Respiration in Plants

All living systems, from a cell to ecosystem, need energy to work. You have already studied that light energy is converted into chemical energy by plants during photosynthesis and this energy is then stored in bonds in complex organic molecules, which all of us consume as food. However, this chemical energy locked in food molecules has to be made available to the cells in usable form of ATP. Respiration is the process by which this energy is released by the oxidation of these organic molecules and made available to the cells. The oxygen required for respiration is obtained from the atmosphere. It means respiration involves two major events:

1. Intake of oxygen from atmosphere and release of CO_2 into the atmosphere–**Breathing** (a physical process)
2. Oxidation of foodstuffs to release energy–**Cellular respiration** (a biochemical process)

Respiration is now defined as a physico-chemical process that involves intake of oxygen by cells, oxidation of respiratory substrates of food, mainly glucose (but also sugars, organic acids, fats and proteins), **with the release of CO_2, H_2O and energy and storage of released energy in the form of ATP.**

The term 'respiration' was first used by animal physiologists to describe the breathing movements of animals, but was subsequently extended to include the chemical reactions by which complex organic substances like carbohydrates, fats and proteins are broken down to release carbon dioxide, water and energy. In plants, respiration is slightly different because:

1. Breathing movements are not performed.
2. Gaseous exchange, typical of animals, is often masked by photosynthesis in the daytime because (i) Oxygen need may not be utilised and (ii) CO_2 may not be released during daytime.

For the above reasons, plant physiologists use the term 'cellular respiration' for the process of oxidation of foods only in living cells.

CELLULAR RESPIRATION

Cells break down organic molecules, mainly carbohydrates, to release energy. If this energy is released at once, there might be a brief blast of light and heat leading to death of the cell. Living things cannot withstand this sudden release of energy, so energy-rich molecules are made to release energy in a stepwise process. This **process of oxidative breakdown of food materials within the cell to release energy and the trapping of this energy for synthesis of ATP is called cellular respiration.**

Do Plants Breathe

Like all living forms, plants also require oxygen for respiration and release carbon dioxide. But unlike animals, plants do not have any specialised organs. For gaseous exchange, they possess stomata in leaves and lenticels in stem. Following are the reasons for the absence of respiratory organs in plants:

1. Each plant part takes care of its own gas exchange needs.
2. There is very little transport of gases from one plant part to another.
3. Plants do not have much demand for gas exchange. Roots, stems and leaves respire at rates far lower than animals do.
4. Leaves are well adapted to take care of their needs of gases during photosynthesis. Furthermore, leaves also utilise oxygen released during photosynthesis.
5. Each living cell in a plant is located quite close to the surface of the plant and hence close to the atmospheric air. Thus, atmospheric gases can easily reach them by diffusion.
6. In stems, the living cells are present beneath the bark and are in contact with air through lenticels.
7. Loose packing of parenchyma cells in leaves, stems and roots provide an interconnected network of air spaces.

TYPES OF RESPIRATION

ending upon the oxidation of food in the presence or absence of oxygen, respiration is of types:

. Aerobic respiration
. Anaerobic respiration

erobic Respiration

It occurs in mitochondria in the presence of oxygen.
It occurs both in plants and animals.
Food (glucose) is completely broken down to carbon dioxide and water.
38 molecules of ATP 2870 kJ are released from one molecule of glucose.
It is completed in two major phases:
(a) **Glycolysis or Anaerobic Phase:** It takes place in cytoplasm and glucose molecule is broken down to 2 molecules of pyruvic acid.

(b) **Aerobic Phase:** It takes place in the presence of oxygen in mitochondria. Pyruvic acid formed during glycolysis is completely broken down to CO_2 and water. It is also called **Krebs' cycle.**

$$\text{Glucose} \xrightarrow{\text{Glycolysis}} \text{Pyruvic acid} \xrightarrow{\text{Krebs cycle}} \text{Carbon dioxide + Water + Energy}$$

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{Enzymes}} 6CO_2 + 6H_2O + 38\text{ ATP (2870 kJ)}$$

2. Anaerobic Respiration

1. It occurs in cytoplasm in the absence of oxygen.
2. It results in incomplete oxidation of food.
3. It occurs in lower organisms like yeast, certain bacteria and fungi. In higher plants and animals it occurs when O_2 is limiting.
4. Only 2 ATP molecules 59 kcal are produced from one glucose molecule.
5. During anaerobic respiration, glucose is first broken down to 2 molecules of pyruvic acid by glycolysis. Further breakdown of pyruvic acid differs in plants and animals.

$$C_6H_{12}O_6 \xrightarrow{\text{Enzymes}} \underset{\text{(Pyruvic acid)}}{2C_3H_4O_3} + 2CO_2 + \text{Energy (59 kcal or 247 kJ or 2ATP)}$$

(a) In yeast, bacteria and other plants, pyruvic acid is broken down to ethyl alcohol and carbon dioxide is released. This type of anaerobic respiration is also known as **alcoholic fermentation.**

$$\text{Pyruvic acid } (C_3H_4O_3) \xrightarrow{\text{Enzymes}} \text{Ethyl alcohol + Carbon dioxide}$$

(b) In anaerobic animals, pyruvic acid is broken down to lactic acid. This is also known as **lactic acid fermentation.**

$$\text{Pyruvic acid } (C_3H_4O_3) \xrightarrow{\text{Enzymes}} \text{Lactic acid}$$

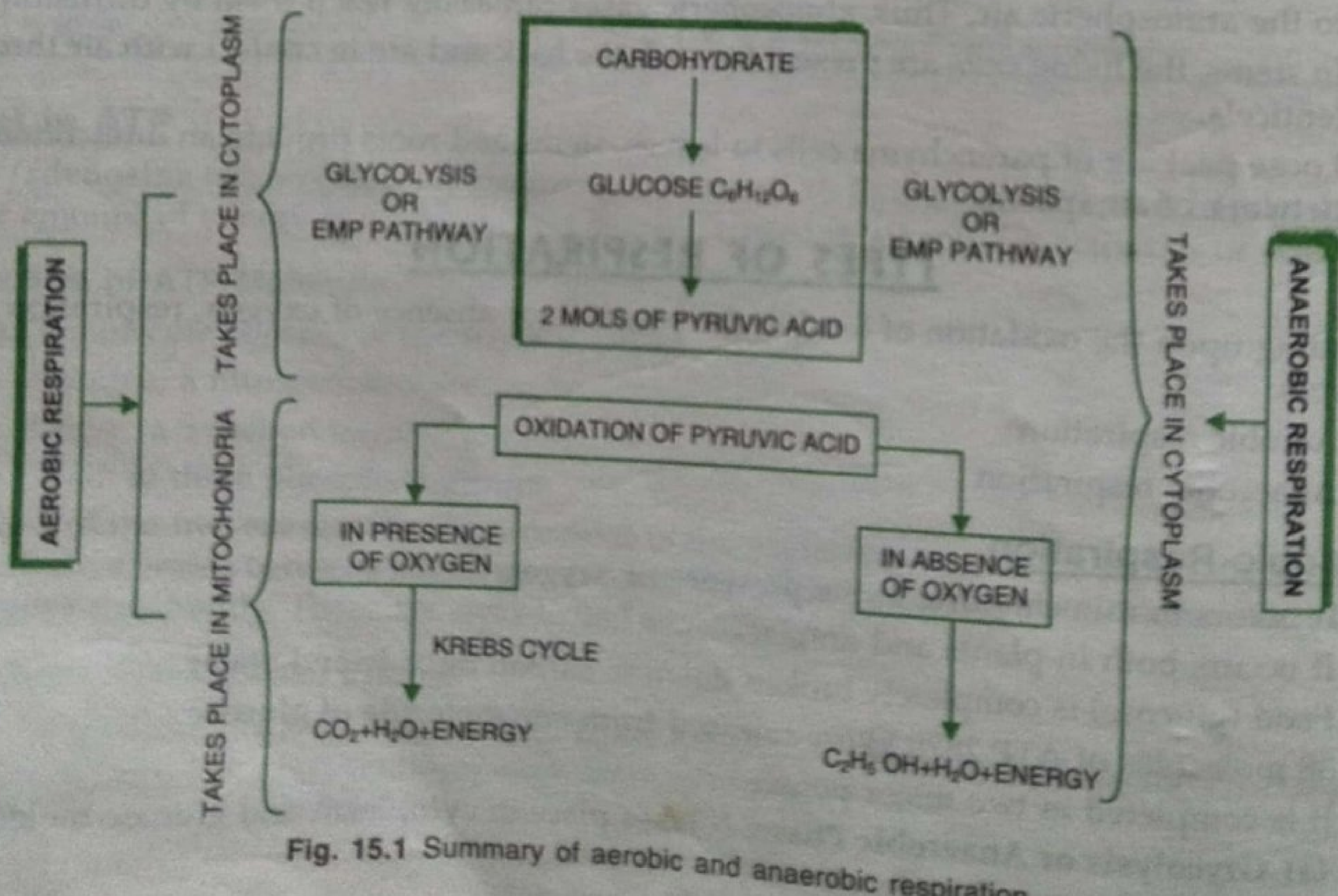

Fig. 15.1 Summary of aerobic and anaerobic respiration

Respiratory Substrates

Respiratory substrates are those organic substances which are catabolised to liberate energy inside the living cells. Glucose (carbohydrate) is main substrate used during cell respiration. The other alternatives are fats and proteins. Fats store energy and are used only after the carbohydrates are consumed. Proteins are used after the carbohydrates and fats have been consumed.

Floating and Protoplasmic Respiration: Respiration which uses carbohydrates or fats as substrate is termed as **floating respiration,** whereas that which uses proteins is called **protoplasmic respiration.** The latter cannot be carried on for long as it uses cell's own material and produces ammonia which is toxic.

