NEET UG BIOLOGY

DISCLAIMER

The content provided herein are created and owned by various authors and licensed to Sorting Hat Technologies Private Limited (“Company”). The Company disclaims all rights and liabilities in relation to the content. The author of the content shall be solely responsible towards, without limitation, any claims, liabilities, damages or suits which may arise with respect to the same.

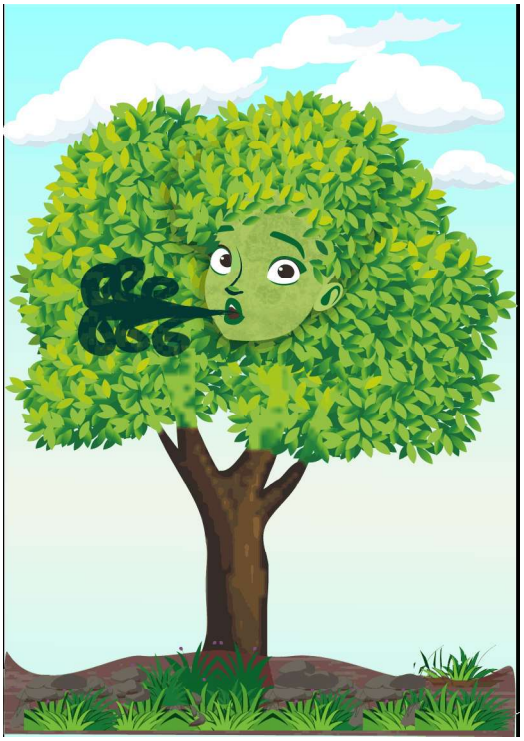
Respiration in Plants

INTRODUCTION

- All cells require energy, the capacity to cause physical or chemical changes in the cells.
- These energy-requiring changes can be biosynthesis, movement, uptake of materials, and development.
- **Phototrophs** obtain light energy directly from the sun and use it to reduce low-energy inorganic molecules like carbon dioxide through photosynthesis. They convert this trapped light energy into chemical energy (stored in the bonds of sucrose, glucose or starch).
- The organisms that cannot harvest solar energy like **chemotrophs** obtain their energy by oxidizing the high-energy molecules synthesised by phototrophs.
- **Respiration** is **different** from **gaseous exchange**, as the former involves biological oxidation of organic molecules along with the release of energy, and the latter involves the intake of oxygen and release of carbon dioxide.

RESPIRATION: MEANING AND CHARACTERISTICS

- The term respiration was coined by **Dutrochet**.
- The term 'respiration' is derived from the latin word 'respirate' which means 'to breathe'.
- Respiration is a catabolic exergonic process, but it is more precisely an **amphibolic process**.
- It is a metabolic process where the free energy released by the oxidation of organic compounds is used to manufacture ATP.
- Substances used for oxidation are known as **respiratory substrates**, for e.g., Carbohydrates (most used), fats, organic acids or proteins.
- Cellular respiration is defined as the flow of electrons via a membrane from a reduced coenzyme to an electron acceptor that is accompanied by ATP production.
- Energy is not released in a single step in respiration to avoid the conversion of complete energy into



Plants during day time produce oxygen, which is more than ten times the carbon dioxide produced at night.

Definition

Respiration: It is a metabolic process where the free energy released by the oxidation of organic compounds is used to manufacture ATP.

Rack Your Brain

Why is the energy not released in a single step during respiration?

heat, nor it is directly used for cellular activities. Instead, the energy is liberated in a controlled fashion in several steps and is mostly stored in high energy bonds of ATP.

- The stepwise release of chemical bond energy enables the cell to utilise a relatively higher proportion of the released energy in ATP synthesis. It minimises the wastage of energy.
- Cellular respiration is similar to combustion (burning of coal, wood, oil, etc.) in terms of
  (i) Complex organic substances breakdown,
  (ii) Oxygen utilisation,
  (iii) Carbon dioxide production, and
  (iv) Release of energy, but there are some fundamental differences between the two processes.

