13. KREBS' CYCLE / CITRIC ACID CYCLE /TCA CYCLE

The pyruvic acid produced in glycolysis enters into Krebs' cycle for further oxidation. Krebs' cycle is also known as citric acid cycle or Tri carboxylic acid (TCA) cycle. This aerobic process takes place in mitochondria where necessary enzymes are present in matrix.

11. Pyruvic acid reacts with CoA and NAD and is oxidatively decarboxylated. One molecule of CO_2 is released and NAD is reduced. Pyruvic acid is converted into acetyl CoA.

$$\text{Pyruvic acid + CoA + NAD} \xrightarrow{\text{Pyruvate dehydrogenase}} \text{Acetyl – COA} + CO_2 + NADH_2$$

12. Acetyl-CoA condenses with oxaloacetic acid in the presence of condensing enzyme and water molecule to form citric acid. CoA becomes free.

$$\text{Acetyl CoA + Oxaloacetic acid} \xrightarrow[+ H_2O]{\text{Condensing enzyme}} \text{Citric acid + CoA}$$

13. Citric acid is dehydrated in the presence of aconitase to form cis – aconitic acid

$$\text{Citricacid} \xrightarrow[- H_2O]{\text{Aconitase}} \text{Cis – Aconitic acid}$$

14. Cis-aconitic acid reacts with one molecule of water to form Isocitric acid

$$\text{Cis-aconitic acid} + H_2O \longrightarrow \text{Isocitric acid}$$

15. Iso-citric acid is oxidized to oxalo succinic acid in the presence of Isocitric dehydrogenase. NADP is reduced to $NADPH_2$ in the reaction.

$$\xrightarrow{\text{IC dehydrogenase}} \text{Oxalo succinic acid} + NADPH_2$$

Isocitric acid + NADP

16. Oxalo succinic acid is decarboxylated in the presence of oxalo succinic decarboxylase to form α - ketoglutaric acid and a second molecule of CO_2 is released.

$$\text{Oxalosuccinic acid} \xrightarrow[\text{Decarboxylase}]{\text{Oxalosuccinic}} \alpha\text{-ketoglutaric acid} + CO_2$$

17. α - ketoglutaric acid reacts with CoA and NAD in the presence of α - ketoglutaric acid dehydrogenase complex and is oxidatively decarboxylated to form succinyl CoA and a third mole of CO_2 is released. NAD is reduced in the reaction.

$$\alpha\text{-keto glutaric acid} + \text{CoA} \xrightarrow[\text{NAD} \quad \text{NADH}_2]{} \text{Succinyl-CoA} + CO_2 + \text{NADH}_2$$

18. Succinyl CoA reacts with water molecule to form succinic acid. CoA becomes free and one molecule of GDP (Guanosine diphosphate) is phosphorylated in presence of inorganic phosphate to form one molecule of GTP.

$$\text{Succinyl-CoA} + \text{GDP} + \text{ip} \xrightarrow{H_2O} \text{Succinic acid} + \text{GTP}$$

GTP may react with ADP to form one molecule of ATP

GTP + ADP → ATP + GDP

19. Succinic acid is oxidized to fumaric acid in the presence of succinic dehydrogenase and co enzyme FAD is reduced in this reaction.

$$\text{Succinic acid} + \text{FAD} \xrightarrow{\text{Succinic acid dehydrogenase}} \text{Fumaric acid} + \text{FADH}_2$$

