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BIOLOGY RESPIRATION IN PLANTS

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RESPIRATION IN PLANTS

CONTACT US:

+91-9939586130

+91-9955930311

aepstudycircle@gmail.com

www.aepstudycircle.com

2ND FLOOR, SATKOUDI COMPLEX, THANA CHOWK, RAMGARH - 829122-JH

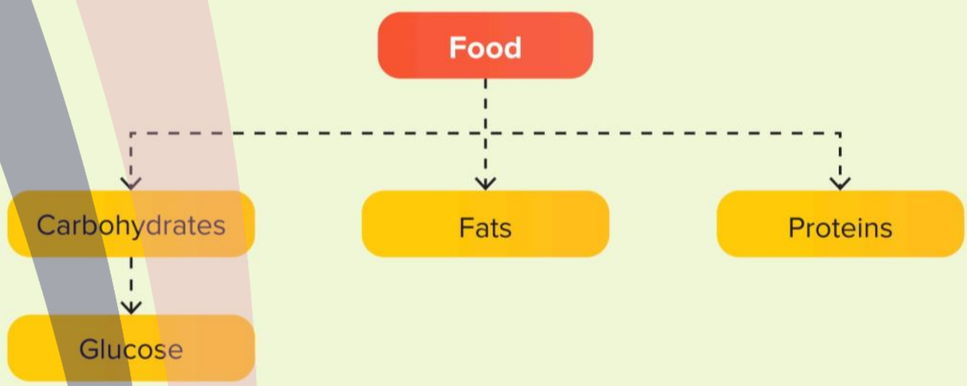
RESPIRATION IN PLANTS

AEROBIC RESPIRATION, ANAEROBIC RESPIRATION, RESPIRATORY SUBSTRATES

Key Takeaways

- Respiration
  - Respiratory substrates
  - Types of respiration
- Aerobic respiration
- Anaerobic respiration
- Types of organisms
- Energy units of a cell
- Do plants breathe?
  - Rate of gaseous exchange in plants
- Respiration vs Combustion

Prerequisites



Respiration

- The breaking of the C-C bonds of the substrates (complex compounds) to release energy is known as **respiration**.
- The process of respiration occurs inside a living cell. Hence, this process is also known as **cellular respiration**.
- Location of respiration: **Cytoplasm** and **mitochondria**

Respiratory substrates

- The compounds broken down during respiration are known as **respiratory substrates**.
- The amount of energy liberated from complete oxidation of 1g of the respiratory substrate in a **bomb calorimeter** (a closed metal chamber filled with oxygen) is its **gross calorific value**.
- The actual amount of energy released by the oxidation of 1g of the respiratory substrate is the **physiological value**.

Respiratory substrates

Carbohydrates
- Primary substrate
- Physiological value: 4 kcal/g
- Gross calorific value: 4.1 kcal/kg

Fats
- Used in absence of carbohydrates
- Physiological value: 9 kcal/g
- Gross calorific value: 9.45 kcal/kg

Proteins
- Used in absence of fats and carbohydrates
- Physiological value: 4 kcal/g
- Gross calorific value: 5.65 kcal/kg

Types of respiration

Based on the respiratory substrate

Floating **respiration**
- Substrates used are **carbohydrates and fats**
- Common mode of respiration
- No toxic products are formed
- Occurs indefinitely throughout the life of the cell

Protoplasmic **respiration**
- Substrates used are **proteins**
- Rare mode of respiration
- Toxic products are formed
- Doesn't occur indefinitely (Only **in legume seeds**, oxidation of proteins is known as **floating respiration**)

Based on the availability of oxygen

Aerobic **respiration**
- Breakdown of glucose occurs in the **presence of oxygen**
- Occurs in the cytoplasm and mitochondria
- Seen in aerobes

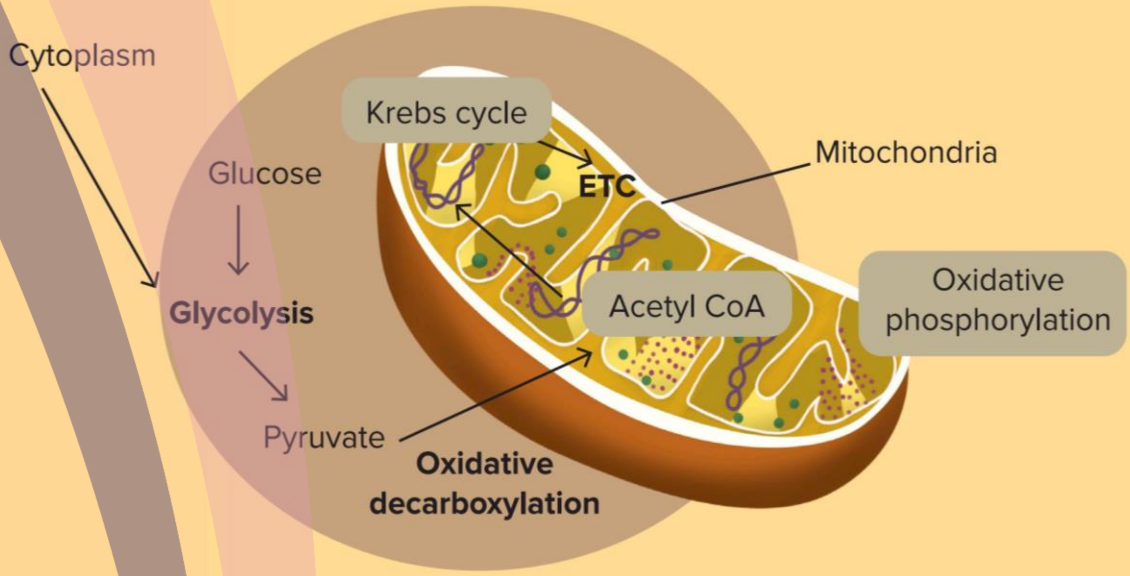
Anaerobic **respiration**
- Breakdown of glucose occurs in the **absence of oxygen**
- Occurs in the cytoplasm
- Seen in anaerobes

Aerobic Respiration

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

Glucose + Oxygen → Carbon dioxide + Water

Steps involved in aerobic respiration



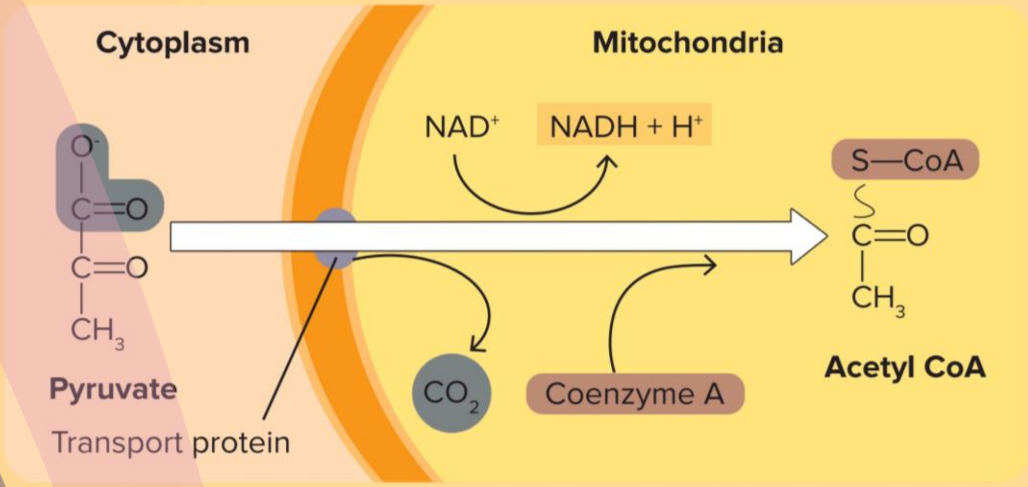
1. Glycolysis

- Glucose is broken down to pyruvate
- Occurs in cytoplasm

Glucose 6C	2 **ATP**	2 **NAD⁺**
↓	↓	↓
	Glycolysis	
↓	↓	↓
Pyruvate 3C	4 **ATP**	4 **NADH**

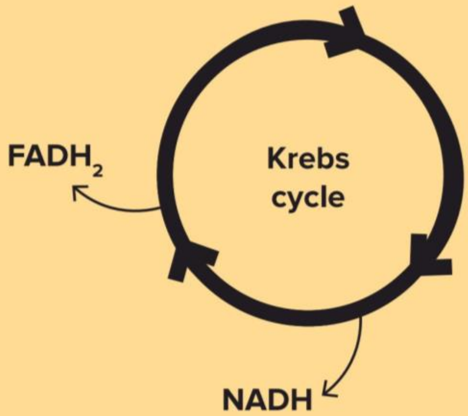
2. Oxidative decarboxylation

- Pyruvate is broken down to acetyl CoA
- Occurs in mitochondria



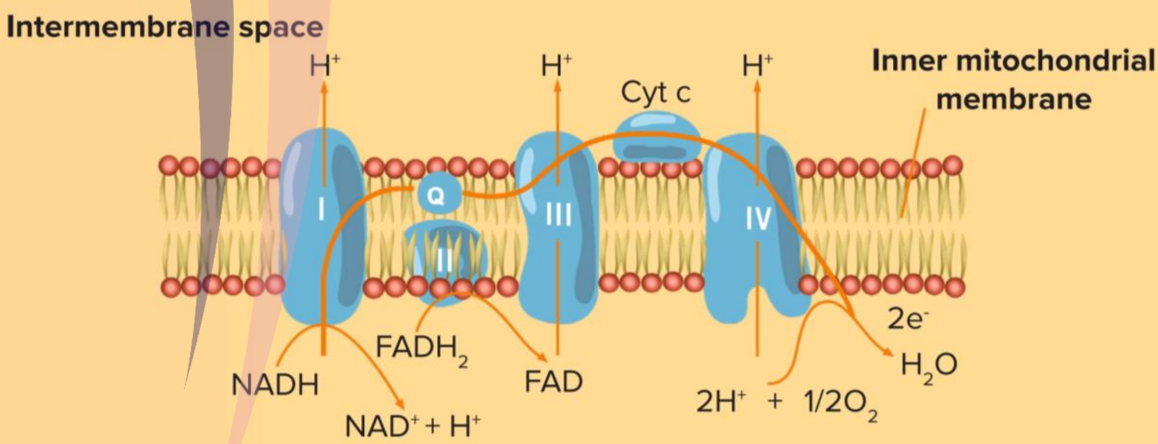
3. Krebs cycle/Citric acid cycle

- NADH and $FADH_2$ are produced in the process.
- Occurs in mitochondria



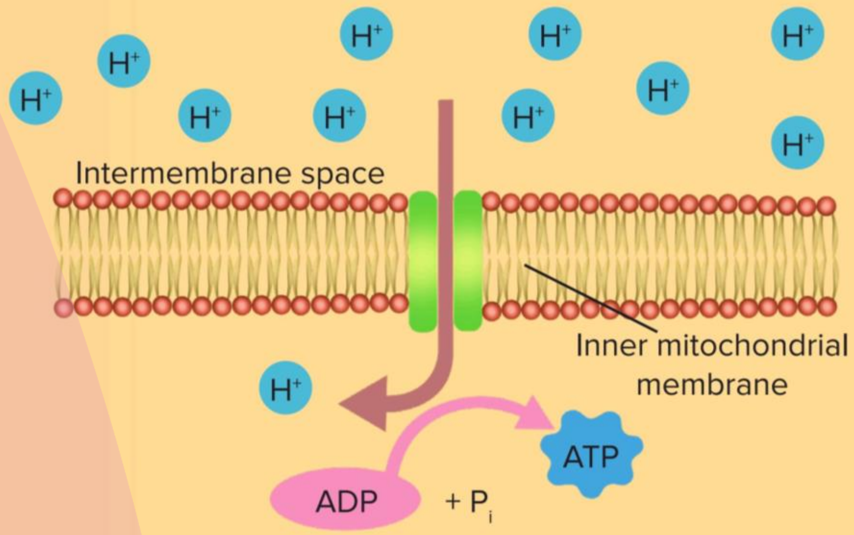
4. Electron transport chain (ETC)

- This step is the precursor of oxidative phosphorylation
- Occurs in mitochondrial membrane

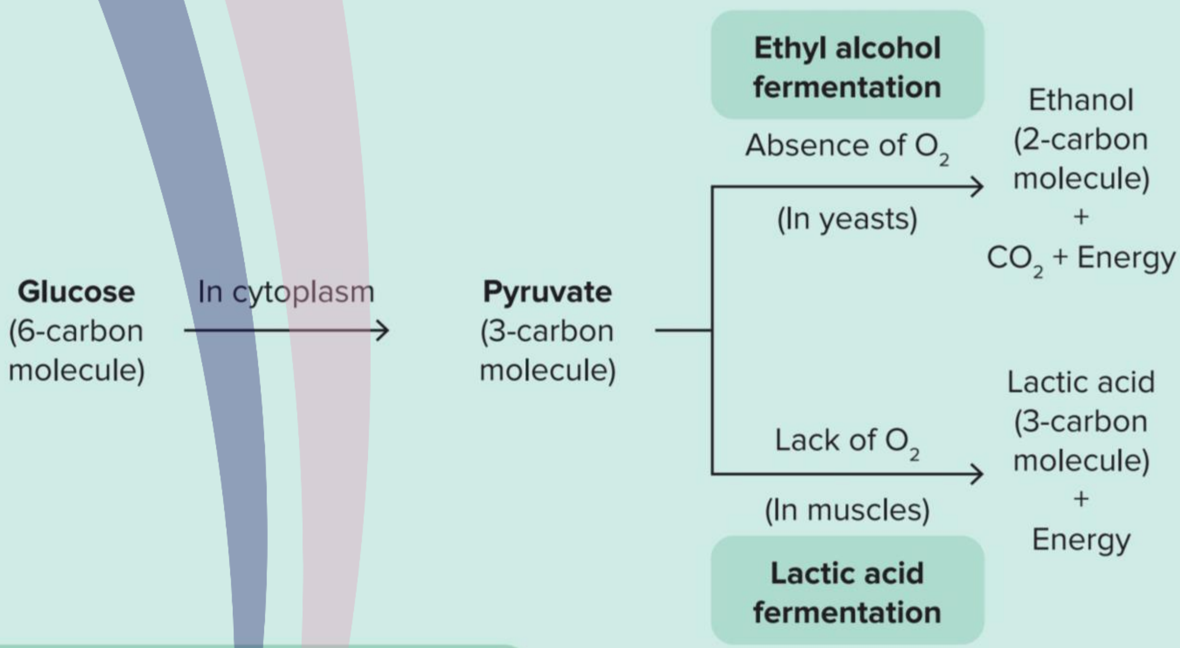


5. Oxidative phosphorylation

- This step is responsible for ATP synthesis
- Occurs across the inner membrane of mitochondria



Anaerobic Respiration



Anaerobic respiration vs Fermentation

- Despite the fact that anaerobic respiration and fermentation are often used interchangeably, there are a few differences between them.
- Fermentation, as a process, is widely used in the production of alcoholic beverages.

Anaerobic respiration	Fermentation
• Occurs within the cell	• Occurs within the cell as well as extracellular
• Type of respiration	• Breakdown of organic nutrients
• No industrial application	• Has industrial application

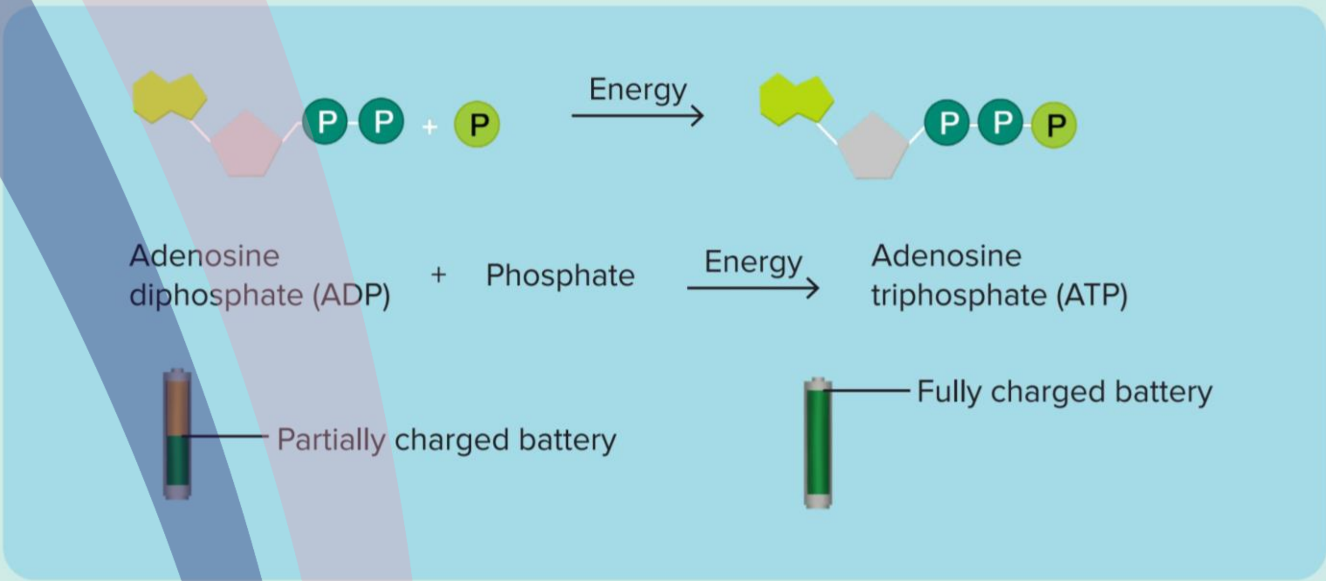
Types of organisms
(Based on utilisation of oxygen)

- Aerobes
  - **Obligate aerobes**
    - Oxygen is absolutely necessary for growth and survival.
    - Example: *Mycobacterium tuberculosis*
  - **Microaerophiles**
    - Oxygen is required for energy production, but organism is harmed by its atmospheric concentration.
    - Example: *Helicobacter pylori*
- Anaerobes
  - **Obligate anaerobes**
    - Normal atmospheric oxygen concentration is fatal.
    - They do not require oxygen for energy production.
    - Example: *Clostridium botulinum*
  - **Aerotolerant organisms**
    - They do not use oxygen for any process but are not harmed by it either.
    - Example: *Streptococci*
  - **Facultative anaerobes**
    - They would prefer if there is no oxygen but would not mind using oxygen for respiration if available.
    - Example: Yeast

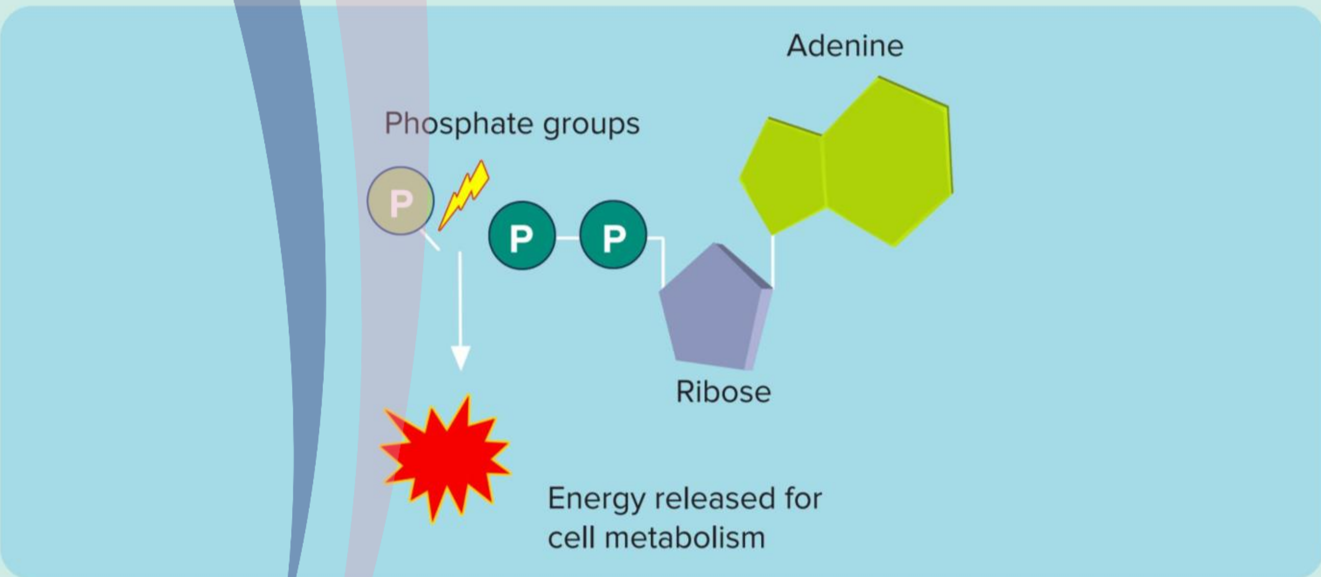
Energy Units of a Cell

ATP: Adenosine triphosphate

- It is referred to as the **energy currency of the cell**.
- ATP is made up of ribose sugar, adenine, and three phosphate molecules.
- The energy generated from the respiration of respiratory substrates is stored in the form of a high-energy bond between **adenosine diphosphate** (ADP) and a **phosphate group** that gives us **adenosine triphosphate** (ATP).



- Whenever the energy is required by a cell for any metabolic reaction, the same energy is utilised from ATP. Breaking down one mole of ATP generates 7.3 kcal of energy.
- **The energy is liberated from the terminal phosphate bond**.



NADH and $FADH_2$

- NADH stands for **nicotinamide adenine dinucleotide hydrogen**
- $FADH_2$ stands for **flavin adenine dinucleotide hydrogen**
- NADH and $FADH_2$ = Reservoirs of ATP
- One NADH yields **three ATP**
- One $FADH_2$ yields **two ATP**

Do Plants Breathe?

- Yes, plants do breathe.
- However, they do not have a dedicated respiratory organ and system for that.
- Each cell has tiny apertures on its surface that facilitates gaseous exchange.

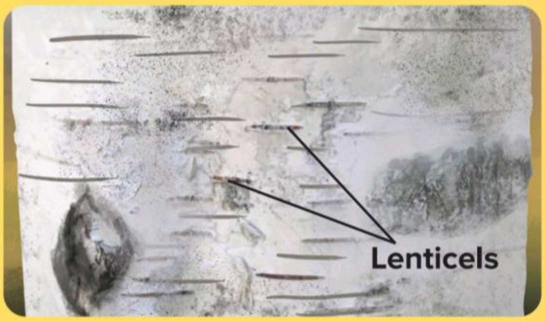
Apertures responsible for gaseous in plants

Stomata

- Present on the surface of leaves
- Opening and closing facilitates gaseous exchange

Lenticels

- Present in thick woody stem and root
- Have loosely packed parenchyma cells that facilitate gaseous exchange



Rate of gaseous exchange in plants

- The rate and requirement of gaseous exchange in plants is lesser than that of animals.
- Large volumes of gases are exchanged only during photosynthesis.
- Oxygen demand for respiration is met through internal production during photosynthesis.

Did you know?

- **Lavoisier**, a biologist and chemist is known for his discovery about the role of oxygen in combustion.
- He had also mentioned that combustion shares several similarities with the process of respiration.

Lavoisier

Respiration vs Combustion

- Combustion is a chemical reaction that results in the burning of a substance in the presence of oxygen and in the release of excessive amounts of heat.
- Although there are some similarities between respiration and combustion such as
  - Substances are broken down in both the cases
  - Oxygen is utilised in the process
  - Energy is released in both the cases

They are significantly different from each other.

Respiration	Combustion
Occurs inside the living cell	Non-cellular process
Biochemical process	Physico-chemical process
A slight increase in the temperature	Temperature becomes very high
Enzymatic process	Non-enzymatic process
Less than 50% of the energy is liberated as heat	Most of the energy is liberated as heat

Summary sheet

Respiratory substrates

- **Carbohydrates** — Primary substrate
- **Fats** — Used in absence of carbohydrates
- **Proteins** — Used in absence of fats and carbohydrates

Types of respiration

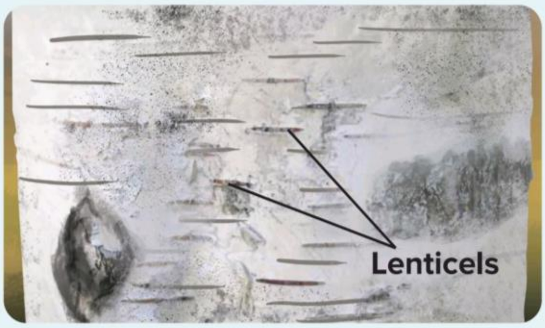
- **Based on the respiratory substrate**
  - Floating **respiration** → Substrates used are **carbohydrates and fats** → Common mode of respiration
  - Protoplasmic **respiration** → Substrates used are **proteins** → Rare mode of respiration
- **Based on the availability of oxygen**
  - Aerobic **respiration** → Breakdown of glucose occurs in the **presence of oxygen**
    - **Steps**
      1. Glycolysis
      2. Oxidative decarboxylation
      3. Krebs cycle
      4. Electron transport chain
      5. Oxidative phosphorylation
  - Anaerobic **respiration** → Breakdown of glucose occurs in the **absence of oxygen**
    - Ethyl alcohol fermentation
    - Lactic acid fermentation

Types of organisms
(Based on utilisation of oxygen)

- **Aerobes**
  - Obligate aerobes — *M. tuberculosis*
  - Microaerophiles — *H. pylori*
- **Anaerobes**
  - Obligate anaerobes — *C. botulinum*
  - Facultative anaerobes — Yeast
  - Aerotolerant organisms — *Streptococci*

Apertures responsible for gaseous exchange in plants

- Stomata
- Lenticels

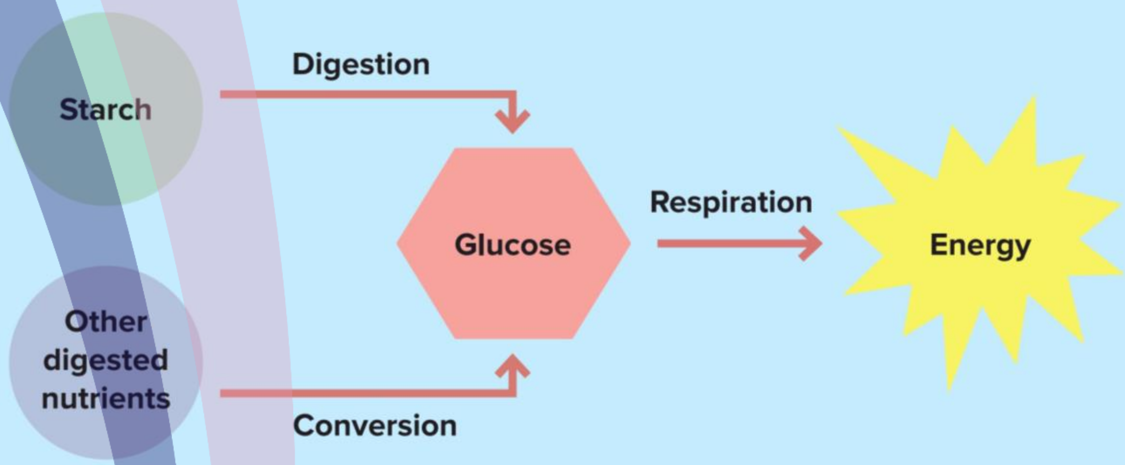


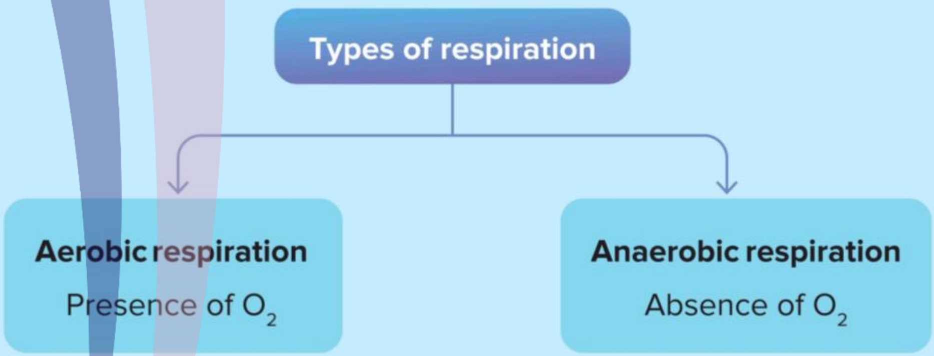
GLYCOLYSIS

Key Takeaways

- Breakdown process of food
- Glycolysis pathway
  - Preparatory stage
  - Payoff stage

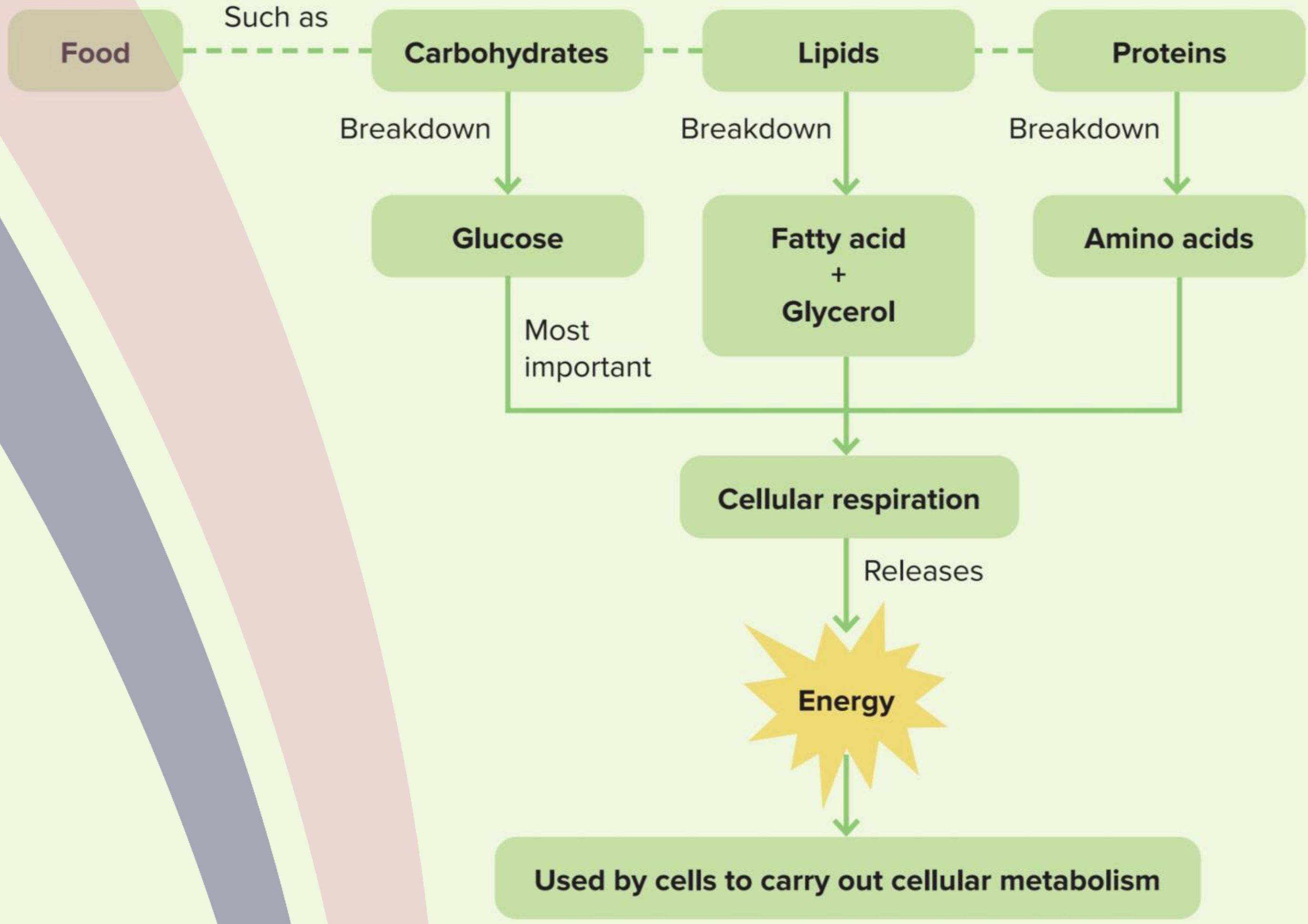
Prerequisites



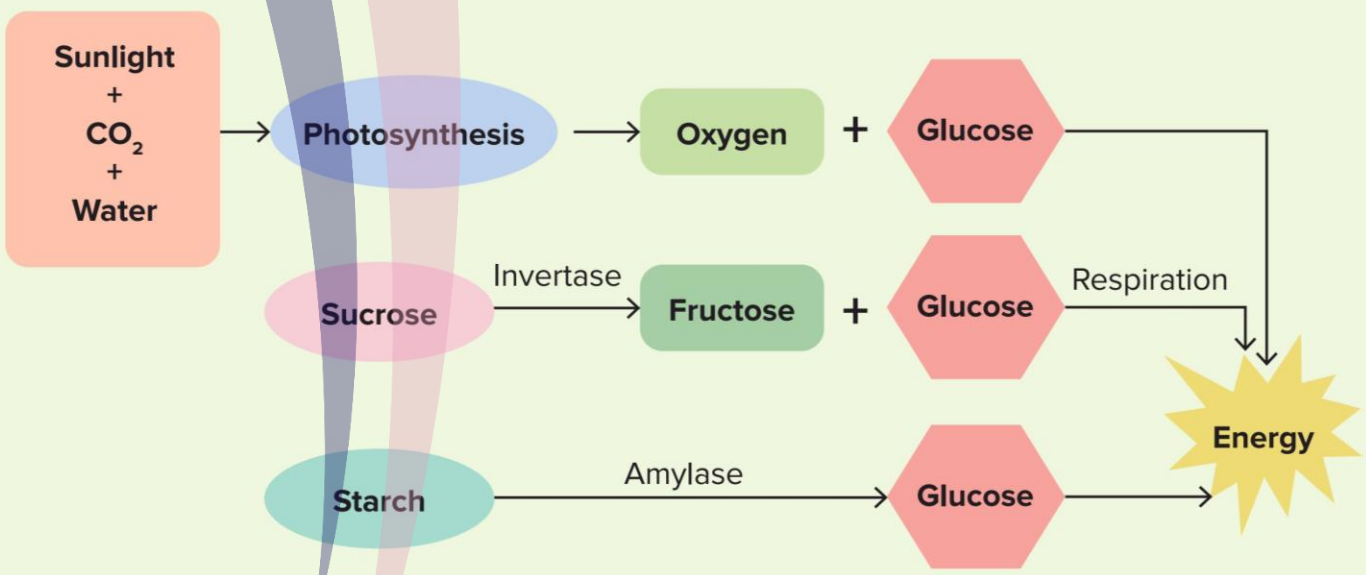


- **Oxidation**
  - It is a chemical process of loss of electrons and hydrogen, or gain of oxygen by a substance.
- **Reduction**
  - It is a chemical process of gain of electrons and hydrogen, or loss of oxygen by a substance.