Previous Year's Question

Life without air would be
(a) Reductional
(b) Free from oxidative damage
(c) Impossible
(d) Anaerobic

Differences between Respiration and Combustion

RESPIRATION	COMBUSTION (BURNING)
1. Biochemical process and occurs inside living cells.	1. Physiochemical and non-cellular process.
2. It is under biological control.	2. It is an uncontrolled process.
3. Energy is released in stages as chemical bonds are broken in steps.	3. Energy is released in a single step as most of the chemical bonds break simultaneously.
4. Only a part of energy is lost as heat.	4. Most of the energy is liberated as heat.
5. Except in few cases, light is not emitted during respiration.	5. Light is often emitted during combustion.
6. Temperature is not allowed to rise.	6. Temperature becomes very high.
7. Most of the energy is trapped in ATP molecules.	7. No ATP is formed during combustion.
8. Each step is catalysed by an enzyme.	8. Enzymes are not involved in combustion.
9. A number of intermediates are formed for the synthesis of different organic compounds.	9. No intermediates are produced in combustion.

GASEOUS EXCHANGE IN PLANTS

- Plants uptake oxygen and release carbon dioxide during cellular respiration. Plants lack any specialised organ for gaseous exchange as each plant part participates in gaseous exchange; also, they do not have great demands for the gaseous

Rack Your Brain

Which is the most favourable respiratory substrate and why?

exchange (O_2 is available within the cell) and there is low distance for diffusion.

- Plants have some specialised structures like **stomata** (in leaves) and **lenticels** (in stems) to assist gaseous exchange. Parts of plants involved in respiration are roots, leaves, stems, etc.
- Plants breathe via cellular respiration. The complete combustion of glucose produces end products like CO_2 and H_2O and yields energy as heat.

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

Respiratory Substrate

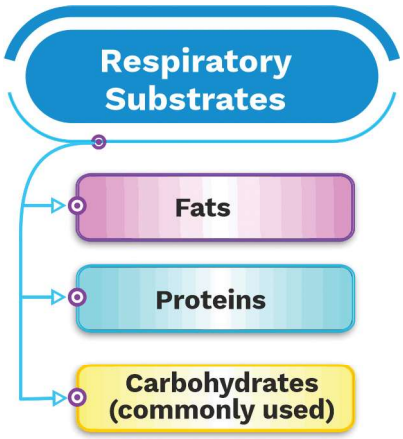
- The organic substances used for oxidation are known as **respiratory substrates**.
- The most used respiratory substrate is **carbohydrate** (glucose).
- Fats are seldom used as respiratory substrates.
- Proteins are rarely used in respiration. In other organs, proteins are employed as respiratory substrate only the situation when carbohydrates and fat reserves have been used up (during long fasting).
- Fats and proteins are not as such used in respiration. Instead, they are initially broken down into intermediates (identical to those in sugar oxidation). The intermediate metabolites from all three sources are finally oxidised through a common oxidative pathway, called the Krebs tricarboxylic acid cycle (TCA cycle).

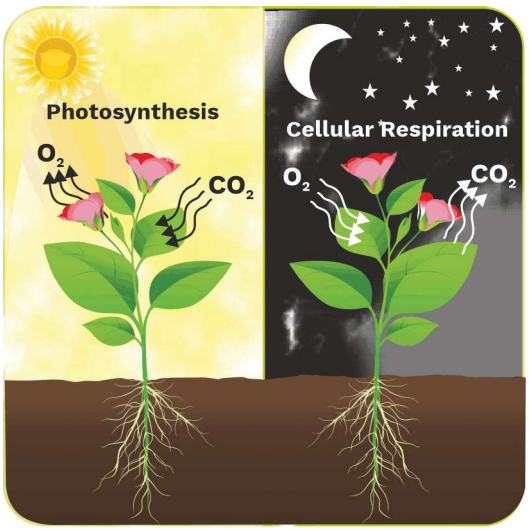
Types of Respiration

- The type of respiratory substrate divides respiration into two types:
  - **Floating respiration:** It involves floating inclusions like **fats** or **carbohydrates** as respiratory substrate.
  - **Protoplasmic respiration:** It involves **proteins** as respiratory substrate.

Gray Matter Alert!!!

Carbohydrates are most used respiratory substrates, but pure proteins and fats are avoided to be used as respiratory substrates.





