon the availability of O_2 Respiration is mainly of two types-

4.6.3 Aerobic Respiration

"When respiration takes place in the presence of oxygen it is termed as aerobic respiration". In other words "When respiration substrates are broken down (oxidized) in the presence of oxygen it is aerobic respiration."

- The process can be shown by the following equation:-

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{Enzyme}} \underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \underset{\text{Energy}}{\text{Energy}} \text{ (38ATP)}$$

- In this process 38 ATP molecules are produced in complete oxidation of one molecule of glucose.

4.6.4 Anaerobic Respiration

"When respiration takes place in the absence of oxygen it is termed as anaerobic respiration". In other words "When respiration substrates are broken down(oxidised) in the absence of oxygen it is anaerobic respiration."

- The process can be shown by the following equation:-

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{Enzyme}} 2\ CH_3CH_2OH + CO_2 + \text{Energy} + 247\ kJ\ (2ATP)$$

Ethyl Alcohol — Carbon dioxide — Energy

- In this process very less quantity of energy is released.

4.7 Biochemical process of Respiration

- The mechanism of biochemical process of Respiration involves following two processes- Glycolysis and Break down of Pyruvic Acid

4.7.1 Glycolysis /EMP pathway

- The term Glycolysis has originated from the Greek words, *glycos* for sugar, and *lysis* for splitting.
- The scheme of Glycolysis was given by Gustav Embden, Otto Meyerhof, and J. Parnas, and is often referred to as the EMP pathway.
- In anaerobic organisms, it is the only process in respiration.
- Glycolysis occurs in the cytoplasm of the cell and is present in all living organisms.
- In this process, glucose undergoes partial oxidation to form two molecules of pyruvic acid.
- In plants, this glucose is derived from sucrose, which is the end product of photosynthesis, or from storage carbohydrates.
- Sucrose is converted into glucose and fructose by the enzyme, invertase, and these two monosaccharides readily enter the glycolytic pathway.
- In Glycolysis, a chain of ten reactions, under the control of different enzymes, takes place to produce pyruvate from glucose.
- The various steps of Glycolysis are as follows-

4.7.1.1Phosphorylation I

- In first step of glycolysis, glucose is phosphorylated to glucose-6-phosphate by ATP in the presence of enzyme Hexokinase (Meyerhof,1927) or glucokinase (e.g., liver) and

$$\text{Glucose} + \text{ATP} \xrightarrow[\text{Hexokinase}]{Mg^{++}} \text{Glucose-6- phosphate} + \text{ADP}$$

- Excess of glucose – 6 – phosphate inhibits Hexokinase but not glucokinase.

4.7.1.2 Isomerization

- Glucose-6 –phosphate is changed to its isomer fructose – 6- phosphate with the help of enzyme phosphohexose isomerase.

$$\text{Glucose-6-phosphate} \xrightarrow[\text{Isomerase}]{\text{Phosphohexose}} \text{Fructose-6-phosphate}$$

- Fructose – 6- phosphate can also be produced directly by phosphorylation of fructose with the help of enzyme Fructokinase.

$$\text{Fructose} + \text{ATP} \xrightarrow[\text{Mg}^{++}]{\text{Fructokinase}} \text{Glucose-6- phosphate} + \text{ADP}$$

4.7.1.3 Phosphorylation II

- Fructose – 6- phosphate is further phosphorylated to fructose-1,6- bisphosphate by ATP in the presence of enzyme phosphofructokinase and Mg^{++} .

$$\text{Fructose-6-phosphate} + \text{ATP} \xrightarrow[\text{Mg}^{++}]{\text{PhosphoFructokinase}} \text{Fructcose-1,6- biphosphate} + \text{ADP}$$

4.7.1.4 Cleavage

- Fructose-1,6- bisphosphate splits into one molecule each of 3- carbon compound, glyceraldehydes 3- phosphate (=GAP or 3-phosphoglyceraldehyde – PGAL) and dicarboxyacetone phosphate (DHAP) in the presence of enzyme aldolase.
- Both these compounds are called Trioses or triose phosphates and are interconvertible with the help of enzyme phosphotriose isomerase.

Fructcose-1, 6- biphosphate
$\downarrow$ *Aldolase*

$$\text{3-PGAL} \xrightarrow[\text{Isomerase}]{Phosphohexose} \text{DHAP}$$

- DHAP is isomerised into PGAL.
- Thus total two molecules of PGAL are formed per molecule of glucose.
- This PGAL acts as connecting link between respiration and photosynthesis.