Breakdown of Food



Sources of glucose



Glycolysis

- It is the **first step** of cellular respiration.
- **'Glycos' means sugar** and **'lysis' means splitting**.
- This pathway was described by:

Gustav Embden

Otto Meyerhof

Jakub Parnas

- Hence, it is also known as Embden-Meyerhof-Parnas pathway or **EMP pathway.**
- It is common to all the living beings.
- Glucose is **partially** broken down in this cycle.
- The equation for glycolysis is,

$$\text{Glucose} \longrightarrow \text{Pyruvic acid} + \text{ATP (Energy)}$$

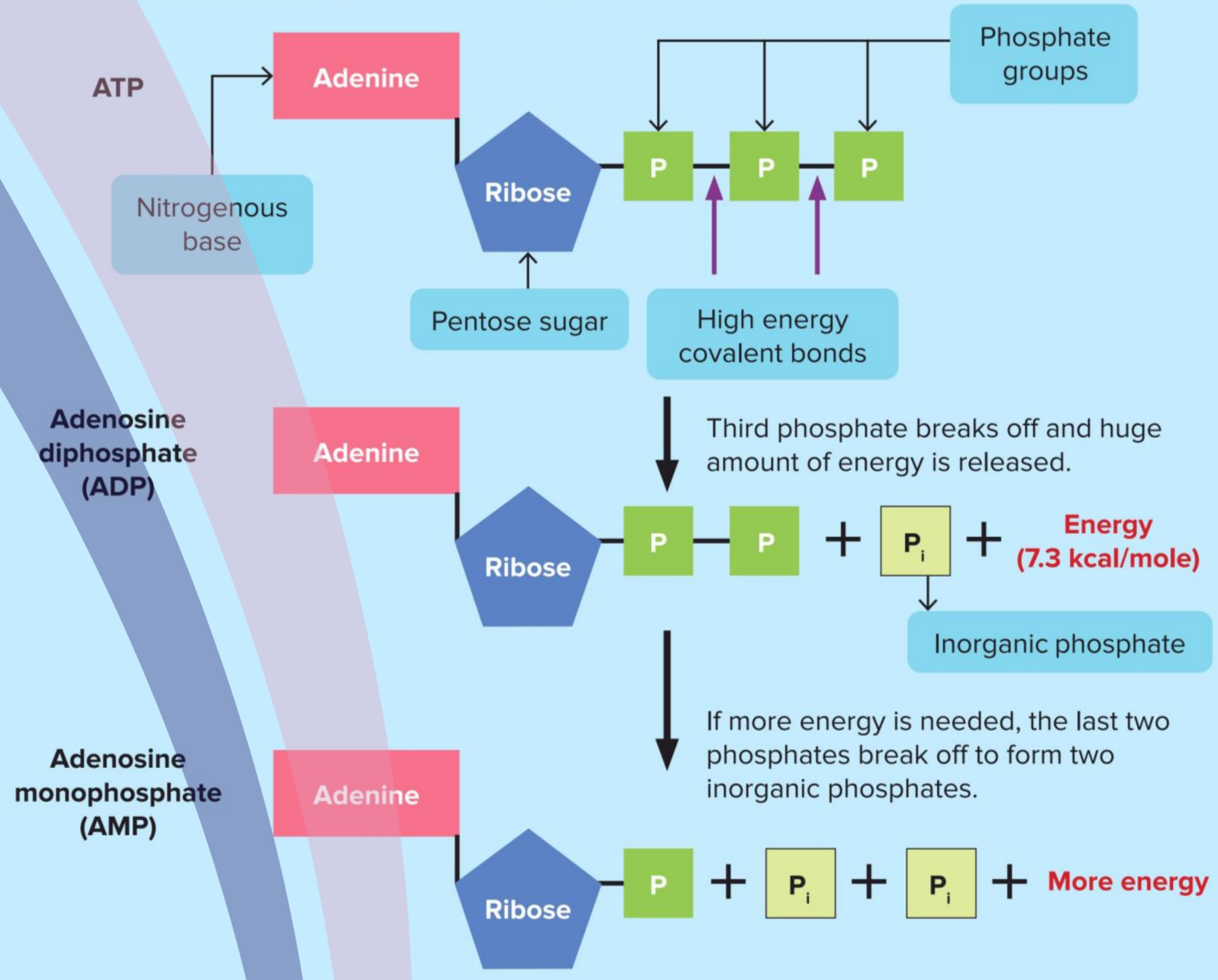
- It does not require oxygen. Hence, it is an **anaerobic reaction.**
- It takes place in the **cytoplasm**.

Did you know?

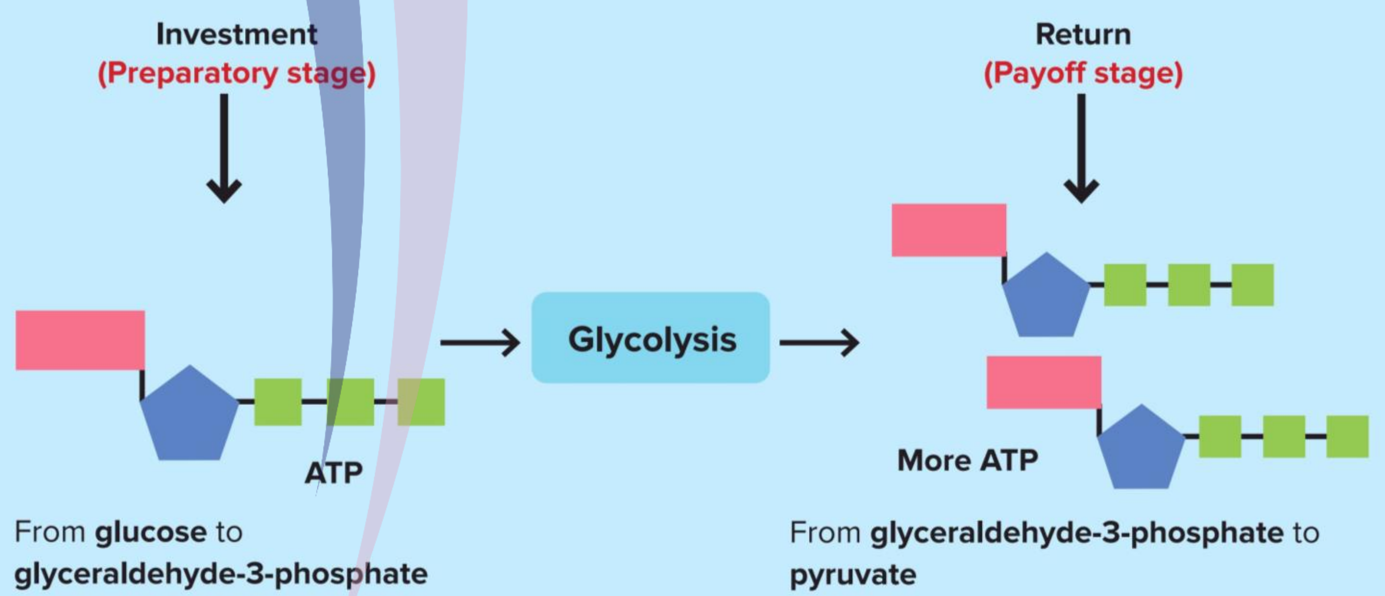
Glycolysis = Business?

- When we set-up a grocery store, we need to invest money. After few years of running the store, we start earning more money than what we have invested.
- Glycolysis is like a business. Initially, the cell needs to invest some ATPs but at the end, more ATP will be generated in return.

Energy in adenosine triphosphate (ATP)



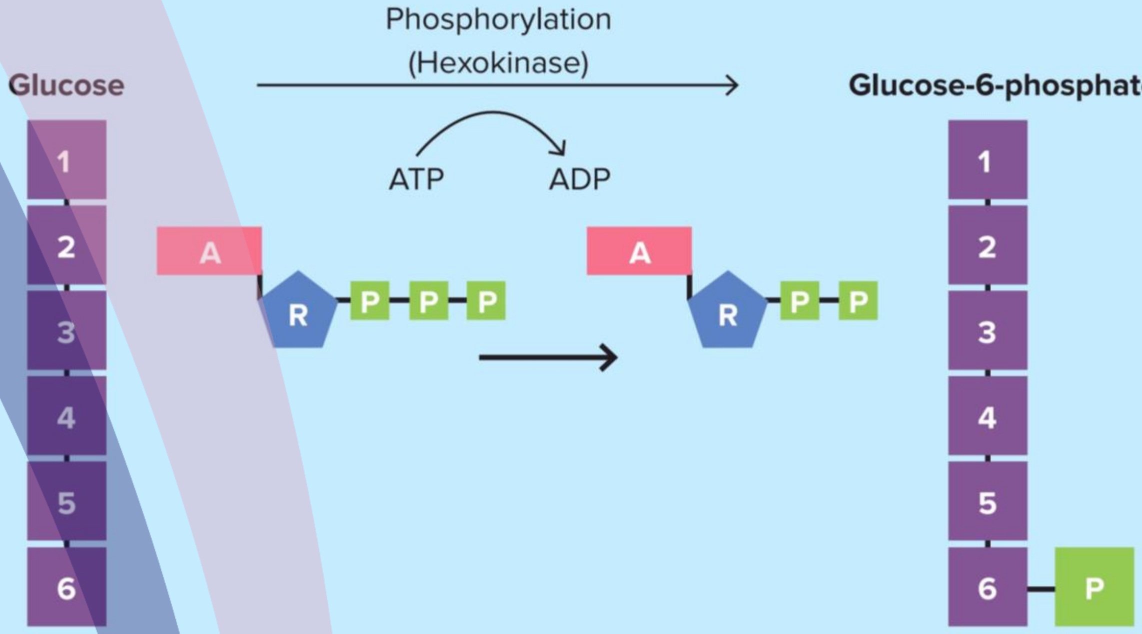
Steps involved in glycolysis



Preparatory stage

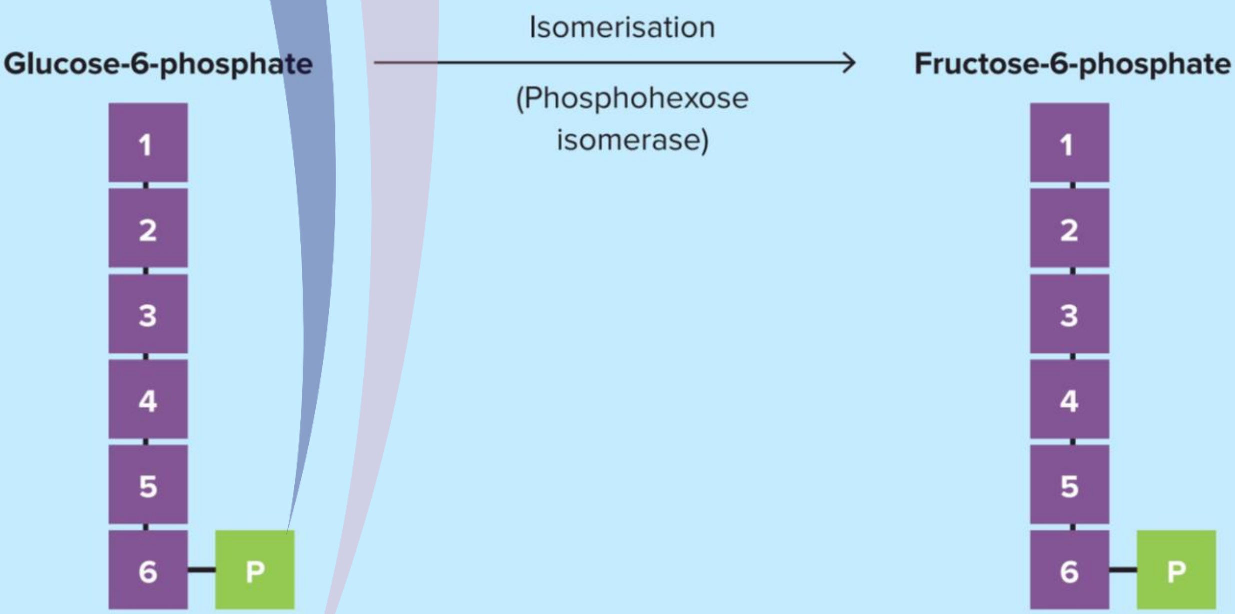
Step 1:

- The first step is the conversion of **glucose to glucose-6-phosphate** with the help of **enzyme hexokinase.**
- **ATP is used** in this reaction in which the third phosphate bond breaks from ATP to join the **sixth carbon** of glucose molecule forming glucose-6-phosphate **(phosphorylation).**



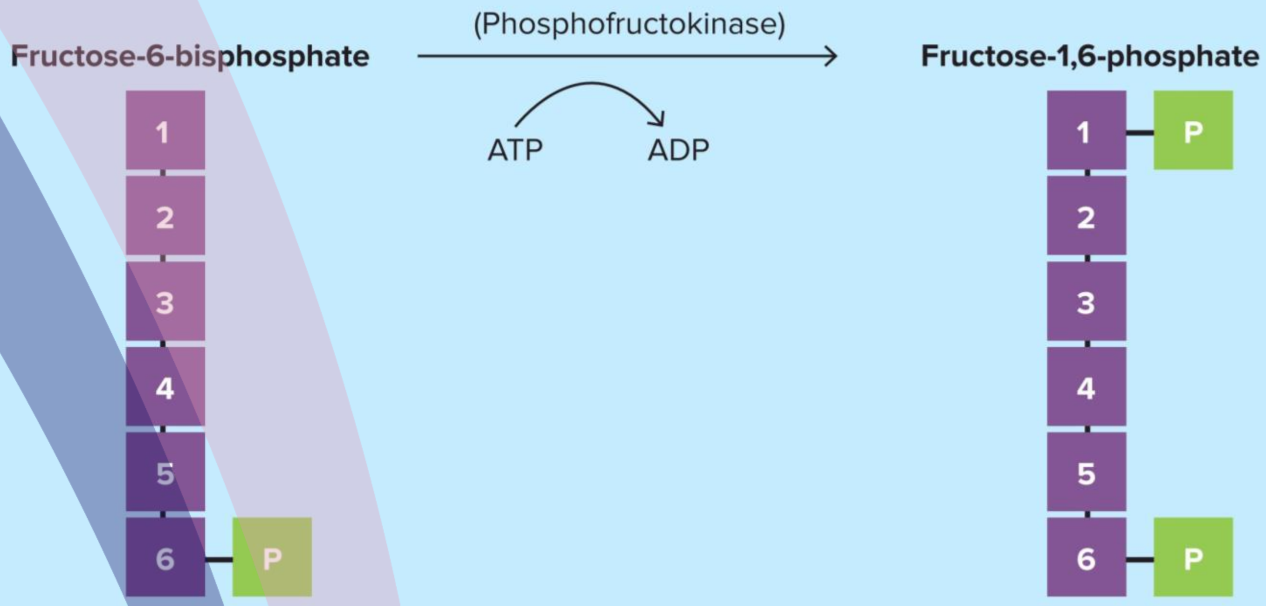
Step 2:

- The second step is the conversion of **glucose-6-phosphate to fructose-6-phosphate** through **isomerisation**.
  - Isomerisation is the conversion of one isomer to another.
    - **Isomers** are molecules with the same chemical formula but with a different structural formula.



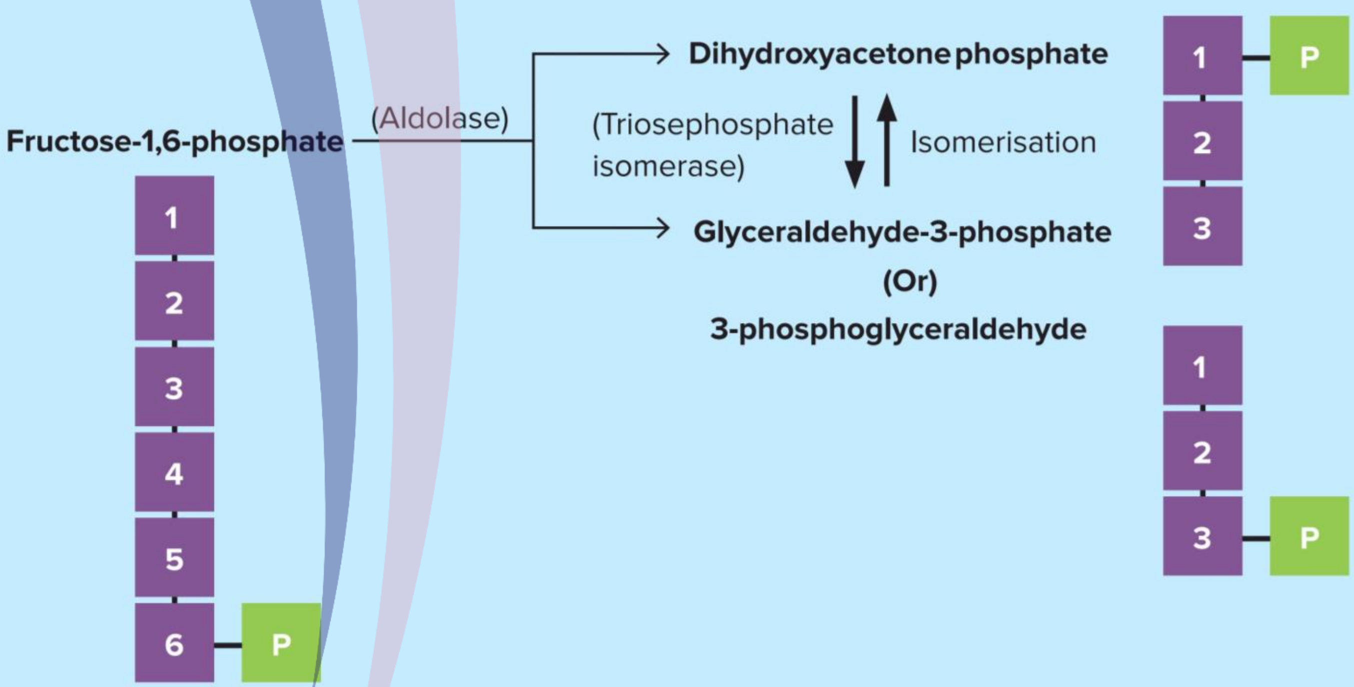
Step 3:

- In the next step, with the help of **another ATP** molecule, **fructose-6-phosphate** is converted to **fructose-1,6-bisphosphate.**
- The last phosphate group breaks off from ATP to join the **first carbon** of fructose-6-phosphate.



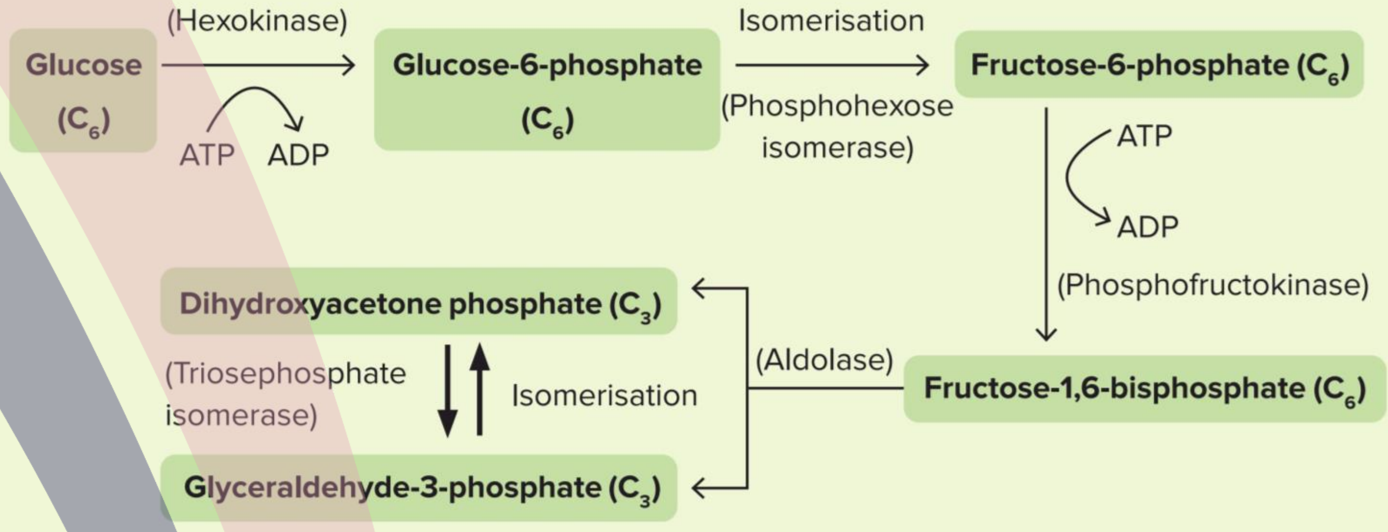
Step 4:

- In the next step, **fructose-1,6-bisphosphate is split** into **two compounds: dihydroxyacetone phosphate** and **glyceraldehyde-3-phosphate.**
- **Dihydroxyacetone phosphate** is then converted into **glyceraldehyde-3-phosphate.**
- After conversion, there are **two molecules** of glyceraldehyde-3-phosphate.



- The given step is the **end of the preparatory stage.**

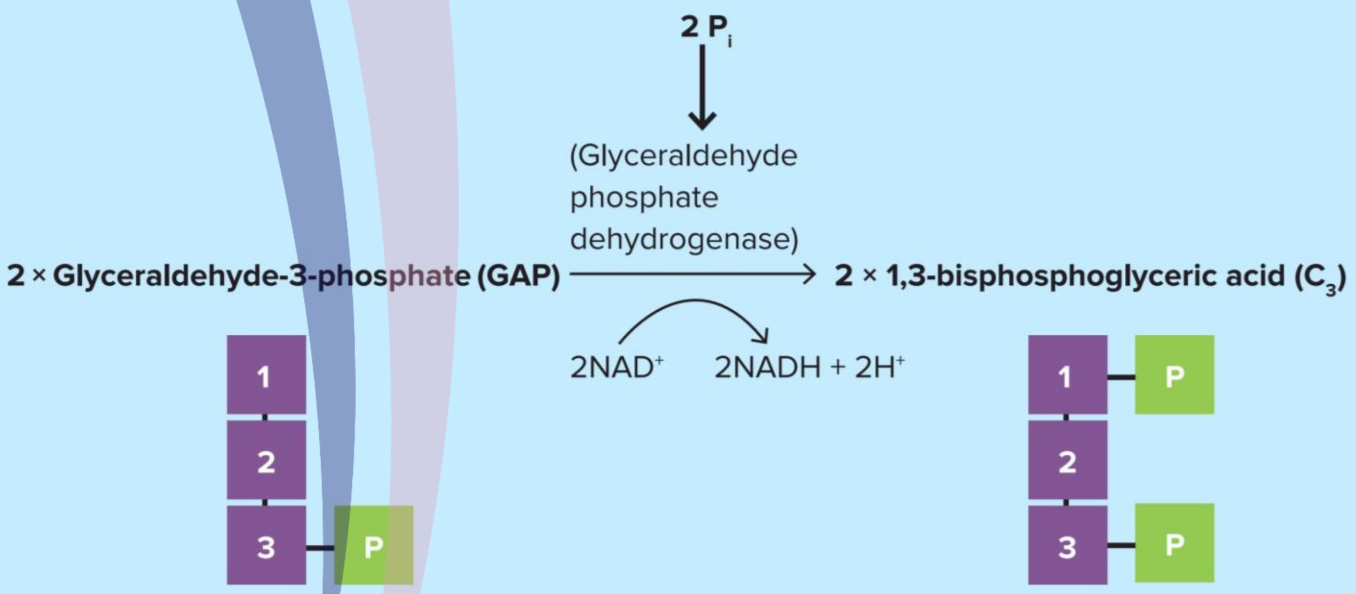
Preparatory stage



Payoff stage

Step 5:

- **Glyceraldehyde-3-phosphate (GAP) is oxidised** to form **1,3-bisphosphoglyceric acid**.
- It is an **exergonic reaction**, since it releases energy.



However, where does this come from?

↓

Oxidation of GAP releases → $2e^- + 2H^+$ + Energy

Energy released is used to take an inorganic phosphate from the solution

- Two electrons and one H^+ are accepted by NAD^+(coenzyme).
- Here, two electrons are used to neutralise the positive charges on H^+ and NAD^+.
- NAD^+ becomes NADH.

↓

$$NAD^+ + 2e^- + 2H^+ \longrightarrow NADH + H^+$$

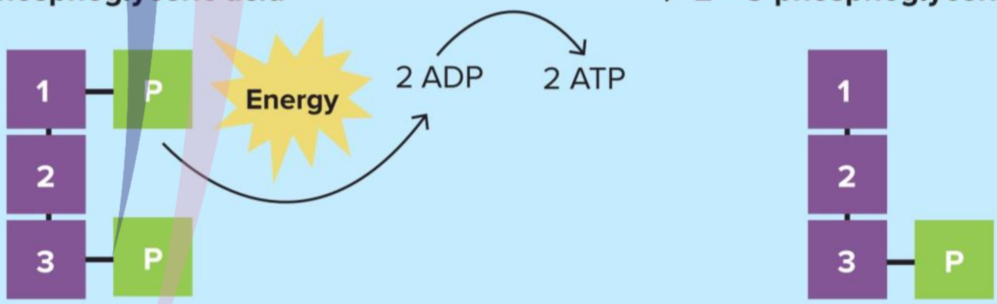
Notes

- One proton and one electron is known as a redox equivalent.
- Whenever something gets oxidised, something else gets reduced.

Step 6:

- The next step is the **first reaction in glycolysis** where **ATP is made.**
- Here, **1,3-bisphosphoglyceric acid** is converted to **3-phosphoglyceric acid.**
- The energy is released when the **high energy bond** between the first carbon and phosphate group is broken.
- The energy released is used to attach the phosphate group to ADP to form ATP.
- As there are two 1,3-bisphosphoglyceric acids, two ATPs are produced.

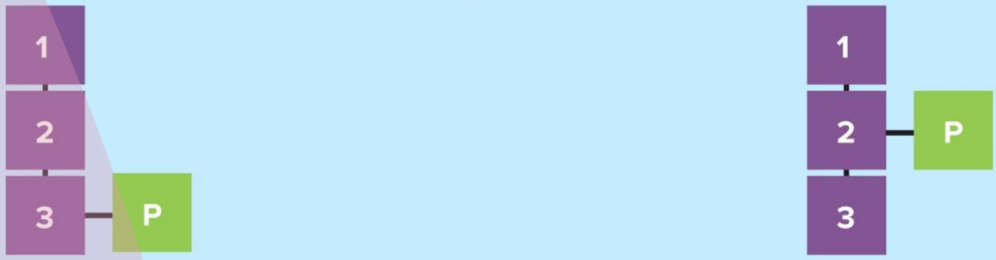
$$2 \times \text{1,3-bisphosphoglyceric acid} \xrightarrow{\text{(Phosphoglycerate kinase)}} 2 \times \text{3-phosphoglyceric acid}$$



Step 7:

- In the next step, **3-phosphoglyceric acid** is **isomerised** to **2-phosphoglycerate** or **2-phosphoglyceric acid.**

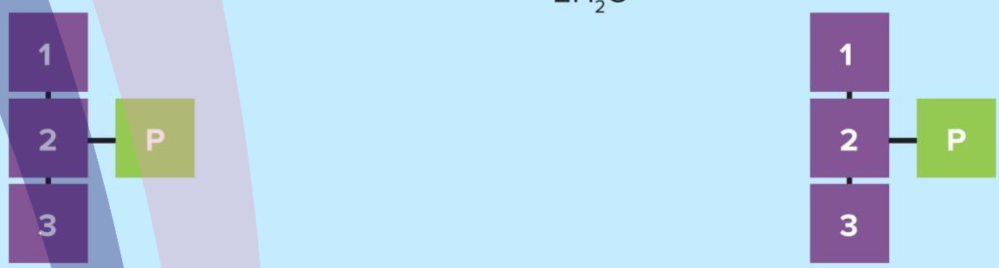
2 × 3-phosphoglyceric acid —Isomerisation (Phosphoglyceromutase)→ **2 × 2-phosphoglycerate**



Step 8:

- 2-phosphoglycerate **loses water** molecule to form **phosphoenolpyruvate**.

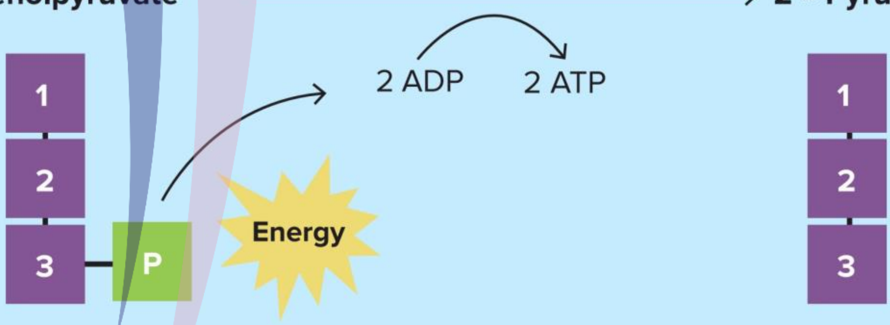
2 × 2-phosphoglycerate —(Enolase), $2H_2O$→ **2×2-phosphoenolpyruvate**



Step 9:

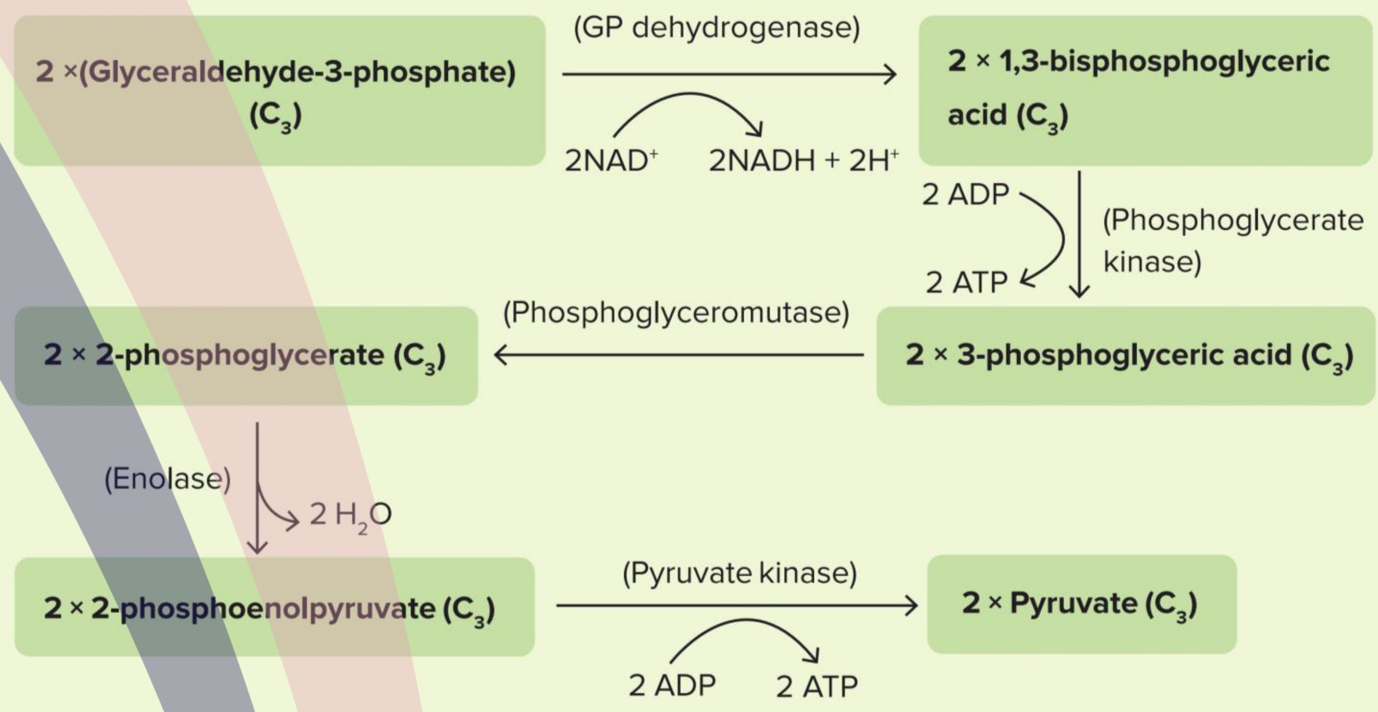
- In the last step of glycolysis, the high-energy bond between the second carbon and the phosphate group is broken down.
- The energy released is used to attach the phosphate group to ADP to form ATP.
- Phosphoenolpyruvate loses the phosphate group to form **pyruvate**.