- The presence or absence of oxygen during oxidation divides respiration into two types:
- **Aerobic respiration**
- **Anaerobic respiration**

AEROBIC RESPIRATION

- It involves the complete oxidation of organic food molecules with the help of oxygen (as a terminal oxidant) into carbon dioxide and water.
- It takes place in **mitochondria** and necessitates oxygen (oxygen-dependent).
- The **final acceptor** of the electron is molecular **oxygen.**
- Energy (686 Kcal or 2870 kJ per molecule of glucose) is liberated during aerobic respiration.

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

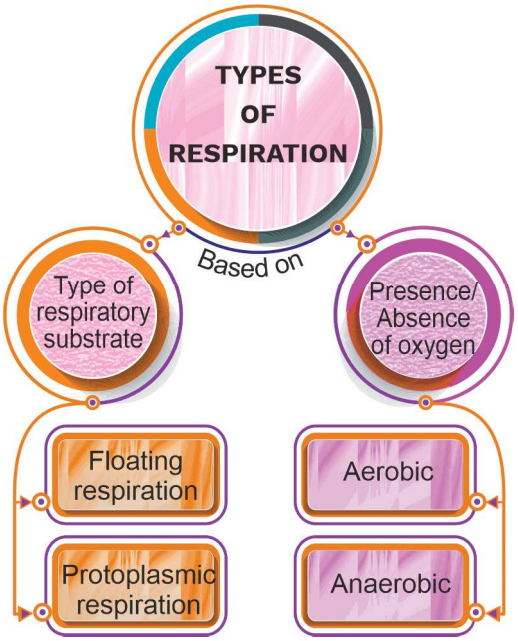
ANAEROBIC RESPIRATION

- It involves incomplete (or partial) oxidation of organic food molecules without oxygen being used as an oxidant.

Previous Year's Question

In which of the following processes CO_2 is not released?

(1) Aerobic respiration in plants
(2) Aerobic respiration in animals
(3) Alcoholic fermentation
(4) Lactate fermentation



Previous Year's Question

Cell respiration is carried out by

(1) Ribosome
(2) Mitochondria
(3) Chloroplast
(4) Golgi bodies

Gray Matter Alert!!!

The net gain of ATP molecules per glucose molecule breakdown in anaerobic (fermentation) and aerobic respiration is 2 molecules and 36 or 38 molecules respectively.

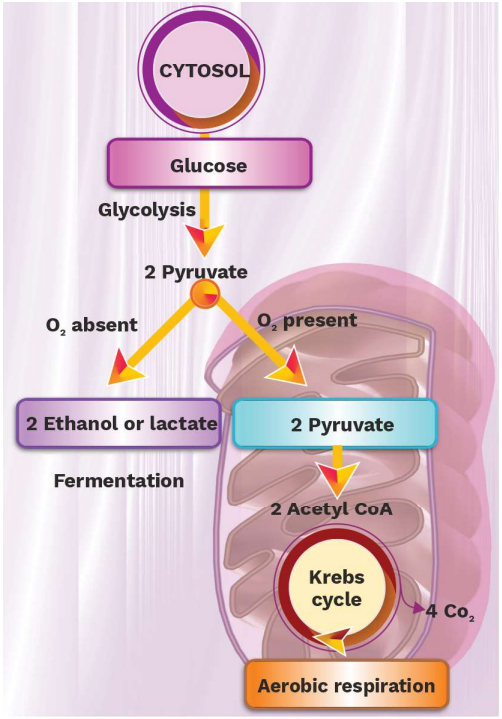
AEROBIC RESPIRATION	FERMENTATION/ ANAEROBIC RESPIRATION
1. It is the normal mode of respiration in plants and animals.	1. It is the normal mode of respiration in some parasitic worms and micro- organisms. Others resort to it temporarily.
2. It uses oxygen for breakdown of the respiratory substrate.	2. It does not use oxygen for breakdown the respiratory substrate.
3. Respiratory substrate is completely oxidised.	3. There is incomplete oxidation of respiratory substrate.
4. It involves exchange of gases between the organism and the environment.	4. Exchange of gases is absent.
5. It yields inorganic end products.	5. At least one of the end products is organic. Inorganic substances may or may not be produced.
6. Consists of three steps: glycolysis, krebs' cycle and terminal oxidation.'	6. Consists of two steps glycolysis and incomplete breakdown of pyruvate.
7. It releases carbon dioxide and water.	7. It may or may not release carbon dioxide. Water is usually not formed.
8. It occurs in cytoplasm and mitochondria.	8. It occurs in cytoplasm only.
9. It involves electron transport system.	9. Electron transport is absent in anaerobic respiration.