4.7.1.5 Phosphorylation and Oxidative Dehydrogenase

- Once 3PGAL is formed, the glycolytic pathway enters the energy conserving phase.
- Each molecule of 3-PGAL is oxidized into1,3-biphosphoglyceric acid (PGAP or BiPGA)by utilizing H3PO4 and H2O in the presence of enzyme glyceraldehydes phosphate dehydrogenase.
- Here, coenzyme NAD+ is reduced to NADH + H+.
- This is the only step in glycolysis where oxidation occurs by removal of hydrogen atom (dehydrogenation) from the molecule.

$$\text{GAP} + H_3PO_4 + \text{NAD}^+ \xrightarrow[\text{Dehydrogenase}]{\text{Glyceraldehydephosphate}} \text{PGAP} + \text{NADP} + H^+$$

- In dehydrogenation 2 hydrogen atoms separate from each molecule of 3PGAL and dissociate into 2 protons and 2 electrons.
- Of these two hydrogen atoms, one complete hydrogen and one extra electron of another hydrogen atom are picked up by NAD^+ and get reduced to form NADH.
- The remaining one proton(H^+) remains free in cytoplasm.

$$2H \rightarrow 2H^+ + 2e^-$$

$$\text{NAD} + 2H^+ + 2e^- \rightarrow \text{NADH} + H^+ + e$$

4.7.1.6 ATP generation I

- One of the two phosphates of PGAP is linked by high-energy bond.
- The PGAP undergoes dephosphorylation to form 3-phosphoglyceric acid (3-PAG) with the help of enzyme phosphoglycerate kinase and co-factor Mg^{++} , ATP is produced by substrate phosphorylation.

$$PGAP + ADP \rightarrow 3PGA + ATP$$

4.7.1.7 Isomerization

- 3PGA undergoes intramolecular rearrangement by phosphoglyceromutase in which phosphate group is shifted from 3rd position to 2nd position to form 2PGA.

$$3PGA \xrightarrow{Phosphglyceromutase} 2PGA$$

4.7.1.8 Dehydration

- 2PGA undergoes dehydration in the presence of enolase and cofactor Mg^{++} to form phosphoenol pyruvic acid (PEP).

$$2PGA \xrightarrow[Mg^{++}]{Enolase} PEP + H_2O$$

4.7.1.9 ATP generation II

- Finally PEP forms pyruvic acid after donating its phosphate to ADP to form ATP in the presence of enzyme pyruvate kinase and co-factor Mg^{++} and K^{+}.
- This ATP synthesis is also direct through substrate level phosphorylation.

$$PEP + ADP \xrightarrow{Pyruvatekinase} 3Pyruvic\ Acid + ATP$$

4.7.1.10 Net Products of Glycolysis

- In glycolysis 2 molecules of ATP are consumed initially in converting glucose to fructose-1, 6-biphosphate.
- Two triose phosphate molecules are formed from one glucose molecule.
- Four molecules of ATP are produced by substrate level phosphorylation.
- Therefore net gain is 2ATP.
- Each molecule of NADH gives rise to 3 molecules of ATP in aerobic condition through ETS.
- Thus two molecules of NADH after entering into mitochondria get oxidized through ETS to form 6ATP.
- Therefore, aerobic glycolysis can produce 2+6=8ATP.
- Anaerobic glycolysis produces only 2 ATP as there is no further oxidation of NADH.
- Thus aerobic glycolysis is 4 times more efficient than aerobic glycolysis.

4.7.2 Kreb's Cycle/TCA cycle/Citric Acid cycle

- The TCA cycle starts with the condensation of acetyl group with oxalo-acetic acid (OAA) and water to yield citric acid.
- The reaction is catalysed by the enzyme citrate synthase and a molecule of CoA is released. Citrate is then isomerised to isocitrate.
- It is followed by two successive steps of decarboxylation, leading to the formation of α-ketoglutaric acid and then succinyl-CoA. In the remaining steps of citric acid cycle, succinyl-CoA is oxidized to OAA allowing the cycle to continue.
- During the conversion of succinyl-CoA to succinic acid a molecule of GTP is synthesised. This is a substrate level phosphorylation.
- In a coupled reaction GTP is converted to GDP with the simultaneous synthesis of ATP from ADP.