2-phosphoenolpyruvate —(Pyruvate kinase)→ **2 × Pyruvate**



- At the end of glycolysis, **two pyruvate molecules** are formed.

Payoff stage



Mnemonic to remember glycolysis!!

In Greece, 6 girls got 6 Figs from 16 Forest trees to make Gourmet Dessert & 13 Boys got 3 Peaches, 2 Plums and PEPpers to make a Pie

In	Greece	Glucose
	6 Girls	Glucose-6-phosphate
got	6 Figs	Fructose-6-phosphate
from	16 Forest trees	Fructose-1,6-phosphate
to make	Gourmet	Glyceraldehyde-3-phosphate
	Dessert	Dihydroxyacetone phosphate
&	13 Boys	1,3-bisphosphoglyceric acid
got	3 Peaches	3-phosphoglyceric acid
	2 Plums	2-phosphoglycerate
and	Peppers	Phosphoenolpyruvate
to make a	Pie	Pyruvic acid

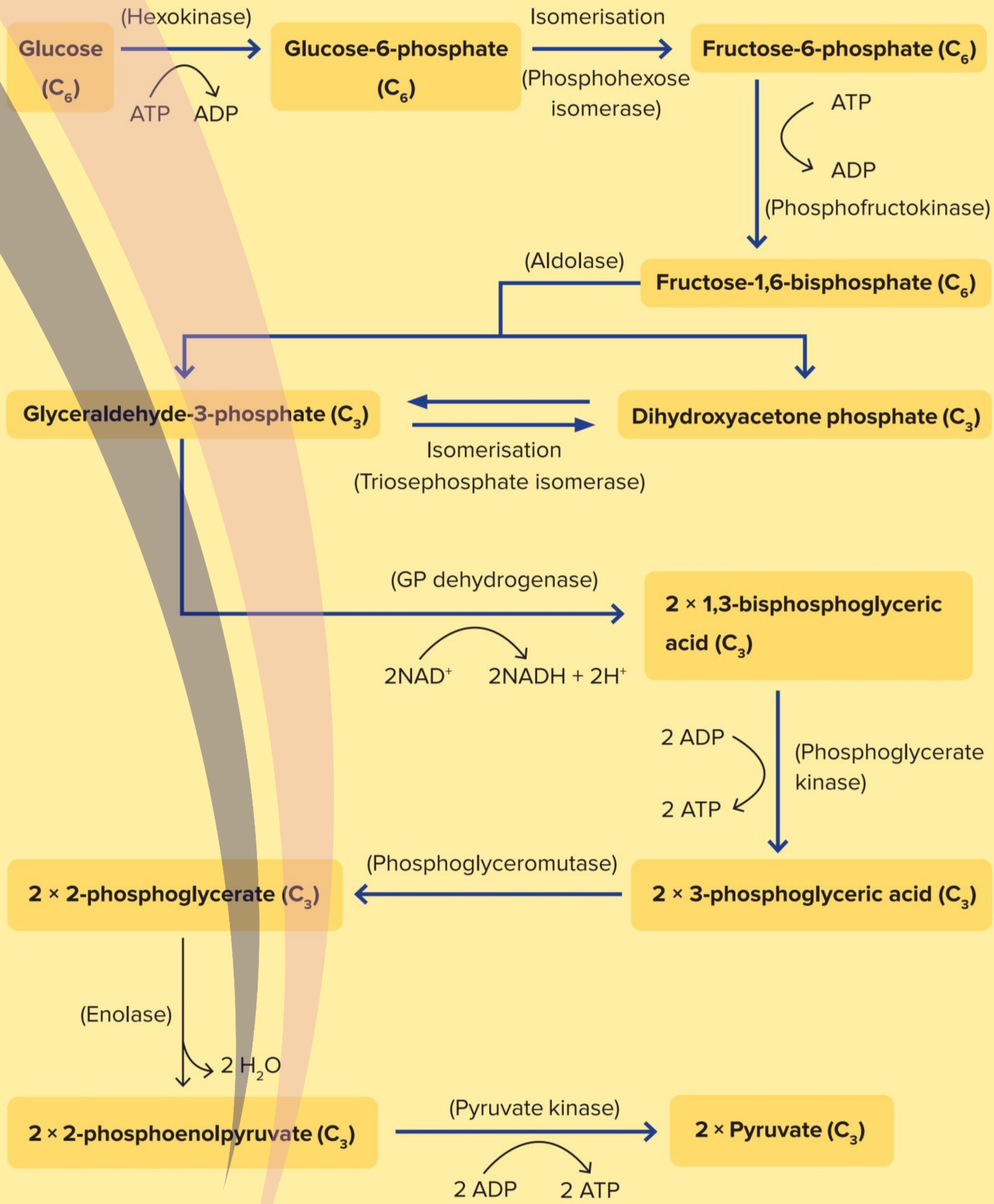
Net profit in glycolysis

Investment/ Return	Step	Number of ATPs gained	Number of ATPs gained per glucose molecule
Investment	Glucose ↓ Glucose-6-phosphate	-1	-1
Investment	Fructose-6-phosphate ↓ Fructose-1,6-phosphate	-1	-1
Return	1,3-Bisphosphoglycerate ↓ 3-phosphoglycerate	1	2
Return	Phosphoenolpyruvate ↓ Pyruvic acid	1	2
Total			2

Investment/ Return	Step	Number of NADH gained	Number of NADH gained per glucose molecule
Return	Glyceraldehyde-3-phosphate ↓ 1,3-bisphospho glyceric acid	1	2
Total			2

Summary sheet

Glycolysis

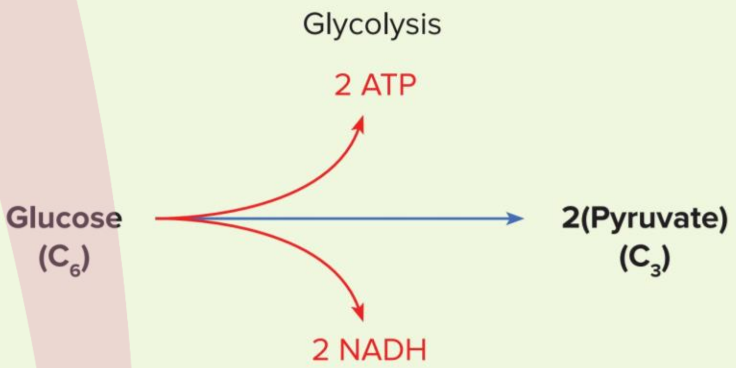


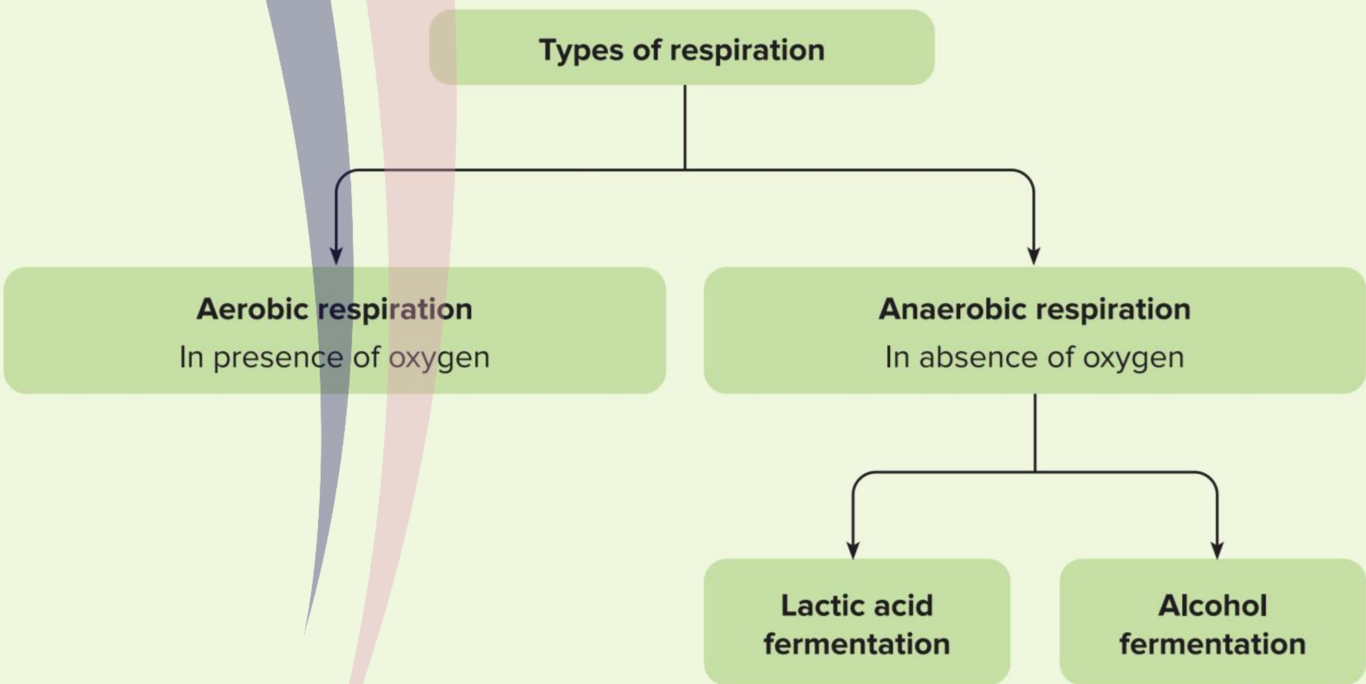
ANAEROBIC RESPIRATION (FERMENTATION), AEROBIC RESPIRATION (OXIDATIVE DECARBOXYLATION)

Key Takeaways

- Lactic acid fermentation
- Alcohol fermentation
- Aerobic respiration
  - → Oxidative decarboxylation

Prerequisites





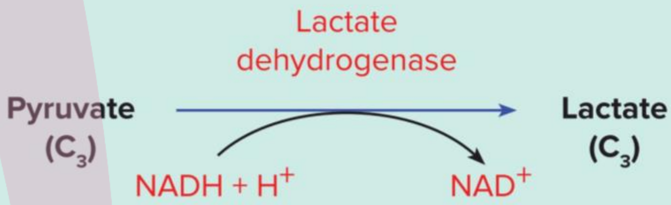
Lactic Acid Fermentation

Story time!

Why does curd taste sour?

- Curd contains bacteria called *Lactobacillus*.
- These bacteria reproduce and produce lactic acid.
- The acid produced thickens the milk and makes the curd sour.

- Fermentation is an **enzyme-catalysed** metabolic process whereby organisms convert **starch or sugar to alcohol or an acid anaerobically and release energy**.
- *Lactobacillus* produces lactic acid from starch or sugar as a result of a type of anaerobic respiration called lactic acid fermentation.
- In this process, the **NADH generated during glycolysis**, gives electrons and hydrogens to pyruvic acid in the presence of **lactate dehydrogenase**, to form **NAD^+** and **lactic acid or lactate**.



Did you know?

We make lactic acid too!

- During strenuous exercise, the body is not able to keep up the constant supply of oxygen required for aerobic respiration, so the muscle cells switch to anaerobic respiration so that they can churn out ATP even in the absence of oxygen.
- Anaerobic respiration churns out ATP at much faster rate.

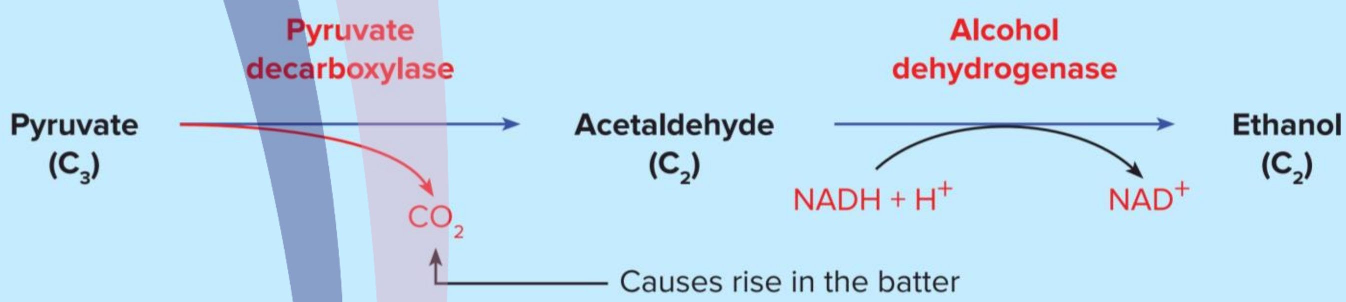
Alcoholic Fermentation

Yummy Dosa!!

Do you know how these dosas are made?

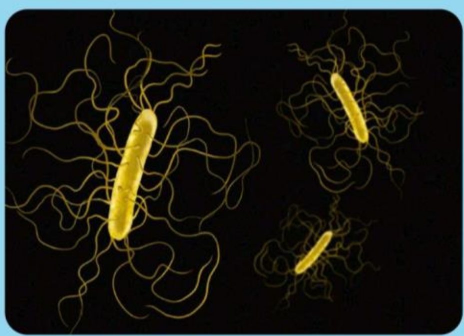
- Dosas are made by grinding down a batter of some dals and rice.
- This batter when left at warm place, rises and forms bubbles.
- But the question is how does the batter rise?
- The rising of dosa batter is due to the release of CO_2 as a result of **alcoholic fermentation**.

- Alcoholic fermentation also starts from pyruvate.
- In the first step of this process, **pyruvic acid breaks** down into **acetaldehyde** and **CO_2 is released**.
- NADH generated during the glycolysis process is used to give electrons and hydrogen to acetaldehyde.
- In the next step, acetaldehyde gets converted into **ethanol** with the help of NADH + H^+.



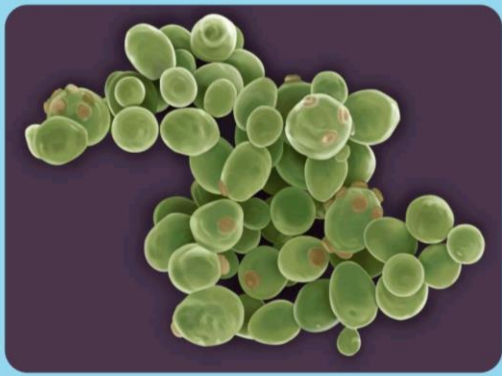
Need for Anaerobic Respiration

- Some organisms have evolved to live in environments without oxygen.
  - *Clostridium difficile* is a deadly anaerobic bacterium that can cause a life-threatening gut infection after prolonged use of antibiotics.
  - This bacterium can be killed in the presence of oxygen.



Clostridium difficile

- Some organisms respire aerobically but in the absence of oxygen, they switch to anaerobic respiration.
  - **Yeast** or ***Saccharomyces cerevisiae*** that is used in bread making is an example.



Saccharomyces cerevisiae

- Anaerobic respiration is fast as it can churn out ATP at a much faster rate, hence is used by muscle cells during strenuous exercise like sprinting.

Drawbacks of Anaerobic Respiration

- It is **inefficient** as less energy is released when compared to aerobic respiration.

Did you know?

Yeast can be killed by their own products!!

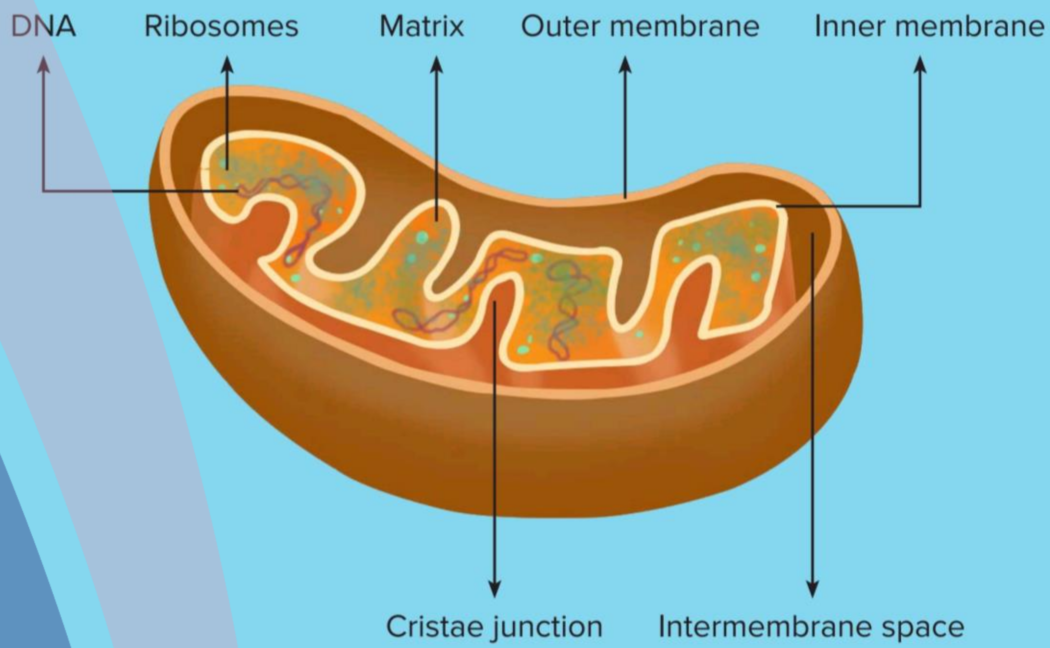
- During alcoholic fermentation, as **yeast** continues to grow and metabolize sugar, the accumulation of **alcohol** becomes toxic and eventually **kills** the cells.
- Most **yeast** strains can tolerate an **alcohol** concentration of about 13% before being killed.

Aerobic Respiration

- It is the **complete oxidation** of organic substances in the **presence of oxygen** and releases CO_2, water, and a large amount of energy present in the substrate.
- The **pyruvate formed in the cytoplasm** during glycolysis **enters mitochondria**, where **aerobic respiration occurs**.

Structure of mitochondria

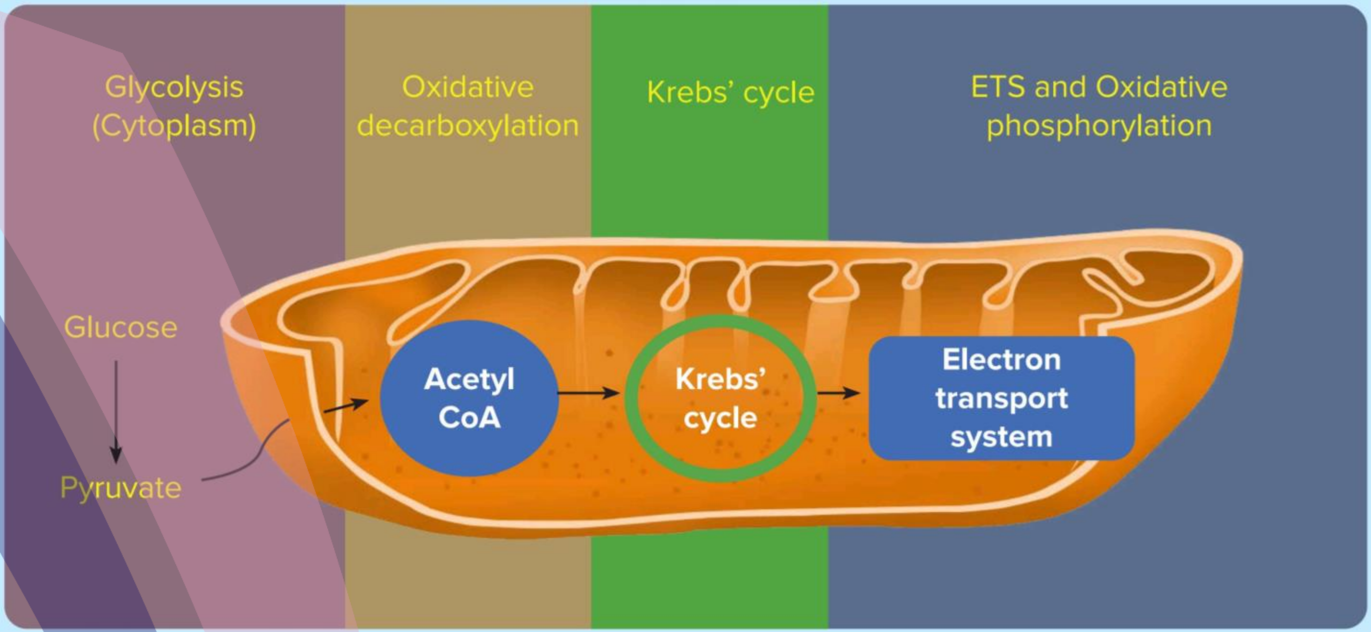
- Found in **eukaryotes**
- **Aerobic respiration** takes place here



- Pyruvate is used to start aerobic respiration.

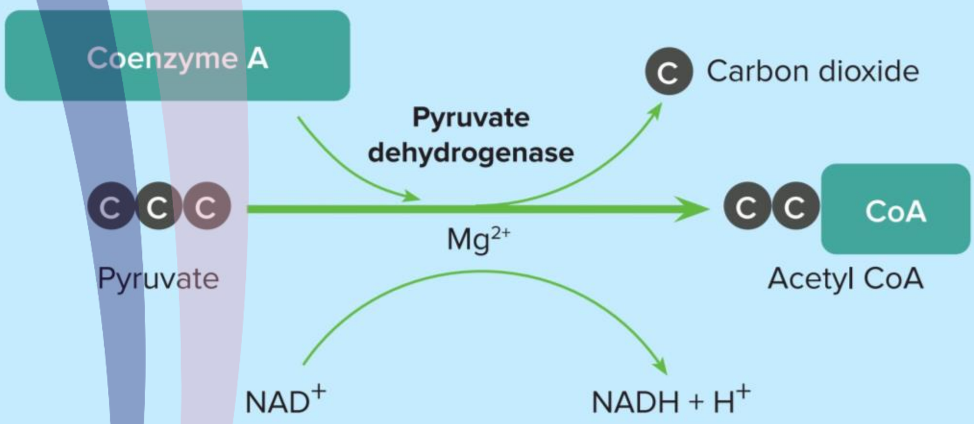
Aerobic respiration in mitochondria

	Oxidative decarboxylation	Krebs' cycle	Electron transport system (ETS) and Oxidative phosphorylation
Steps →	Oxidative decarboxylation	Krebs' cycle	Electron transport system (ETS) and Oxidative phosphorylation
Occurs in →	Mitochondrial matrix	Mitochondrial matrix	Inner mitochondrial membrane

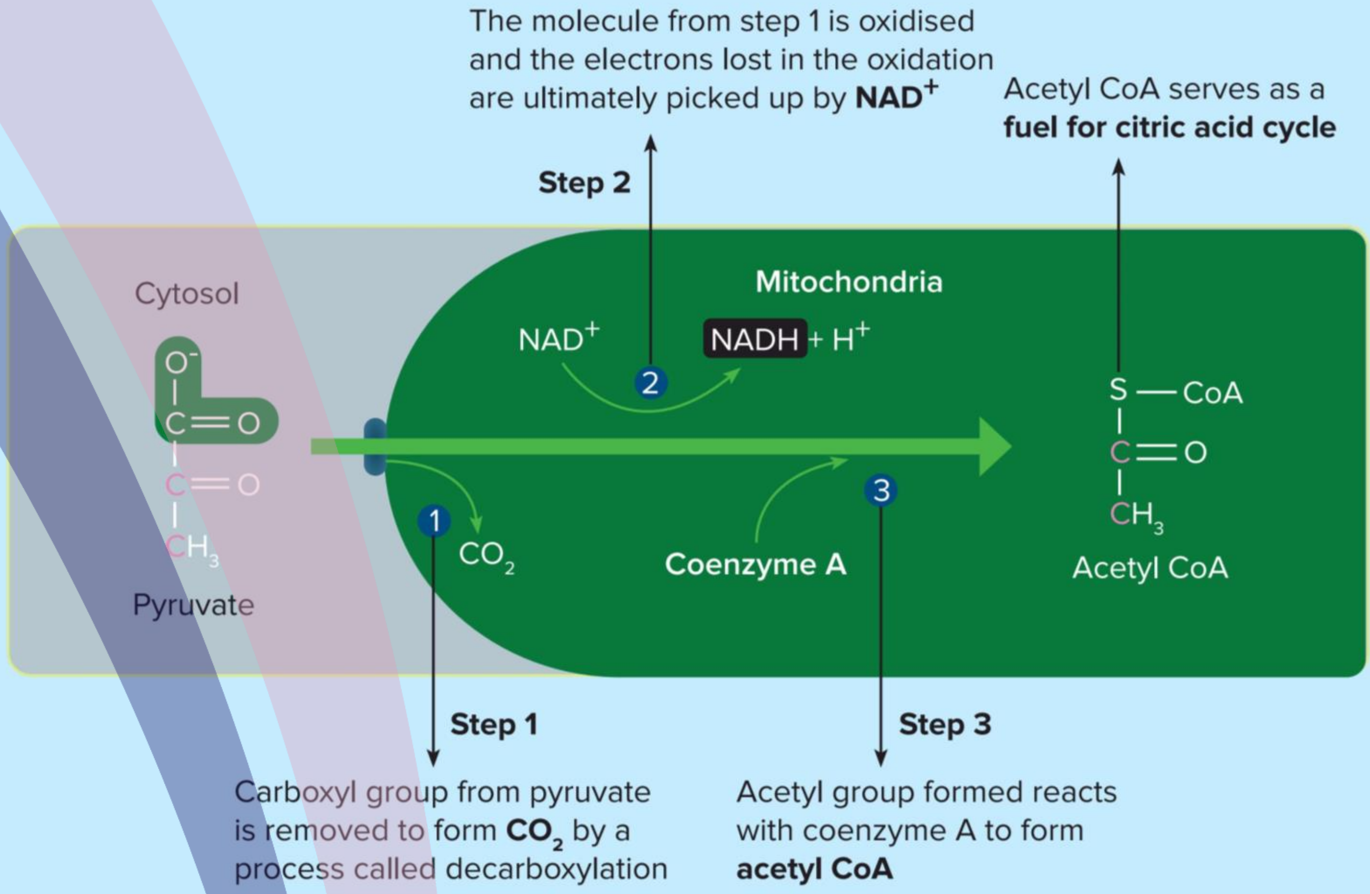


Oxidative decarboxylation

- It is the **connecting link** between glycolysis and Krebs' cycle.
- Pyruvate undergoes **decarboxylation** and **oxidation** to form the final product called **acetyl CoA**.
- Acetyl CoA serves as a fuel for the next step i.e., citric acid cycle or Krebs' cycle.
- The steps in oxidative decarboxylation are carried out by a complex set of reactions catalysed by **pyruvate dehydrogenase**.
- The reactions require the participation of several coenzymes, including NAD^+ and coenzyme A and also Mg^{2+}.

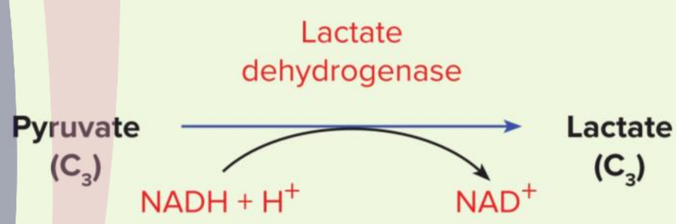


Steps of oxidative decarboxylation

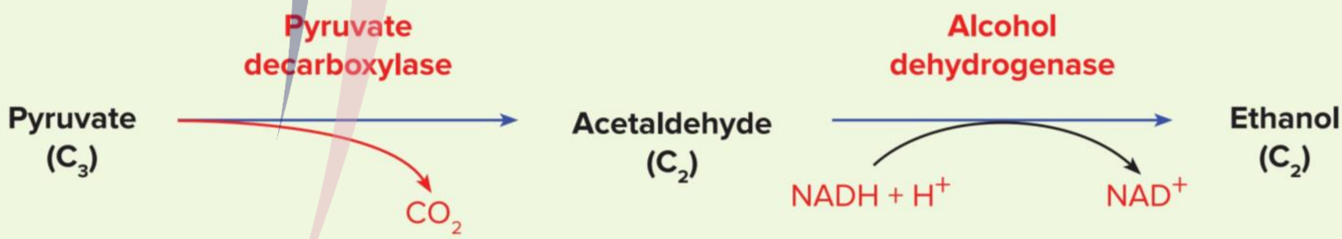


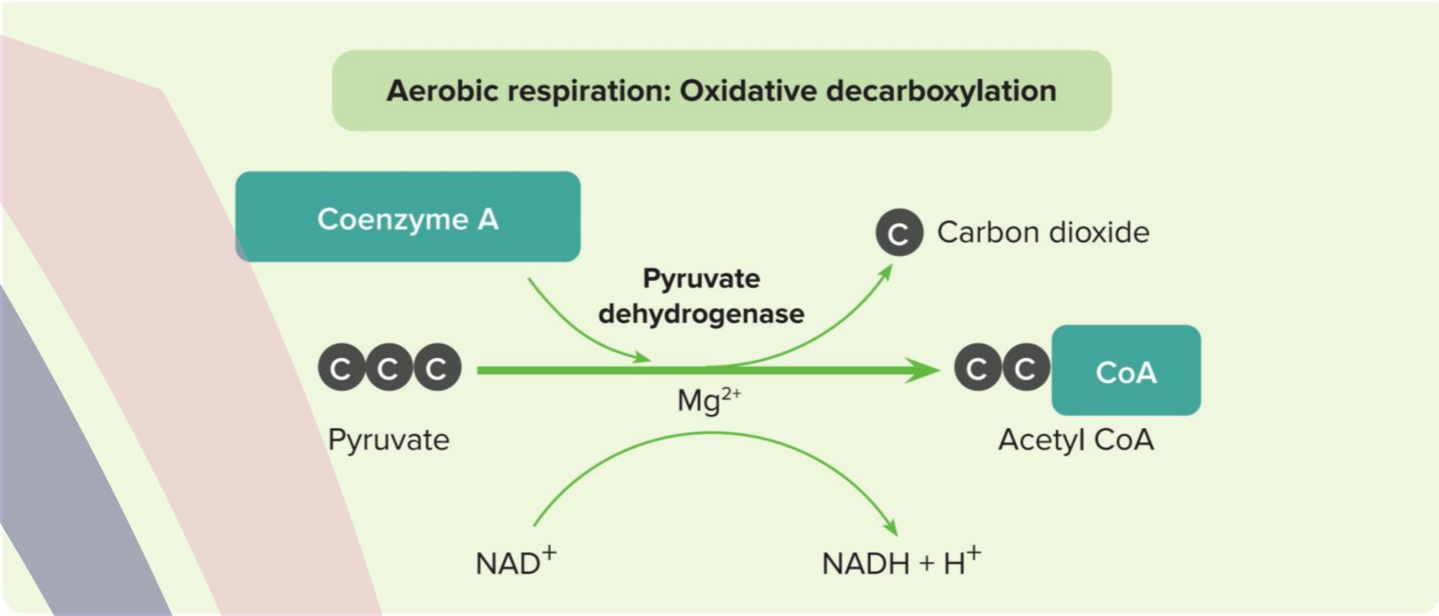
Summary Sheet

Lactic acid fermentation



Alcoholic fermentation




Aerobic respiration: Oxidative decarboxylation
Coenzyme A
C Carbon dioxide
Pyruvate dehydrogenase
C C C
Pyruvate
Mg2+
C C CoA
Acetyl CoA
NAD+
NADH + H+

KREBS' CYCLE, ENERGETICS OF KREBS' CYCLE, SIGNIFICANCE OF KREBS' CYCLE

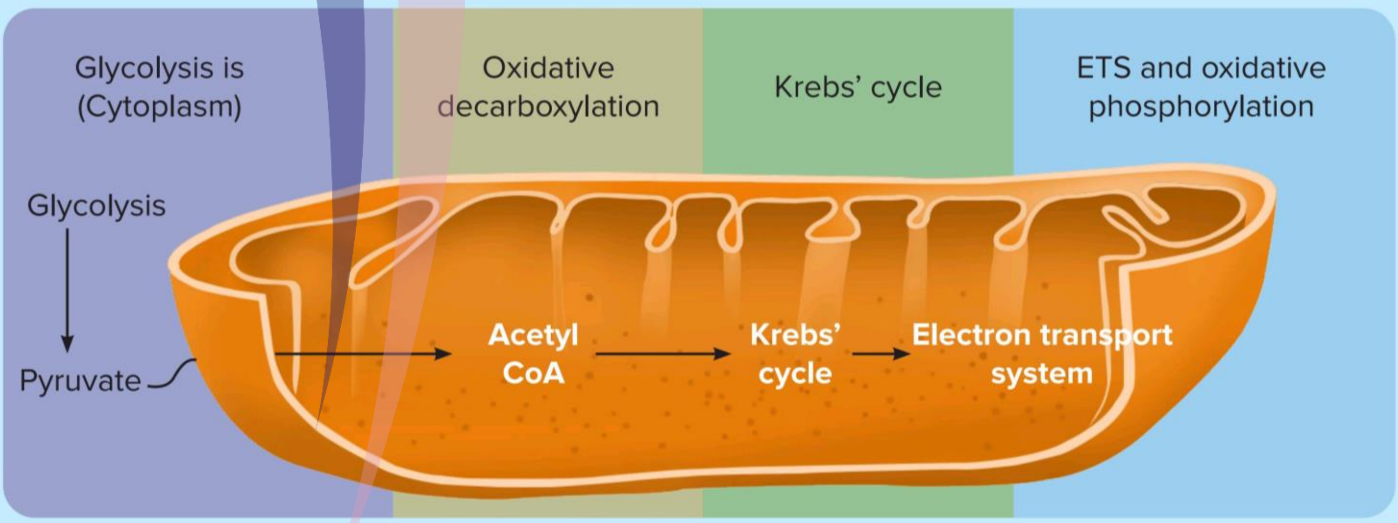
Key Takeaways

- Krebs' cycle
  - Steps of Krebs' cycle
  - Overall inputs and products of Krebs' cycle
  - Significance of Krebs' cycle