It takes place in the **cytoplasm** in the **absence of oxygen** and releases a small amount of energy.

- The common products released as a result of anaerobic respiration are carbon dioxide and ethyl alcohol or lactic acid.
- Compounds such as sulphate, fumarate or nitrate act as the terminal electron acceptor.

$$C_6H_{12}O_6 \xrightarrow{Enzymes} \underset{\text{ethyl alcohol}}{2C_2H_5OH} + \text{Energy (247 kJ)}$$

- It is the most common mode of respiration in some microorganisms (e.g., yeast and some bacteria) and parasitic worms.
- In microorganisms, the term fermentation is often used in place of anaerobic respiration.
- In higher organisms, anaerobic respiration occurs as a temporary measure.



THE MITOCHONDRION: THE REACTION HUB

- Mitochondria are the site of all the metabolic respiratory reactions in eukaryotes.
- It is a double membrane structure where the **outer membrane** is **freely permeable** to ions and small molecules due to the presence of transmembrane channel proteins known as **porins**.
- The **inner membrane** bears **specific carriers** for the inward transport of pyruvate and fatty acids as it is selectively permeable.
- The mitochondrion consists of many infoldings called **cristae** that accommodate respiratory complexes and helps in increasing the surface area.
- The spaces created due to infoldings of cristae provide a region where protons are pumped during electron transport.
- It is the ultimate site for the synthesis of ATP and thus it is called as the '**powerhouse of the cell**'.

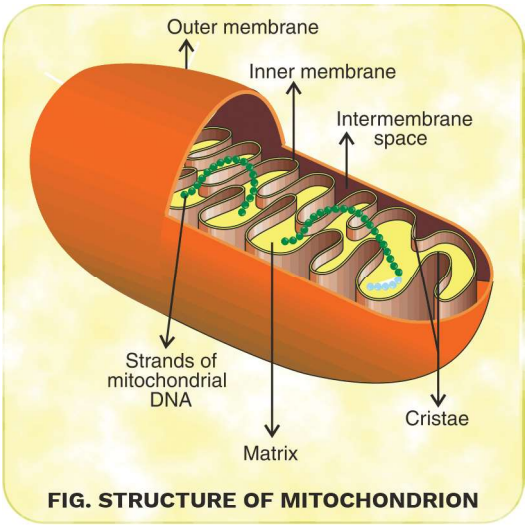


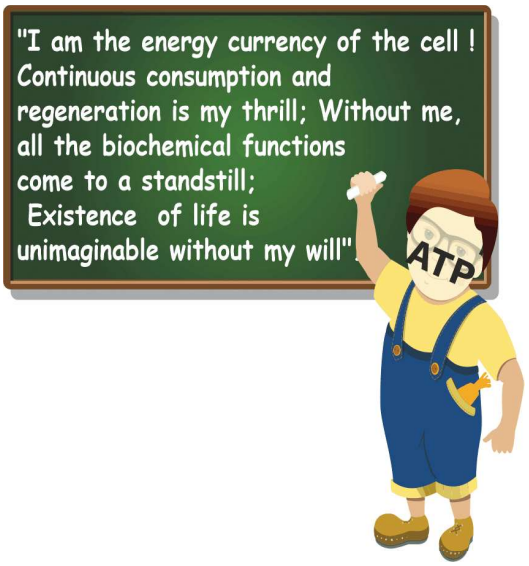
FIG. STRUCTURE OF MITOCHONDRION

ATP-The Ultimate aim of Respiratory Breakdown

- The term Adenosine triphosphate (ATP) was discovered by Karl Lohmann (1929).
- Fritz Lipmann (1941) is called as the 'father of ATP cycle' for discovering the synthesis and breakdown of ATP.
- It is also known as the **'energy currency of the cell'.**
- It consists of an **adenine, a ribose and a triphosphate moiety.**
- Energy is trapped in ATP because it produces the required amount of energy instantly.
- About **8.15 kcal or 34 KJ** of energy is released per hydrolysis of one molecule of ATP.
- It can store small packets of energy as soon as the energy becomes available and minimise the wastage of energy.
- Formation of ATP linked with the oxidation of **NADH and $FADH_2$** and ETS is called **oxidative phosphorylation** while ATP formation directly by

Rack Your Brain

Which type of respiration occurs in skeletal muscles during strenuous exercise?



the oxidation of substrate without ETS is called **substrate level phosphorylation**.