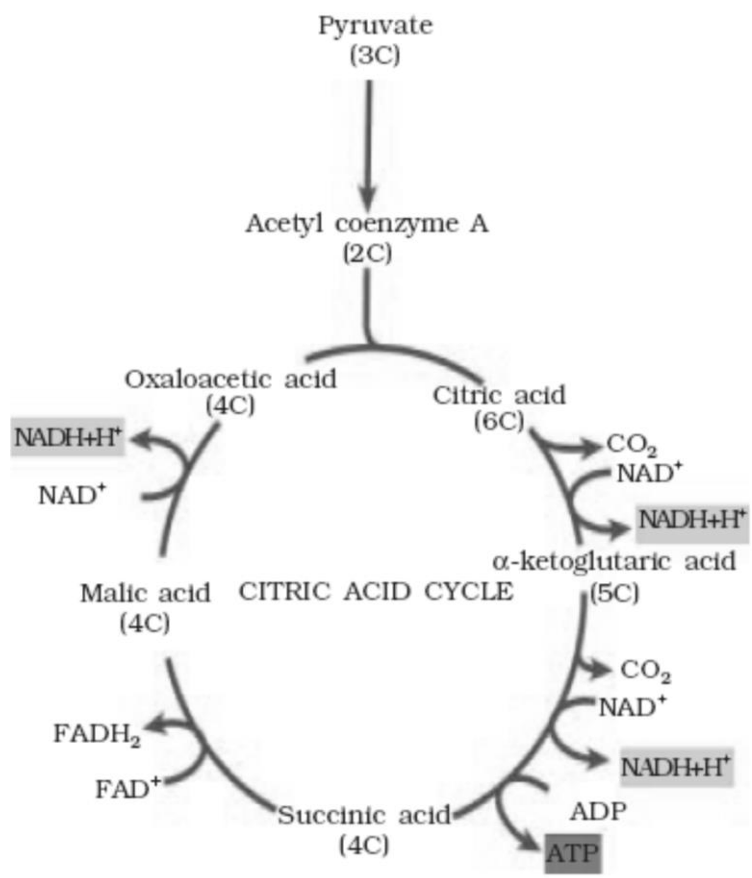
- Also there are three points in the cycle where NAD+ is reduced to NADH + H+ and one point where FAD+ is reduced to FADH2.
- The continued oxidation of acetic acid via the TCA cycle requires the continued replenishment of oxalo-acetic acid, the first member of the cycle.
- In addition it also requires regeneration of NAD+ and FAD+ from NADH and FADH2 respectively.
- The summary equation for **Kreb's Cycle** may be written as follows:

STEPS	SUBSTRATE	ENZYME	END-PRODUCT
Condensation of Acetyl Group	Acetyl-CoA + OAA $+H_2O$	Citric Acid Synthetase	Citric Acid, Coenzyme-A (6C)
Rearrangement	Completed in two steps: • Citric Acid • Cis-Aconitic Acid+ H_2O	Aconitase enzyme Aconitase enzyme	Cis-Aconitic Acid+ H_2O Iso-Citric Acid(6C)
Dehydrogenation (-2H)	Iso-citric Acid + NAD^+	Isocitrate dehydrogenase (Cofactor-Mn^2+)	Oxalosuccinate + NADH + H^+ (6C)
Decarboxylation ($-CO_2$)	Oxalosuccinate	Oxalosuccinate decarboxylase	α-ketoglutaric acid+ CO_2 (5C)
Decarboxylation (-2H,$-CO_2$)	Completed in two steps: • α-ketoglutarate + H_2O + NAD^+ Coenzyme A • Succinyl-CoA + GDP +pi	α-Ketoglutarate dehydrogenase complex Succinate thiokinase	Succinyl-CoA +NADH + H + CO_2 Succinate + Coenzyme A + GTP (substrate level phosphorylation)
Dehydrogenation	Succinate + FAD (H-acceptor) FAD= Flavin Adenine Dinucleotide)	Succinate dehydrogenase	Fumarate + $FADH_2$ (4C)
Hydration	Fumarate + H_2O	Fumarase	Malate
Dehydrogenation	Malate + NAD^+ (H-acceptor)	Malate dehydrogenase	Oxaloacetic acid + NADH
Rearrangement	3-PGA	Phosphoglyceromutase	2-PGA (Phosphoglycerate)
Dehydration	2-PGA	Enolase (Cofactor Mg^{++})	Phosphoenol pyruvate + H_2O
Dephosphorylation	Phosphoenol pyruvate + ADP	Pyruvate kinase and K+, Mg^{++})	Pyruvate +ATP

4.7.3 Significance of Kreb's cycle

- During Kreb's Cycle, carbon skeletons are obtained for use in growth and maintenance of cell.
- It provides many intermediate compounds required in fat and nitrogen metabolisms.
- It is the major pathway for the synthesis of reduced coenzymes and controlled release of energy during respiration.

- Acetyl CoA helps in the synthesis of fatty acids, cutin, aromatic compounds, phytol chain of chlorophyll, carotenoids, steroids and Gibberllins.
- Succinyl CoA takes part in the synthesis of pyrrol ring of chlorophyll, cytochromes, phytochrome, etc.
- Oxaloacetic acid produces aspartic acid, alkaloids and pyrimidines.
- It is a common pathway for the oxidation of fats, proteins and carbohydrates.
- It is the major pathway for the synthesis of reduced coenzymes and controlled release of energy during respiration.
- α-Ketoglutaric acid produces glutamic acid.