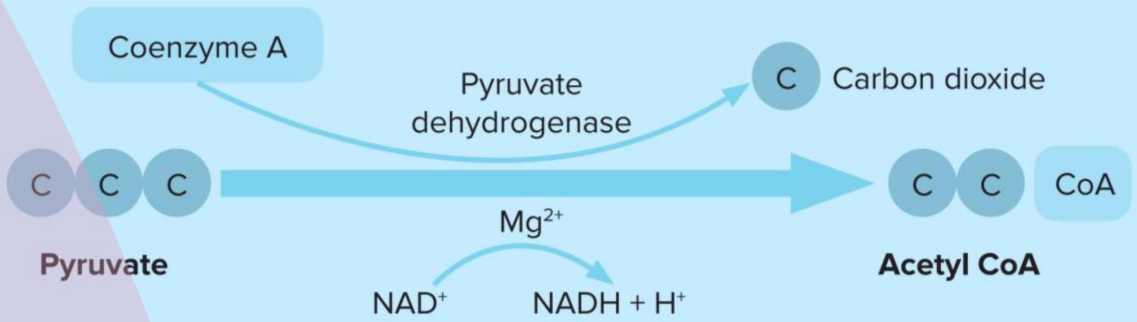
Prerequisites

Aerobic respiration in mitochondria

Steps	Oxidative decarboxylation	Krebs' cycle	Electron transport system (ETS) and oxidative phosphorylation
Occurs in	Mitochondrial matrix	Mitochondrial matrix	Inner mitochondrial membrane



- **Oxidative decarboxylation**



Krebs' Cycle

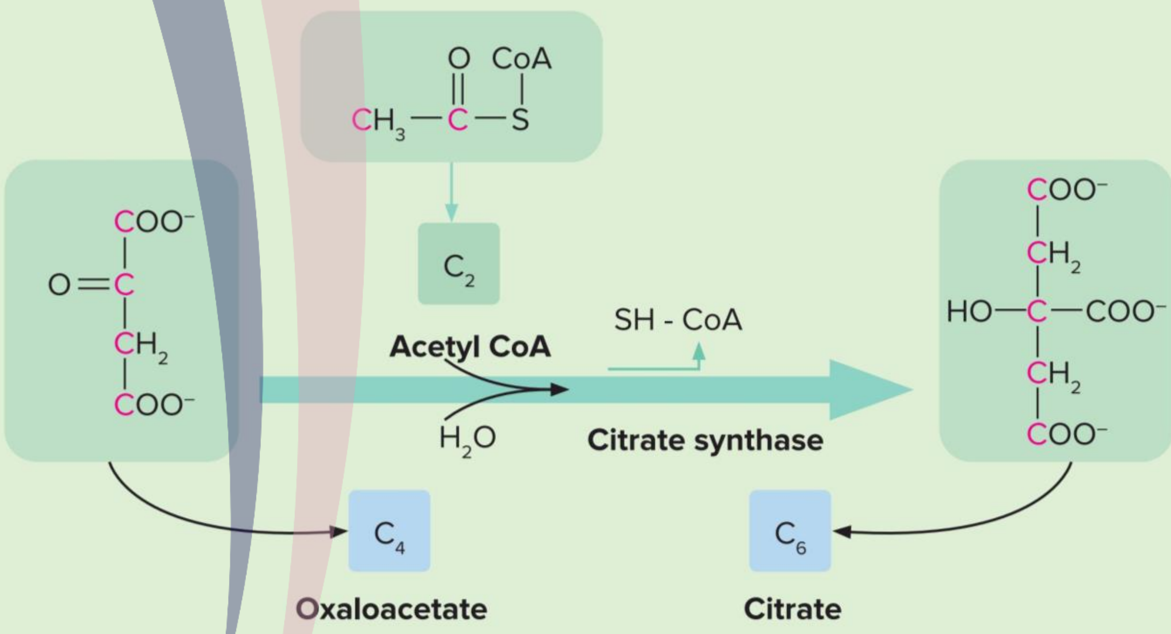
Hans Krebs

- It is named after the scientist **Hans Krebs** who first elucidated it.
- It takes place in the **mitochondrial matrix**.

Steps of Krebs' cycle

Step 1

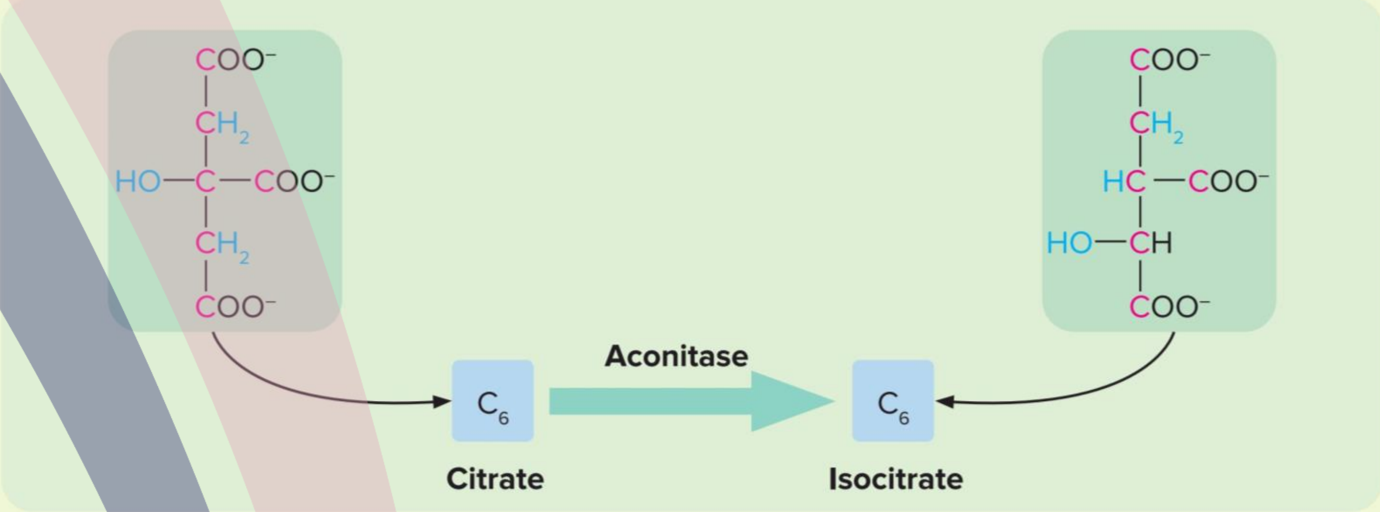
- This cycle starts with the **condensation of acetyl CoA with oxaloacetic acid** (OAA) and water to **yield citric acid**.
  - The reaction is catalysed by an enzyme **citrate synthase**, and a molecule of **CoA** is released.



  - The **first compound** formed during the cycle is **citrate**. Hence, the cycle is also known as the **citric acid cycle**.
  - Citric acid is also known as tricarboxylic acid. Hence, the Krebs' cycle is also known as the **tricarboxylic acid cycle (TCA cycle)**.

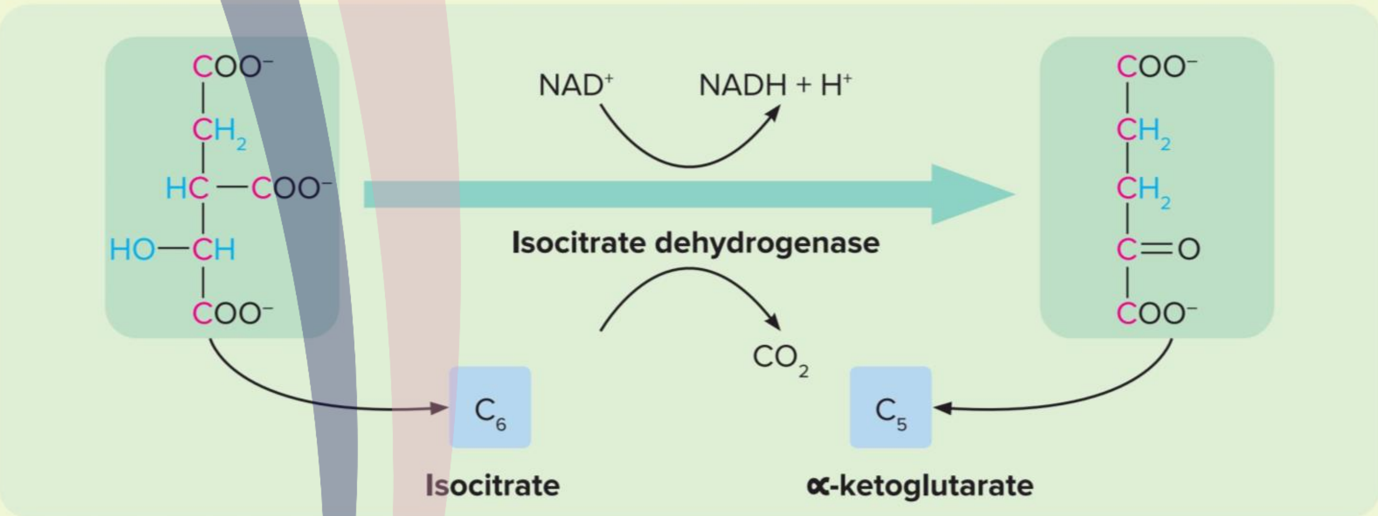
Step 2

- In the next step, citrate is **isomerised to isocitrate** in the presence of **aconitase**.
  - Isocitrate is better suited for the next step of oxidation-reduction reactions.



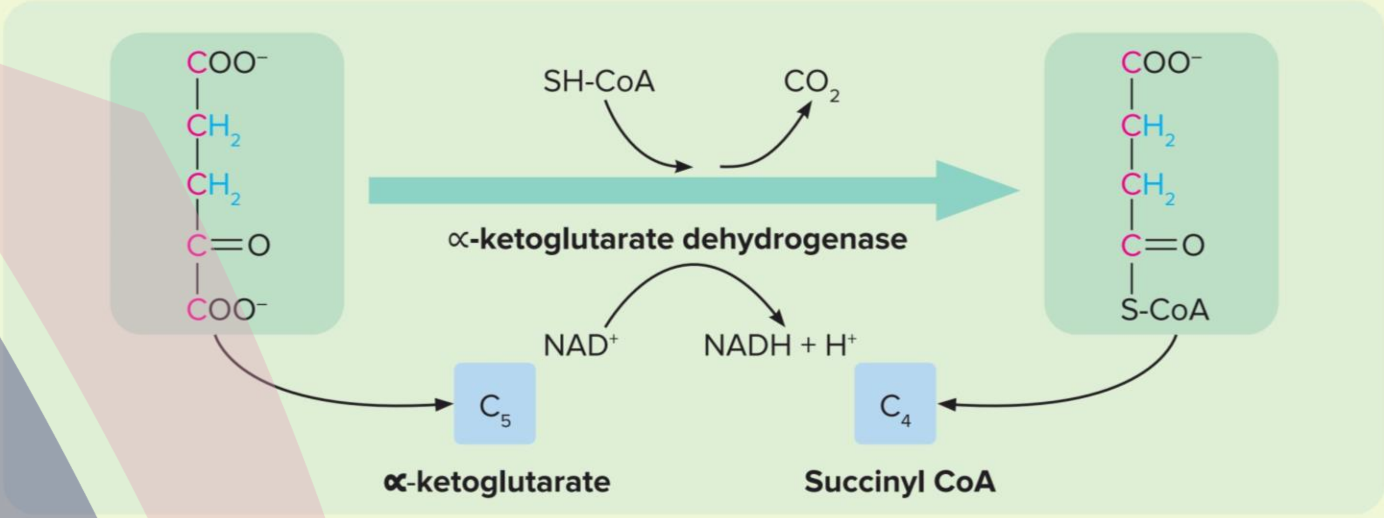
Step 3

- Isocitrate undergoes **oxidative decarboxylation** to form **α-ketoglutarate** catalysed by isocitrate dehydrogenase.
- In this process, **NAD^+ is reduced to NADH** + H^+ and **CO_2 is released**.



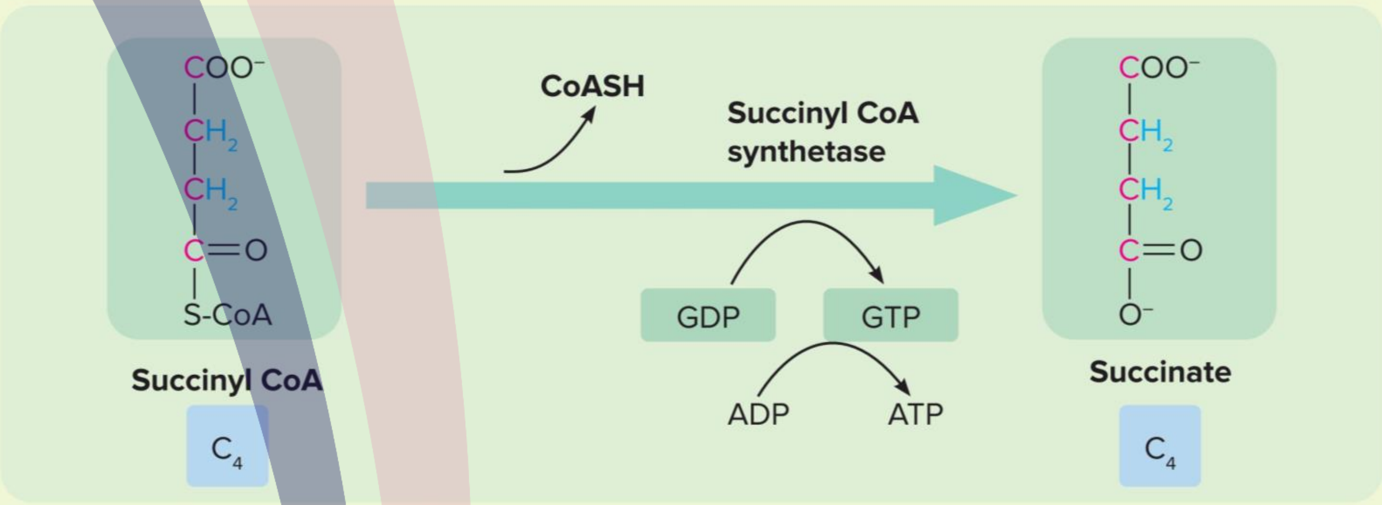
Step 4

- In the fourth step, **α-ketoglutarate** undergoes **oxidative decarboxylation** to form **succinyl CoA**.
  - This reaction is catalysed by **α-ketoglutarate dehydrogenase**.
  - In this process as well, **NAD^+** undergoes **reduction** to form **NADH + H^+** and **CO_2 is released**.



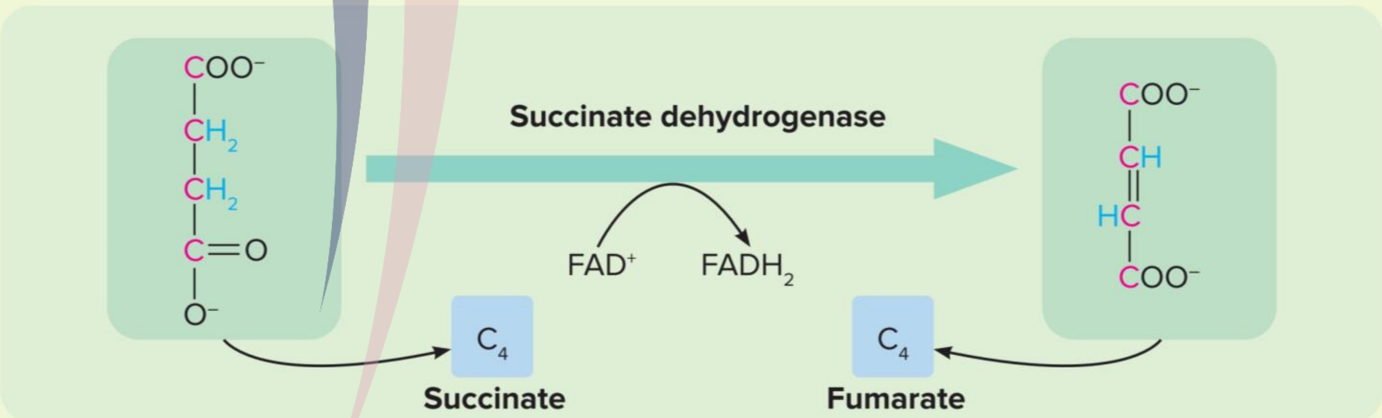
Step 5

- **Succinyl CoA synthetase** catalyses the conversion of succinyl CoA to succinate.
  - **GTP** is formed in this reaction, which is further used to generate ATP.



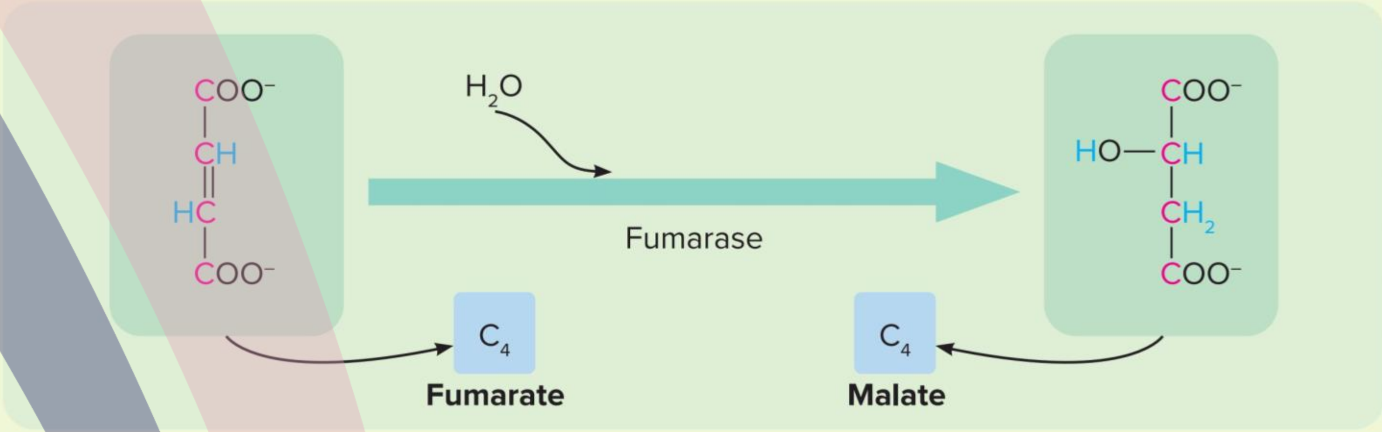
Step 6

- **Succinate dehydrogenase** (SDH) is an enzyme found in the inner mitochondrial membrane that is an integral component of the mitochondrial respiratory chain.
  - It catalyses the conversion of **succinate to fumarate**.
  - Two hydrogen atoms are removed from the succinate and added to FAD^+ to form **$FADH_2$**.



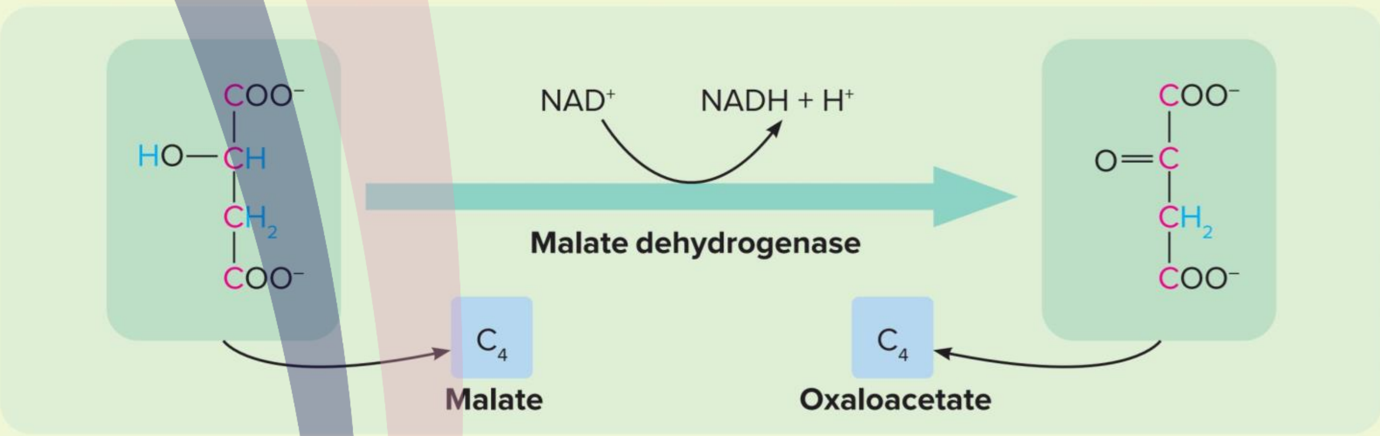
Step 7

- **Water** is added to fumarate to form another four-carbon molecule known as **malate**.

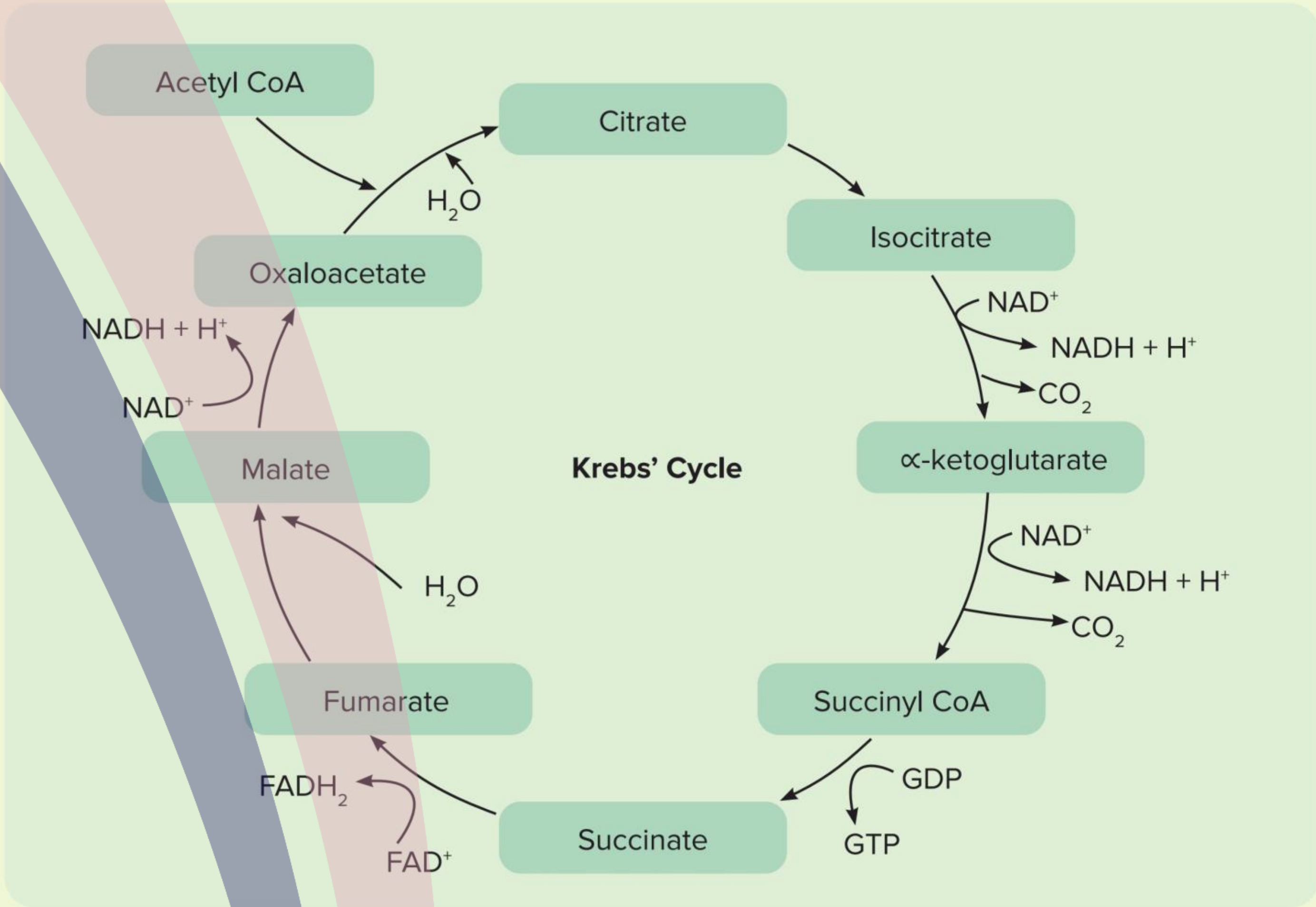


Step 8

- Malate dehydrogenase catalyses the **conversion of malate** to **oxaloacetate**.
  - In this process, **NAD^+ is reduced to NADH**.
  - Oxaloacetate is regenerated. It is an acceptor molecule.



Overall inputs and products of Krebs' cycle



Input	→	Product
Acetyl CoA		CoASH
+		+
3 NAD^+		3 NADH
+		+
FAD^+		$3H^+$
+		+
GDP		$FADH_2$
+		+
P_i		GTP
+		+
$2H_2O$		$2CO_2$

Mnemonic to remember Krebs' cycle

Our City Is Kept Safe and Secure From Malice Mobsters

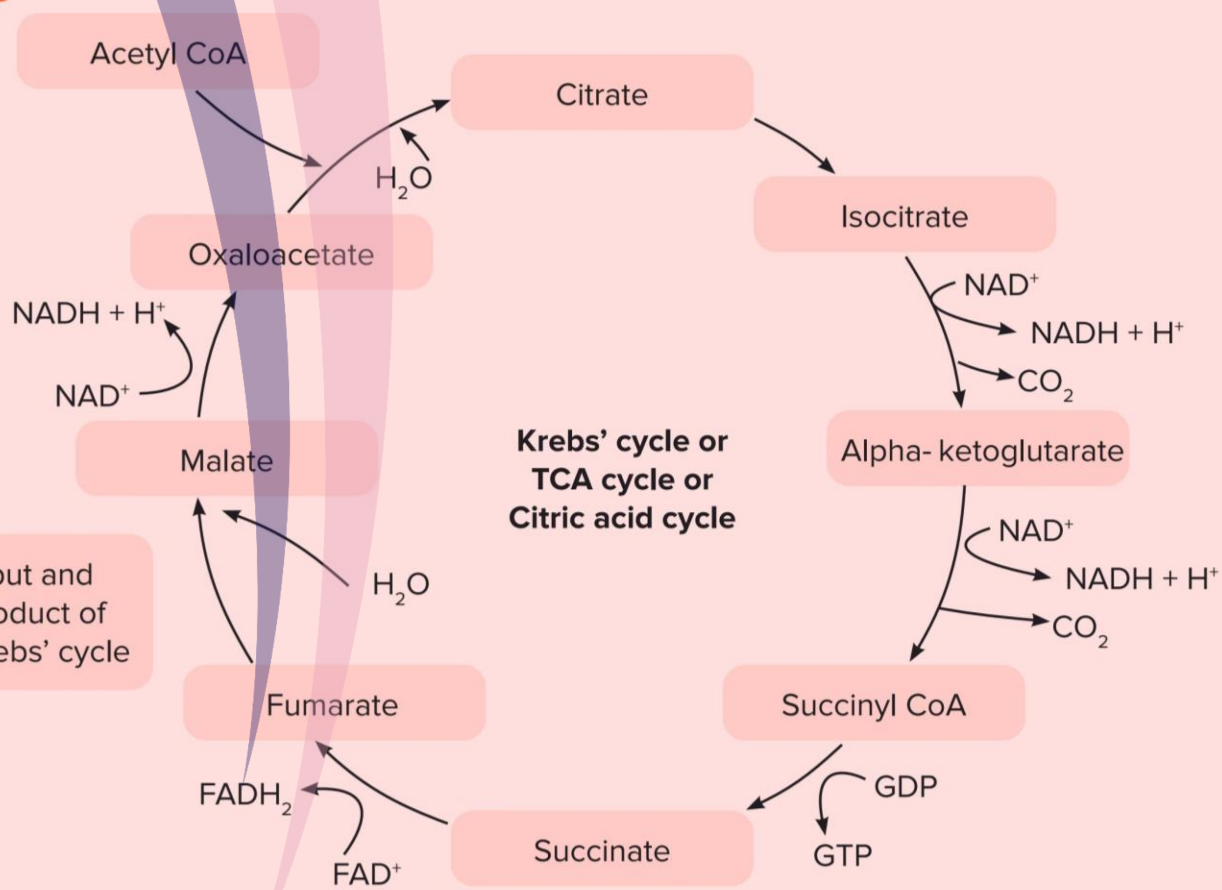
	Our	Oxaloacetate
	City	Citrate
	Is	Isocitrate
	Kept	Alpha-ketoglutarate
	Safe	Succinyl CoA
and	**Secure**	Succinate
	From	Fumarate
	Malice Mobsters	Malate

Significance of Krebs' cycle

- The TCA cycle is **amphibolic**, i.e., it serves as a catabolic as well as an anabolic pathway.
- Acetyl CoA is modified in the mitochondria to **produce energy precursors** for the **electron transport chain** or oxidative phosphorylation.
- Molecules produced in this reaction are the building blocks of a large number of important processes like the synthesis of fatty acids, cholesterol, and amino acids for building proteins.