TABLE 15.2 Differences between Protoplasmic and Floating Respiration

Protoplasmic Respiration	Floating Respiration
1. It occurs rarely particularly in case of starvation.	1. It is a continuous process.
2. It uses proteins as substrate.	2. It uses carbohydrates and fats as substrates.
3. It produces toxic ammonia which is harmful to the cells.	3. It does not produce any toxic material.
4. It may kill the cell as it uses cell's own material.	4. It does not harm the cell as it uses cell's own storage material.

Respiratory Quotient (R.Q.)

Respiratory quotient (R.Q.) is the ratio of volume of CO_2 produced and the volume of oxygen consumed over a specific period of time by a unit tissue, organ or organism.

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

We know that the equal number of gas molecules occupy the same volume, RQ can also be defined as the ratio of molecules of CO_2 evolved in respiration to the volume of O_2 consumed over a unit period of time by a tissue, organ or organism.

or $$RQ = \frac{\text{Molecules of } CO_2 \text{ evolved}}{\text{Molecules of } O_2 \text{ consumed}}$$

RQ depends upon the type of respiratory substrate (glucose, fats, proteins and organic acids.)

1. **RQ Equal to Unity:** Glucose is the main carbohydrate used for respiration. The equation for respiration with glucose as a substrate is:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{Energy} \quad RQ = \frac{6\,CO_2}{6\,O_2} = 1 \text{ or unity}$$

2. **RQ Less than One:** Fats contain much less O_2 than carbohydrates. When fats are used as a substrate, the RQ is less than 1. Therefore, much more O_2 is needed to oxidise fat molecules.

Example: Fat tripalmitin as substrate:

$$\underset{\text{Tripalmitin}}{2(C_{51}H_{98}O_6)} + 145O_2 \rightarrow 102\,CO_2 + 98\,H_2O \qquad RQ = \frac{102\,CO_2}{145\,O_2} = 0.7$$

$$C_{57}H_{104}O_6 + 80\ O_2 \rightarrow 57\ CO_2 + 52\ H_2O \qquad RQ = \frac{57\ CO_2}{80\ O_2} = 0.71$$

Triolein

Proteins also contain lesser oxygen than carbohydrates, the RQ is less than 1. RQ for proteins is equal to 0.9.

3. **RQ More than One:** Organic acids contain more oxygen than carbohydrates, so they need less oxygen for their oxidation. When organic acids such as oxalic acid or malic acid are used as substrate, RQ is more than 1.

$$2(COOH)_2 + O_2 \rightarrow 4CO_2 + 2H_2O \qquad RQ = \frac{4\ CO_2}{1O_2} = 4$$

Oxalic acid

$$C_4H_6O_5 + 3\ O_2 \rightarrow 4CO_2 + 3H_2O \qquad RQ = \frac{4CO_2}{3O_2} = 1.3$$

Malic acid

4. **RQ is Infinity:** It is recorded in case of anaerobic respiration where CO_2 is evolved but O_2 is not consumed, e.g., alcoholic fermentation.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad RQ = \frac{2CO_2}{\text{Zero } O_2} = \text{Infinity } (\infty)$$

5. **RQ is Zero:** In this case oxygen is consumed but CO_2 is not evolved. This happens in succulent plants, e.g., *Opuntia*. All the CO_2 produced during respiration is fixed internally in photosynthetic activity during the day.

Importance

RQ gives information about:

1. Type of respiration occurring in organism
2. Type of substrate or food being used
3. Normal nutrition or starvation condition

RQ of Different Substrates

• Carbohydrate (glucose)	: 1 (Aerobic respiration)
• Fats and Proteins	: Less than 1 (Fats-app. 0.7, Proteins-app. 0.9)
	Infinity (Anaerobic respiration)
• Organic Acids	: More than 1 (Fermentation)
• Succulents Plants	: Zero

MECHANISM OF AEROBIC RESPIRATION

Aerobic respiration occurs inside the cells and procceds with the help of enzymes. It is a catabolic process of complete oxidation of a respiratory substrate forming carbon dioxide and water as end products. The common respiratory substrate is **glucose** which is formed by hydrolysis of starch or glycogen. In plants, starch is broken down to glucose by two types of enzymes, ***amylase*** and ***maltase.***

$$\text{Starch} + H_2O \xrightarrow{\text{Amylase}} \text{Maltose} \xrightarrow{\text{Maltase}} \text{Glucose}$$

Sucrose is another source of glucose. It is hydrolysed into glucose and fructose by the enzyme **invertase.**

$$\text{Sucrose} + H_2O \xrightarrow{\text{Invertase}} \text{Glucose} + \text{Fructose}$$

Major steps of aerobic respiration are:

1. **Glycolysis:** Breaking down of glucose to pyruvate.
2. **Oxidation of pyruvate** to acetyl CoA.
3. **Krebs' cycle:** Oxidation of acetyl CoA to CO_2 and H_2O and release of energy as NADH and $FADH_2$ molecules.
4. **Electron Transport chain:** High energy electrons of NADH and $FADH_2$ pass through a sequence of electron carriers.
5. **Oxidative Phosphorylation:** Energy of electrons is utilised in phosphorylation of ADP to ATP.

Glycolysis or EMP Pathway (Embdens Meyerhof and Parnas Pathway)

Glycolysis is also called **EMP pathway** as the steps of glycolysis were worked out by German scientists, **Embdens, Meyerhof** and **Parnas** in 1930s. The breakdown of glucose to pyruvate or pyruvic acid is called **glycolysis.** Glycolysis occurs in the cytoplasm of cells in all living organisms. In anaerobic organisms, it is the only process of respiration.

Common Pathway: Initial steps of glycolysis are common to both aerobic and anaerobic respiration. Therefore, glycolysis is called the **common pathway** for both types of respiration.

The various steps involved in glycolysis are:

1. Energy Spending Phase (Preparatory Phase)
2. Splitting Phase (Splitting and Rearrangement Phase)
3. Energy Conserving Phase (Pay off Phase)

Energy Spending Phase

Three reactions occur in the conversion of glucose to fructose 1,6-biphosphate.

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GLYCOLYSIS

Energy spending phase-

Sucrose (photosynthesis)
↓ Invertase
Glucose + Fructose (Respiratory sub)
↓ ATP → ADP | Hexokinase, Mg^{+2}
Glucose 6 (PO_4) | fructokinase Mg^{+2}
↓ Isomerase
Fructose 6 (PO_4)
ATP → ADP ↓ Phosphofructokinase, Mg^{+2}
Fructose 1,6 bi (PO_4)
↓ Aldolase
Phosphotriose Isomerase — Splitting phase

★ 3 phosphoglyceraldehyde ⇌ Dihydroxyacetone phosphate

Energy Conserving phase

H_3PO_4 → Pi from H_3PO_4 & not from ATP.
NAD → $NADH + H^+$
↓
1, 3 biphosphoglyceraldehyde. ★ phosphorylation dehydrogenation pair of hydrogen atoms removed $2e^-$ & $2H^+$
Substrate level Pp
↓ ADP → ATP diphosphoglycerokinase.
3 phosphoglyceric acid
Isomerisation ↓ phosphoglyceromutase
2 Phosphoglycerate

One hydrogen atom accepted NAD & one extra e^-
$2H^+ + 2e^- + NAD \rightarrow NADH + H^+$

Dehydration ↓ Enolase → H_2O
Phosphoenol pyruvic acid
↓ ADP → ATP
pyruvic acid (3C)

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Glucose + $2NAD^+$ + 2ADP + $2H_3PO_4$

$\downarrow$ glycolysis

2 pyruvic Acid + 2NADH + 2ATP + $2H^+$

(B) Oxidative Decarboxylation of pyruvic acid to Acetyl Co-A (Mitochondria matrix)

Pyruvic Acid (3-C)

lipoicacid | CoA, Thiamine pyro PO_4, pyruvate dehydrogenase

NAD^+ (Coenzyme) $\rightarrow$ $NADH + H^+$

$\rightarrow CO_2$

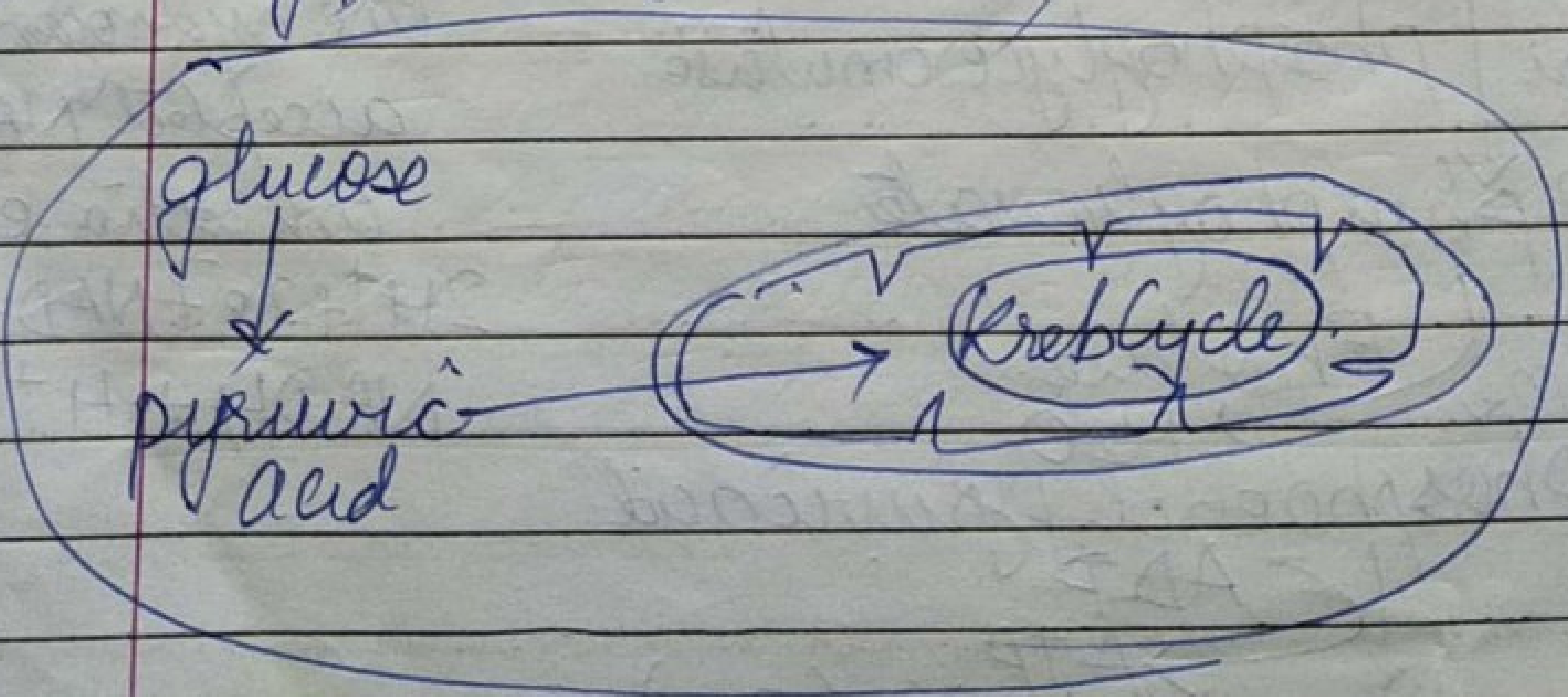
$\downarrow$

Acetyl-CoA (2-C)