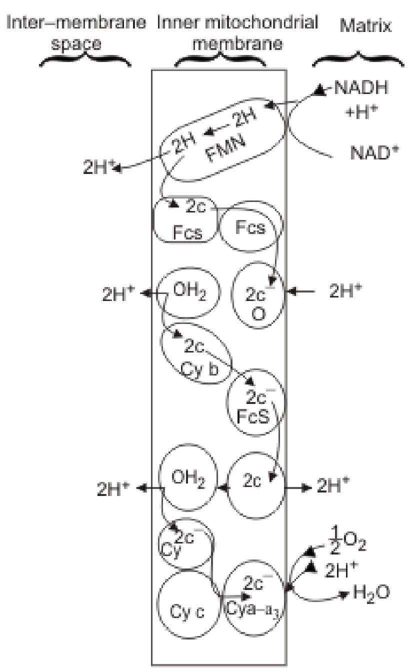


The citric Acid Cycle

NET Gain of ATP	
Glycolysis	= 8 ATP
Link Reaction	3x2 =6 ATP
Kreb's Cycle- Through NADH $+H^+$	3x3x2 = 18 ATP
-Through $FADH_2$	1x2x2 = 4 ATP
-Through substrate phosphorylation	1x 2 = 2ATP
	38 ATP

4.7.4 Oxidative Phosphorylation/Electron Transport System (ETS)

- The whole process by which oxygen effectively allows the production of ATP by phosphorylation of ADP.
- It is the synthesis of ATP, which occurs, with the help of energy obtained from oxidation of reduced co-enzyme formed in cellular respiration.
- ATP synthesis is an endothermic and oxidative process that occurs on the inner mitochondrial membrane of eukaryotes and inner side of cell membrane in prokaryotes.
- In photosynthetic eukaryotes, mitochondria are the major site of ATP production in the dark but in daylight, chloroplast produces most of the ATP.
- ATPs are synthesized by the energy evolved during the electron transport.
- In the electron transport process the reduced coenzymes $NADH_2$ and $FADH_2$ produced in glycolysis and Kreb's cycle are oxidized in the presence of oxygen.
- The reduced coenzymes cannot directly combine with oxygen to form water. These processes are accompanied by the evolution of energy, which is used for the formation of ATP.
- Electron transport is coupled to the formation of ATP.
- During aerobic oxidation of one glucose molecule 38 ATP molecules are produced.
- ATPs are the energy currency of the cell. Thus it shows that the aerobic process of oxidative phosphorylation is the major energy transducing mechanism of the cell concerned.



Electron Transport System

4.7.5 Synthesis of ATP during Glycolysis

- From substrate phosphorylation
  Total Gain = 4 ATP
  Net Gain = 2 ATP
- From $NADH_2$
  - The $NADH_2$ formed during glycolysis is in the cytoplasm.
  - It must enter to ETS to produce ATP.
  - The inner mitochondrial membrane is impermeable to $NADH_2$.

- So, a special electron carrier system is located in inner mitochondrial membrane.
- It picks up the electrons from hydrogen of $NADH_2$ present in cytoplasm, transfers them across the membrane and delivers them to the electron carries inside the mitochondrion.
- There are two shuttle systems.

a. Glycerol phosphate shuttle system

- It is less efficient and present in skeletal muscles and brain cells or most eukaryotic cells.
- It transfers electrons of hydrogen of $NADH_2$, of cytoplasm to FAD of mitochondria which reduced to $FADH_2$ and produces 2 ATP through ETS (4 ATP from 2 mole of $FADH_2$).
- If this dominates-

Total Gain in Glycolysis is 8 ATP
Net Gain in Glycolysis 6 ATP

b. Malate Aspartate shuttle system

- It is more efficient and present in heart , liver and kidney cells.
- It transfers electrons of hydrogen of $NADH_2$ of cytoplasm to NAD of mitochondria which reduced to $NADH_2$ and produces 3 ATP through ETS (6 ATP) from 2 mole of $NADH_2$.