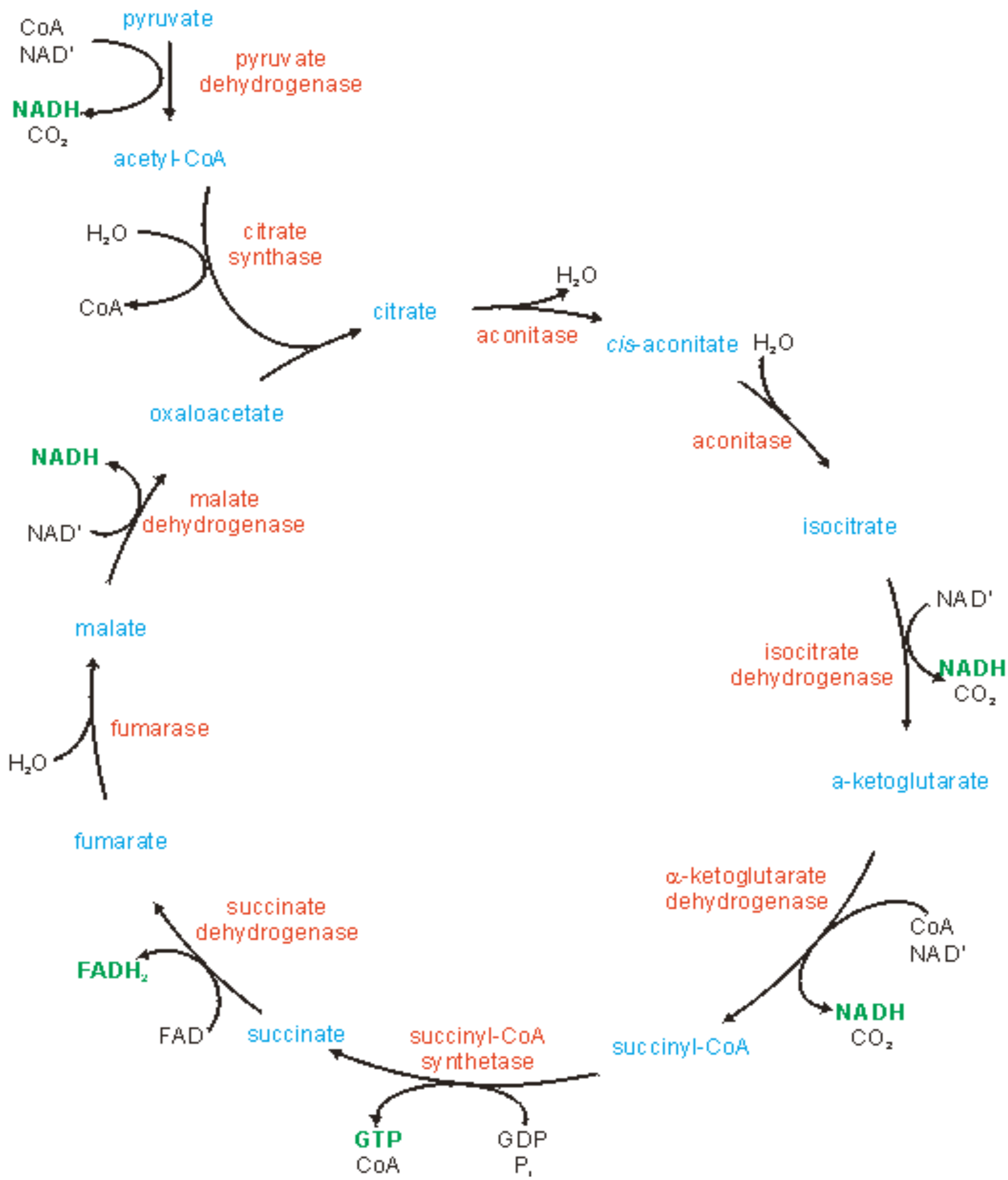
20. One mole of H_2O is added to Fumaric acid in the presence of fumarase to form malic acid.

$$\text{Fumaric acid} + H_2O \xrightarrow{\text{Fumarase}} \text{Malic acid}$$

21. In the last step, malic acid is oxidized to oxaloacetic acid in the presence of malic dehydrogenase and one molecule of coenzyme i.e. NAD is reduced.

$$\text{Malic acid} + \text{NAD} \xrightarrow{\text{Malic dehydrogenase}} \text{Oxaloacetic acid} + NADH_2$$

KREBS CYCLE or TCA CYCLE



Pentose phosphate pathway (ppp) / Hexose mono phosphate (hmp) shunt/ Phosphogluconate pathway / Warburg and Dicken's pathway

The pentose phosphate pathway occurs in the cytoplasm outside the mitochondria and it is an alternative pathway to glycolysis and Kreb's cycle. The presence of some compounds like iodoacetate, fluorides, arsenates etc. inhibit some steps in glycolysis and that leads to the alternate pathway. This pathway was discovered by Warburg and Dicken (1938). This pathway does not produce ATP but it produces another form of energy called reducing power in the form of NADPH. It is not oxidized in the electron transport system but, it serves as hydrogen and electron donor in the biosynthesis of fatty acids and steroids. The pentose phosphate pathway consists of two distinct phases. In the first phase, hexose is converted into pentose and in the second phase, pentose is reconverted in to hexose.