$\rightarrow$ Kreb cycle. (Mitochondria matrix)

Sir Hans Kreb

(3-COOH grp) TCA (citric acid)



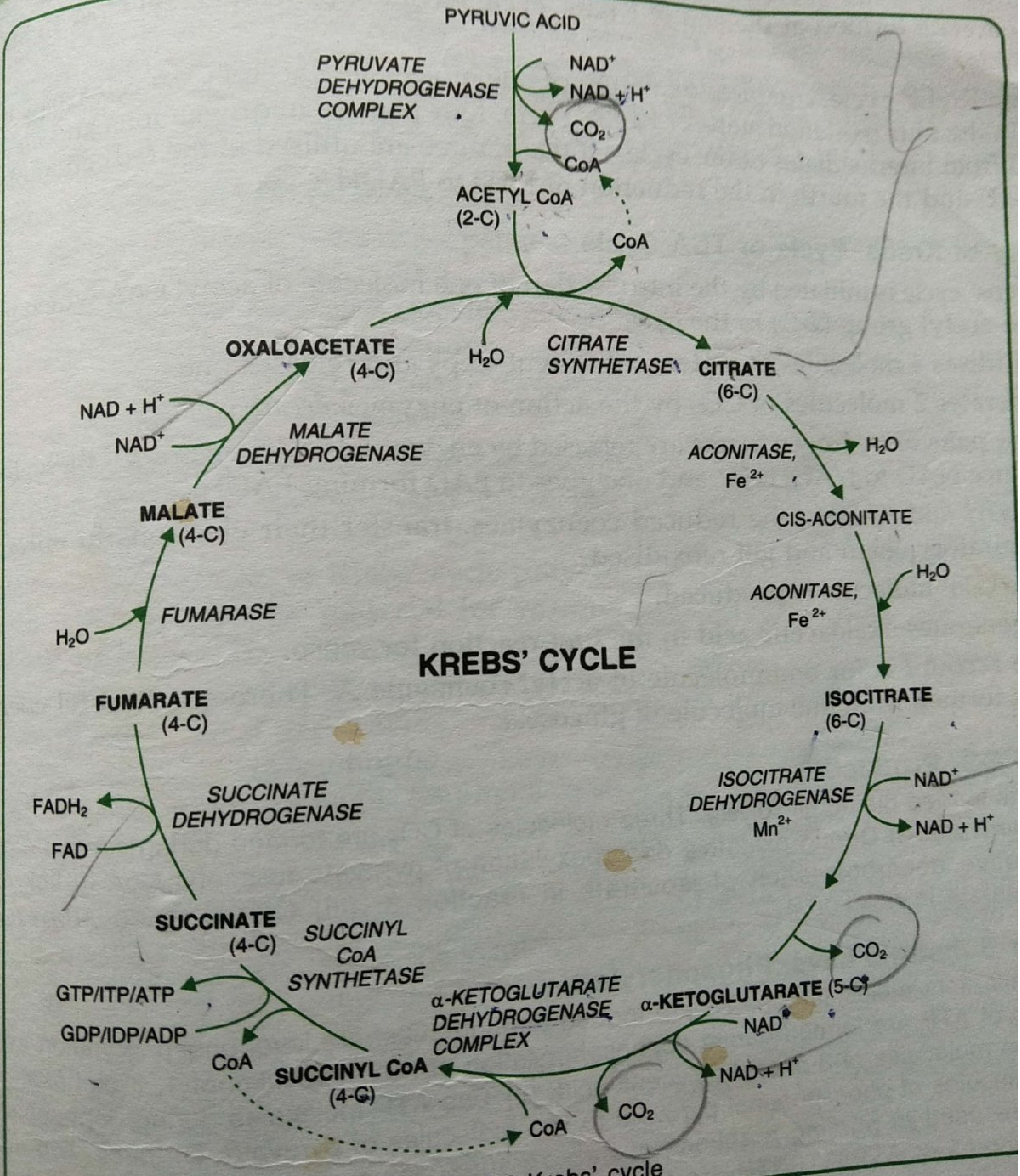


Fig. 15.3 Krebs' cycle

6. **Dehydrogenation (Oxidation of Succinate):** In this step, 4-carbon su... dehydrogen... with the action of enzyme *succinic dehydrog*... received by FAD (flavi...

molecules formed from one molecule of glucose.

Sites of CO_2 Production

NO CO_2 is formed during glycolysis. Three molecules of CO_2 are formed during complete oxidation of one pyruvate: (i) During oxidative decarboxylation of pyruvate to acetyl CoA in link reaction. (ii) Oxidative decarboxylation of isocitrate in reaction 3. (iii) Oxidative decarboxylation of α-ketoglutarate in reaction 4.

Sites for Substrate Level Phosphorylation

In glycolysis, four molecules of ATP are formed through substrate level phosphorylation as (i) Two molecules of ATP are formed during dephosphorylation of two molecules of 1, 3-diphosphoglyceric acid to two molecules of 3-phosphoglyceric acid. (ii) Two ATP molecules during dephosphorylation of two molecules of phoosphoenol pyruvate to two molecules of pyruvate. Of these, two molecules of ATP are used in priming reactions of hexose sugar, glucose to fructose 1-6, biphosphate. (iii) Two moles of ATP/GTP/ITP are formed through substrate level phosphorylation from two molecules of succinyl CoA to succinate (GTP in plants and ITP in animals).

Sites for Reduced Coenzymes

During complete oxidation of one glucose molecule, the reduced coenzymes are formed as following sites: (i) Two molecules of $NADH^+.H$ are formed in glycolysis during oxidation of two molecules of glyceraldehyde 3-phosphate to 1, 3-biphosphoglycerate. (ii) Two molecules of $NADH^+.H$ are produced in link reaction when two pyruvate molecules are oxidatively decarboxylated to acetyl CoA. (iii) In Krebs' cycle, 6 molecules of $NADH^+.H$ and two molecules of $FADH_2$ are formed two each during (a) oxidation of isocitrate to α-ketoglutarate: 2 $NADH^+.H$, (b) oxidative decarboxylation of α-ketoglutate to form succiynl CoA: 2 $NADH^+.H$ (c) dehydrogenation of succinate to form fumarate: 2 $FADH_2$ (d) dehydrogenation of malate to oxaloacetate: 2 $NADH^+.H$.

Therefore, net number of coenzymes formed from one molecule of glucose-10 NADH + H and FADH = $FADH_2$ with a gain of 4 ATP molecules.

Terminal Oxidation & Phosphorylation in Respiration.

* Reduced NAD^+ & FAD ($NADH+H^+$ & $FADH_2$) reduce Oxygen to H_2O.
* Transfer of H^+ & e^- to O_2 ~~ms~~ from reduced coenzyme is thermodynamically not possible. NADH oxidized at redox potential $-0.32V$
  O_2 reduced at $+0.82V$ potential
  Gap of $+1.14V$
* To facilitate transfer many cytochromes & carrier molecules having redox potential (intermediate) are arranged in a series. This sequence of electron carrier — Electron Transport Chain.

Phosphoglyceraldehyde, pyruvic acid, isocitrate, α-keto-glutarate etc oxidized, release of 2H ⟶ reduced coenzyme.

Oxidative Phosphorylation

The electron transport ~~through~~ down to energy gradient through electron transport system leads to formation of ATP from ADP & inorganic phosphate

Components of electron transport

→ Include cytochrome b, 2 types of cytochrome c, ubiquinone, flavoprotein (FMN or FAD), Fe-S protein, enzyme cytochrome oxidase associated with cytochrome a & a_3.

→ These components are arranged in four kind of complexes.