4.7.6 Synthesis of ATP during Kreb's Cycle

	One Turn (One Mole.)	**Two Turn (Two Mole.)**
Oxidation decarboxylation through ETS	3 ATP	6 ATP
Kreb's cycle (a) Through ETS		
From $NADH_2$ (3 mole.)	9 ATP	18 ATP
From $FADH_2$	2 ATP	4 ATP
Through substrate phosphorylation	1 GTP (ATP)	2 GTP (ATP)
	15 ATP	**30 ATP**

4.7.7 Pentose-phosphate pathway (PPP)

- The glucose is broken down into CO_2 and water during aerobic respiration.
- It is the principle pathway of respiration.
- Oxidation of glucose also takes place by another pathway called Pentose phosphate pathway.
- In this pathway, glucose by phosphate (6C) produced during the early stages of glycolysis.
- The reaction occurs in the presence of the enzyme called glucose-t-phosphate dehydrogenase.
- It generates NADPH. The 6- phosphogluconate molecule is again oxidized by the enzyme 6- phosphogluconate dehydrogenase.
- After this one molecule each of ribulose-5-phosphate, carbon dioxide and NADPH are formed.
- 22 Ribulose-3-phosphate undergoes many changes to produce cytolytic intermediates like glyceraldehyde-3-phosphate and fructose-6-phosphate.
- All these reactions take place in the cytoplasm of the cells.

4.7.8 Oxidative Decarboxylation of Pyruvic Acid

- The pyruvic acid (3c) generated in the glycolysis, undergoes oxidative decarboxylation and forms acetyl CoA (activated acetate).
- It occurs in matrix of mitochondria.
- This reaction is catalysed by enzyme complex Pyruvate dehydrogenase which is composed of three enzyme units-
  - Pyruvate decarboxylase
  - Lipoate acetyl transferase
  - Lipoate dehydrogenase
- The entire sequence requires 5 cofactors – Mg^{++}, CoA, Lipoic Acid, NAD^+ and TPP.
- Formation of Acetyl CoA occurs in following steps-

$$\text{Pyruvic Acid} + \text{TPP} \xrightarrow[\text{Decarboxylase}]{\text{Pyruvate}} \text{TPP-acetate} + CO_2$$

$$\text{TPP-acetate} + \text{Lipoic acid} \xrightarrow[\text{Acetyltransferase}]{\text{Lipoate}} \text{Acetylhydrolipoate} + \text{TPP}$$

$$\text{Acetylhydrolipoate} + \text{CoA} \xrightarrow[\text{Dehydrogenase}]{\text{Lipoate}} \text{Acetyl CoA}$$

$$\text{Reduced Lipoic acid} + \text{FAD} \rightarrow \text{Lipoic acid} + FADH_2$$

$$FADH_2 + NAD^+ \xrightarrow[\text{Dehydrogenase}]{\text{Dihydrolipoate}} \text{FAD} + \text{NADH} + H^+$$

- Enzyme dihydrolipoate dehydrogenase is a flavoprotein with tight bound FAD.
- FAD is first reduced to $FADH_2$ and then $FADH_2$ reduces NAD+ to NADH.
- The overall reaction of decarboxylation of Pyruvic acid is-

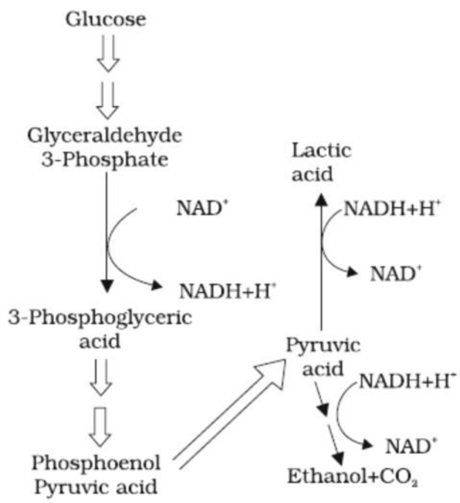
$$\text{Pyruvic Acid} + \text{CoA} + \text{NAD} \xrightarrow[\text{Enzyme complex}]{\text{Pyruvate Dehydrogenase}} \text{Acetyl CoA} + NADH_2 + CO_2$$

- So each molecule of Pyruvic acid forms one molecule of CO_2 and one molecule of acetyl coenzyme A.
- It is called gateway step or link reaction.
- It acts as connecting link between glycolysis, Kreb's cycle and oxidation of fats.
- It is irreversible reaction which occurs in matrix of mitochondria and produces two molecules of each of $NADH^+$, H^+, CO_2 and Acetyl CoA.
- The two molecules of $NADH^+$, H^+ on oxidation produce $2H_2O$ and 6 ATP through ETS.
- Acetyl CoA is connecting link between glycolysis and Kreb's Cycle.