In the process, oxidation of glucose 6 phosphate leads to the formation of 6 phosphogluconic acid (pentose phosphate). Since glucose is directly oxidized without entering glycolysis, it is called as *direct oxidation.*

6 Glucose 6 phosphate +12 NADP $\longrightarrow$ 5 Glucose 6 Phosphate + 12 $NADPH_2$+ 6 CO_2

It provides ribose sugars for the synthesis of nucleic acids and is also required for shikimic acid pathway. Although ATP is not produced, NADPH is produced and serves as hydrogen and electron donor in the biosynthesis of fatty acids and steroids. The pathway is also called as *phosphogluconate pathway* as the first product in this pathway is phosphogluconate.

OXIDATIVE PHOSPHORYLATION

C. TERMINAL OXIDATION OF THE REDUCED COENZYMES / ELECTRON TRANSPORT SYSTEM AND OXIDATIVE PHOSPHORYLATION

The last step in aerobic respiration is the oxidation of reduced coenzymes produced in glycolysis and Krebs' cycle by molecular oxygen through FAD, UQ (ubiquinone), cytochrome b, cytochrome c, cytochrome a and cytochrome a_3 (cytochrome oxidase).

Two hydrogen atoms or electrons from the reduced coenzyme ($NADH_2$ or $NADPH_2$) travel through FAD and the cytochromes and ultimately combines with $1/2O_2$ molecule to produce one molecule of H_2O. This is called as *terminal oxidation*.

The terminal oxidation of each reduced coenzyme requires $1/2O_2$ molecule and 2H atoms (i.e. 2 e^- + $2H^+$) to produce one H_2O molecule. Except for flavoproteins (like FAD) and ubiquinone (UQ) which are hydrogen carriers, the other components of electron transport chain (cytochromes) are only electron carriers i.e. they cannot give or take protons (H^+)

During the electron transport, FAD and the iron atom of different cytochromes get successively reduced (Fe^{++}) and oxidized (Fe^{+++}) and enough energy is released in some places which is utilized in the photophosphorylation of ADP molecules in the presence of inorganic phosphate to generate energy rich ATP molecules. Since, this oxidation accompanies phosphorylation; it is called as *oxidative phosphorylation*.

One molecule of ATP with 7.6 Kcal.energy is synthesized at each place when electrons are transferred from

1. Reduced $NADH_2$ or $NADPH_2$ to FAD
2. Reduced cytochrome b to cytochrome c
3. Reduced cytochrome a to cytochrome a_3

Thus, oxidation of one molecule of reduced $NADH_2$ or $NADPH_2$ will result in the formation of 3 ATP molecules while the oxidation of $FADH_2$ lead to the synthesis of 2 ATP molecules.

According to the most recent findings, although in eukaryotes terminal oxidation of mitochondrial NADH / NADPH results in the production of 3 ATP molecules but that of extra mitochondrial NADH / NADPH yields only 2 ATP molecules. Therefore, the two reduced coenzyme molecules (NADH) produced per hexose sugar molecule during Glycolysis will yield only 2x2:4 ATP molecules instead of 6 ATP molecules. Complete oxidation of a glucose molecule (hexose sugar) in aerobic respiration results in the net gain of 36 ATP molecules in most eukaryotes.

One glucose molecule contains about 686 Kcal. Energy and 38 ATP molecules will have 273.6 Kcal energy. Therefore about 40% (273.6/686) energy of the glucose molecule is utilized during aerobic breakdown and the rest is lost as heat. Since huge amount of energy is generated in mitochondria in the form of ATP molecules, they are called as *Power Houses of the cell*.

ATP molecules contain energy in terminal pyrophosphate bonds. When these energy rich bonds break, energy is released and utilized in driving various other metabolic processes of the cell.

Differences between oxidative phosphorylation and Photophosphorylation

	Oxidative phosphorylation	**Photophosphorylation**

1	It occurs during respiration	Occurs during photosynthesis
2	Occurs inside the mitochondria (inner membrane of cristae)	Occurs inside the chloroplast (in the thylakoid membrane)
3	Molecular O_2 is required for terminal oxidation	Molecular O_2 is not required
4	Pigment systems are not involved	Pigment systems, PSI and PSII are involved
5	It occurs in electron transport system	Occurs during cyclic and non cyclic electron transport
6	ATP molecules are released to cytoplasm and used in various metabolic reactions of the cell	ATP molecules produced are utilized for CO_2 assimilation in the dark reaction of photosynthesis

Efficiency of respiration

The total energy content of one molecule of glucose is 686 Kcal. Out of this energy, available free energy is 673.6 Kcal and the energy content of ATP molecule is calculated as 7.3 Kcal. The efficiency of respiration may be expressed as follows.