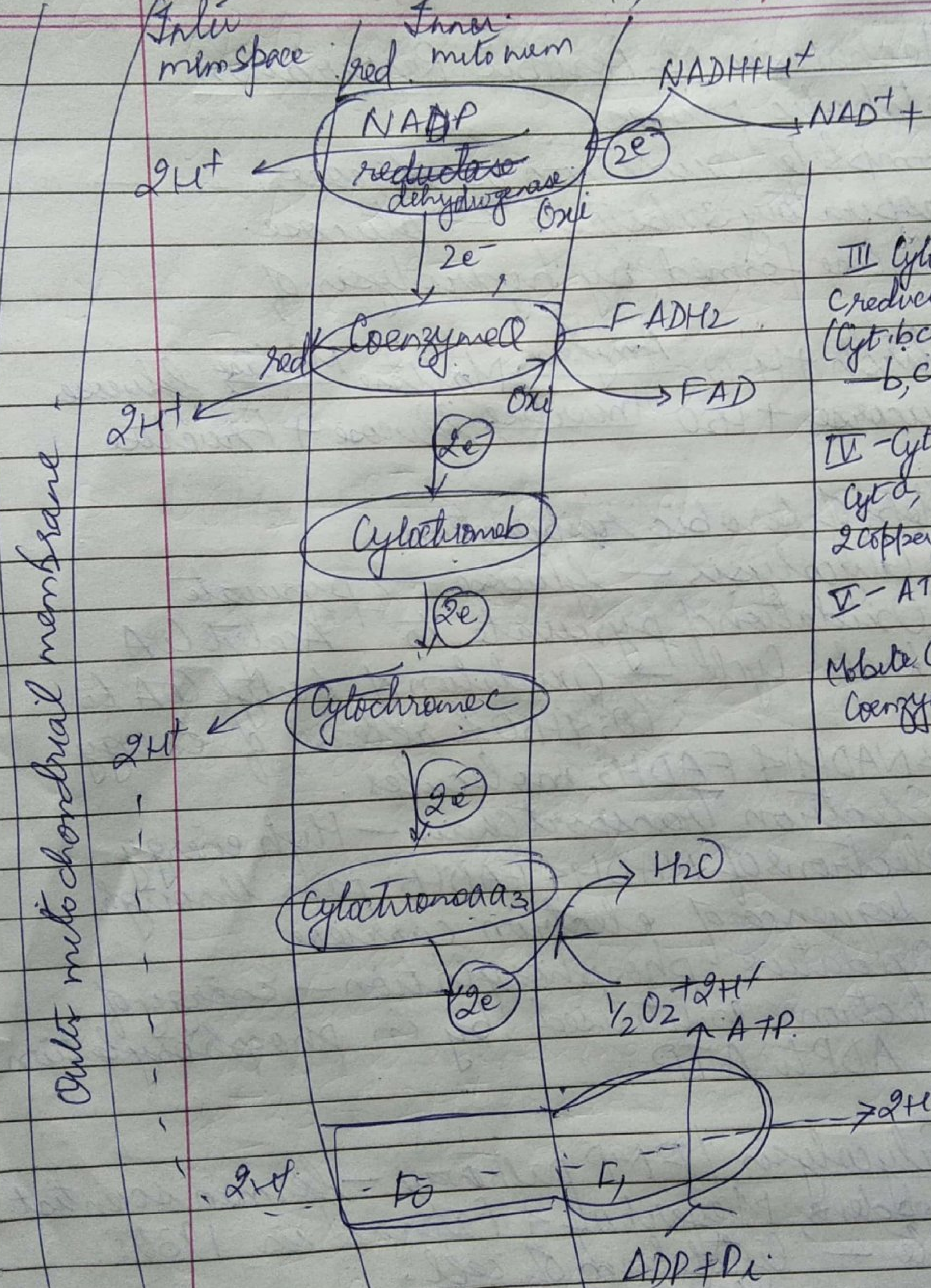
→ Complex I (NADH dehydrogenase)
→ Complex II (Succinate dehydrogenase)
→ Complex III (Cytochrome bc_1 complex)
→ Complex IV (Cytochrome oxidase complex)

→ Complex V – ATP Synthetase – ATP synthesis

→ Inner mitochondrial membrane.

→ Reduced coenzymes ($NADH+H^+$/$FADH_2$) transfer electron & protons through electron transport system

Complex I NADP dehydrogenase – NADH dehydrogenase, FMN, Fe-S.
II. Succinate dehydrogenase – Succinate dehydrogenase, FAD, FeS

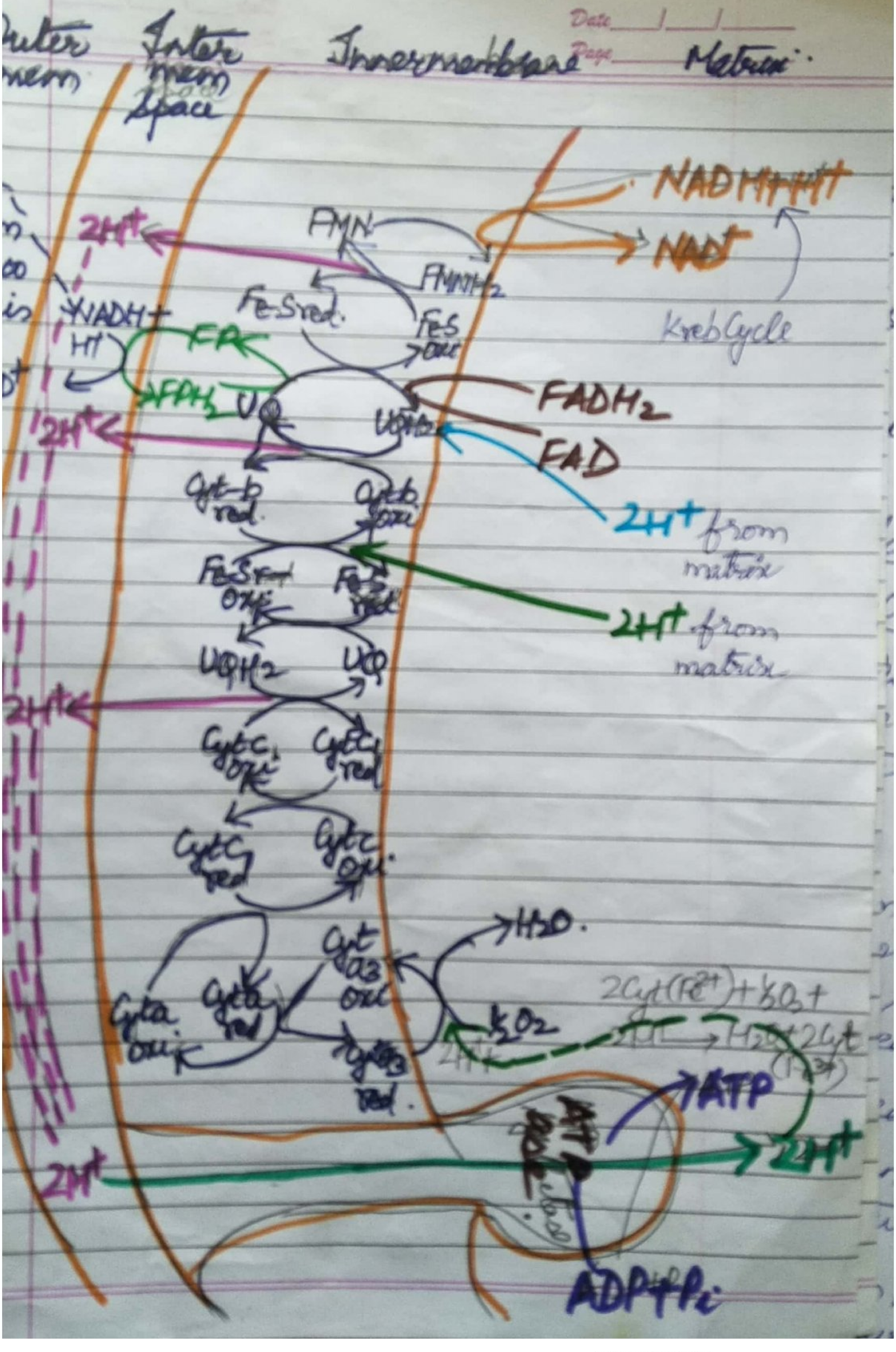


III Cytochrome C reductase (Cyt bc$_1$ complex) – b, c$_1$, Fe-S.

IV – Cyt C oxidase
Cyt a, Cyt a3 + 2 copper centre

V – ATPase

Mobile Carrier Coenzyme Q.



Outer mem
Inter mem space
Innermembrane
Matrix
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NAD
FMN
FMNH2
Fe-S red.
Fe-S oxi
Kreb Cycle
NADH+H+
FP
FPH2
UQ
UQH2
FADH2
FAD
2H+
2H+ from matrix
2H+ from matrix
Cyt-b red.
Cyt-b oxi
Fe-S oxi
Fe-S red
UQH2
UQ
Cyt c1 oxi
Cyt c1 red
Cyt c red
Cyt c oxi
Cyt a3 oxi
Cyt a3 red.
Cyt a oxi
Cyt a red
H2O.
½O2
2Cyt(Fe2+)+½O2+
ATP
ATP ase
ADP+Pi

The enzyme cytochrome oxidase is tightly bound to inner mitochondrial membrane. It has inseparable Cyt a & Cyt a_3 & to 2 Cu^+ ions. Both Fe & Cu undergo reversible changes in their oxidation state

$$\begin{cases} Fe^{2+} \rightleftharpoons Fe^{3+} + e^- \\ Cu^+ \rightleftharpoons Cu^{++} + e^- \end{cases}$$

during electron transport by cytochrome oxidase.

Mechanism of Oxidative Phosphorylation –

CHEMIOSMOTIC COUPLING HYPOTHESIS –

Enzymatic complex ATPase / Coupling factor.