MECHANISM OF RESPIRATION

- **Respiration involves five major stages:**
  - Glycolysis
  - Pyruvate Oxidation
  - Tricarboxylic Acid Cycle (TCA cycle)
  - Electron Transport System (ETS)
  - ATP Synthesis or Oxidative Phosphorylation
- Glycolysis is common to both aerobic and anaerobic respiration.
- The stages glycolysis, pyruvate oxidation, and tricarboxylic acid cycle (TCA cycle) involve substrate oxidation and simultaneous reduction of coenzymes.

Previous Year's Question

Oxidative phosphorylation is

(1) Formation of ATP by transfer of phosphate group from a substrate to ADP

(2) Oxidation of phosphate group in ATP

(3) Addition of phosphate group to ATP

(4) Formation of ATP by energy released from electrons removed during substrate oxidation

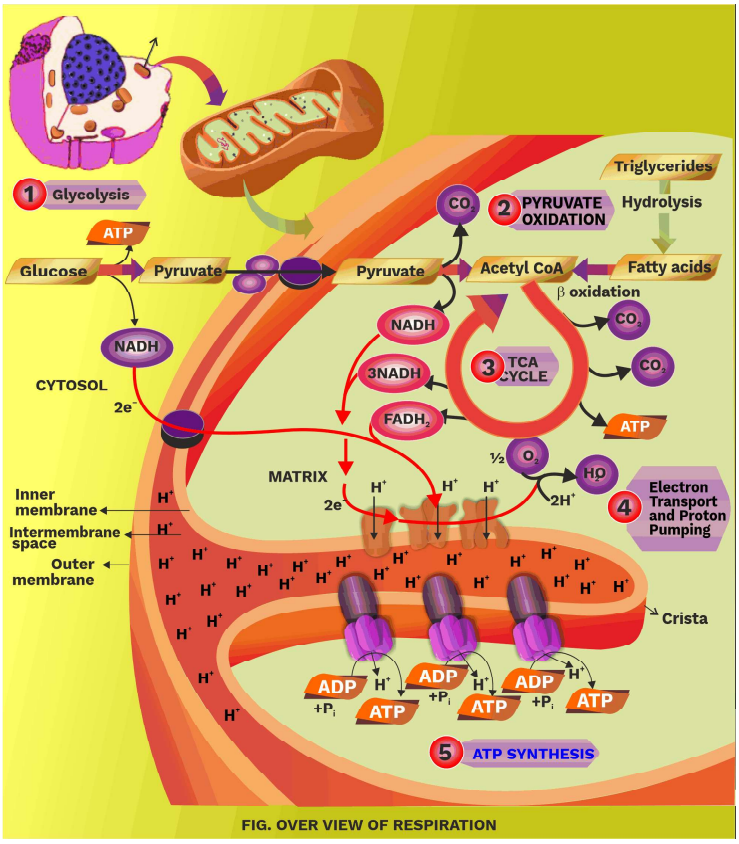


FIG. OVER VIEW OF RESPIRATION

- The stages Electron Transport system (ETS) and ATP Synthesis involve coenzyme reoxidation and the generation of ATP.