$$\text{Efficiency of respiration} = \frac{\text{Kcal of energy conserved in ATP}}{\text{Total free energy available}} \times 100$$

$$\text{Efficiency of aerobic respiration} : \frac{38 \times 7.3}{673.6} \times 100 : 41\ \%$$

$$\text{Efficiency of anaerobic respiration} : \frac{2 \times 7.3}{47} \times 100 : 31\ \%$$

$$\text{Efficiency of fermentation} : \frac{2 \times 7.3}{40} \times 100 : 36.5\ \%$$

Respiratory quotient

The ratio of the volume of CO_2 released to the volume of O_2 taken during respiration is called as respiratory quotient and is denoted as RQ

$$RQ = \frac{\text{Volume of } CO_2}{\text{Volume of } O_2}$$

Value of RQ

The value of RQ depends upon the nature of the respiratory substrate and the amount of O_2 present in respiratory substrate.

1. When **carbohydrates** such as hexose sugars are oxidized in respiration, the value of RQ is 1 or unity because volume of CO_2 evolved equals to the volume of O_2 absorbed.

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

Glucose

$$RQ = \frac{\text{volume of } CO_2}{\text{volume of } O_2} = \frac{6}{6} = 1 \text{ or unity}$$

2. When **fats** are the respiratory substrate, the value of RQ becomes less than one because fats are poorer in O_2 in comparison to carbon and they require more O_2 for their oxidation,

$$2C_{51}H_{98}O_6 + 145O_2 \rightarrow 102CO_2 + 98H_2O$$

Tripalmitin

$$RQ = \frac{\text{volume of } CO_2}{\text{volume of } O_2} = \frac{102}{145} = 0.7$$

(Fats are oxidized in respiration usually during the germination of fatty seeds).

3. When **organic acids** are oxidized in respiration, the value of RQ becomes more than one. It is because organic acids are rich in O_2 and require less O_2 for their oxidation.

$$C_4H_6O_5 + 3O_2 \rightarrow 4CO_2 + 3H_2O$$

Malic acid

$$RQ = \frac{\text{volume of } CO_2}{\text{volume of } O_2} = \frac{4}{3} = 1.3$$

Energy budgeting

Stages	Gain of	Consumption	Net gain of

	ATP	of ATP	ATP
Glycolysis			
1) Glucose ⟶ Glucose 6 PO4		1	
2) Fructose 6 PO4 ⟶ Fructose 1,6 di PO4		1	
3) 1,3 diphosphoglyceraldehyde ⟶ 1,3 diphospho glyceric acid	6		
4) 1,3 diphospho glyceric acid ⟶ 3 phosphoglyceric acid	2		
5) 2 phosphoenol pyruvic acid ⟶ Pyruvic acid	2		
Total	10	-2	8
Kreb's cycle			
6) Pyruvic acid ⟶ Acetyl CoA	3		
7) Isocitric acid ⟶ Oxalosuccinic acid	3		
8) ketoglutaric acid ⟶ Succinyl CoA	3		
9) Succinyl Co A ⟶ Succinic Acid	1		
10) Succinic acid ⟶ Fumaric Acid	2		
11) Malic acid ⟶ Oxaloacetic acid	3		
Total ATP mol. produced per Pyruvic acid	15		15
Total ATP mol. produced for 2 Pyruvic acids	15 x 2:30		30
Grand Total	40	-2	8+ 30 = 38

FACTORS AFFECTING RESPIRATION

A. External factors

1. Temperature

Temperature has profound influence on the rate of respiration. Optimum temperature for respiration is about 30°C, minimum 0°C and maximum about 45°C. At low temperature, the respiratory enzymes becomes inactive, consequently the rate of respiration falls. It is due to this fact that the quality of fruits and vegetables stored at low temperature does not deteriorate. At very high temperature, respiration slows down and may even be stopped due to denaturation of the respiratory enzymes.

2. Oxygen

In complete absence of O_2, anaerobic respiration takes place while aerobic respiration stops. In higher plants, the anaerobiosis produces large amount of alcohol which is toxic to plants. If some amount of O_2 is available, anaerobic respiration slows down and aerobic respiration starts. The concentration of O_2 at which aerobic respiration is optimum and anaerobic respiration is stopped, is called as *extinction point.*

It is observed that under anaerobic conditions, much more sugar is taken up per quantity of yeast present than it is consumed in the presence of oxygen. The inhibition on the rate of carbohydrate breakdown by oxygen is called as *Pasteur's effect*.