→ Has a stalk & headpiece

→ Headpiece – extends towards matrix – F_1 headpiece

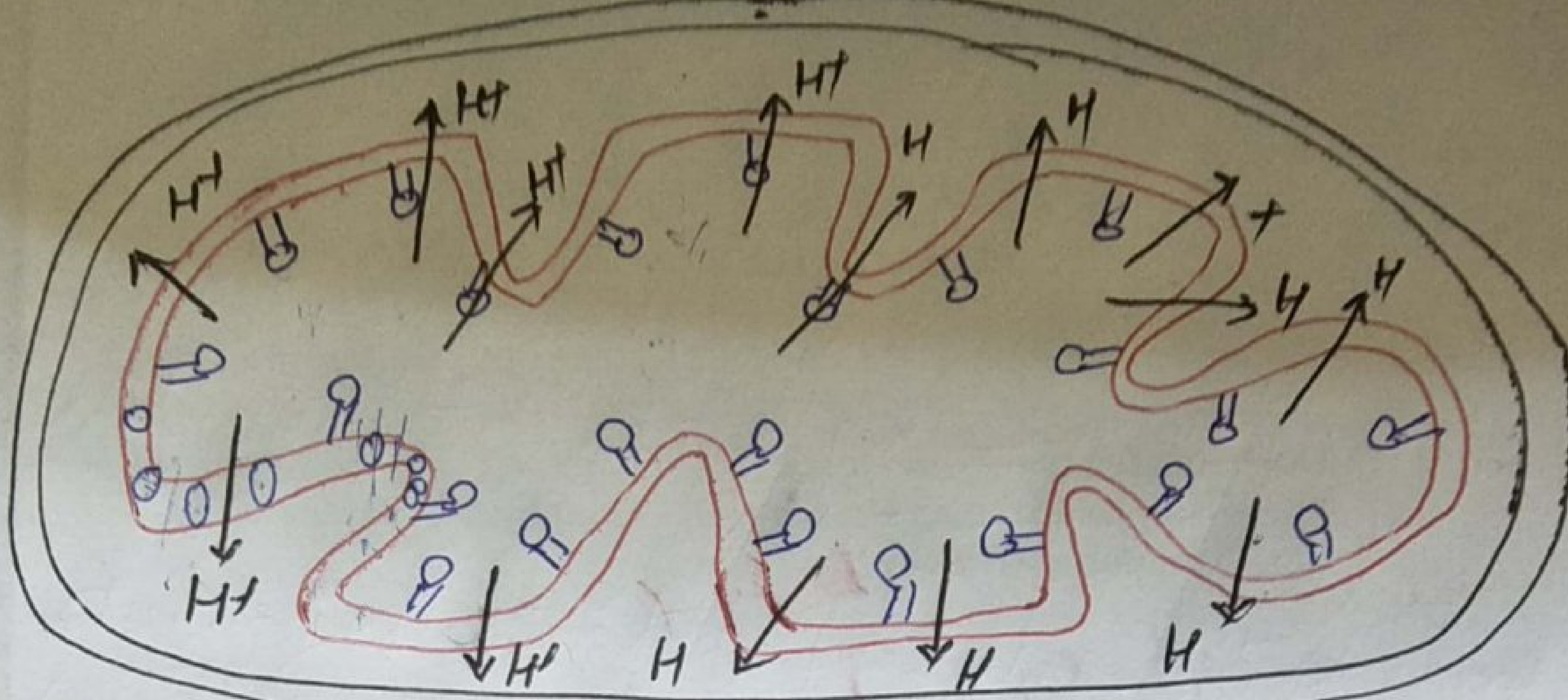
Stalk – Embedded in inner mitochondrial membrane. – Fo stalk

→ Inner mitochondrial membrane – permeable to water, Impermeable to protons & other ions except at points where respiratory chain & ATPase system are plugged in the membrane.

→ Respiratory chain arranged in such a way that electrons move in an inward direction & protons flow in an outward direction

→ Reduced NADH released from Kreb's Cycle, when enters in ETS, transport 3 pairs of H^+ across inner mitochondrial membrane to inter membrane space.

→ NADH from glycolysis & $FADH_2$ from Kreb Cycle also transport 2 pairs of H^+ proton



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→ The unidirectional flow of H^+ protons towards outerside results in the accumulation of hydrogen protons in intermembrane space.

→ The pH of outer surface of inner mitochondrial membrane lowers due to conc. of H^+ positive charge. Thus a pH gradient is generated across inner mitochondrial membrane.

→ Generation of pH gradient

→ Generation of proton conc. gradient

→ k/as proton electrochemical gradient / proton motive force.

→ Intermembrane space $\xrightarrow{\text{electrons}}$ mitochondrial matrix

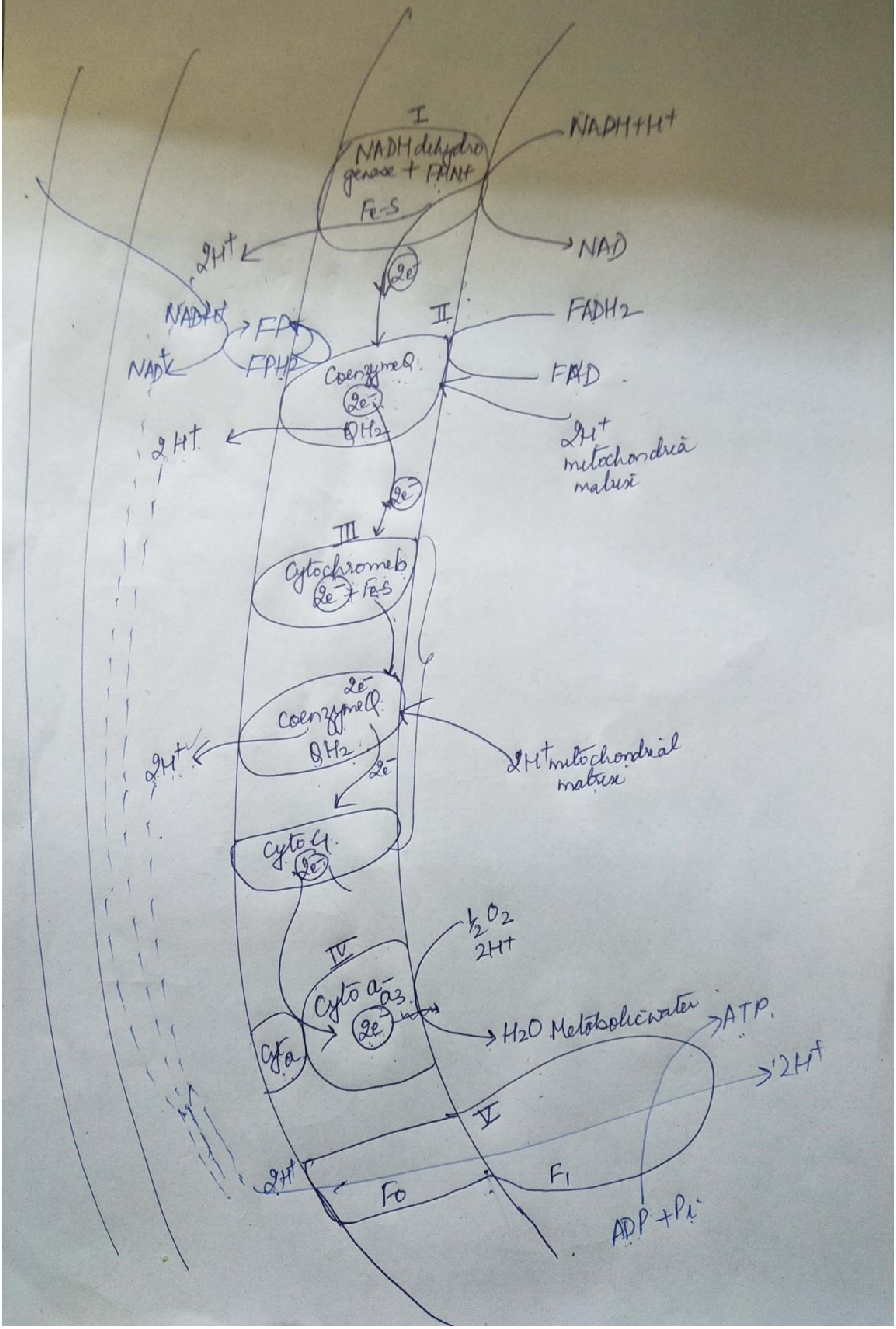
Return flow of proton down the gradient → activation of ATPase → phosphorylation of ~~ATP~~ ADP to ATP.

→ Inward flow of $2H^+$ through ATPase → 1 ATP.

→ 1 NADH — glycolysis — 3 ATP

→ 1 NADH — Krebs Cycle — 3 ATP

→ 1 $FADH_2$ — Kreb's Cycle — 2 ATP.



I
NADH dehydrogenase + FMN+
Fe-S
NADH+H+
NAD
2H+
NADH
FP
FPH2
NAD+
II
FADH2
FAD
Coenzyme Q
2e-
QH2
2H+
2H+ mitochondria matrix
III
Cytochrome b
2e- + Fe-S
Coenzyme Q
QH2
2H+
2H+ mitochondrial matrix
Cyto C1
2e-
IV
1/2 O2
2H+
Cyto a-a3
2e-
Cyt a
H2O Metobolic water
ATP
2H+
V
F1
Fo
2H+
ADP + Pi