4.7.9 Fermentation

- In fermentation, say by yeast, the incomplete oxidation of glucose is achieved under anaerobic conditions by sets of reactions where pyruvic acid is converted to CO2 and ethanol.
- The enzymes, pyruvic acid decarboxylase and alcohol dehydrogenase catalyse these reactions.
- Other organisms like some bacteria produce lactic acid from pyruvic acid.
- In animal cells also, like muscles during exercise, when oxygen is inadequate for cellular respiration pyruvic acid is reduced to lactic acid by lactate dehydrogenase.
- The reducing agent is $NADH^+H^+$ which is reoxidised to NAD^+ in both the processes.

- In both lactic acid and alcohol fermentation not much energy is released; less than seven per cent of the energy in glucose is released and not all of it is trapped as high energy bonds of ATP. Also, the processes are hazardous – either acid or alcohol is produced.
- Yeasts poison themselves to death when the concentration of alcohol reaches about 13%.



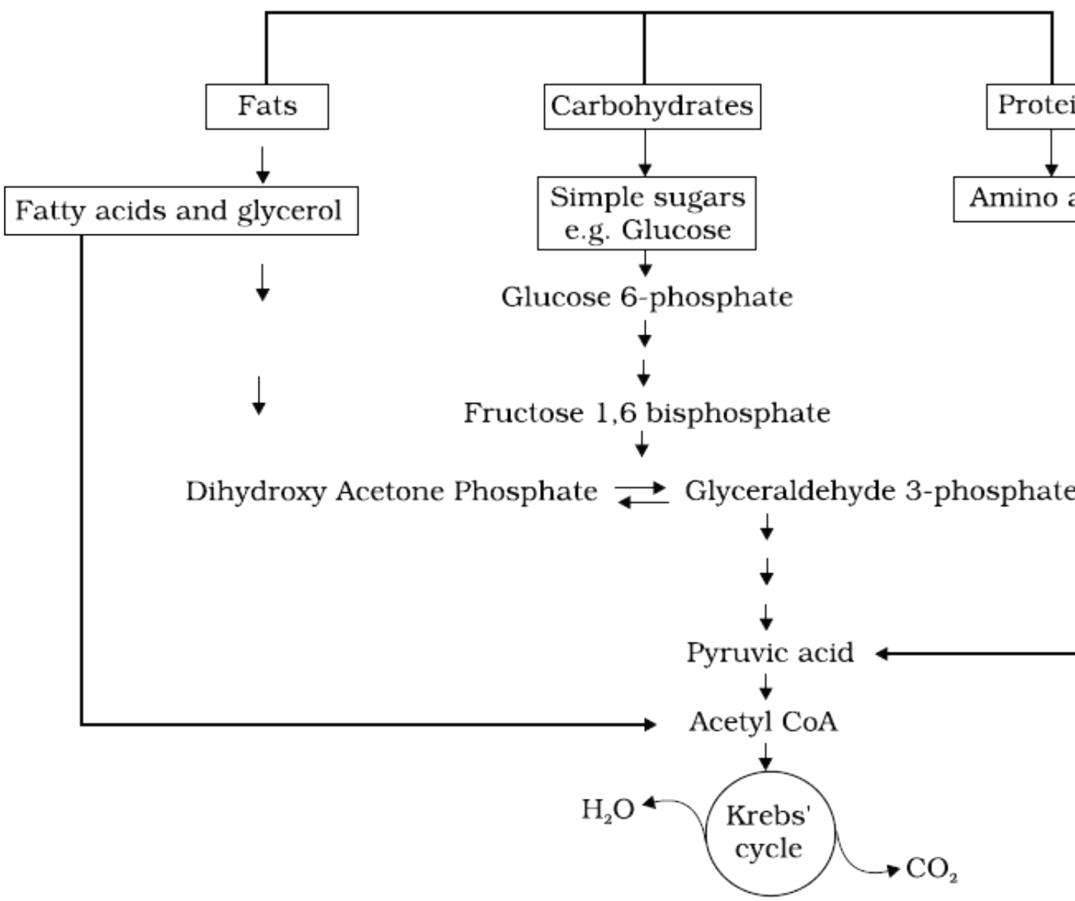
4.7.10 The Respiratory Balance Sheet

- It is possible to make calculations of the net gain of ATP for every glucose molecule oxidised; but in reality this can remain only a theoretical exercise.
- These calculations can be made only on certain assumptions that:
  - There is a sequential, orderly pathway functioning, with one substrate forming the next and with Glycolysis, TCA cycle and ETS pathway following one after another.
  - The NADH synthesised in Glycolysis is transferred into the mitochondria and undergoes oxidative phosphorylation.
  - None of the intermediates in the pathway are utilised to synthesise any other compound.
  - Only glucose is being respired – no other alternative substrates are entering in the pathway at any of the intermediary stages.
  - But this kind of assumptions are not really valid in a living system; all pathways work simultaneously and do not take place one after another; substrates enter the pathways and are withdrawn from it as and when necessary; ATP is utilised as and when needed; enzymatic rates are controlled by multiple means.
  - Yet, it is useful to do this exercise to appreciate the beauty and efficiency of the living system in extraction and storing energy.
  - Hence, there can be a net gain of 36 ATP molecules during aerobic respiration of one molecule of glucose.