Summary Sheet

Input and product of Krebs' cycle



ELECTRON TRANSPORT CHAIN OR OXIDATIVE PHOSPHORYLATION, RESPIRATORY BALANCE SHEET

Key Takeaways

- Role of NADH and $FADH_2$
- Electron transport system (ETS) or Oxidative phosphorylation
  - Complexes involved
  - Electron transport process
- Respiratory balance sheet

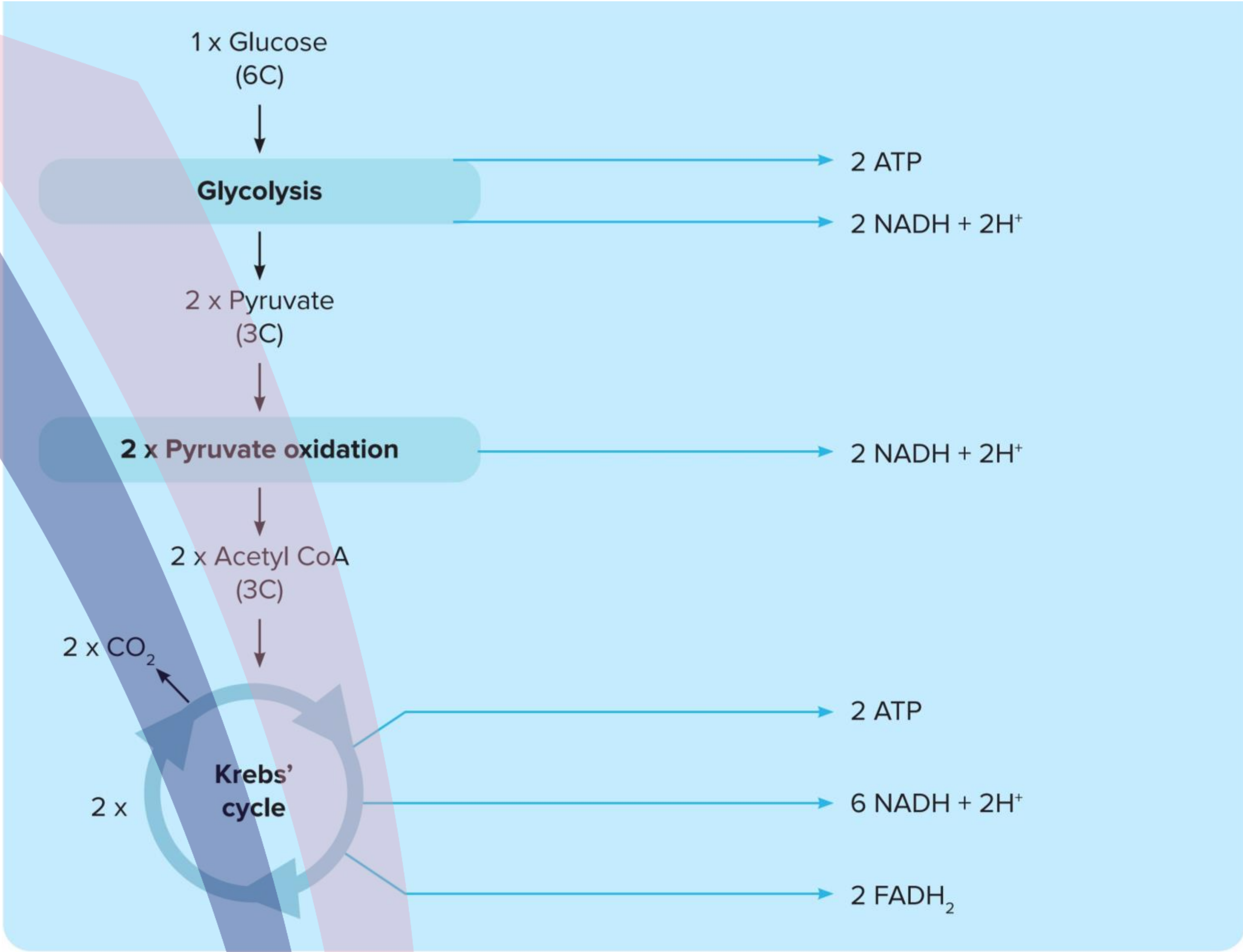
Prerequisites

- Aerobic respiration

$$\underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2} \longrightarrow \underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \text{Energy}$$

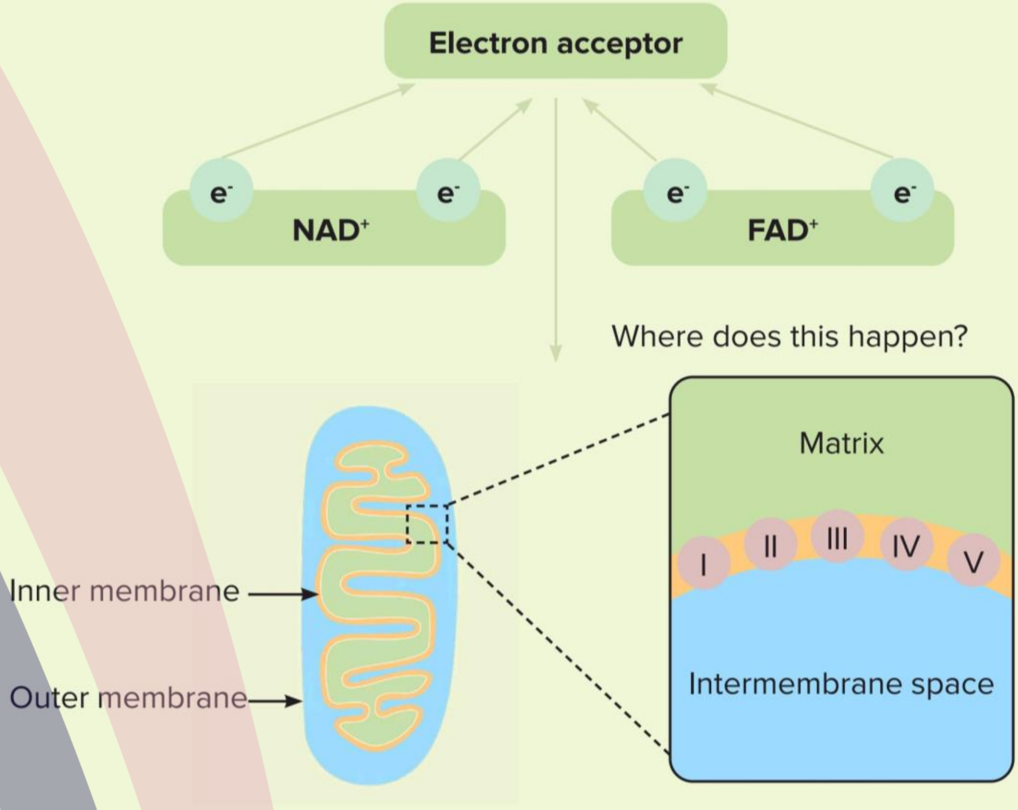
- Aerobic respiration: Steps

Glycolysis
↓
Pyruvate oxidation
↓
Tricarboxylic acid (TCA) cycle
↓
Electron transport system (ETS)



Role of NADH and $FADH_2$

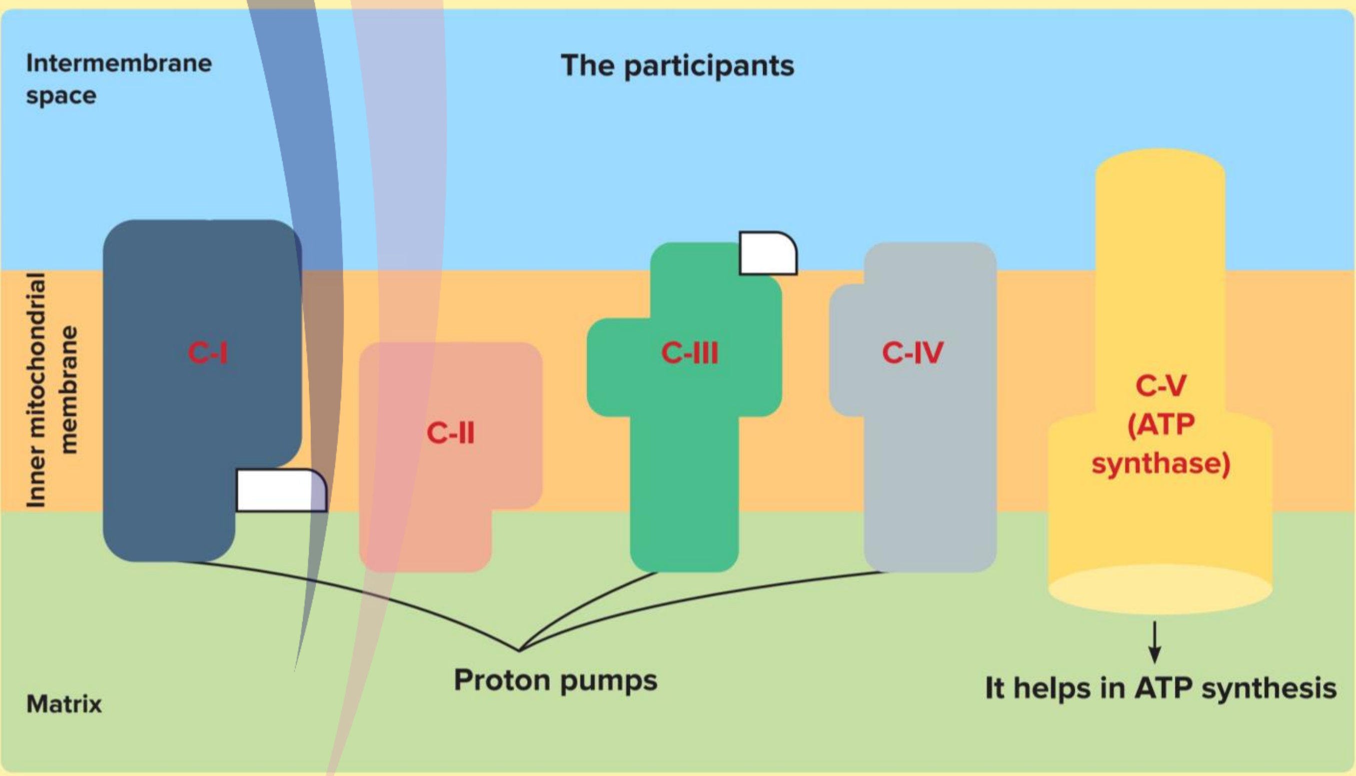
- The initial steps of aerobic respiration produce many molecules of:
  - ATP
  - NADH
  - $FADH_2$
- ATP is used as the **energy currency** in the cell to power biological processes.
- NADH and $FADH_2$ are:
  - **Co-factors:** They are non-protein chemical compounds or metallic ions that are required for the enzyme's activity as a catalyst.
  - **Electron carriers:** Both carry two electrons per molecule from the earlier respiration processes.
- The electrons from NADH and $FADH_2$ are donated to an electron acceptor.
- Transfer of electron occurs through a series of steps that are meant to create a lot of ATP.



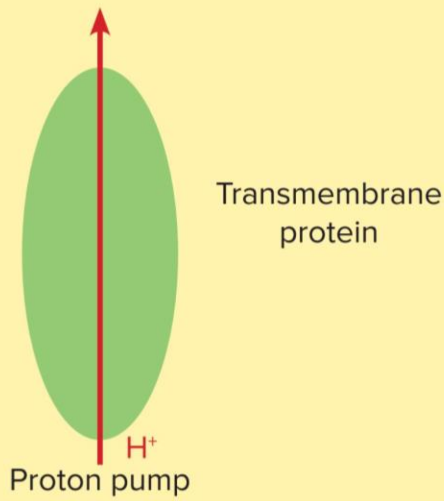
Within the mitochondria, the transfer of electrons occur in the **inner mitochondrial membrane.**

Electron Transport System

- The transfer of electrons occurs through the following setup in the inner mitochondrial membrane.



- There are **four complexes** that transfer the electrons from NADH and $FADH_2$ to the electron acceptor.
- The fifth complex known as **complex V** or **ATP synthase** helps in the synthesis of ATP.
- Electrons are passed through the **proton pumps** into the intermembrane space.
    - Phospholipid bilayer cell membranes are impermeable to H^+ ions and protons.
    - Sometimes, the pumping of protons may require energy, but in this case, the energy comes from the transport of electrons.

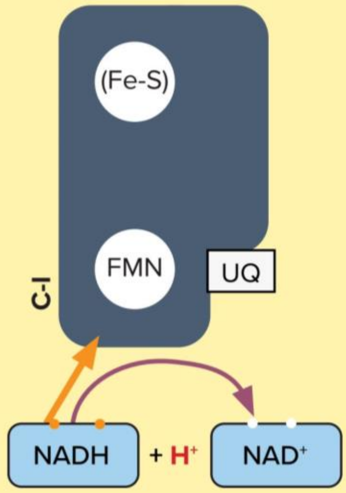


Complex I

- It is the **first complex** through which electrons enter.

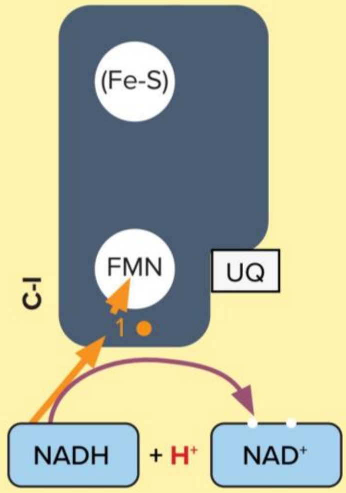
NADH → Complex I

- Electrons from NADH produced in the Krebs' cycle come to **complex 1 NADH dehydrogenase (C-I)**.
- **C-I consists of two prosthetic groups**, FMN (flavin mononucleotide) and (Fe-S).
    - **Prosthetic group** is a tightly bound, specific, non-polypeptide unit required for the biological function of some proteins.
- **Ubiquinone (UQ)** is a **mobile electron carrier** closely associated with C-I.
- NADH gives up two electrons and gets oxidised to NAD^+.



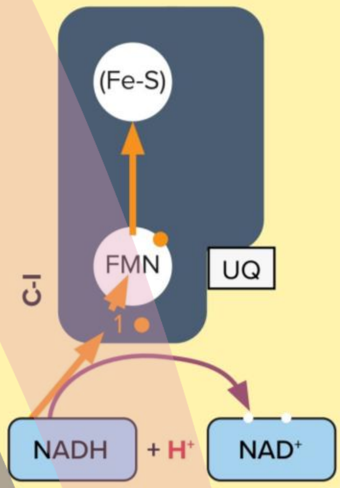
Electrons → FMN

- Even though NADH gives up two electrons, the electrons are carried one at a time.
- So, the **path of only one electron** is shown.
- These electrons (one by one) are passed on to **FMN**.
    - FMN is a tightly bound (to its enzymes) cofactor that can accept (or donate) two electrons, but accepts one at a time.



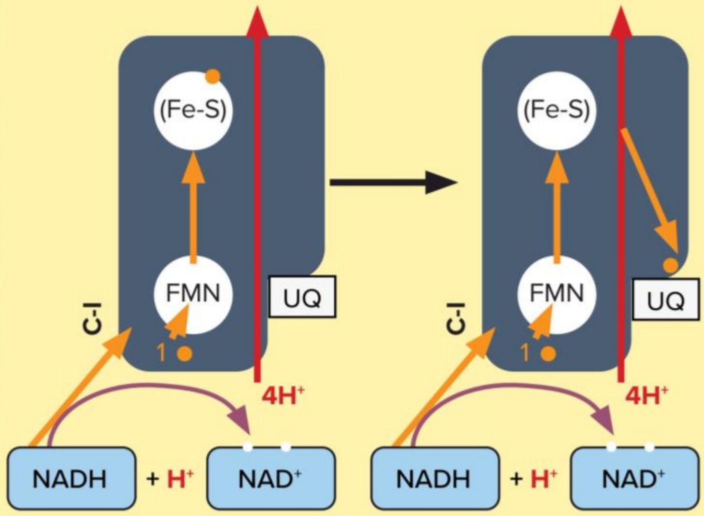
FMN → (Fe-S)

- Electrons then move to the **iron-sulphur cluster**, where **Fe^{3+}** gets reduced to **Fe^{2+}**.



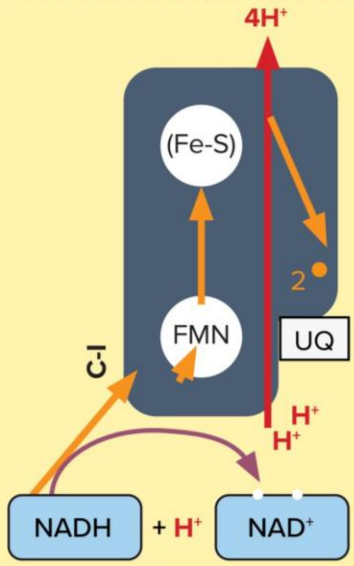
Protons pumped

- C-I being a **proton pump**, for every pair of electron that pass through it, it pumps **4 H^+** into the intermembrane space from the matrix.



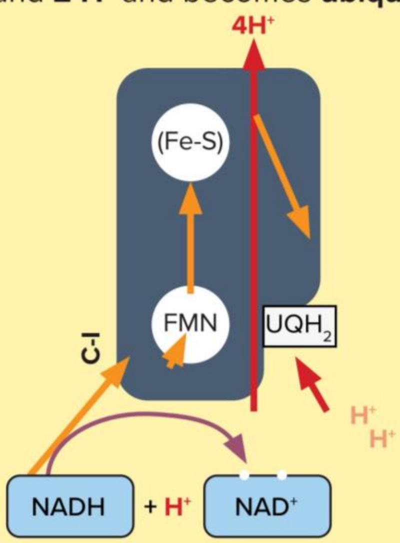
Complex I → Ubiquinone

- In this step, electrons are accepted by an electron carrier known as **ubiquinone (UQ)**.
  - It is also a hydrogen carrier as it carries **two electrons** (the other electron also follows the same path and is carried by ubiquinone) along with **two H^+** ions from the matrix to the next stage.

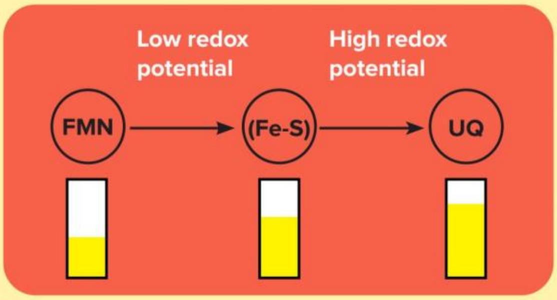


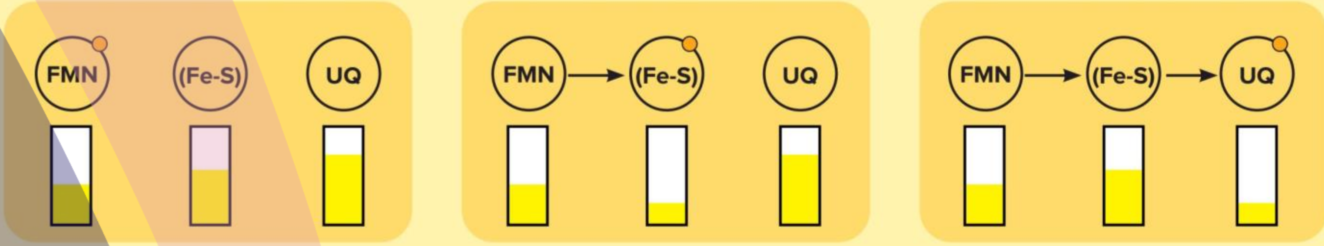
Ubiquinone → Ubiquinol

- UQ transports the **two electrons** and **2 H^+** and becomes **ubiquinol (UQH_2)**.



What drives the movement of electrons?





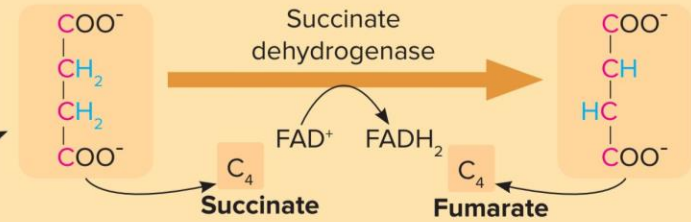
- FMN with an electron has a lower potential as compared to (Fe-S); hence, it loses the electron to (Fe-S).

- Potential of FMN goes up and that of (Fe-S) reduces.
- (Fe-S) transfers its electron to UQ as it has more potential than that of FMN.

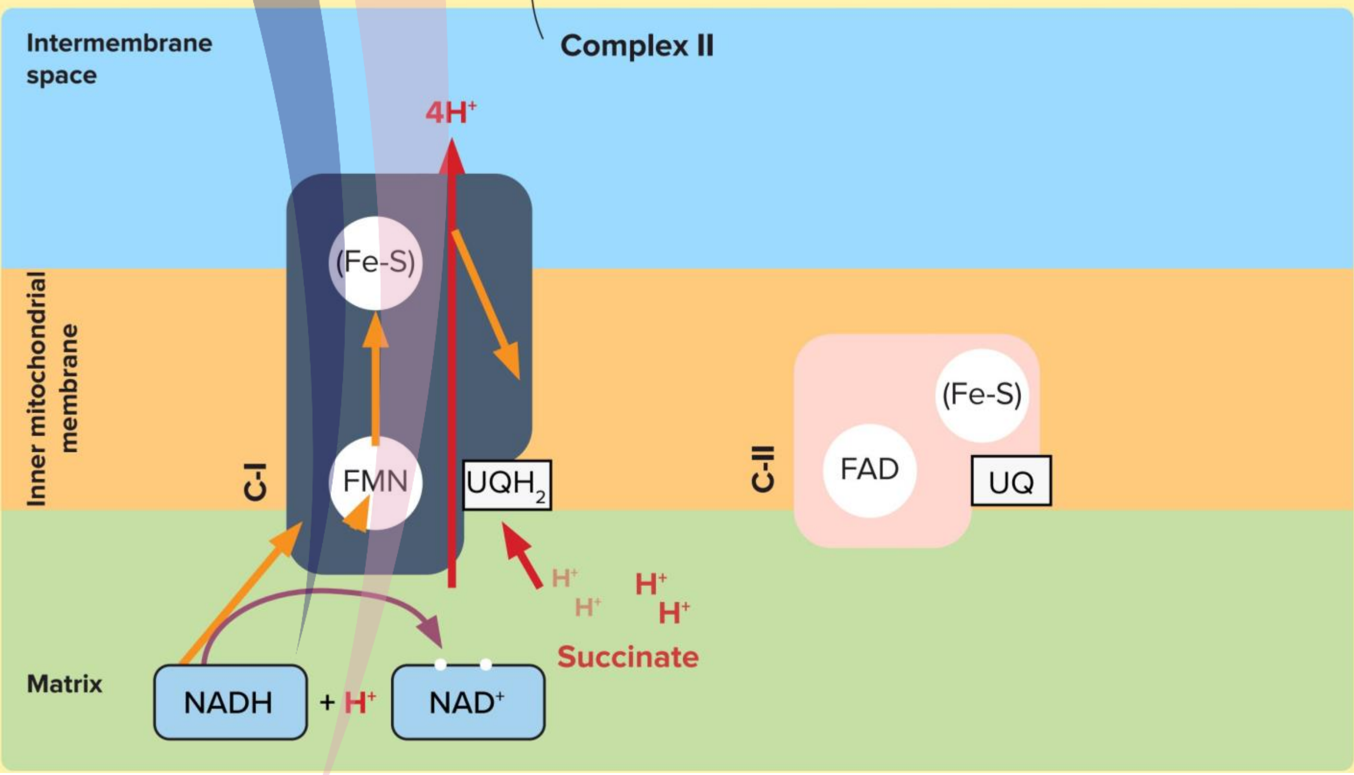
- Potential of (Fe-S) goes up and that of UQ reduces.
- Once the two electrons build up in UQ, it takes up 2 H^+ to become UQH_2.

Complex II

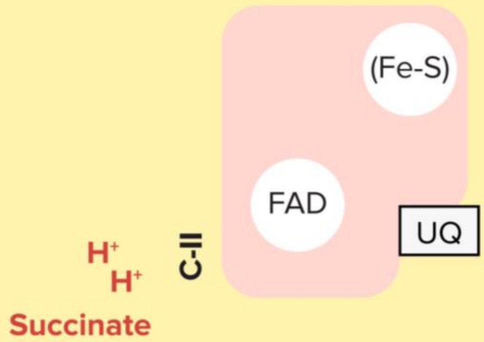
- When succinate is converted into fumarate, there is removal of 2 H^+ from succinate and they are added to FAD^+ to from $FADH_2$.



Recall

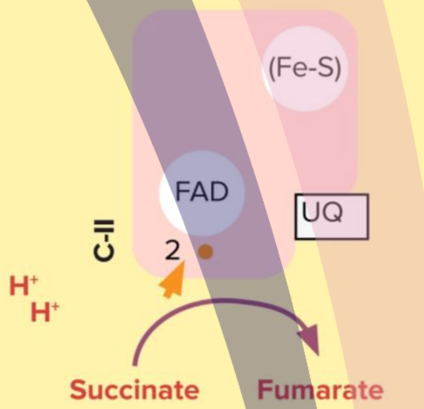


- **Succinate dehydrogenase complex II (C-II)** consists of flavin adenine dinucleotide **(FAD)** which is like FMN and carries electrons one at a time.
- Complex II also has an **(Fe-S)** cluster.
- UQ, the mobile electron carrier, is also present.
- **Succinate** and **hydrogen** are present in the matrix



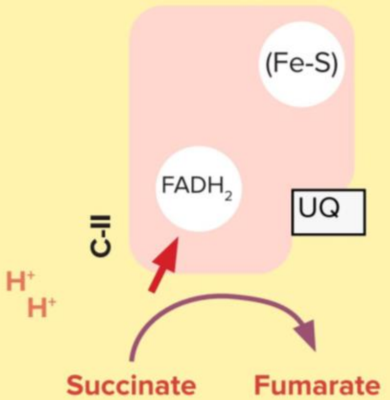
Succinate → Fumarate

- The reaction occurs in the TCA cycle, where **succinate is converted into fumarate** and donates two electrons to C-II.



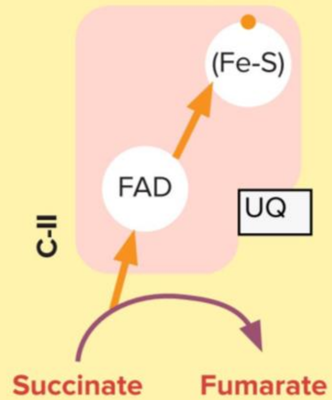
FAD → $FADH_2$

- **FAD** is **converted into $FADH_2$** by taking up both the electrons from the succinate and hydrogen from the matrix.



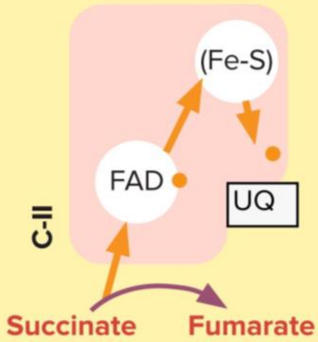
$FADH_2$ → (Fe-S)

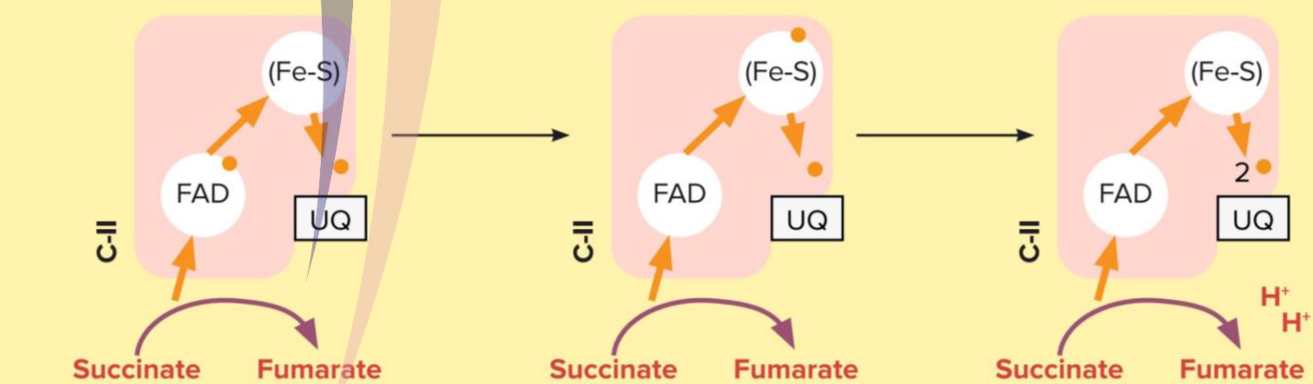
- The electrons from $FADH_2$ move to the **iron-sulphur cluster**, where Fe^{3+} is reduced to Fe^{2+}.
- $FADH_2$ loses 2 H^+ and becomes FAD.



Complex II → UQ

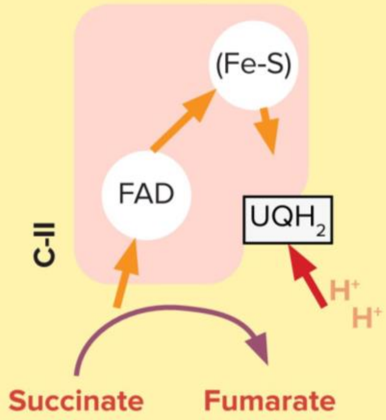
- One electron is present on the cusp near UQ, but UQ requires **two electrons** and **two protons**.
- One electron is transferred at a time.
- **H^+** is present in the matrix.
- Once the **two electrons** are built up, UQ is ready to take up the electrons.



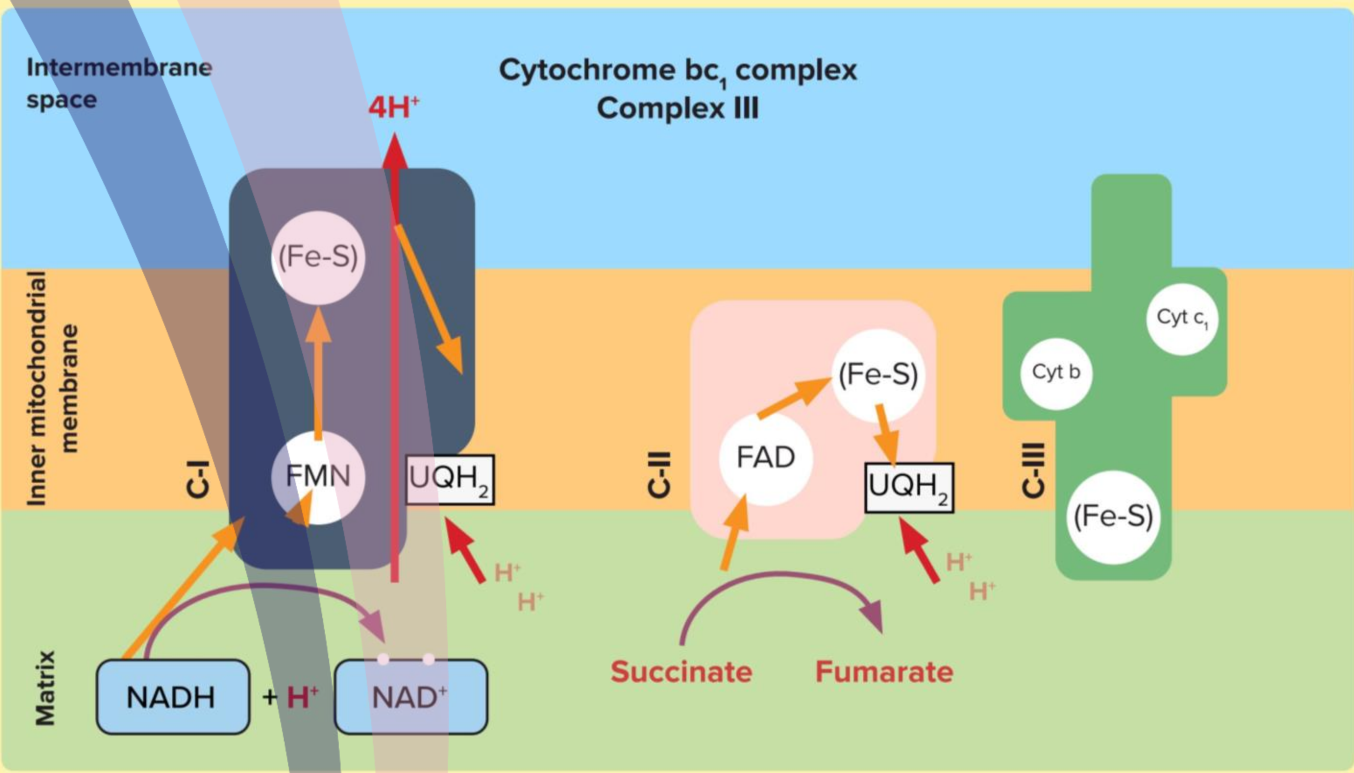


$UQ \rightarrow UQH_2$

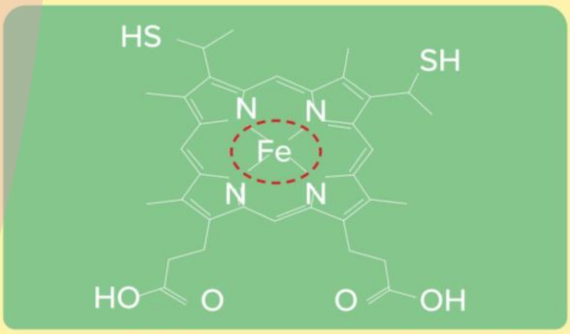
- UQ picks up the **two electrons** and **two protons** and becomes **UQH_2**.



Complex III



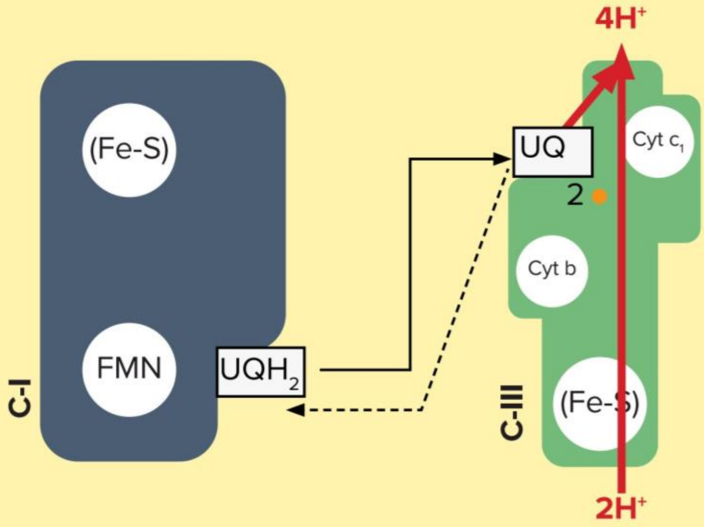
- Complex III consists of **cytochrome b**, **cytochrome c_1**, and **(Fe-S) cluster**.
  - **Cytochrome is a ring-like structure** around Fe, similar to haemoglobin. However, it **carries electrons** instead of oxygen. It is classified on the basis of the heme they possess.



- UQH_2 that is formed from C-I and C-II gets ready to move to C-III.

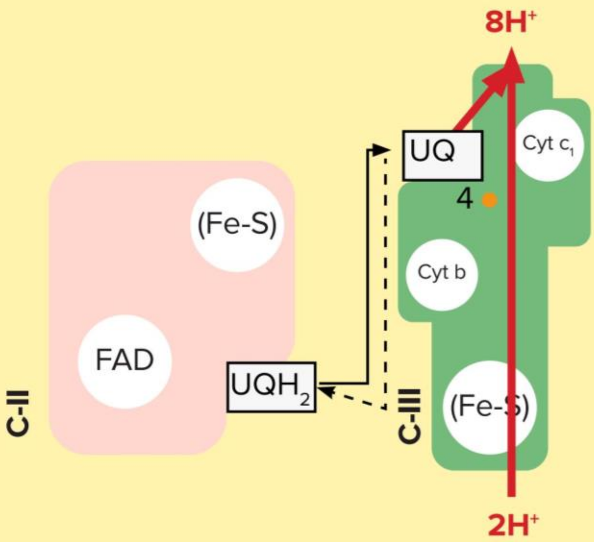
UQH$_2$ from C-I → C-III

- **Two electrons** and **two protons** from UQH$_2$ are transferred to Complex III.
- C-III being a proton pump, pumps **two H$^+$ ions per electron**.
- Therefore, four H+ are pumped **for every two electrons**, where another **2 H$^+$ come from C-III** itself.
- At the same time, UQ also moves back to C-I.