Role of shuttle in energy production system -

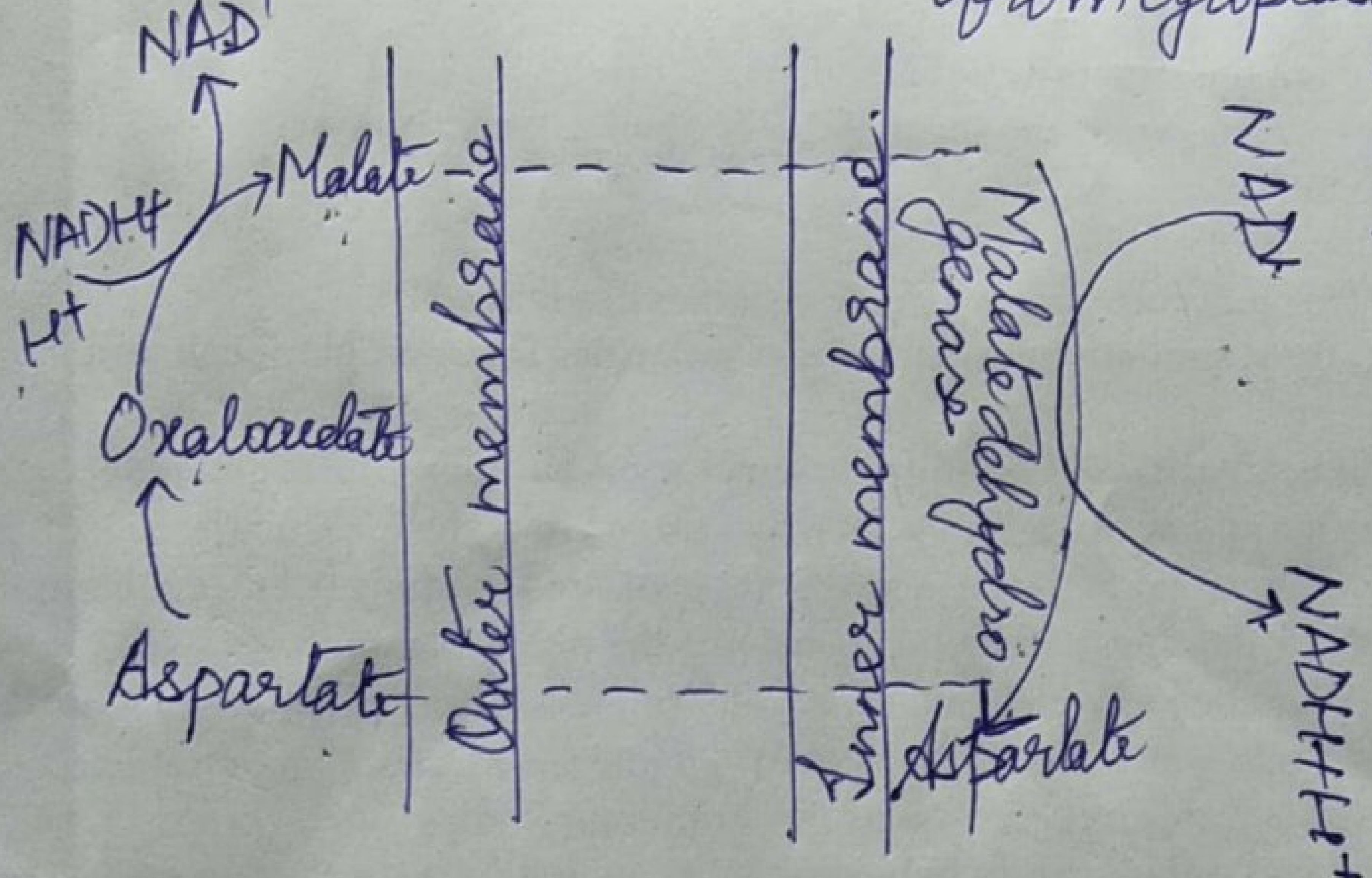
Glycolysis - 2 ($NADH+H^+$)

ETC - Inner mitochondrial membrane.

- Impermeable to $NADH+H$.
- Reduced $NADH+H$ ⟶ hands over reducing power to another coenzyme ⟶ inside mitochondrion by means of special chemicals ⟶ SHUTTLE.

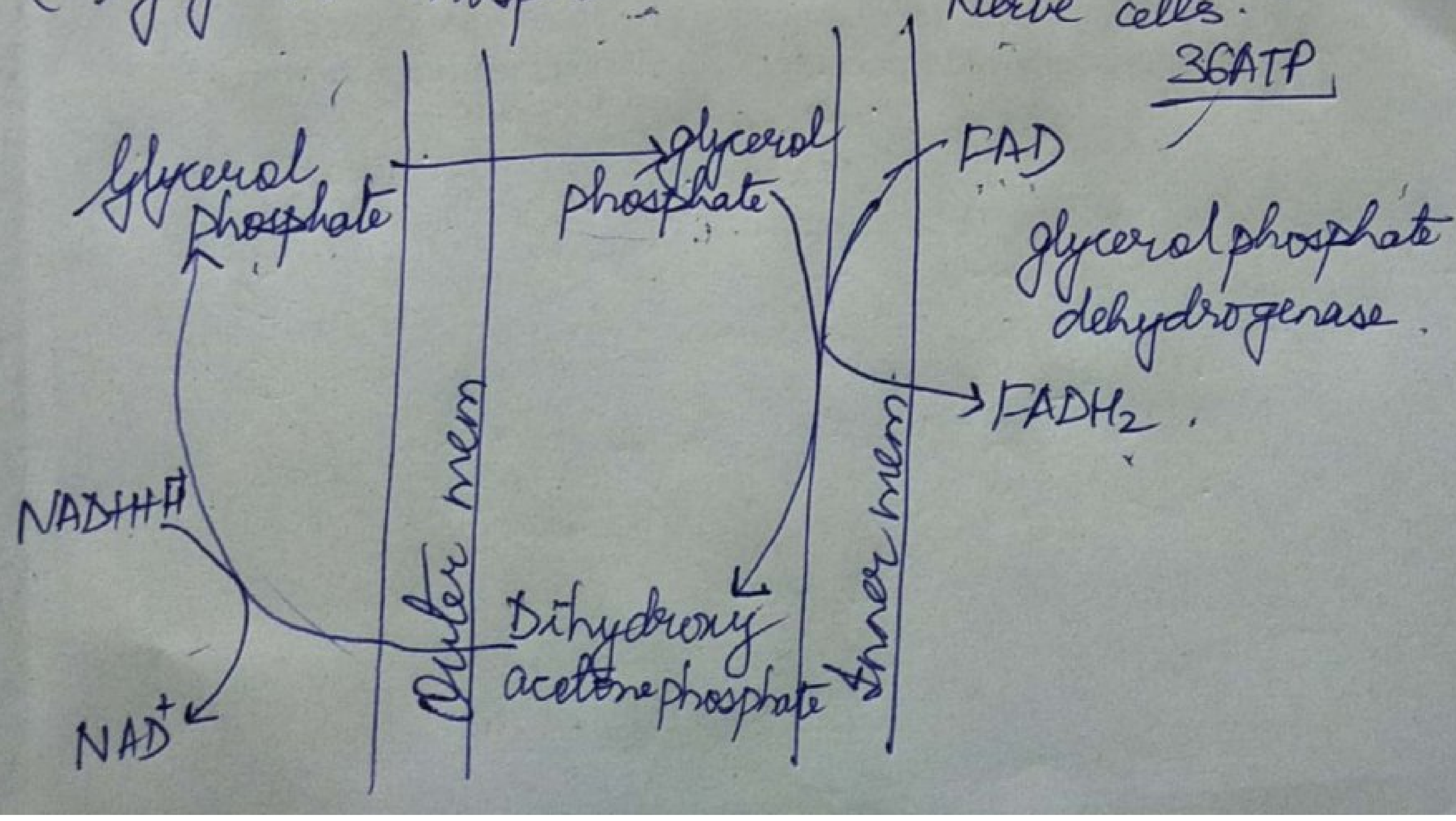
(1) Malate - Aspartate shuttle - Mitochondria of cells of heart, liver, kidney, transfer elections from cytoplasm to NAD inside mitochondria

38ATP



(2) Glycerol - Phosphate Shuttle - Skeletal muscles, Nerve cells.

36ATP



~~Glucose → Glu6(PO4)~~. Glycolysis	ATP/Coenzyme released	Consumed	Net gain
1) Glucose → Glu 6 (PO_4)	—	1	
2) Fructose 6(PO_4) → Fru 1,6 bis(PO_4)	—	1	
3) 1,3 Bisphosphoglyceraldehyde → 1,3 bisphosphoglycericacid	2NADH+H+ = 6ATP (3×2)	—	2ATP – consumed – pyruvicacid to mitochondria
4) 1,3 Bisphosphoglyceric acid → 3 Phosphoglyceric acid	2ATP		
5) 2 Phosphoenol pyruvic acid → pyruvic acid	2ATP		
	10ATP	2ATP	8ATP
Krebs Cycle –			
6) Pyruvicacid → ~~Succ~~ AcetylCoA	2NADH+H+ = 3×2 = 6ATP		
7) Isocitricacid → α-Keto gluteric acid	2NADH+H+ (3×2 = 6ATP)		
8) α-ketoglutericacid → Succinyl COA	2(NADH+H+) (3×2 = 6ATP)		
9) SuccinylCoA → SuccinicAcid	2ATP		
10) Succinic acid → FumaricAcid	2FADH2 (2×2 = 4ATP)		
11) Malic acid → Oxaloaceticacid	2NADH+H+ (3×2 = 6ATP)		
	38ATP	2 –	30ATP
			38ATP −2ATP
			36ATP — Eukaryotic acid

AMPHIBOLIC PATHWAY

Respiratory pathway is considered to be a catabolic pathway because it involves breakdown of glucose into CO_2 and water. But we know, in addition to glucose, products of fats and proteins also enter Krebs' cycle or TCA cycle whenever body has glucose deficiency. For example:

1. Fatty acids enter respiratory pathway as **acetyl CoA.**
2. Glycerol enters the path as PGAL (3-phosphoglyceraldehyde).
3. Amino acids (the monomers of proteins) enter at some stage in Krebs' cycle or as pyruvate or as acetyl CoA.

However, when the organism needs fatty acids for the synthesis of fats, acetyl CoA is withdrawn from respiratory pathway. Similarly, during breakdown and synthesis of proteins, respiratory intermediates make their entry or are withdrawn from the pathway.

This respiratory pathway is involved in both anabolic and catabolic activities, it is now considered as an **amphibolic pathway.**

FERMENTATION (ANAEROBIC RESPIRATION)

Definition

Anaerobic respiration is incomplete breakdown of carbohydrates (glucose) to release energy in the complete absence of oxygen. It is called **fermentation** in case of microorganisms yielding compounds such as alcohols, organic acids, etc.

Occurrence

Anaerobic respiration occurs in some bacteria, yeast, other fungi, roots of some waterlogged plants, in some parasitic worms, and muscles when there is shortage of oxygen supply during fast running or doing exercise. Process of anaerobic respiration was first described by **Pasteur** in 1860.

In anaerobic respiration, oxidation occurs in the absence of oxygen. In this case, electrons are accepted by a pyruvate and acetaldehyde and not by oxygen.