4.7.11 Amphibolic Pathway

- Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration.

- Other substrates can also be respired, as has been mentioned earlier, but then they do not enter the respiratory pathway at the first step.
- Fats would need to be broken down into glycerol and fatty acids first. If fatty acids were to be respired they would first be degraded to acetyl CoA and enter the pathway.
- Glycerol would enter the pathway after being converted to PGAL.
- The proteins would be degraded by proteases and the individual amino acids (after deamination) depending on their structure would enter the pathway at some stage within the Krebs' cycle or even as pyruvate or acetyl CoA.
- Since respiration involves breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway.
- Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate.
- But when the organism needs to synthesise fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it.
- Hence, the respiratory pathway comes into the picture both during breakdown and synthesis of fatty acids.
- Similarly, during breakdown and synthesis of protein too, respiratory intermediates form the link.
- Breaking down processes within the living organism is catabolism, and synthesis is anabolism.
- Because the respiratory pathway is involved in both anabolism and catabolism, it would hence be better to consider the respiratory pathway



4.7.12 Respiratory Quotient

"During aerobic respiration, O_2 is consumed and CO_2 is released. The ratio of the volume of CO_2 evolved to the volume of O_2 consumed in respiration is called the **respiratory quotient** (RQ) or respiratory ratio."

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of O2 consumed}}$$

- The respiratory quotient depends upon the type of respiratory substrate used during respiration.
- When carbohydrates are used as substrate and are completely oxidized, the RQ will be 1, because equal amounts of CO_2 and O_2 are evolved and consumed, respectively, as shown in the equation below :

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

$$RQ = \frac{6\ CO_2}{6\ O2} = 1.0$$

- When fats are used in respiration, the RQ is less than 1. Calculations for a fatty acid, tripalmitin, if used as a substrate is shown:

$$2(C_{51}H_{98}O_6) + 145O_2 \longrightarrow 102CO_2 + 98H2O + \text{Energy}$$

$$RQ = \frac{102\ CO_2}{145\ O2} = 0.7$$

- When proteins are respiratory substrates the ratio would be about 0.9.
- In living organisms respiratory substances are often more than one; pure proteins or fats are never used as respiratory substrates.

4.7.13 Compensation Point

- The **compensation point** is the amount of light intensity on the light curve where the rate of photosynthesis exactly matches the rate of respiration.
- At this point, the uptake of CO_2 through photosynthetic pathways is exactly matched to the respiratory release of carbon dioxide, and the uptake of O_2 by respiration is exactly matched to the photosynthetic release of oxygen.
- In C_3 plants, the CO_2 compensation point is usually much higher (25 to 100 μl.l^{-1}).
- Hence, it can be said that there is very little leakage of CO_2 into the external atmosphere from C_3 plants.

4.7.14 Energy Relation

- The total energy yield from 38 ATP molecules comes to 38 x 34 = 1292 KJ. (One ATP molecule yields 34 KJ of energy).
- Energy released by one molecule of glucose on complete oxidation corresponds to 2870KJ.
- Thus, the efficiency
  $= \frac{1292}{2870}\ x\ 100$
  = 45%
- It shows that only a part of this energy is used to make ATP and much of the energy generated during respiration is released in the form of heat.

4.8 Difference between Photosynthesis & Respiration

Photosynthesis	Respiration
Photosynthesis is an anabolic process in which organic compounds are synthesised.	Respiration is an catabolic process in which organic compounds are broken down.
Photosynthesis is endergonic process.	Respiration is exergonic process.
There is gain in weight in Photosynthesis.	In Respiration there is loss of weight.
Photosynthesis absorbs sunlight.	In Respiration light is not absorbed.
In Photosynthesis solar or light energy is changed into chemical energy.	In Respiration potential chemical energy is released which is then transformed into several types.
Photosynthesis is restricted to only plants and some lower organisms.	Respiration is found in all types of organisms.
Photosynthesis occurs in only green parts or cells of the plants.	Respiration occurs in all parts or cells of the organisms.
Photosynthesis occurs during day time.	Respiration continues both during day and night.
Organelles involved in Photosynthesis are chloroplasts.	Respiration takes place in cytosol and mitochondria.
A plant can survive without Photosynthesis for a few days.	No organism can live without Respiration for long.
Raw materials for Photosynthesis are carbon dioxide and water.	Raw materials for Respiration are glucose and oxygen.
Products of Photosynthesis are oxygen and organic substances.	Products of Respiration are carbon dioxide and water.
Photosynthesis consumes carbon dioxide and liberates oxygen.	Respiration consumes oxygen and liberates carbon dioxide.
Photosynthesis performs photophosphorylation.	Respiration performs oxidative phosphorylation.
Photosynthesis forms and uses ATP and NADPH.	Respiration liberates NADH, NADPH, $FADH_2$ and ATP. They are not used in respiration but are meant for other metabolic processes.