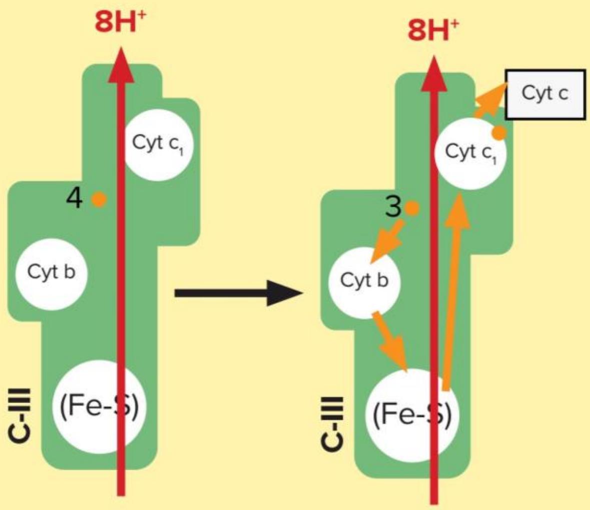
UQH$_2$ from C-II → C-III

- **Two electrons** and **two protons** from **C-II** are transferred to **C-III**.
- Another pair of protons is also transferred from C-III.
- A total of **four protons** are pumped from **C-III** into the intermembrane space.
- At the same time, UQ moves back to C-II.
- Therefore, a **total of eight protons are pumped out** (four due to the movement of two electrons from C-I to C-III and another four due to the movement of two electrons from C-II to C-III).

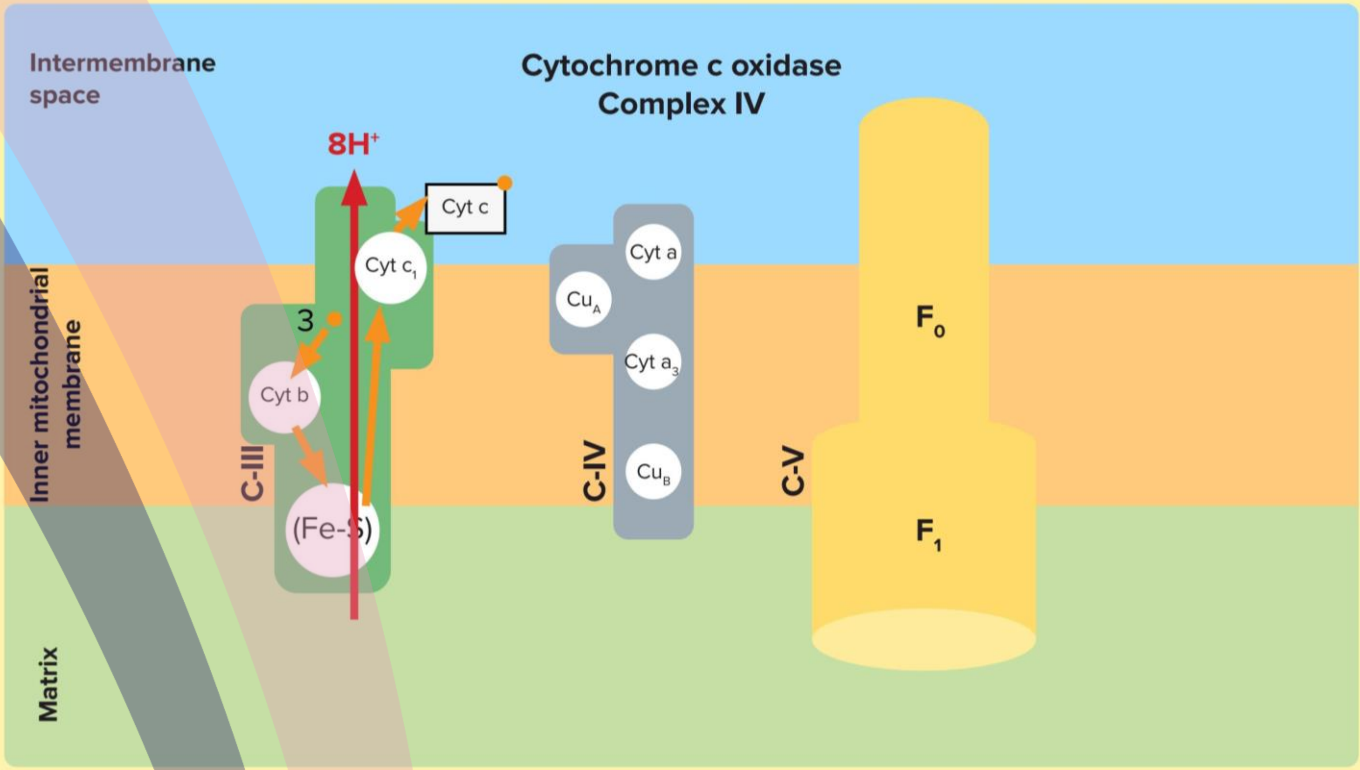


Electron → Cyt b → (Fe-S) → Cyt c$_1$

- All the **four electrons pass one by one** through each complex.
- Each electron passes one at a time to **Cyt b** and then to **(Fe-S)**, where **Fe^{3+}** is reduced to **Fe^{2+}**.
- Electron then moves from **(Fe-S) to Cyt c$_1$**.
- **Cyt c** is reduced by the addition of electron from Cty c$_1$.
    - **Cyt c is a carrier protein** attached to the surface of inner membrane.



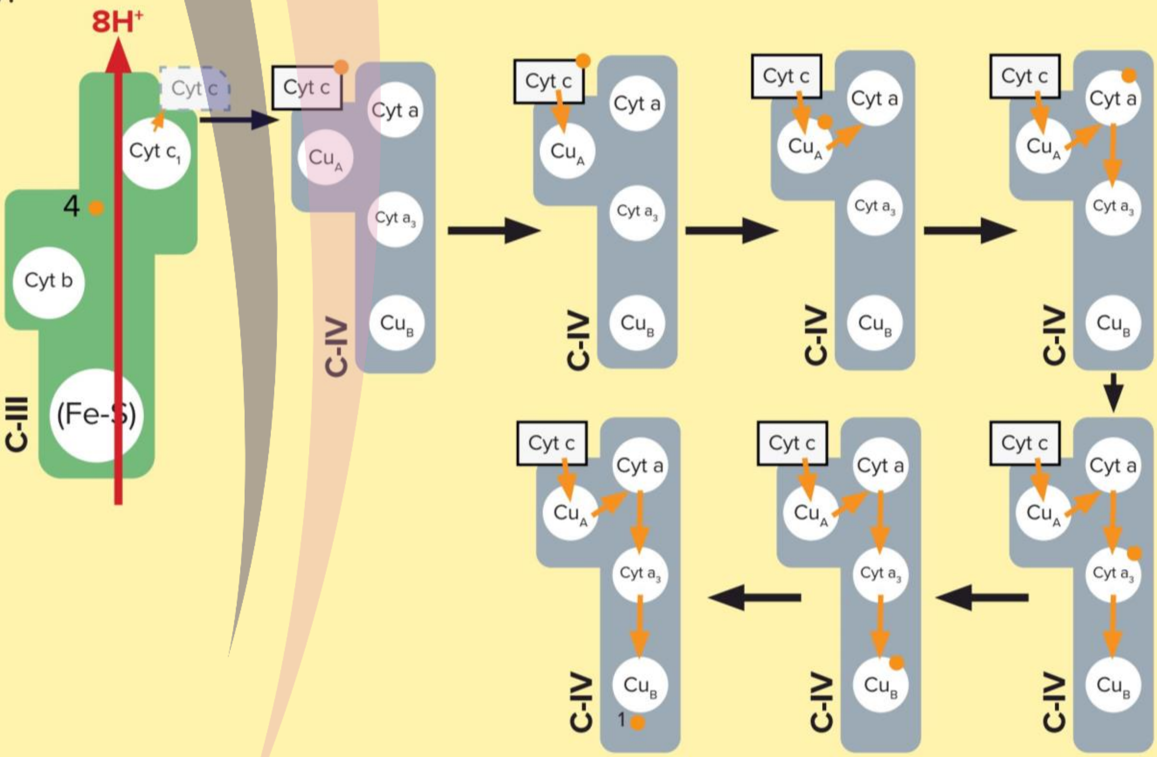
Complex IV



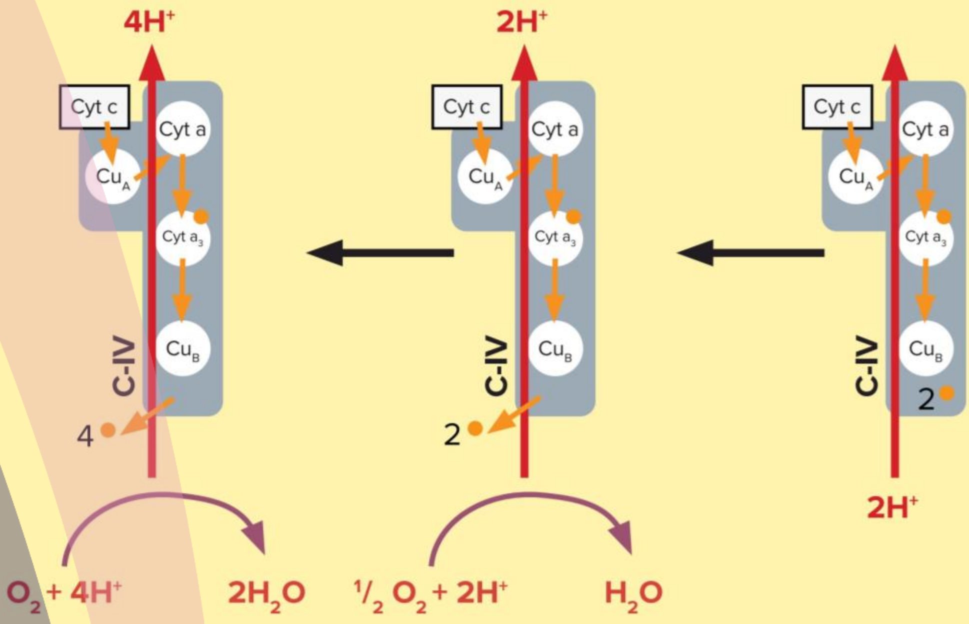
- **C-IV** consists of **cytochrome a, cytochrome a_3, copper a, and copper b**.

Cytochrome c → C-IV

- Electrons move from **Cyt c of C-IV to (Cu_A → Cyt a → Cyt a_3 → Cu_B)**.
- As only one electron can pass through each complex, **one electron** is available at the end of **C-IV**.



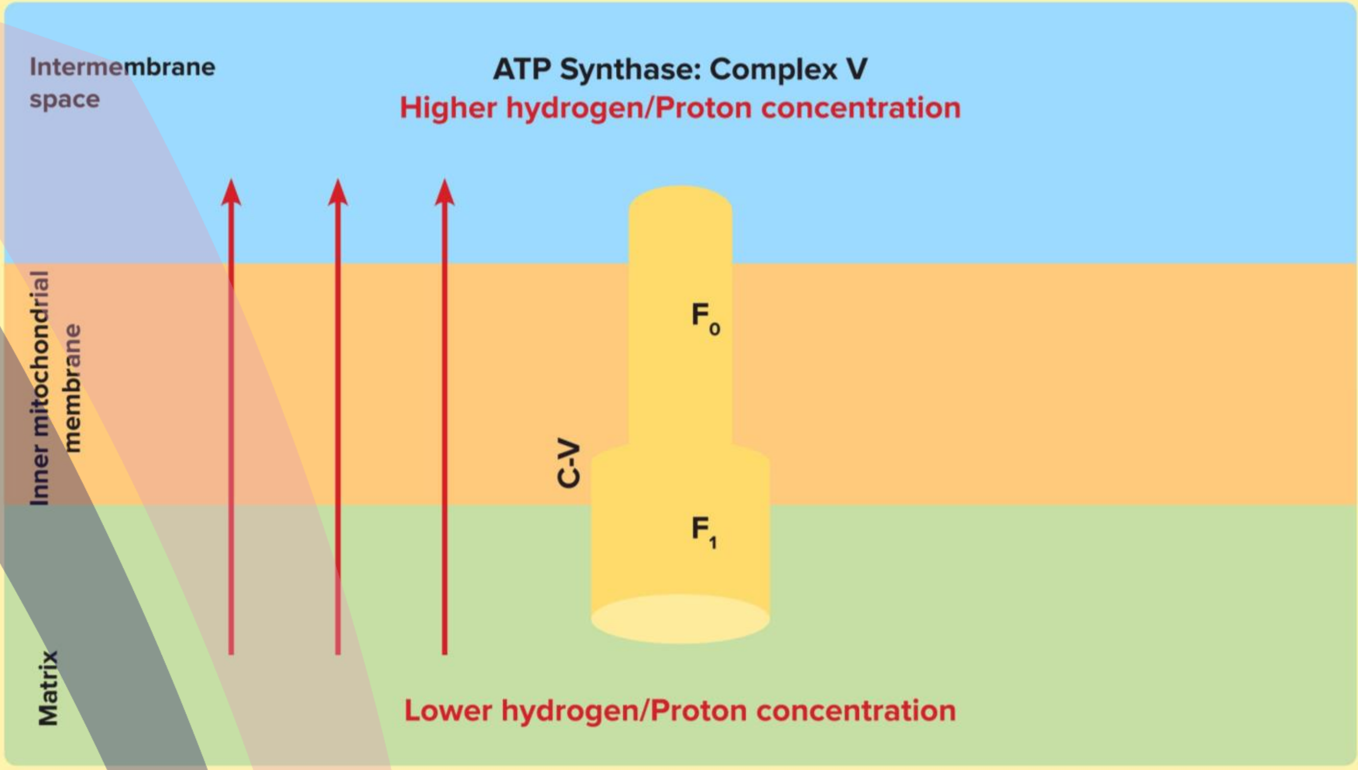
- Another electron also follows the same path.
- As **two electrons** come into **C-IV**, it pumps out two protons into the intermembrane space.
- **Two electrons** are transferred to oxygen, which then bind to **2 H⁺** to yield water.
- **Oxygen** is the **final electron acceptor**.
- The remaining two electrons also follow the same path.
  - Hence, **two more H⁺** are pumped into the **intermembrane space** and another molecule of water is produced.



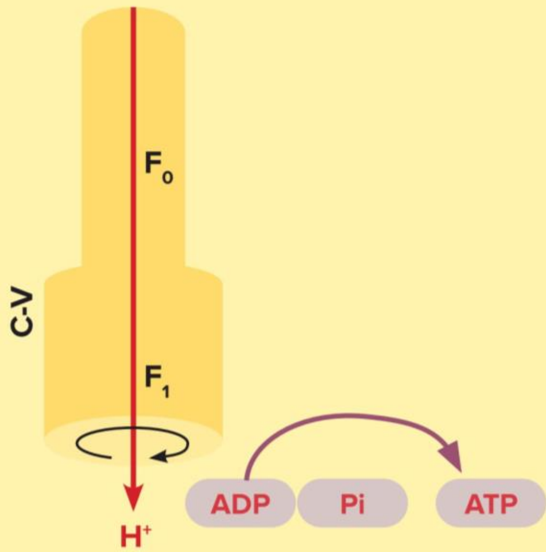
- Unlike photophosphorylation, where light energy is utilised for the production of proton gradient required for phosphorylation, in respiration, the energy of oxidation-reduction is utilised for the same process.
- It is for this reason that the process is known as **oxidative phosphorylation**.

ATP Synthase

- The **concentration of protons is higher in the matrix**.
- The **proton pump transfers** these **protons to the intermembrane space** from the matrix.
- Now, the intermembrane space has a higher proton concentration relative to the matrix.
- On the other hand, **electrons are transferred to the matrix**.
- This process creates the **electrochemical gradient**, which is also known as the **proton motive force**.

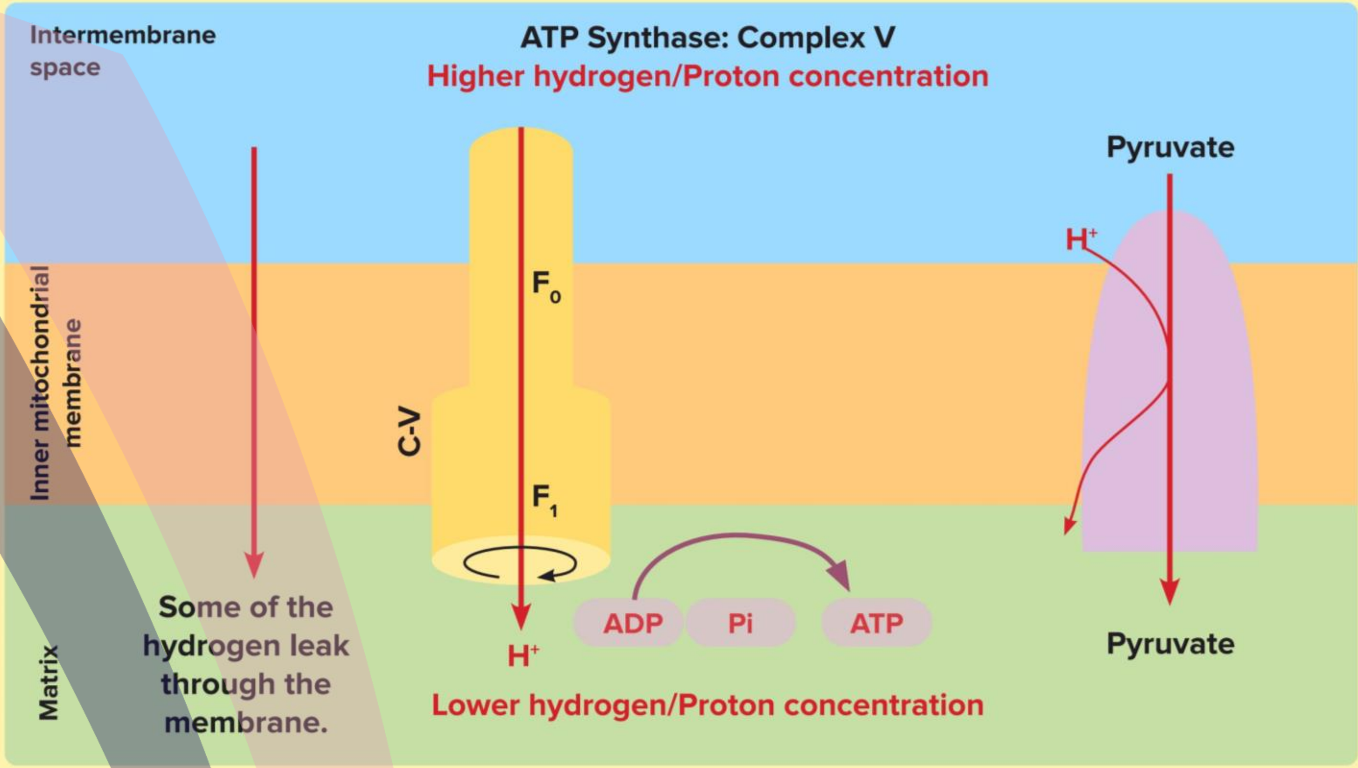


- The proton motive force makes the **hydrogen pass through ATP synthase** and thus helps in its rotation.
- As ATP synthase rotates, it phosphorylates **ADP to form ATP**.
- Due to the electrochemical gradient, **H^+ passes through F_0** from the intermembrane space to the matrix.
- **Rotation of F_1 forms ATP**.

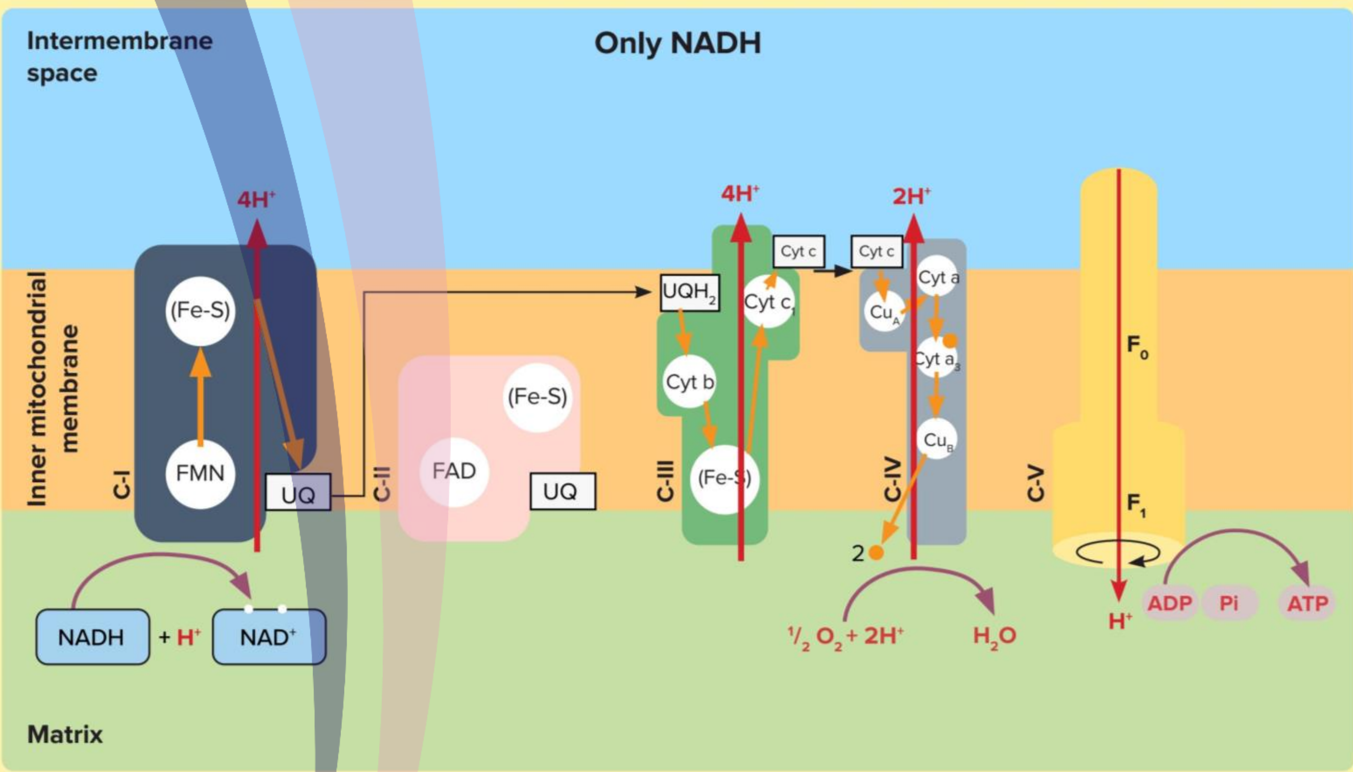


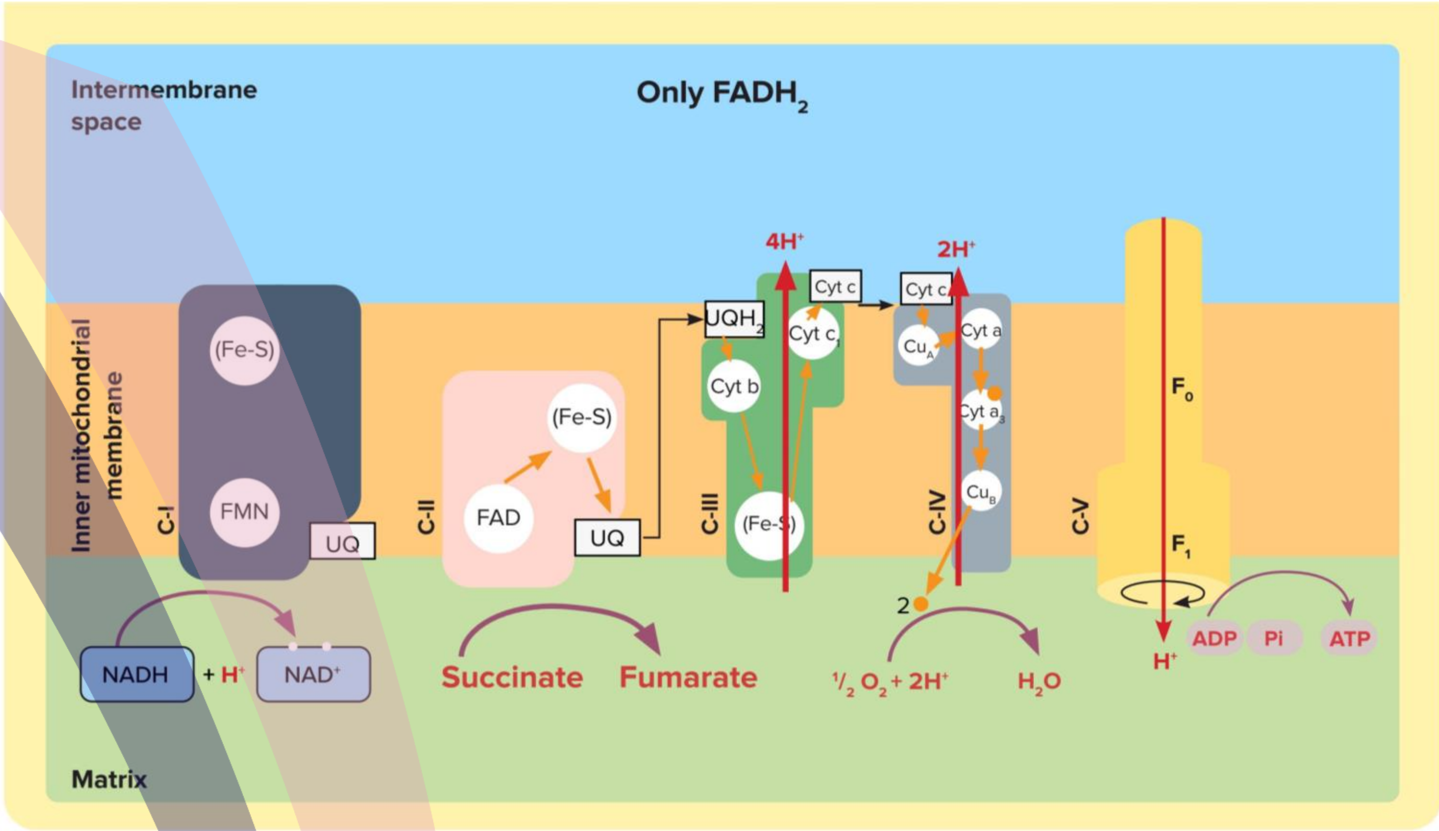
Issues related to proton transfer

- **All H^+ do not enter through ATP synthase.**
  - Sometimes, the **membrane is leaky** and because of the concentration gradient, the **H^+ can leak** into the **matrix**, reducing the H^+ available for ATP synthase.
- H^+ can be used for other purposes, such as **transporting pyruvate into mitochondria** via a **symport mechanism**.



NADH and $FADH_2$ can also go through the system separately.



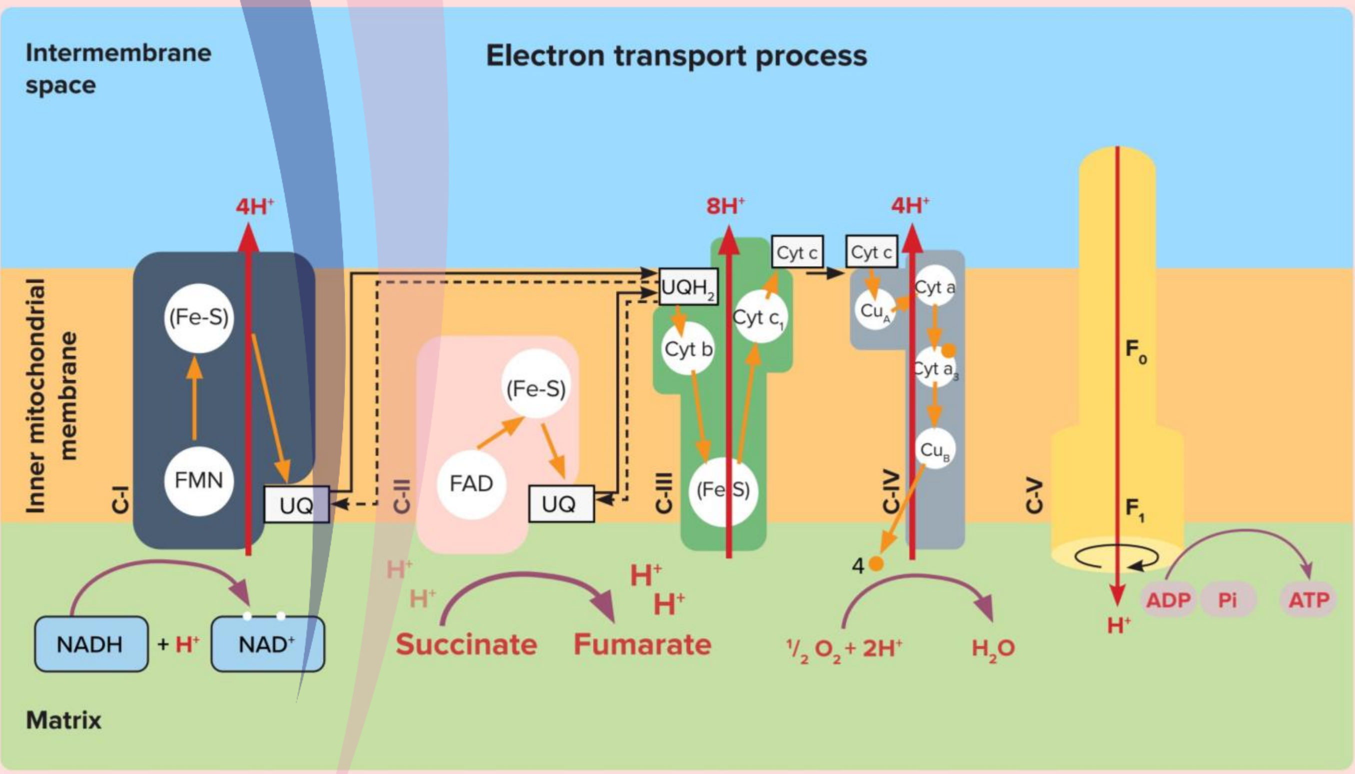


Respiratory Balance Sheet

Expectation	Reality
NADH (e⁻, e⁻) —ETS→ 3 ATP	NADH (e⁻, e⁻) —ETS→ 2.5 ATP
$FADH_2$ (e⁻, e⁻) —ETS→ 2 ATP	$FADH_2$ (e⁻, e⁻) —ETS→ 1.5 ATP
Glycolysis → 2 ATP; 2 NADH → 6 ATP	Glycolysis → 2 ATP; 2 NADH → 5 ATP
2 X Pyruvate oxidation → 2 NADH → 6 ATP	2 X Pyruvate oxidation → 2 NADH → 5 ATP
2 x Krebs cycle → 2 ATP; 6 NADH → 18 ATP; 2 $FADH_2$ → 4 ATP	2 x Krebs cycle → 2 ATP; 6 NADH → 15 ATP; 2 $FADH_2$ → 3 ATP
Net yield 38 ATP	Net yield 32 ATP

• Always in **sequence** ◦ Glycolysis → TCA cycle → ETS	• Pathway works **simultaneously** ◦ So, a molecule produced in one cycle may be used somewhere else, thereby reducing the number of ATPs produced.
• None of the intermediates in the pathway are utilised to synthesise any other compound.	• The entry and exit of molecules in the cellular respiration pathway can occur at any of the stages. ◦ It can be used to build other molecules, including amino acids, nucleotides, lipids, and carbohydrates.
• Transfer of **NADH** requires **no energy**	• **NADH** produced during glycolysis needs to be transferred to mitochondria from cytoplasm, which requires **1 ATP per NADH**. ◦ Therefore, the net yield is **36 (ideal)** and **30 in the reduced case**. As in both the cases, 2 NADH from glycolysis need to be transferred.