Mechanism of Fermentation

Glycolysis breaks down glucose into pyruvic acid, 2 ATP and 2 $NADH_2$. In aerobic respiration, $NADH_2$ transfers its hydrogen to oxygen via electron transport chain. In the absence of oxygen, pyruvic acid acts as a hydrogen acceptor. The complex breaks down into **ethyl alcohol** in plants and microorganisms but into lactic acid in animals and some bacteria. Based on the end product, fermentation is of two types namely **alcoholic fermentation** and **lactic acid fermentation.**

1. Alcoholic Fermentation: It takes place in some bacteria, yeast and *Rhizopus*. It is utilised in brewing industry for preparing beverages like rum, beer and whisky. It involves following steps.

(a) **Decarboxylation** of pyruvic acid with the help of enzyme **pyruvate decarboxylase** and enzyme **thiamine pyrophosphate** (TPP). Zinc acts as a cofactor. This reaction produces acetaldehyde and carbon dioxide.

$$\text{Pyruvate} \xrightarrow[\text{TPP+Zn}]{\textit{Pyruvate decarboxylase}} \underset{\text{(ethanal)}}{\text{Acetaldehyde}} + CO_2\uparrow$$

(b) **Acetaldehyde** is reduced to ethyl alcohol (ethanol) by accepting hydrogen from $NADH_2$. The process is catalysed by enzyme ***ethanol dehydrogenase.*** One glucose molecule produces two molecules of ethyl alcohol.

$$\text{Acetaldehyde} + NADH_2 \xrightarrow[\textit{dehydrogenase}]{\textit{Alcohol}} C_2H_5OH + NAD^+$$

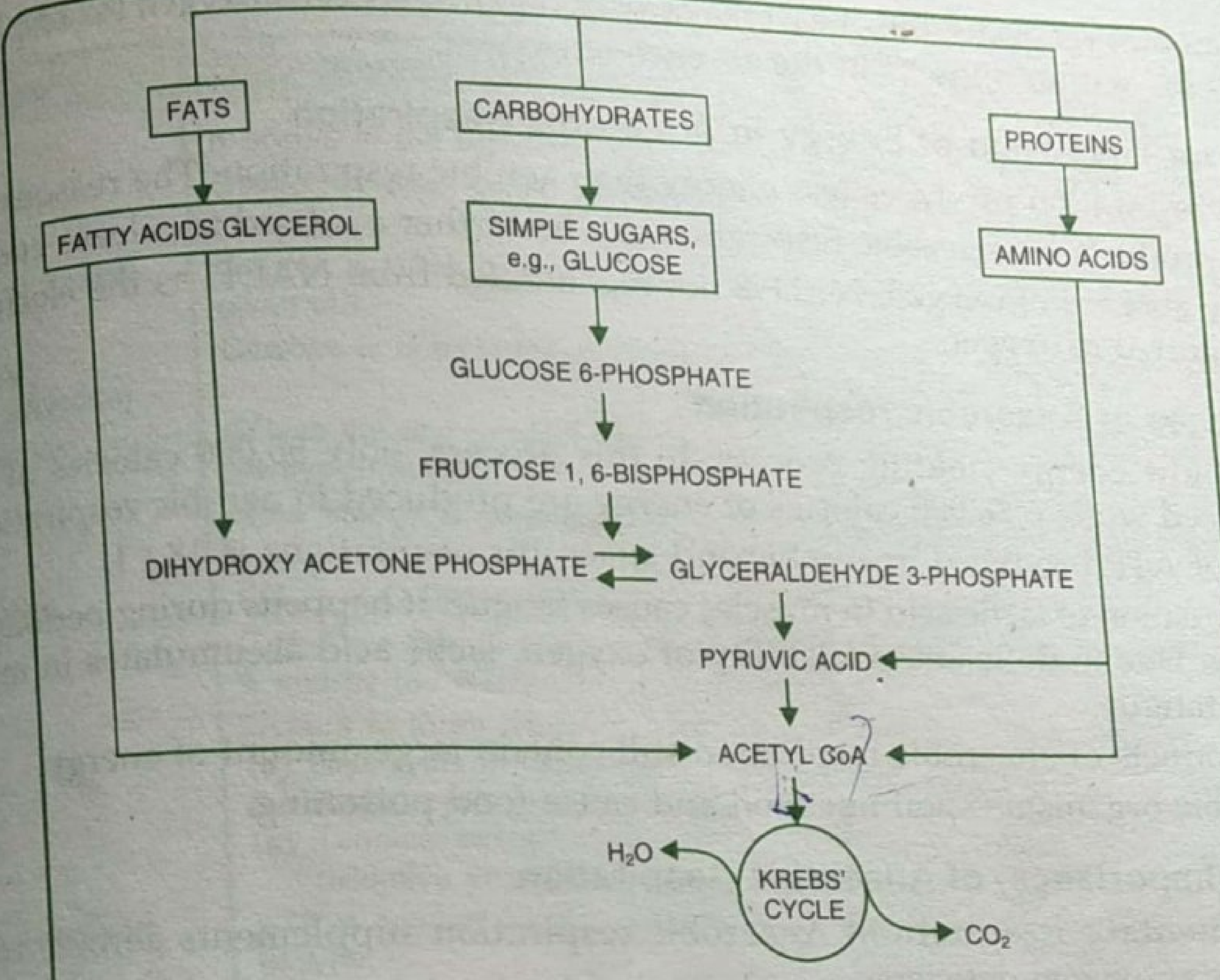


Fig. 15.8 Interrelationship among metabolic pathways showing respiration mediated breakdown of different organic molecules to CO_2 and H_2O

Alcohol is poisonous. So its accumulation beyond a certain limit may kill the yeast cells and stop their multiplication. In the presence of oxygen, yeast cells respire aerobically, breaking down sugar completely to CO_2 and H_2O.

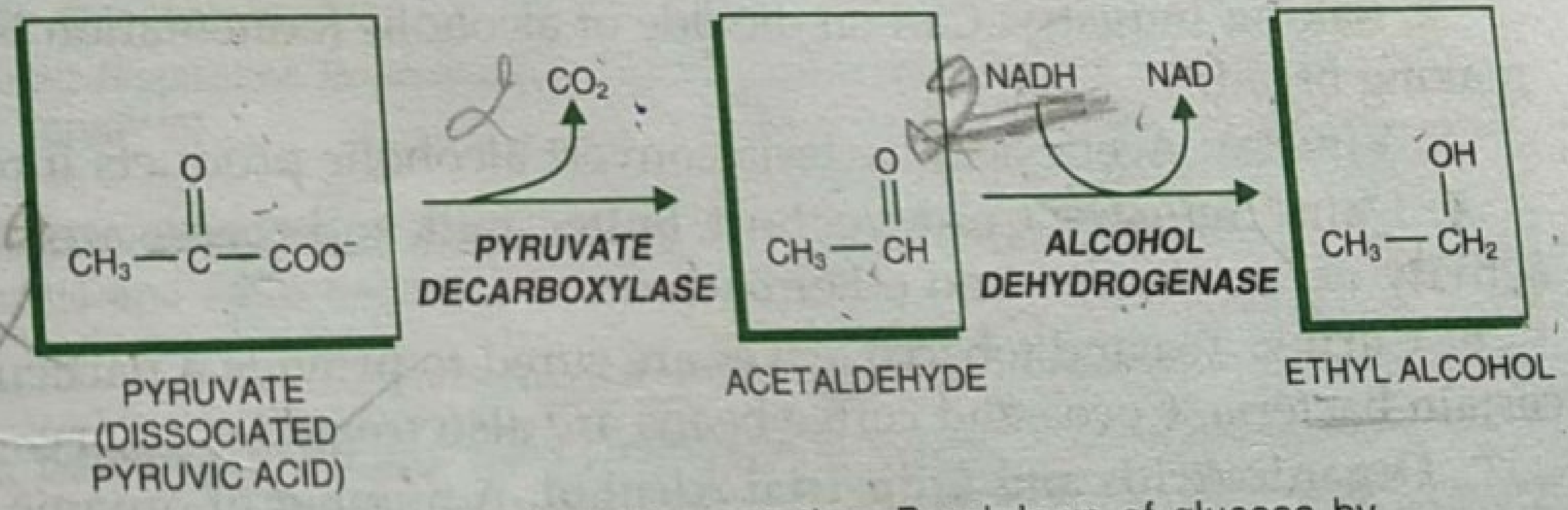


Fig. 15.9 Alcoholic fermentation: Breakdown of glucose by yeast yielding ethyl alcohol

2. Lactic Acid Fermentation: It occurs in lactic acid bacteria, some fungi and muscles. In lactic acid fermentation, pyruvic acid produced in glycolysis is directly reduced by $NADH_2$ to lactic acid. The reaction is catalysed by the enzyme *lactic hydrogenase*. One molecule of glucose gives two molecules of lactic acid.