GLYCOLYSIS

- The term Glycolysis is derived from two Greek words *glycos* (which means sugar) and *lysis* (which means splitting).
- It is also called **EMP** (**Embden-Meyerhof-Parnas**) pathway, in the honour of three German scientists Gustav Embden, Otto Meyerhof, and J. Parnas who gave the scheme of glycolysis.
- Glycolysis takes place in the **cytoplasm** and all the enzymes required are present in the cytoplasm.
- It is the only process that takes place in anaerobic organisms thus is known as universal pathway.
- Glycolysis is independent of oxygen.
- The breakdown of glucose commences with glycolysis.
- It involves the oxidation of glucose(or similar hexose sugar) into two molecules of a 3-C compound–pyruvic acid, releasing some energy (as ATP and $NADH_2$).
- Glucose is derived from sucrose (which is the end product of photosynthetic carbon reactions in plants) or from stored carbohydrates.
- It is a major pathway in organs where mitochondria are absent or few e.g., cornea, erythrocytes.
- The cardiac muscle is not well adapted for glycolysis and thus it cannot survive in the absence of oxygen for long.
- It produces many intermediates that branch other reactions.
- It involves ten sequences of enzyme catalysed reactions which are divided into three main substages:
  - **Preparatory phase**
  - **Splitting phase**
  - **Energy generation phase**

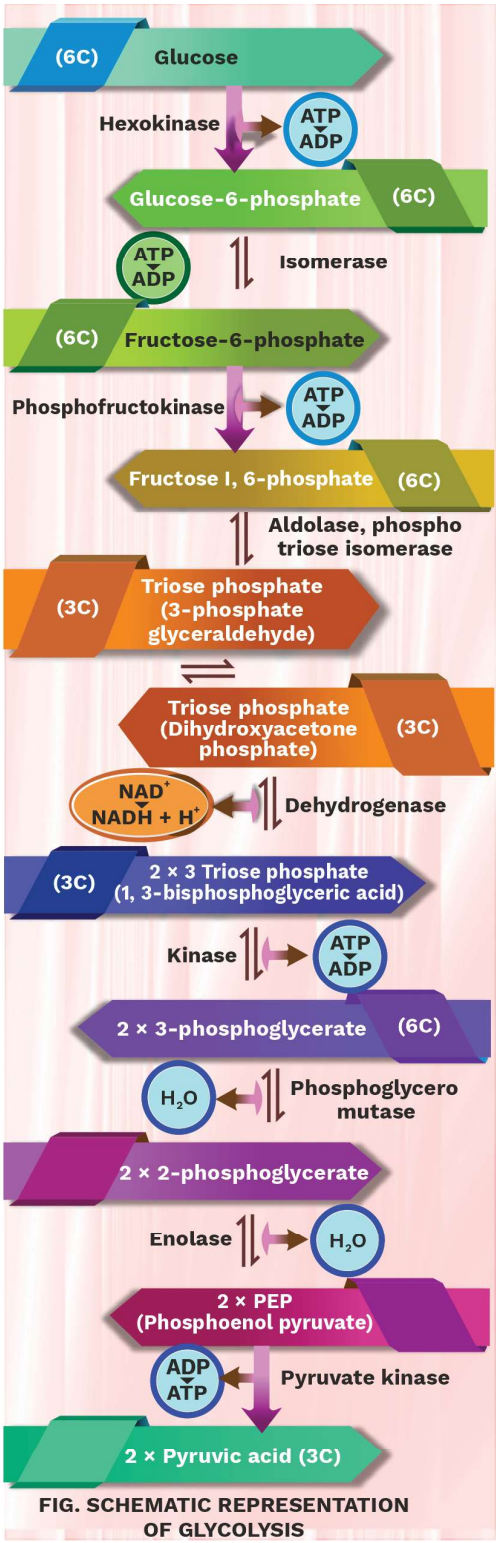


FIG. SCHEMATIC REPRESENTATION OF GLYCOLYSIS

Preparatory Phase

Step 1: Phosphorylation: In the presence of enzyme hexokinase and Mg^{2+}, glucose is phosphorylated to glucose-6-phosphate with the breakdown of ATP. It is an irreversible step.

Step 2: Isomerisation: Glucose-6-phosphate is isomerised to fructose-6-phosphate with the help of enzyme phosphohexose isomerase (phosphogluco isomerase). It is a reversible conversion of aldose sugar to ketose sugar.

Step 3: Phosphorylation: Fructose-6-phosphate is phosphorylated to form fructose 1,6-bisphosphate with the help of ATP, in presence of enzyme phosphofructokinase and Mg^{2+}. It is an irreversible reaction catalyzed by an allosteric enzyme Phosphofructokinase-1.