Summary Sheet



INTER RELATIONSHIP AMONG METABOLIC PATHWAYS, FACTORS AFFECTING RATE OF RESPIRATION, RESPIRATORY QUOTIENT

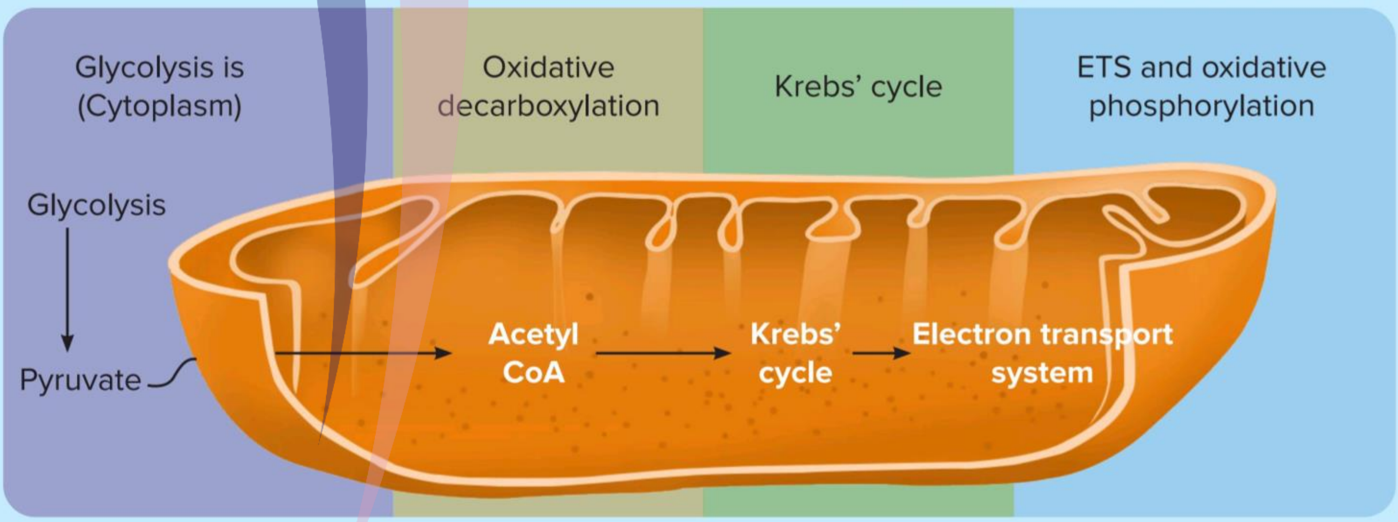
Key Takeaways

- Respiration of fats
  - Transformation of fatty acids
  - Transformation of glycerol
- Respiration of proteins
- Catabolism in respiration
- Respiratory pathway in the synthesis of respiratory substrate precursors
- Factors affecting the respiration rate in plants
- Respiratory quotient in plants

Prerequisites

Aerobic respiration in mitochondria

Steps →	Oxidative decarboxylation	Krebs' cycle	Electron transport system (ETS) and oxidative phosphorylation
Occurs in →	Mitochondrial matrix	Mitochondrial matrix	Inner mitochondrial membrane



Respiratory substrates

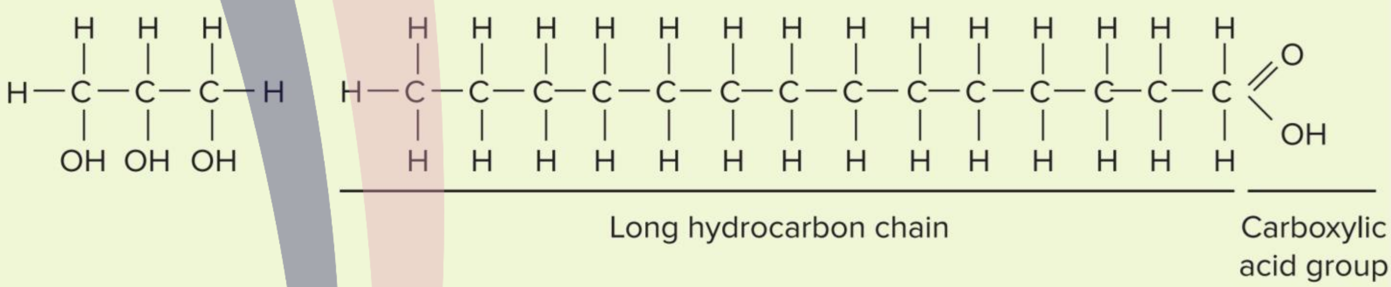
- **Carbohydrates** — Primary substrate
- **Fats** — Used in absence of carbohydrates
- **Proteins** — Used in absence of fats and carbohydrates

Respiration of Fats

- In the **absence of carbohydrates**, fats are utilised as respiratory substrates.
- To utilise fats for respiration, they need to be broken down.

Components of fats

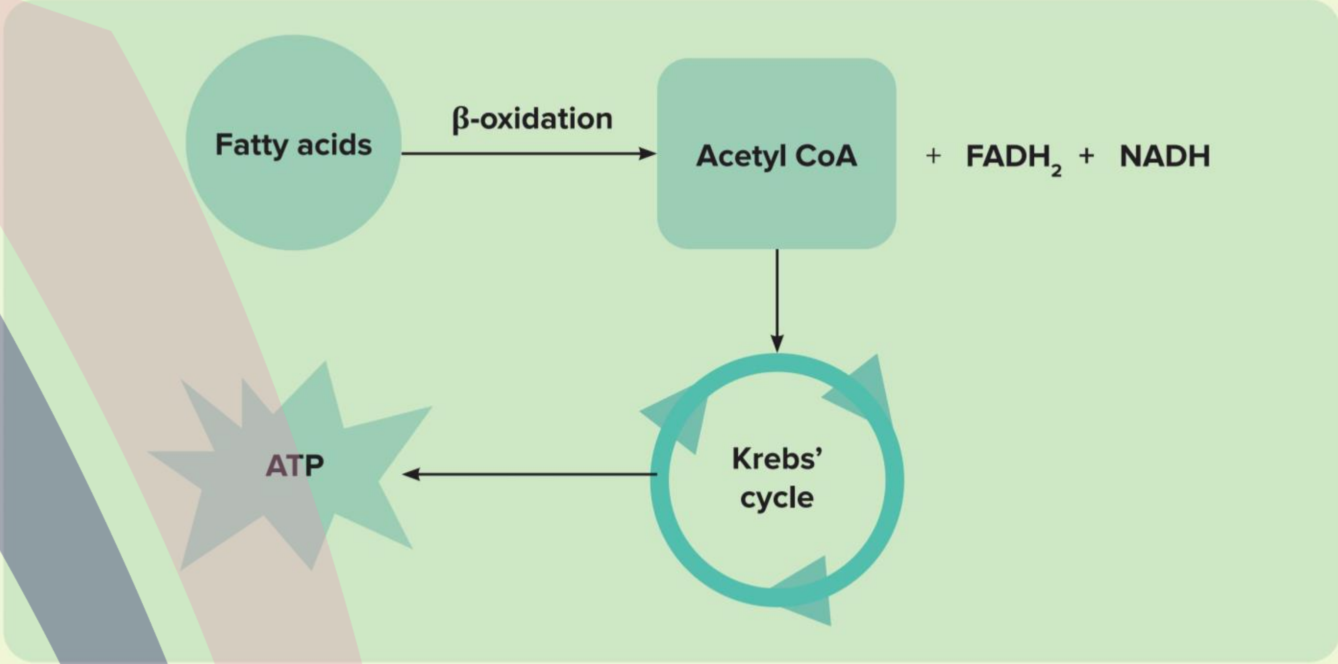
- **Glycerol**
- **Fatty acids**



- Once broken down into fatty acids and glycerol, each of the components undergo transformation to enter the respiratory cycle, and they eventually yield energy (ATP).

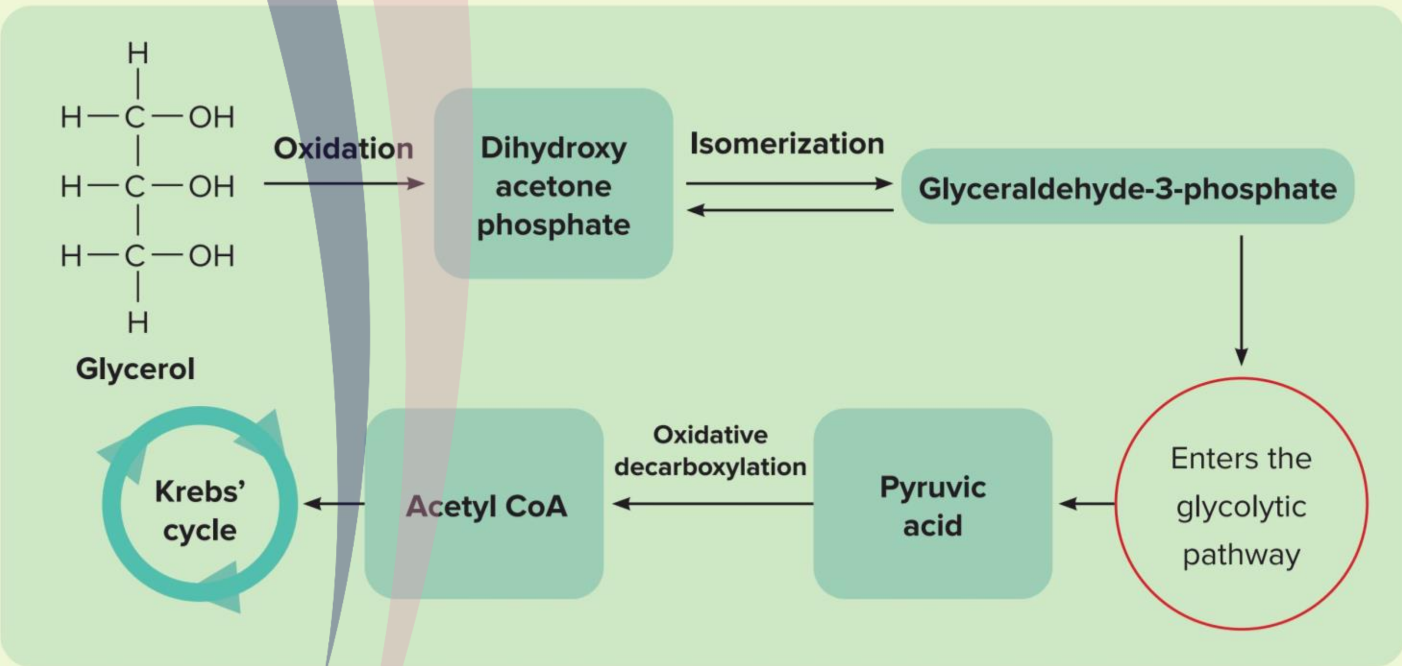
Transformation of fatty acids

- Fatty acids are first degraded to **acetyl CoA**.
- Fatty acids undergo **β-oxidation** in the mitochondria to produce:
  - Acetyl CoA
  - $FADH_2$
  - NADH
- This transformation is known as **β-oxidation** because the **beta carbon of the fatty acid** undergoes **oxidation** to transform into a **carbonyl group**.
- **Acetyl CoA** then enters the **Krebs' cycle** and is utilised in energy production.



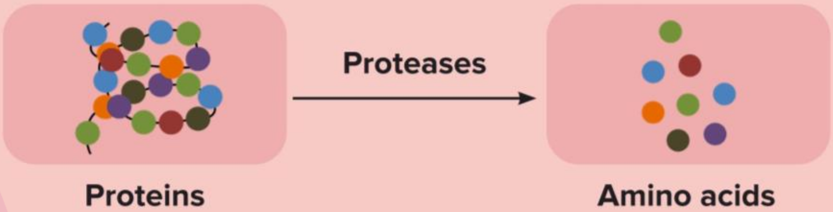
Transformation of glycerol

- **Glycerol** undergoes **oxidation** to form **dihydroxyacetone phosphate**.
- Dihydroxyacetone phosphate isomerises into **glyceraldehyde-3-phosphate** and vice versa.
- Glyceraldehyde-3-phosphate is an intermediate of **glycolytic pathway**. It enters the glycolytic pathway and is metabolised to **pyruvic acid**.
- Pyruvic acid then undergoes **oxidative decarboxylation** to form **acetyl CoA**.
- Acetyl CoA then enters the **Krebs' cycle** and is utilised in energy production.

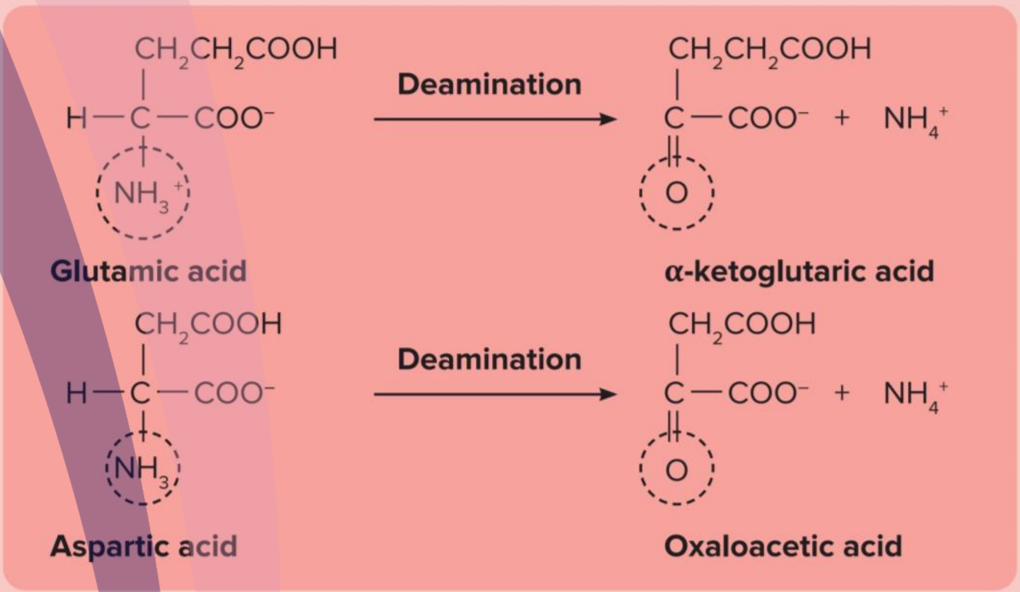


Respiration of Proteins

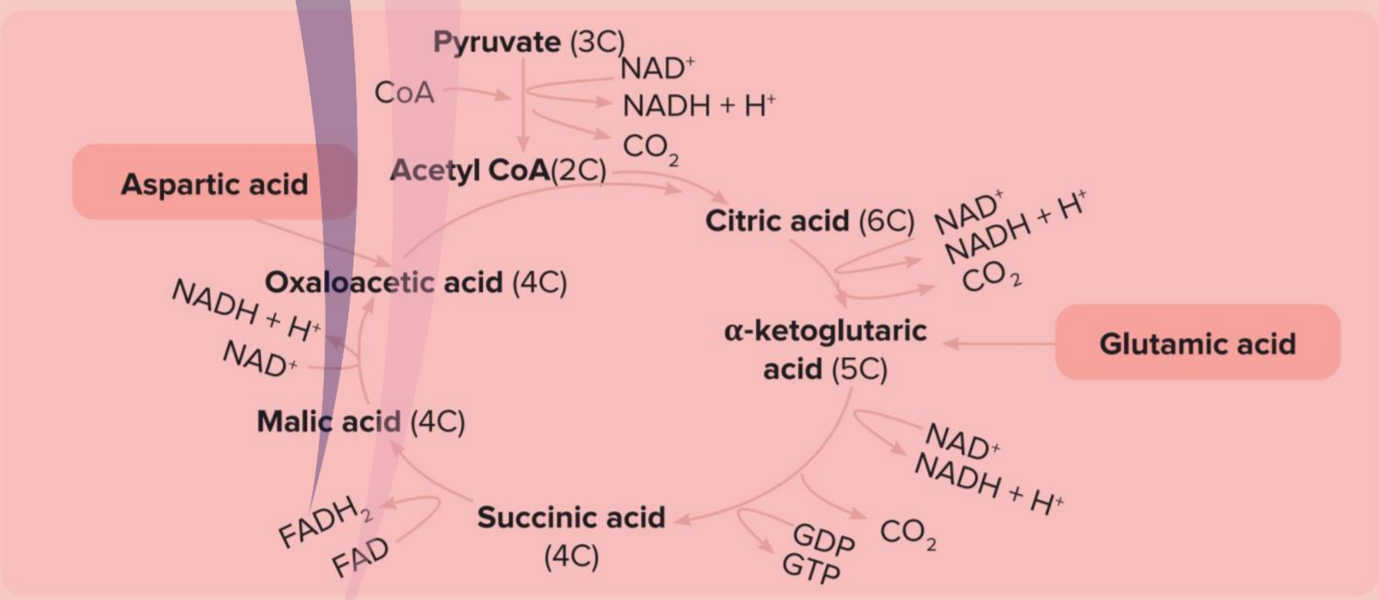
- In the **absence of carbohydrates and fats**, proteins are utilised as respiratory substrates.
- Proteins are complex molecules made up of chains of amino acids. Therefore, they cannot be utilised directly.
- Thus, proteins are broken down into constituent amino acids with the help of **proteases**.



- Depending on their structure, the amino acids then enter the respiratory pathway at some stage within the Krebs' cycle or even as **pyruvate** or **acetyl CoA**.
- For example, glutamic acid and aspartic acid undergoes deamination and transforms into α-ketoglutaric acid and oxaloacetic acid respectively.
- The products then enters the Krebs' cycle and is utilised in energy production.

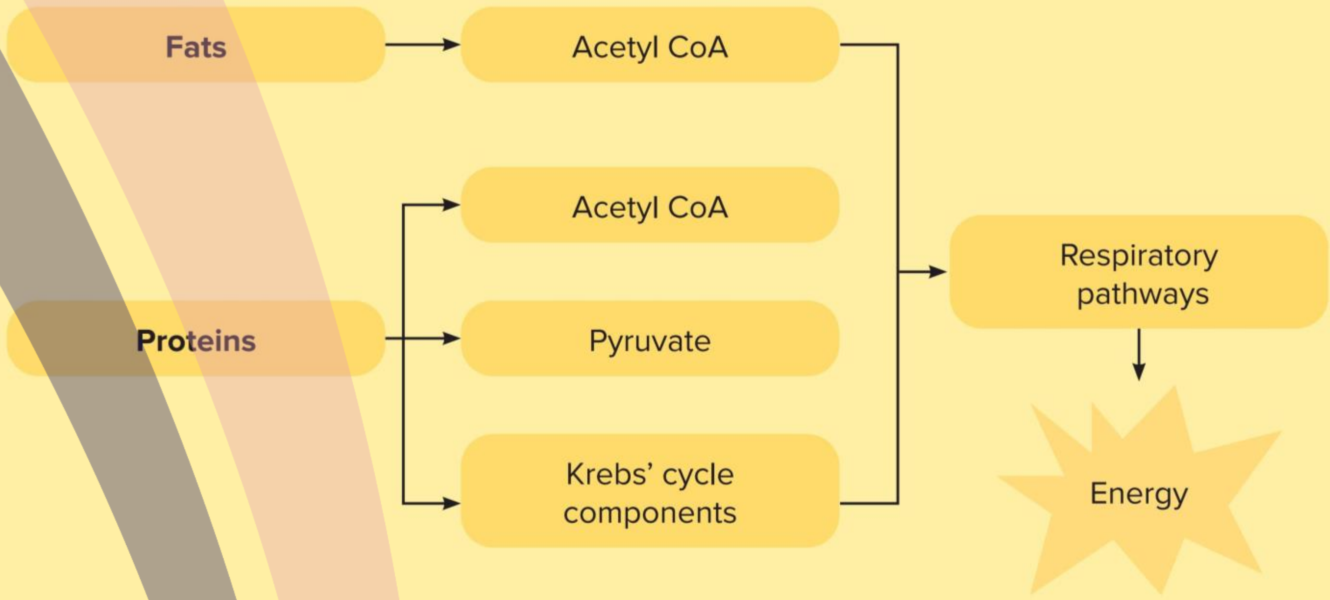


Paths of aspartic acid and glutamic acid towards the Krebs cycle



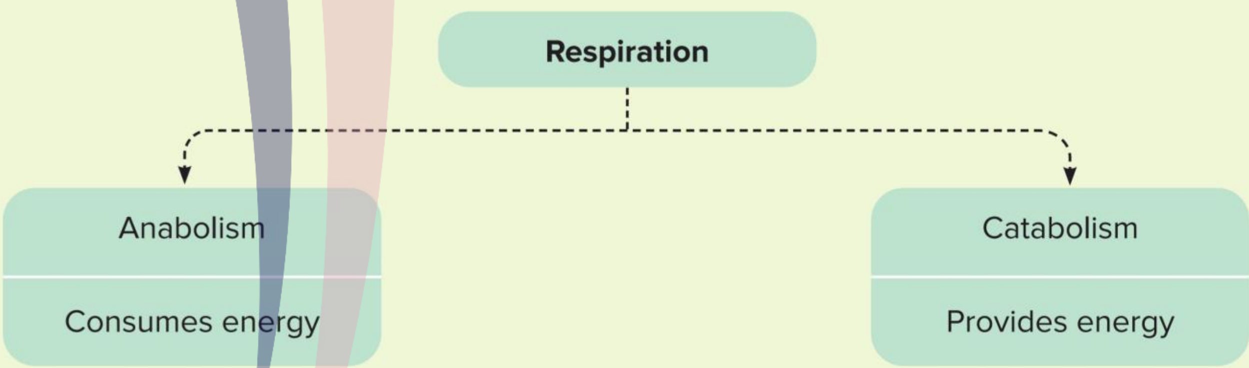
Catabolism in Respiration

- The **breakdown of larger molecules** into smaller and simpler molecules is known as **catabolism**.
- The breakdown of carbohydrates, proteins, fats, etc., is a catabolic reaction.
- In the process of breaking down the complex molecules, energy is released, which happens during respiration.



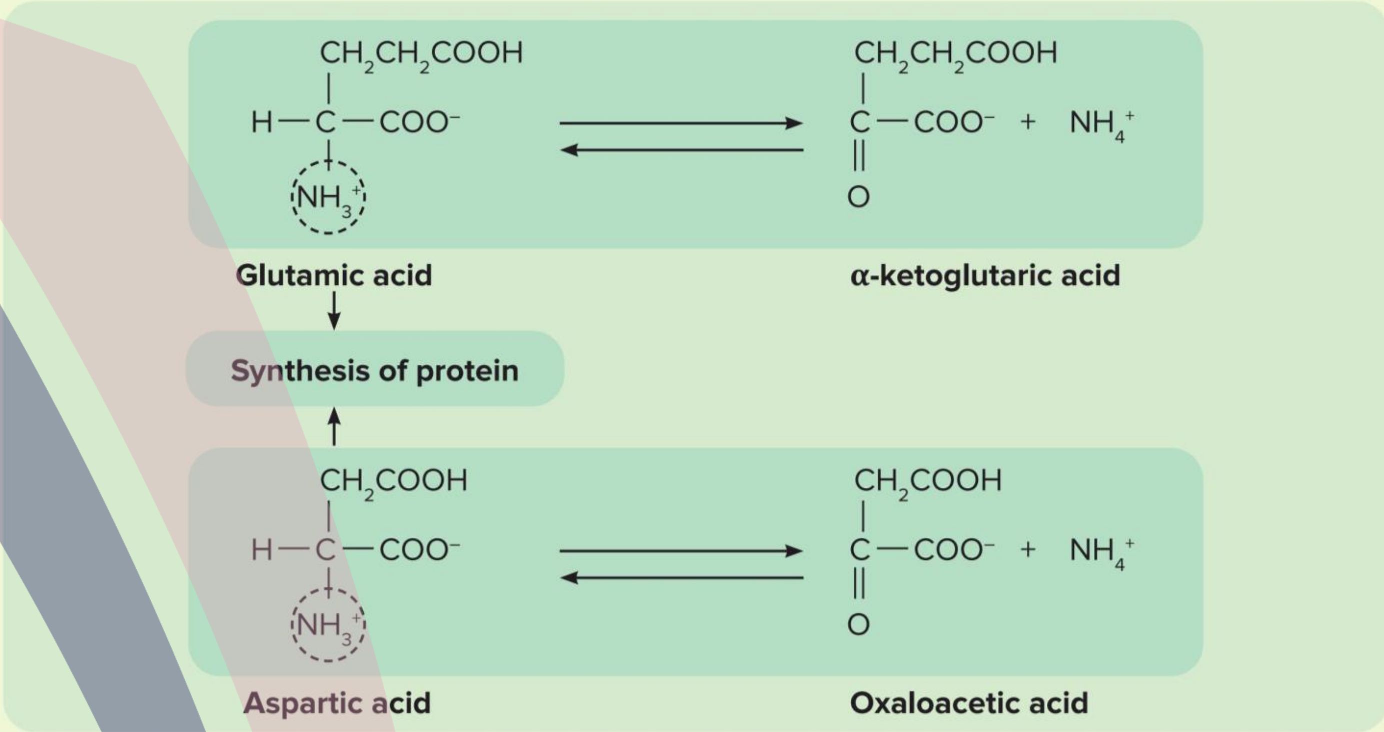
Respiratory Pathway in Synthesis

- Respiratory pathways not only utilise respiratory substrates but also replenish their quantity in the body.
- Respiration catabolises carbohydrates, proteins and fats to yield energy.
- It also anabolises simple molecules from its pathway to provide body with carbohydrates, proteins and fats (by reversing the catabolic reactions we studied).



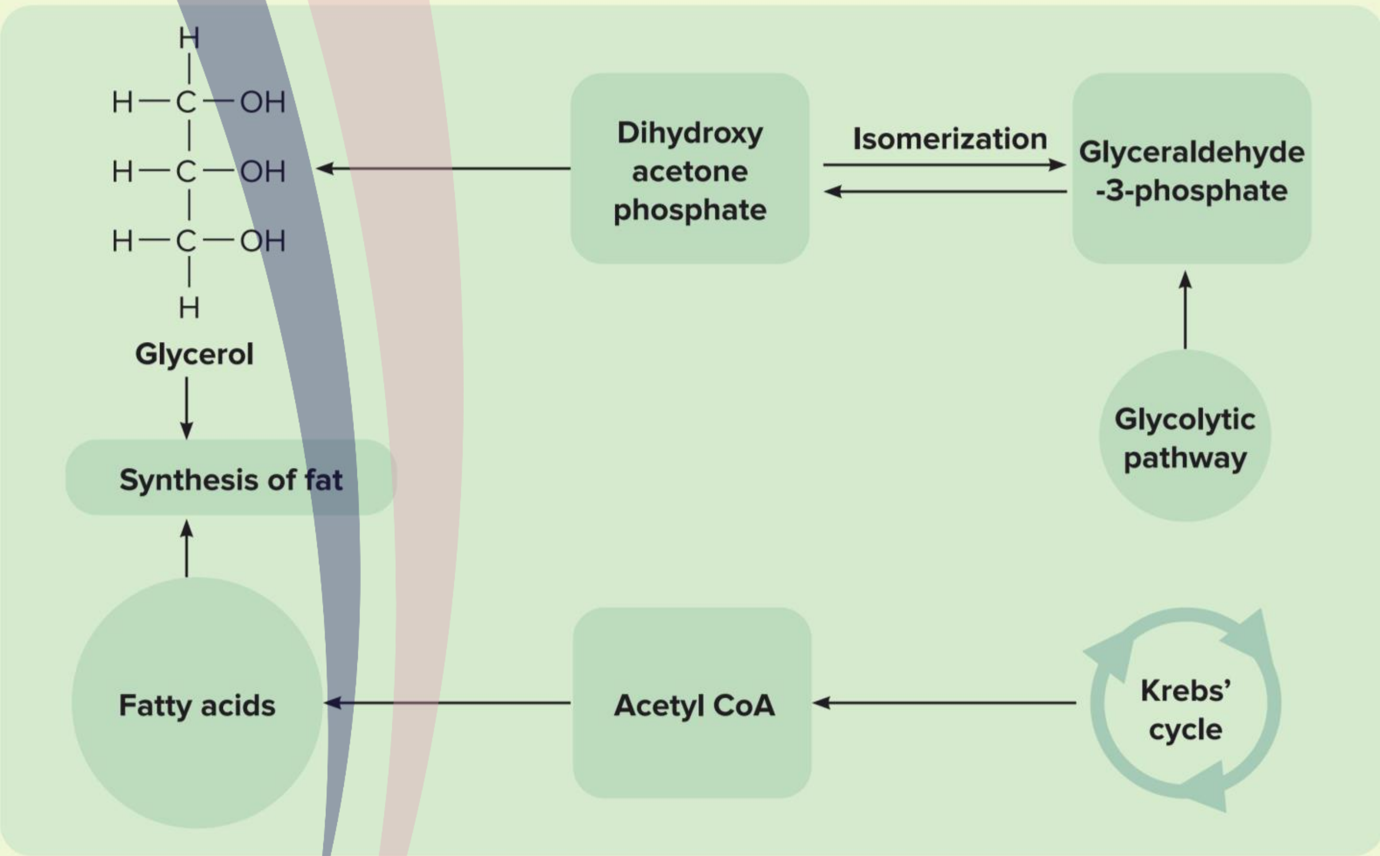
Synthesis of protein precursors

- Proteins are synthesised from **α-ketoglutaric acid** and **oxaloacetic acid**.

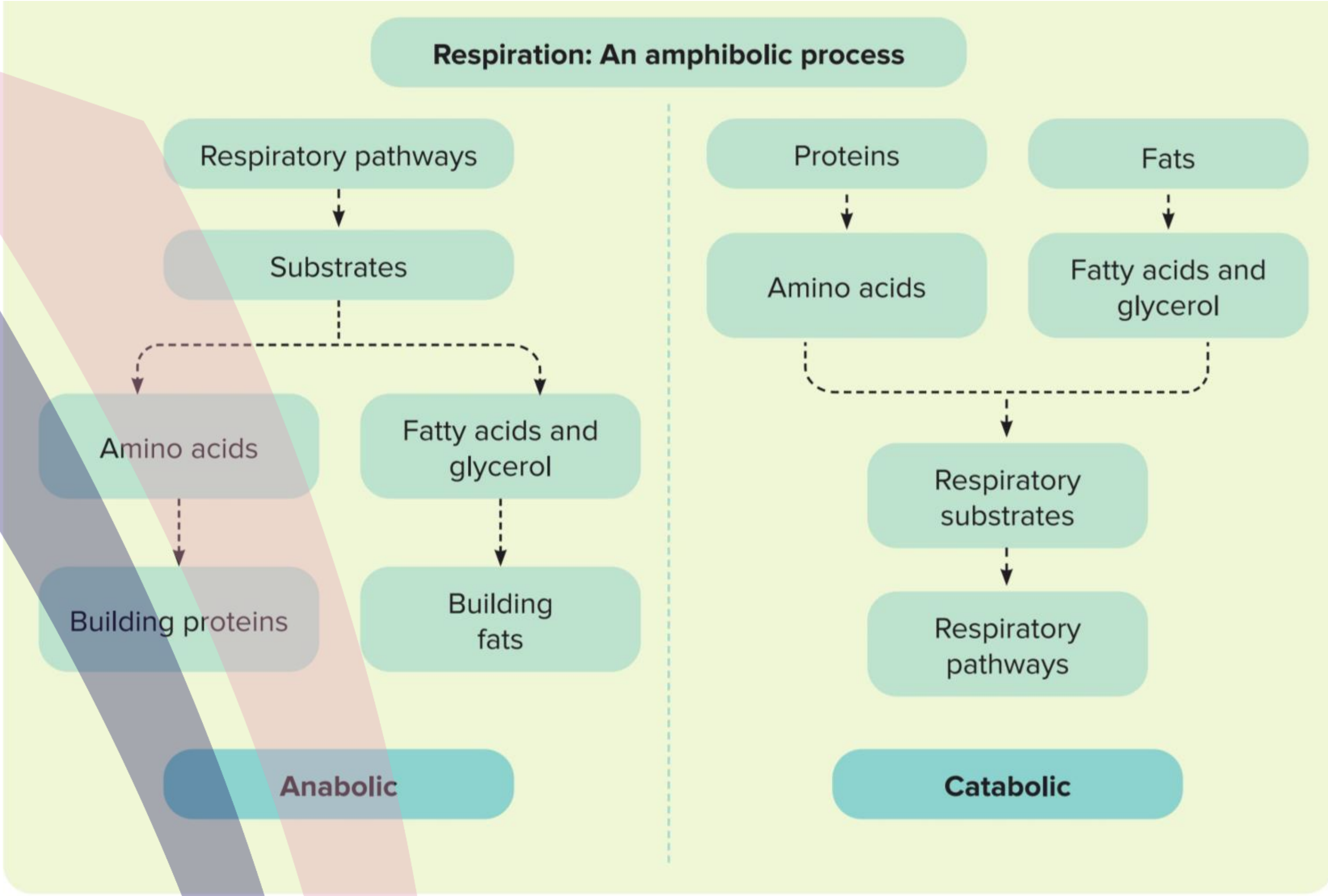


Synthesis of fat precursors

- Similarly, fats are synthesised from **acetyl CoA** and **dihydroxyacetone phosphate**.

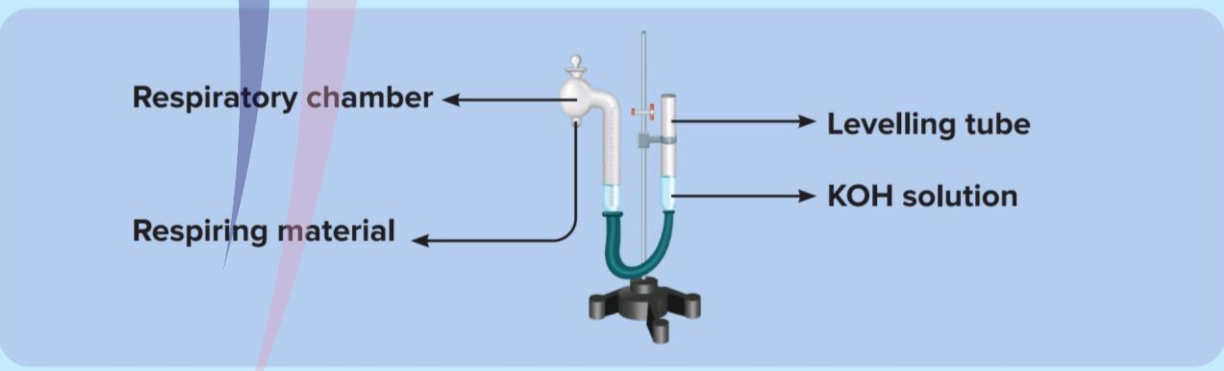


- Since respiration indulges in both catabolic and anabolic pathways, it is referred to as an **amphibolic pathway**.