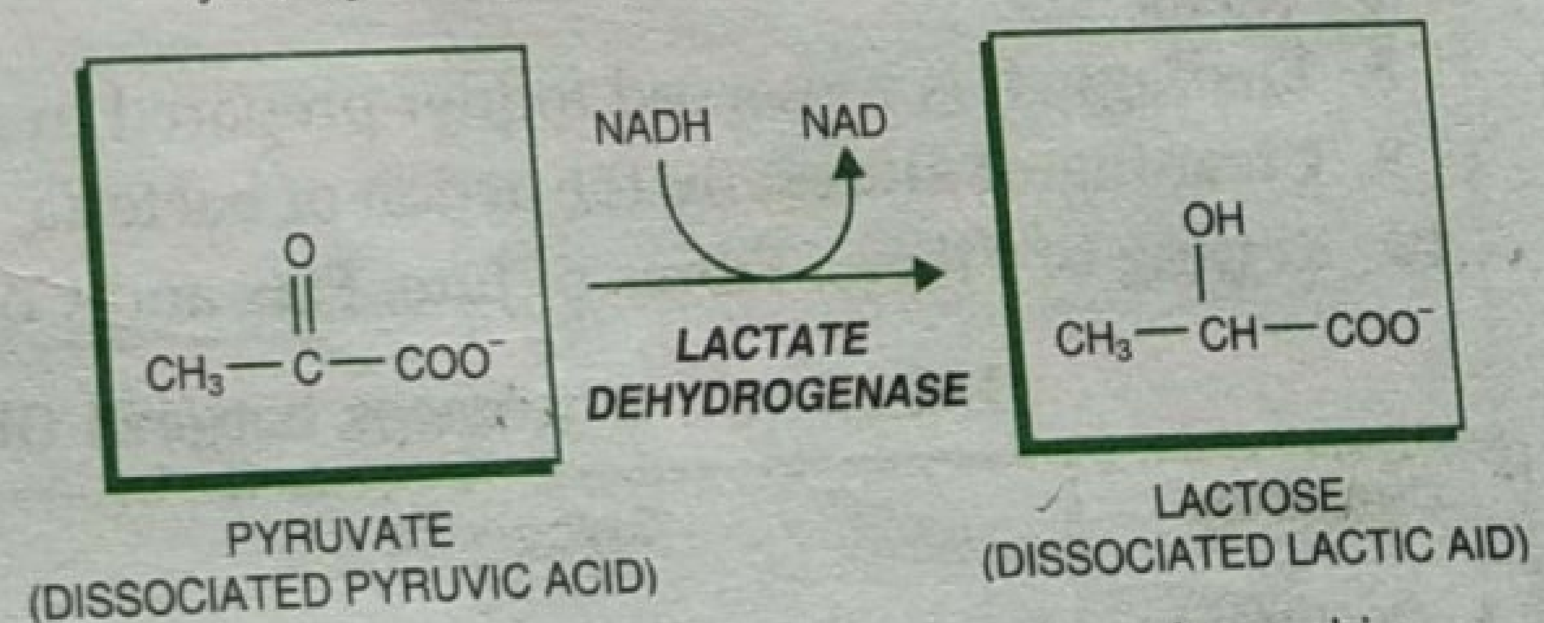


Fig. 15.10 Lactic acid fermentation: Anaerobic breakdown of glucose in muscle cells yielding lactic acid

$$\text{Pyruvic acid} + NADH_2 \xrightarrow[\textit{dehydrogenase}]{\textit{Lactic}} \text{Lactic acid} + NAD^+$$

Energy Yield in Fermentation

Energy yield in fermentation is about 5% of the energy obtained by aerobic respiration. This small amount of enegy is just sufficient to maintain the activities of yeast, many bacteria and other anaerobic organisms. But, a vast majority of organisms needs oxygen for respiration. These organisms die within minutes in the absence of oxygen.

Reasons for Less Yield of Energy in Anaerobic Respiration

Anaerobic respiration produces less energy than aerobic respiration. The reasons are:

1. End products of anaerobic respiration can be further oxidised to release energy.
2. In the absence of oxygen, NAD is not regenerated from NADH as the electrons are not transported to oxygen.

Disadvantages of Anaerobic respiration

1. It is a low energy yielding process. In this process, only 50,000 calories of energy are produced while 6,86,000 calories of energy are produced in aerobic respiration.
2. Ratio of ATP produced in aerobic and anaerobic respirations is 18 : 1.
3. Accumulation of lactic acid in muscles causes fatigue. It happens during periods of intense activity. Due to deficient availability of oxygen, lactic acid accumulates in muscles and causes fatigue.
4. End products of anaerobic respiration still contain large amount of energy.
5. Anaerobic organisms spoil our food and cause food poisoning.

Advantages (Importance) of Anaerobic Respiration

1. **Supplementary Respiration:** Anaerobic respiration supplements aerobic respiration during periods of oxygen deficiency.
2. **Brewing Industry:** Alcoholic fermentation is used in brewing industry for the production of various types of beers, whisky and wines.
3. **Baking Industry:** Carbon dioxide of alcoholic fermentation is used in baking industry for making bread.
4. **Vinegar:** Acetic acid bacteria convert alcoholic products into vinegar.
5. **Dairy Industry:** Curd, yoghurt, butter, milk and cheese are prepared by the fermentation activity of *Lactobacillus* and other bacteria.
6. **Curing:** Tea and tobacco leaves are cured to provide a particular aroma by the activity of certain bacteria. Cocoa and coffee beans are also treated similary.
7. **Organic Acids and Industrial Alcohol:** A number of organic acids (*viz.* lactic acid, citric acid, gallic acid, gluconic acid, etc.) and industrial alcohol are produced by fermentive activity of microbes.
8. **Ensilage:** It is preserved fodder prepared by fermentive activity of bacteria.
9. **Cleaning of Hides:** By the action of bacteria, hides are cleaned of hair and other tissues.
10. **Retting of Fibres:** Fibres of Jute, Flax and Coconut are separated by bacterial action.

TABLE 15.6 Differences between Glycolysis and Fermentation

Character	Glycolysis	Fermentation
1. Occurrence	Takes place in both aerobic and anaerobic respirations.	Takes place only in anaerobic respiration.
2. Substrate	Glycolysis starts with glucose.	Fermentation begins with pyruvic acid (the end product of glycolysis).
3. End product	Two molecules of pyruvic acid per glucose molecule.	One molecule of ethyl alcohol or lactic acid is formed per molecule of pyruvate.
4. NADH.H	Two molecules of $NADH_2$ are produced per glucose molecule.	$NADH_2$ is not formed during fermentation.
5. ATP	2ATP are obtained at the end of glycolysis.	ATP is not formed.

1. **Malate-aspartate Shuttle System:** It passes 2 H from NADH. H to NAD in mitochondrial wall. It is a more efficient shuttle system. (More efficient shuttle)

$$\underset{\text{(in cytosol)}}{NADH_2} \rightarrow \underset{\text{(inside mitochondria)}}{NAD} \rightarrow NADH_2$$

These 2 H atoms generate 3 ATP. This shuttle operates in liver, heart and kidney cells.

2. **Glycerol-phosphate Shuttle System:** It passes 2 H from $NADH_2$ to FAD inside mitochondria. It is less efficient shuttle system and is present only in the muscle cells and nerve cells. Here 2 H atoms generate only 2 ATP. (Less efficient shuttle)

$$\underset{\text{(in cytosol)}}{NADH_2} \rightarrow \underset{\text{(inside mitochondria)}}{FAD} \rightarrow FADH_2$$

Glycerol phosphate shuttle uses 2 ATP molecules during transport of $NADH_2$ to FAD. It means in muscles and nerve cells, only 36 ATP are generated instead of 38.

In prokaryotic cells, there is net gain of 38 ATP molecules from each glucose molecule during aerobic respiration, because they do not have mitochondria, there is no additional consumption for NADH transport.

Advantages of Stepwise Energy Release

1. Energy is released in steps and in small amounts. This prevents sudden rise of body temperature.
2. Wastage of energy is avoided because cell gets plenty of time to store energy in ATP.
3. Intermediate products of respiration can be used in different metabolic pathways, as discussed in significance of Krebs' cycle.
4. Energy produced can be regulated according to the need of the cell or body.

Respiratory Balance Sheet

Calculations of the net gain of ATP of every glucose molecule is made on certain assumptions;

1. Various steps in respiratory process (Glycolysis, Krebs' cycle, ETS) occur in a sequence and follow an orderly pathway.
2. Only glucose is used as respiratory substrate. No other alternative substrate enters in the the respiratory pathway at any intermediate stage.
3. NADH generated during glycolysis is transported into mitochondria and undergoes complete oxidative phosphorylation.
4. Any of the intermediate compounds formed during Krebs' cycle or during glycolysis is not utilised in any other pathway, i.e., all of them are dedicated to complete respiratory pathway.

In any living system, such assumptions are not valid because all the pathways work simultaneously and substrate from one pathway enter other pathways or are withdrawn from other pathways as and when needed.

Efficiency of Aerobic Respiration

Each mole of ATP yields 34 kJ or 7.3 kcal of energy. The energy yield from 38 ATP (during aerobic respiration of one mole of glucose) comes to 34 × 38 = 1292 kJ or 38 × 7.3 = 277.4 kcal The energy yield from complete oxidation of glucose is 2870 kJ or 686 kcal. Therefore, efficiency of aerobic respiration is:

$$\frac{1292}{2870} \times 100 = 45\% \text{ or } \frac{277.4}{686} = 40\%$$

It is evident from above that only 40–45% of energy liberated during complete oxidation of 1 mole glucose is used in making ATP and the rest is released as heat.

CLASSIFICATION ALGAE

RHODOPHYTA
Aquatic
Thallus – Unicellular filamentous
Pseudoparenchymatous lace like
sheet like, Ribbon like
Cell Structure – Cellwall – pectin, cellulose, carrageenin
Mucopolysaccharides (phycocolloids) agar
Photosynthetic pigment – chl a, chl b
phycobilin (phycoerythrin)
– Red-colour
– Absorb blue green light of spectrum – short wavelength, penetrate deep – Redalgae deep water
Reproduction – Vegetative
Asexual, Sexual

CHLOROPHYTA
Phycocolloids Absent
Mostly – freshwater
Thallus – Unicellular, colonial filaments
Sheet, Some attached – Substratum
Cell Structure – Shape – vary, uninucleated
Some multinucleated
– Thalokoids of chloroplast –

Cupshaped, Ribbon like, Discoid, girdle shaped
Chloroplast – starch – Pyrenoid
– Chla, Chlb carotene
– Flagellated form – photo receptor

Reproduction – Vegetative, Asexual – zoospores, akinete autospore
Sexual – Iso, Aniso & Oogamous
Eg – Chlamydomonas, Chlorella, Spirogyra

PHAEOPHYTA
Aquatic
Thallus – filament, Kelp
Cell – Colloidal – Algin – Mucilage
– Cellwall – cellulose
– Chromatophore – Chla, chl b
fucoxanthin (Brown colour)
Reproduction – Vegetative
– Asexual
– Sexual