4.9 Factors Affecting Respiration

- Many external and internal factors affecting the rate of respiration are as follows-

4.9.1 External Factors

- Temperature-Temperature is the most important factor for respiration. Mostly plants respire between 0ºC to 30ºC. With every 10ºC rise of temperature from 0ºC to 30ºC the rate of respiration increases 2 to 2.5 times.

- Temperature Coefficient Q_{10} = 2 to 2.5
- Maximum rate of respiration takes place at 30ºC. Above 30ºC, there is an initial rise , soon followed by a decline.
- Higher the temperature above this limit, more is the initial rise but more is the decline and earlier is the decline in the rate of respiration.
- Below 0ºC the rate of respiration is greatly reduced although in some plants respiration takes place even at -20ºC .Dormant seeds kept at -50ºC survive.
- Oxygen –
- Respiration is aerobic or anaerobic depending upon the presence or absence of oxygen. Air has 20.8% oxygen which is more than enough keeping in view the requirements of plants. On decreasing the amount of oxygen to 1.9% in the environment aerobic respiration become negligible but anaerobic respiration takes place.
- Water- With increase in the amount of the rate of respiration increase. In dry seeds which have 8-12% of water the rate of respiration is very low but as the seeds imbibe water the respiration increases. The life of seeds decreases with increase of water. The rate of respiration of seeds increase with increase of water because water causes hydrolysis, the activity of respiratory enzymes is increased.
- Light-Respiration takes place in night also which show that light is not essential for respiration. But light effects the rate of respiration indirectly by increasing the rate of photosynthesis due to which concentration of respiratory substrates is increased. More the respiratory substrate is increased. More the respiratory substrate more is the rate of respiration.
- Carbon Dioxide- If the amount of CO_2 in the air is more than usual the rate of respiration is decreased. In 1950 Heath has shown that the stomata are closed at higher concentration of CO_2, due to which oxygen does not penetrate the leaf and rate of respiration is lowered.

4.9.2 Internal Factors

- Age of protoplasm- The rate of respiration is high in actively growing cells e.g., dividing root cells of shoot and apex.
- Concentration of respiratory substrate- With increase in the amount of respiratory substrate, the rate of respiration increases.

4.10 Points to Remember

- Plants unlike animals have no special systems for breathing or gaseous exchange.
- Stomata and lenticels allow gaseous exchange by diffusion. Almost all living cells in a plant have their surfaces exposed to air.
- The breaking of C-C bonds of complex organic molecules by oxidation cells leading to the release of a lot of energy is called cellular respiration. Glucose is the favoured substrate for respiration.
- Fats and proteins can also be broken down to yield energy. The initial stage of cellular respiration takes place in the cytoplasm.
- Each glucose molecule is broken through a series of enzyme catalysed reactions into two molecules of pyruvic acid. This process is called glycolysis.
- The fate of the pyruvate depends on the availability of oxygen and the organism. Under

anaerobic conditions either lactic acid fermentation or alcohol fermentation occurs.

- Fermentation takes place under anerobic conditions in many prokaryotes, unicellular eukaryotes and in germinating seeds.
- In eukaryotic organisms aerobic respiration occurs in the presence of oxygen.
- Pyruvic acid is transported into the mitochondria where it is converted into acetyl CoA with the release of CO_2.
- AcetylCoA then enters the tricarboxylic acid pathway or Krebs' cycle operating in the matrix of the mitochondria. NADH + H^+ and $FADH_2$ are generated in the Krebs' cycle.
- The energy in these molecules as well as that in the NADH + H^+ synthesised during glycolysis are used to synthesise ATP.
- This is accomplished through a system of electron carriers called electron transport system (ETS) located on the inner membrane of the mitochondria. The electrons, as they move through the system, release enough energy that are trapped to synthesise ATP.
- This is called oxidative phosphorylation. In this process O_2 is the ultimate acceptor of electrons and it gets reduced to water.
- The respiratory pathway is an amphibolic pathway as it involves both anabolism and catabolism.
- The respiratory quotient depends upon the type of respiratory substance used during respiration.