3. Carbon dioxide

Higher concentration of CO_2 in the atmosphere especially in the poorly aerated soil has retarding effect on the rate of respiration.

4. Inorganic salts

If a plant or tissue is transferred from water to salt solution, the rate of respiration increases (called as *salt respiration*).

5. Water

Proper hydration of cells is essential for respiration. Rate of respiration decreases with decreased amount of water, so much so, that in dry seeds, the respiration is at its minimum. It is because in the absence of a medium, the respiratory enzymes become inactive.

6. Light

The effect of light is indirect on the rate of respiration through the synthesis of organic food matter in photosynthesis.

7. Wound or injury

Injury or wounds result in increased respiration as the plants in such a state require more energy which comes from respiration. The wounded cells become more meristematic to form new cells for healing the wound.

Internal factors

1. Protoplasmic factors

The amount of protoplasm in the cell and its state of activity influence the rate of respiration.

- The rate of respiration is higher in young meristematic cells which divide actively and requires more energy. Such cells have greater amount of protoplasm and no vacuoles.

- In old mature tissues, the rate of respiration is lower because of lesser amount of active protoplasm

2. Concentration of respiratory substrate

Increased concentration of respirable food material brings about an increase in the rate of respiration.

Under starvation conditions, such as in etiolated leaves, the rate of respiration slows down considerably. If such etiolated leaves are supplied with sucrose solution for few days even in dark conditions, the rate of respiration increases.

Differences between Photorespiration and Dark respiration

	Photorespiration	Dark /Mitochondrial respiration
1	It occurs in the presence of light	It occurs in the presence of both light and dark.
2	The substrate is glycolate	The respiratory substrate may be carbohydrate, fat or protein.
3	It occurs in chloroplast, peroxisome and mitochondria	The process occurs in the cytoplasm and mitochondria
4	It occurs in temperate plants like, wheat and cotton (mainly in C3 plants)	It occurs in C4 plants (maize and sugar cane)
5	It occurs in the green tissues of plants	It occurs in all the living plants(both green and non green)
6	The optimum temperature is 25- 35ºC	It is not temperature sensitive
7	This process increases with increased CO_2 concentration.	This process saturate at 2-3 percent O_2 in the atmosphere and beyond this concentration there is no increase.
8	Hydrogen peroxide is formed during the reaction	Hydrogen peroxide is not formed.
9	ATP molecules are not produced,	Several ATP molecules are produced.
10	Reduced coenzymes such as $NADPH_2$, $NADH_2$ and $FADH_2$ are not produced.	Reduced coenzymes such as $NADPH_2$, $NADH_2$ and $FADH_2$ are produced.
11	One molecule of ammonia is released	No ammonia is produced

	per molecule of CO_2 released.	
12	Phosphorylation does not occur	Oxidative phosphorylation occurs.

Differences between respiration and photosynthesis

	Respiration	Photosynthesis
1	It is catabolic process resulting in the destruction of stored food	It is an anabolic process resulting in the manufacture of food.
2	Light is not essential for the process	Light is very much essential
3	Oxygen is absorbed in the process	Oxygen is liberated
4	Carbon dioxide and water are produced	Carbon dioxide is fixed to form carbon containing compound
5	Potential energy is converted into Kinetic energy	Light energy is converted into chemical energy (potential energy)
6	Glucose and oxygen are the raw materials	Carbon dioxide and water are the raw materials
7	Energy is released during respiration and hence it is an exothermic process.	Energy is stored during photosynthesis and hence it is an endothermic process
8	Reduction in the dry weight	Gain in the dry weight
9	Chlorophyllous tissues are not necessary	Chlorophyllous tissues are essential for the process

Differences between aerobic respiration and fermentation

	Aerobic respiration	Fermentation
1	It occurs in all living cells of the plants throughout the day and night	Occurs outside the plant cells and in certain microorganisms
2	It takes place in the presence of oxygen	Absence of oxygen
3	The end products are CO_2 and H_2O	End products are CO_2 and alcohol or other organic acids
4	It is not toxic to plants	It is toxic to plants
5	Complete oxidation is food material is	Incomplete oxidation is observed

	observed	
6	Large amount of energy (673 kCal) is released per glucose molecule	Very small amount of energy (21 kCal) is released per glucose molecule
7	The complete oxidation yields 38 ATP molecules	The incomplete oxidation in fermentation yields only two ATP molecules
8	The enzyme, zymase is not required but many other enzymes and coenzymes are required	Zymase is required in the case of carbohydrates