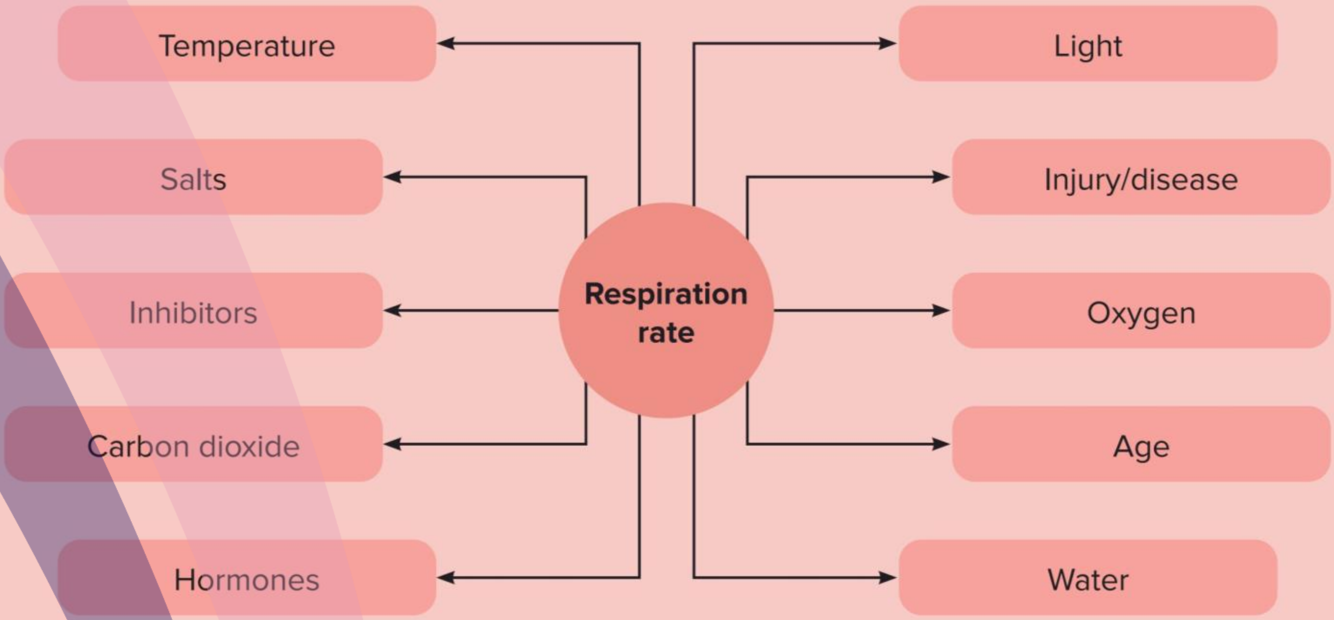


Did you know?

- Just like how speed is measured using a speedometer, rate of respiration too can be measured using **respirometer**.
- A respirometer is a device that is used to measure the rate of respiration of a living organism by measuring its rate of exchange of oxygen and /or carbon dioxide.
- The apparatus consists of a graduated tube attached at right angles to a bulbous respiratory chamber in its upper end.
- The desired plant material, whose respiration is to be determined, is placed in the respiratory chamber.
- The KOH acts as an absorbent for CO_2.
- Based on the intake of CO_2, the level of KOH solution increases in the tube, which can be measured.



Factors Affecting Respiration Rate in Plants



Temperature

(a) The rate of respiration is directly proportional to the temperature.

(b) **Increase in temperature = Increase in the rate of respiration**

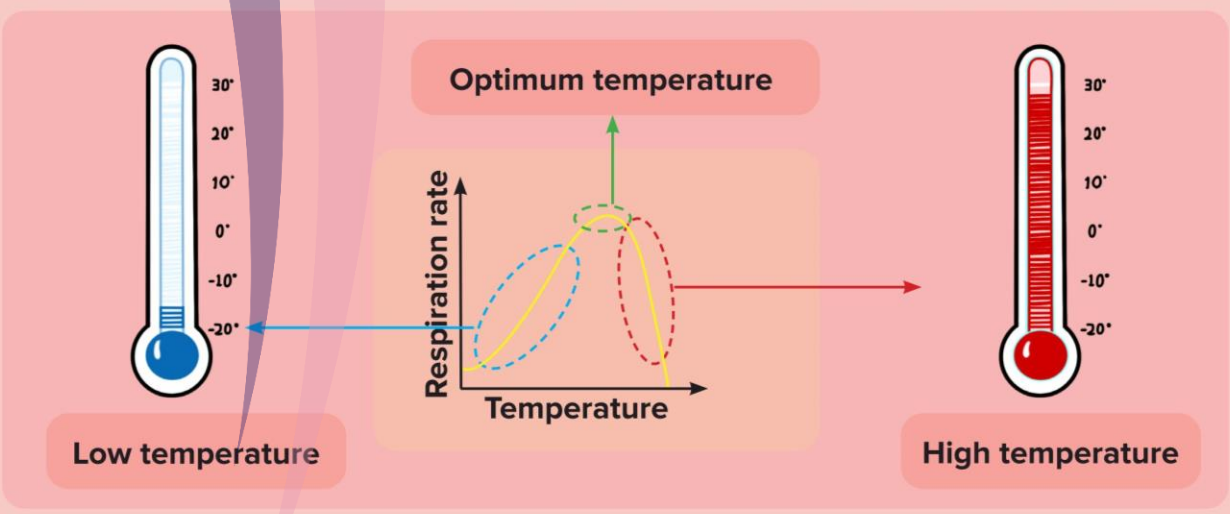
(i) This happens because within the functional temperature range, the **rate of an enzyme-catalysed reaction increases** with the **increase in temperature**.

(ii) The increase in temperature causes excessive movement of respiratory enzymes and the substrates that lead to more collisions.

(iii) Hence, the increase in temperature increases enzyme activity and therefore, increases the rate of respiration.

(c) However, this trend is followed only till a certain temperature known as **optimum temperature**.

(d) Beyond the optimum temperature, the rate of respiration decreases due to **denaturation of the respiratory enzymes**.



Oxygen concentration

(a) The rate of respiration is directly proportional to the concentration of oxygen.

(b) **Increase in the concentration of oxygen = Increase in the rate of respiration**

(i) This happens because **oxygen is the electron acceptor** that helps in the generation of energy and **synthesis of ATP**.

(c) However, this is **not true for facultative anaerobes**.

(i) These organisms display the **Pasteur effect**.

Pasteur effect: Inhibition of anaerobic respiration

Under high O_2 conditions → Sudden shift from anaerobic to aerobic respiration → Less ATP

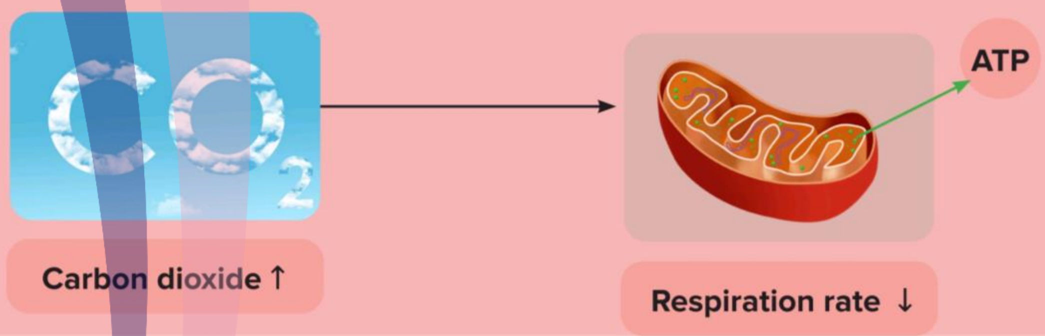
Carbon dioxide concentration

(a) **The rate of respiration** is inversely proportional to the **concentration of carbon dioxide**.

(b) **Increase in the concentration of carbon dioxide = Decrease in the rate of respiration**

(i) This happens because of the closing of the stomata during conditions of high carbon dioxide concentration.

Rate of respiration ∝ 1 / Carbon dioxide concentration



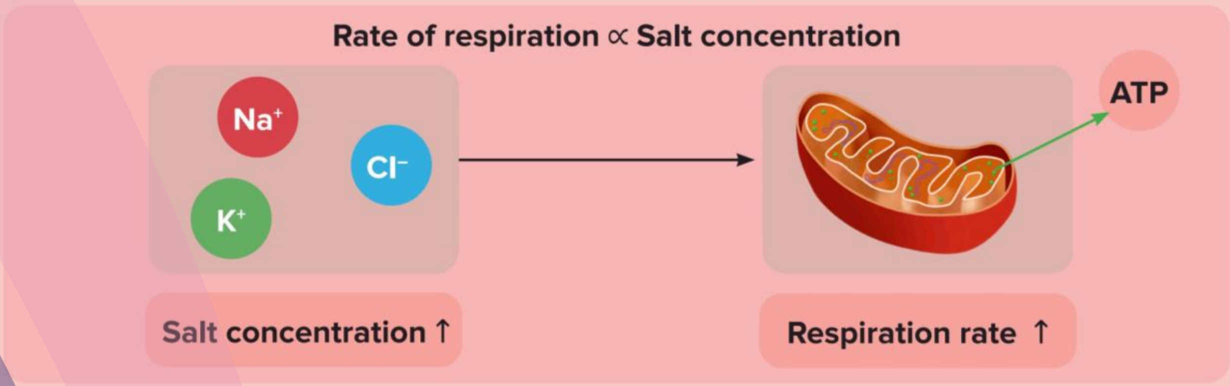
Salt concentration

(a) The rate of respiration is directly proportional to the concentration of salts.

(b) If a plant is transferred from water to salt solution, its respiration increases. This is known as **salt respiration**.

(c) **Increase in the concentration of salt = Increase in the rate of respiration**

(i) This happens because the absorption of ions requires more metabolic energy, which results in the increase in the rate of respiration.



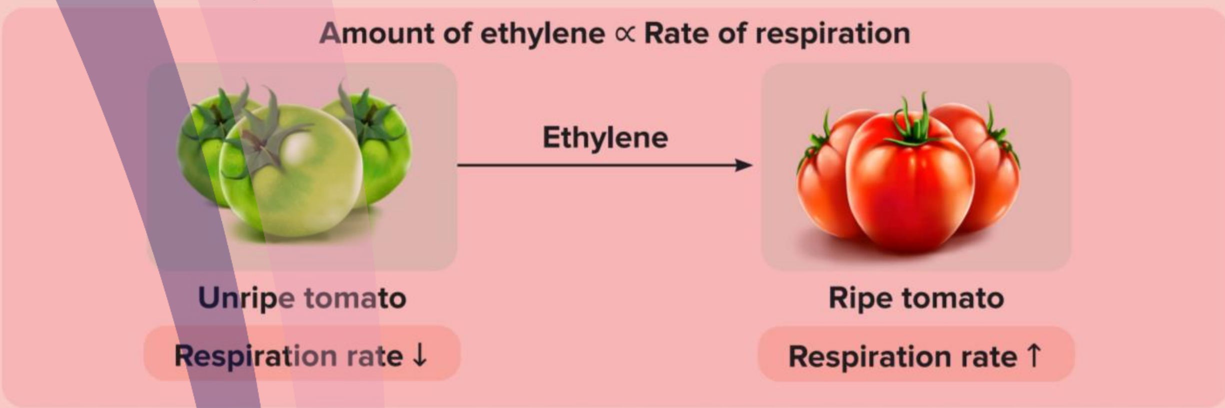
Hormone concentration

(a) The rate of respiration is directly proportional to the concentration of the ethylene hormone.

(b) **Increase in the concentration of ethylene = Increase in the rate of respiration**

(i) Ethylene is responsible for initiating the process of ripening.

(ii) During ripening, more and more starch is converted into glucose that increases the rate of respiration.



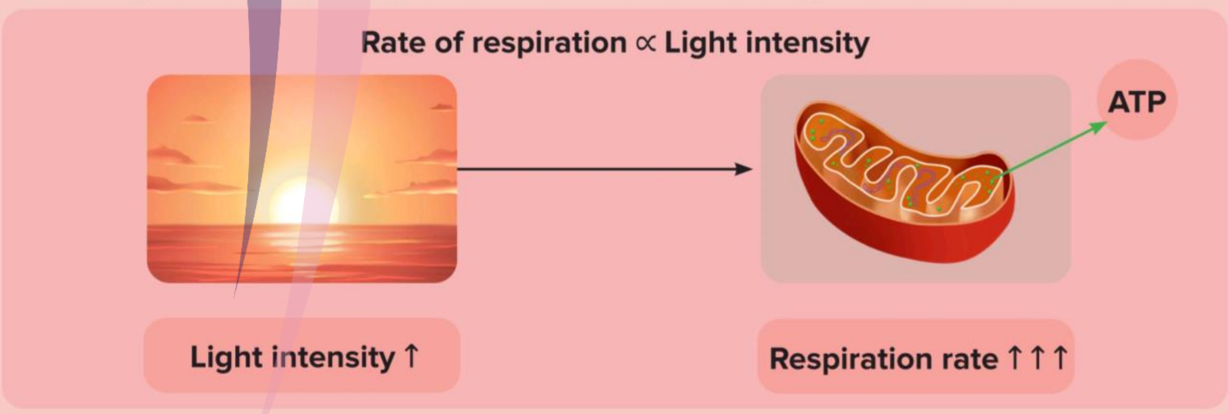
Intensity of light

(a) The rate of respiration is directly proportional to the intensity of light.

(b) **Increase in the intensity of light = Increase in the rate of respiration**

(i) This is because light controls the stomatal opening and the production of respiratory substrates.

(ii) Higher intensity of light promotes stomatal opening.

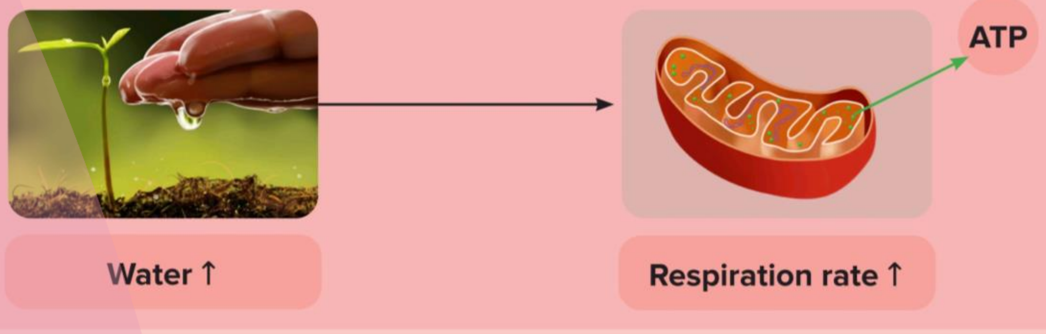


Water

(a) The rate of respiration is negatively affected by lack of water.

(b) In the presence of water, carbohydrates are converted into soluble sugar, which increases the rate of respiration.

Respiration rate ∝ Water content



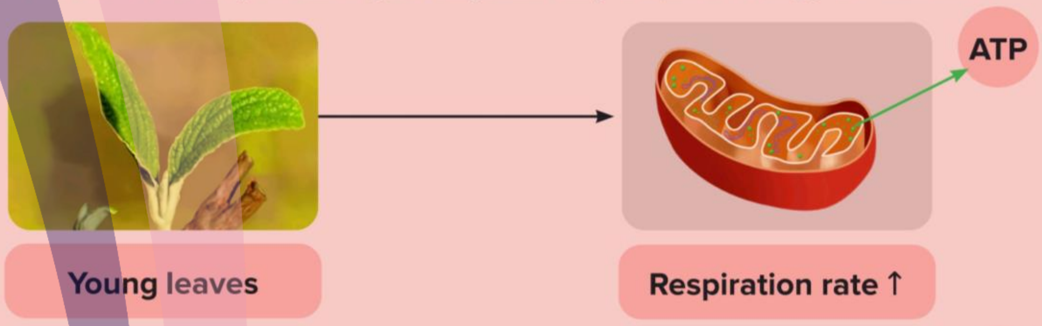
Age

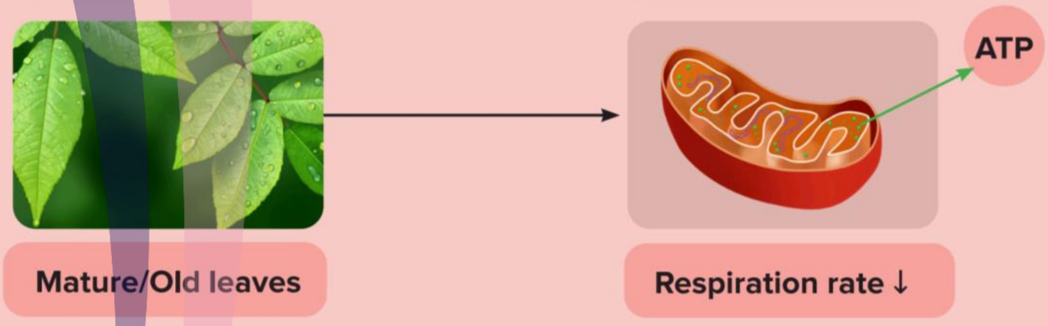
(a) **Respiration** is the **highest** at the **meristem apex**.

   (i) This is because the meristem apexes are growing tissues. Therefore, they require more energy to divide rapidly.

(b) Inversely, the **respiration rate is lower** in **mature leaves**.

   (i) This is because they are not growing and only require energy for survival.





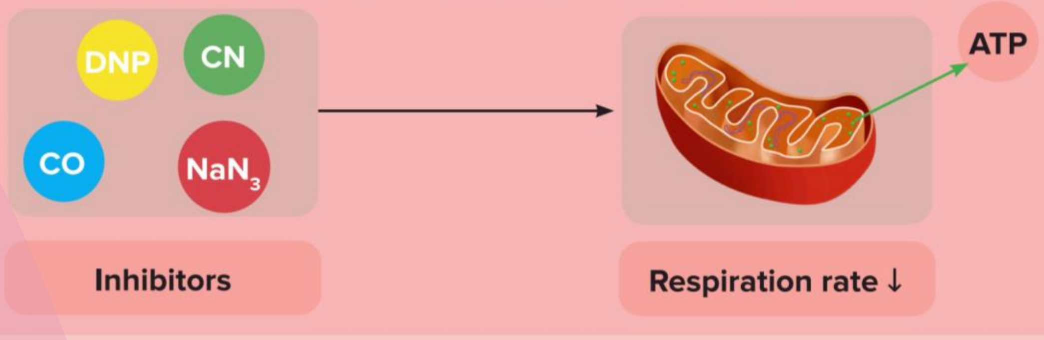
Inhibitors

(a) The presence of certain chemicals like **cyanide, azides, dinitrophenol, carbon monoxide, rotenone, antimycin**, etc., **slow down respiration**.

   (i) These chemicals inhibit respiratory enzymes such as cytochrome complex by binding to their active sites.

(b) For example, cyanide binds to cytochrome c oxidase and inactivates the enzyme, resulting in the inhibition of respiration.

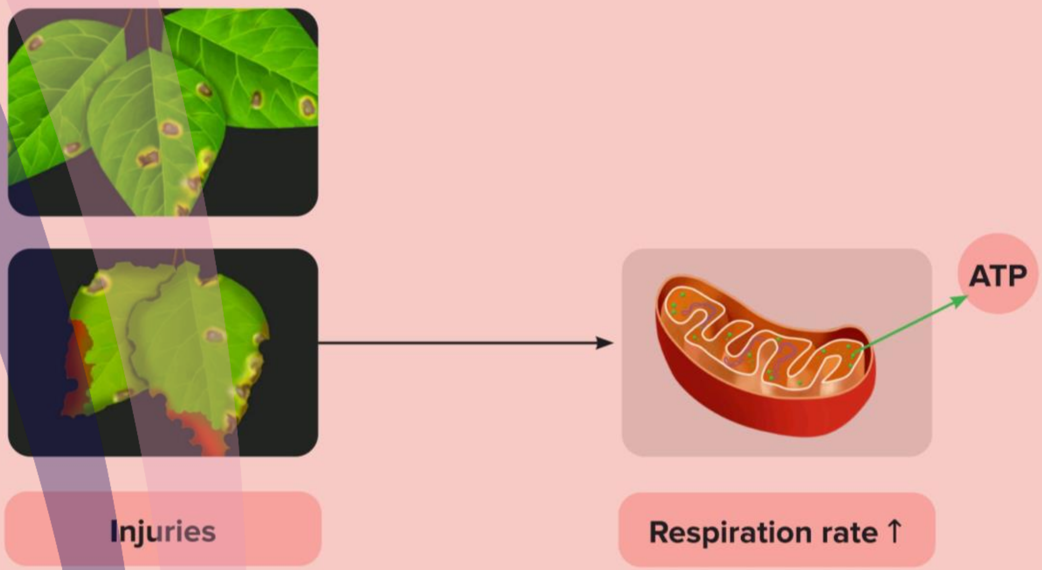
Rate of respiration $\propto$ 1 / Inhibitors concentration



Injuries, diseases, and wounds

(a) Respiration tends to increase during injuries, diseases, and wounds.

(i) This is because plants require a huge amount of energy for repairing the wounds, and this energy is provided by excessive respiration.



Respiratory Quotient in Plants

- It is the ratio of the volume of CO_2 evolved to the volume of O_2 consumed.

$$\text{Respiratory quotient (RQ)} = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

- Different respiratory substrates have different respiratory quotients.

Glucose

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + H_2O + ATP$$

$$RQ = \frac{6\,CO_2}{6\,O_2} = 1$$

Tripalmitin

$$2(C_{51}H_{98}O_6) + 145\,O_2 \longrightarrow 102\,CO_2 + 98\,H_2O + ATP$$

$$RQ = \frac{102\,CO_2}{145\,O_2} = 0.7$$

Albumin

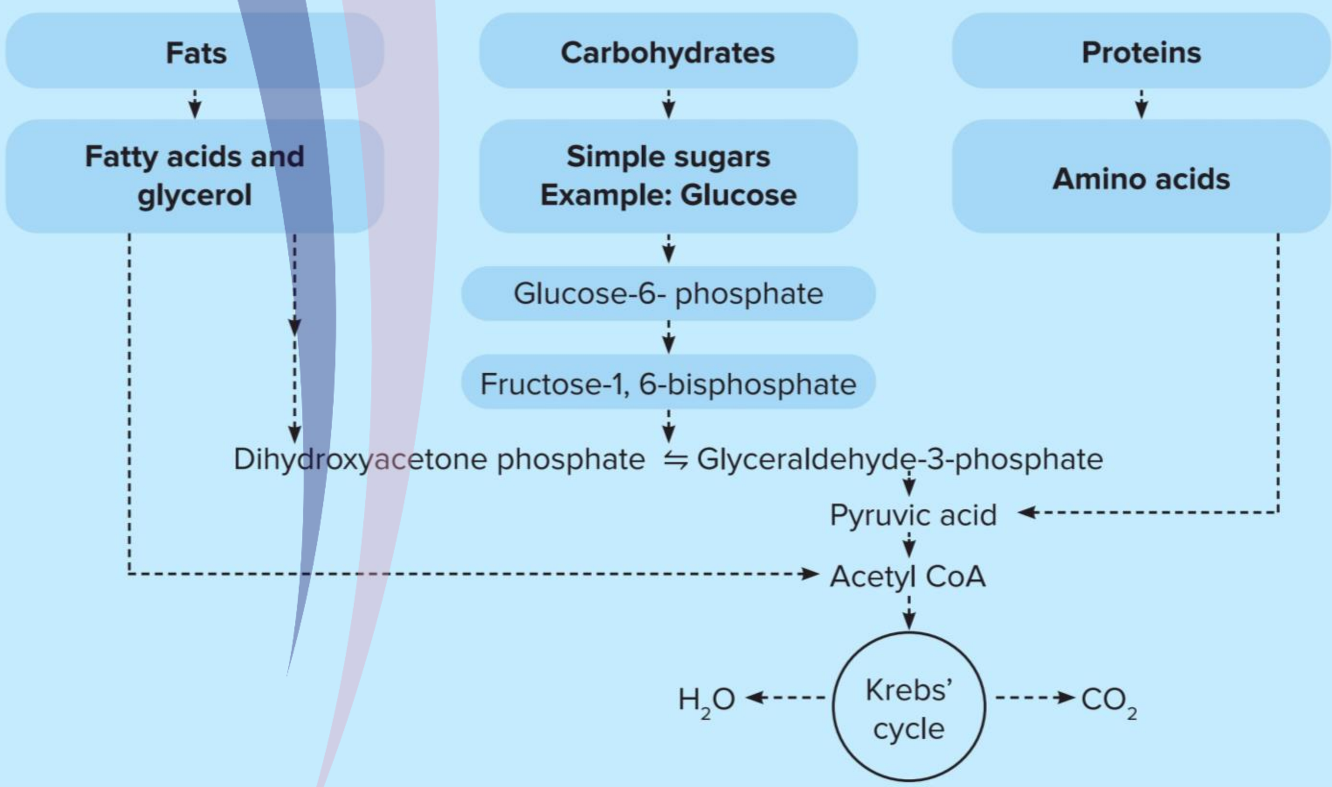
$$C_{72}H_{112}N_{18}O_{22}S + 77\,O_2 \longrightarrow 63\,CO_2 + 38\,H_2O + SO_3 + 9\,CO(NH_2)_2 + ATP$$

$$RQ = \frac{63\,CO_2}{77\,O_2} = 0.8$$

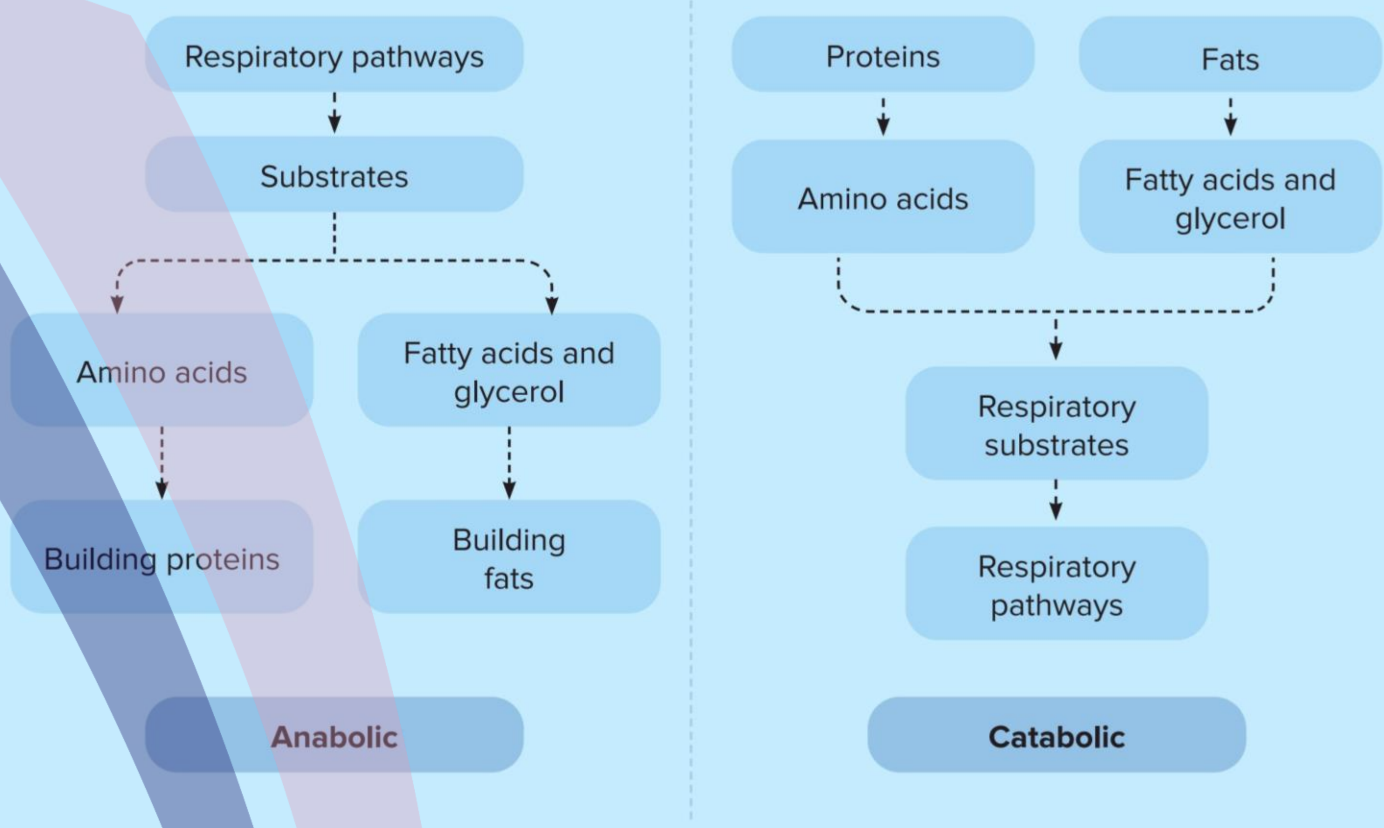
- The respiratory quotient gives the information about the respiratory substrates.

Substrates	Respiratory quotient
Carbohydrates	1
Fats	0.7
Proteins	About 0.9

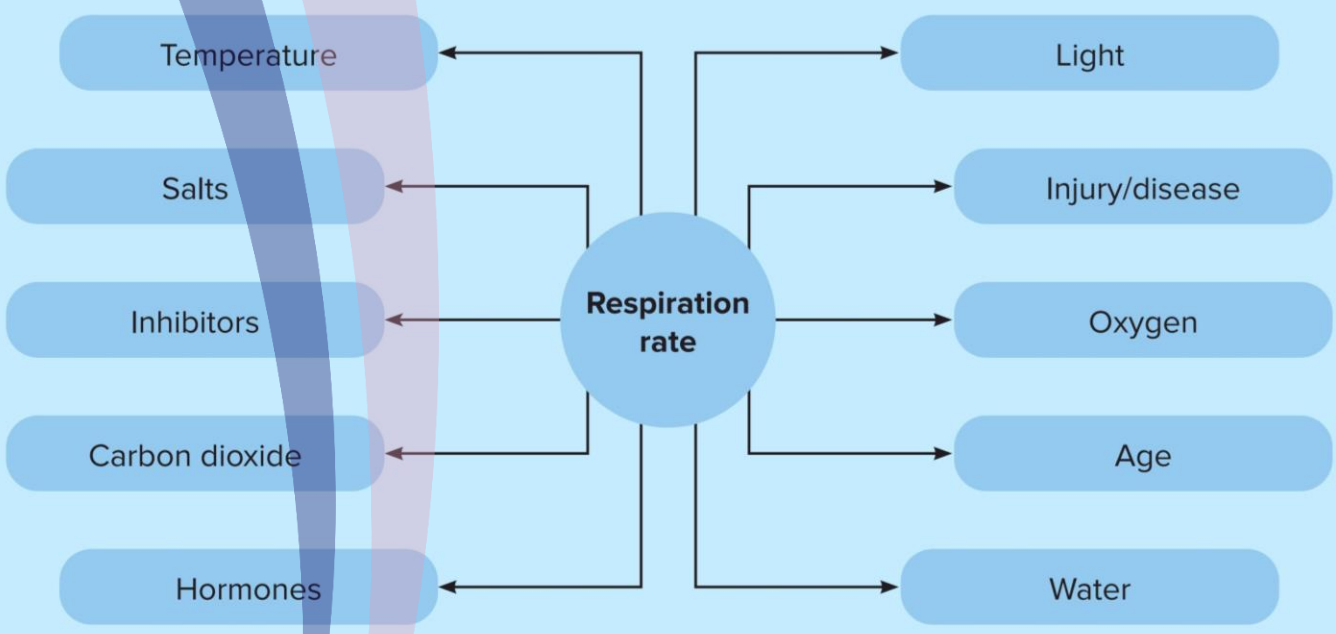
Summary Sheet



Respiration: An amphibolic process



Factors affecting the rate of respiration in plants



Factor	Effect on the rate of respiration
Temperature ↑	It increases till the optimum temperature and beyond, which sees a sharp decline.
Oxygen concentration ↑	Rate of respiration ↑
Carbon dioxide concentration ↑	Rate of respiration ↓
Salt concentration ↑	Rate of respiration ↑
Hormone concentration (Ethylene) ↑	Rate of respiration ↑
Intensity of light ↑	Rate of respiration ↑
Water ↑	Rate of respiration ↑
Age ↑	Rate of respiration ↓
Inhibitors ↑	Rate of respiration ↓
Injuries, diseases, and wounds ↑	Rate of respiration ↑

↑ = **Increase** ↓ = **Decrease**

Respiration quotient

$$\text{Respiratory quotient (RQ)} = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

Substrates	Respiratory quotient
Carbohydrates	1
Fats	0.7
Proteins	About 0.9