Splitting Phase

Step 4: Splitting: Fructose 1, 6-bisphosphate is then splitted into two 3-C molecules glyceraldehyde-3 phosphate (PGAL) and dihydroxyacetone phosphate (DHAP) with the help of enzyme aldolase. This is a reversible step.

Step 5: Isomerization: Dihydroxy acetone phosphate is further tranformed into glyceraldehyde-3-phosphate with the help of enzyme phosphotriose isomerase. This interconversion is reversible.

Energy Generation Phase

Step 6: Dehydrogenation and Phosphorylation: Glyceraldehyde 3-phosphate molecules are oxidised in the presence of enzyme Glyceraldehyde-3-phosphate dehydrogenase. The molecules lose hydrogen to NAD^+ to form NADH + H^+ and accepts inorganic phosphate from phosphoric acid (H_3PO_4) to form

Gray Matter Alert!!!

Glycolysis takes place both in aerobic and anaerobic respirations, in anaerobic respiration glycolysis produces lactic acid while in aerobic respiration it produces pyruvic acid.

Previous Year's Question

The overall goal of glycolysis, Krebs cycle and the electron transport system is the formation of:

(1) ATP in small stepwise units
(2) ATP in one large oxidation reaction
(3) Sugars
(4) Nucleic acids

Rack Your Brain

Why can't the cardiac muscle survive without oxygen for long?

Gray Matter Alert!!!

Iodoacetate is an inhibitor of Glyceraldehyde-3-phosphate dehydrogenase as it forms a covalent derivative of the -SH group of the active site of the enzyme and inactivates it.

1, 3-bisphosphoglycerate. This step is reversible.

Step 7: Dephosphorylation (ATP Formation): In this step, a high-energy phosphate group is transferred from 1, 3-bisphosphoglycerate to ADP.

In the presence of enzyme phosphoglycerate kinase, 1, 3-bisphosphoglycerate is converted into 3-phosphoglycerate.

One molecule of ADP is phosphorylated to ATP in the reaction.

As ATP is formed from a substrate without the involvement of ETS, this step is a good example of substrate-level phosphorylation. This reaction is also reversible.

Step 8: **Isomerization:**

3-phosphoglycerate is converted into its isomer 2-phosphoglycerate by the enzyme phosphoglycerate mutase. This reaction is also reversible.

Step 9: **Dehydration:** A molecule of water in the presence of enzyme enolase and Mg^{2+} is removed from 2-phosphoglycerate to produce phosphoenolpyruvate. This reaction is also reversible.

Note: **Fluoride** is a **competitive inhibitor** that inhibits enolase in this step.

Step 10: **Dephosphorylation (ATP Formation):** This step involves the transfer of a high energy phosphate group from phosphoenolpyruvate to ADP, which forms ATP with the help of the enzyme pyruvate kinase in the presence of Mg^{2+} and K^{+}. This produces pyruvate and a molecule of ATP by substrate-level phosphorylation. This step is **irreversible.**

The net reaction of glycolysis is as follows:

Previous Year's Question

The number of substrate level of phosphorylations in one turn of citric acid cycle is

(1) One
(2) Two
(3) Three
(4) Four

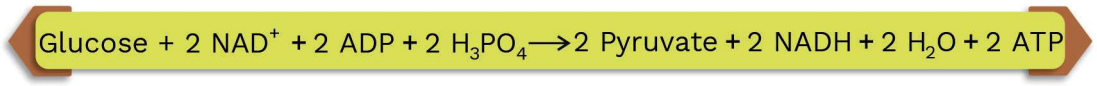
Previous Year's Question

Pyruvate dehydrogenase activity during aerobic respiration requires

(1) Calcium
(2) Iron
(3) Cobalt
(4) Magnesium

Gray Matter Alert!!!

Pasteur effect: While studying fermentation by yeast, louis Pasteur noticed that the utilisation of glucose was reduced to seven folds when the anaerobic yeast was exposed to air. He concluded that oxygen inhibits glycolysis.



Net products of glycolysis

Reaction	Product/ Reactant
Phosphorylation of glucose to form fructose 1, 6-bisphosphate	2 ATP Consumed
Substrate-level phosphorylation (conversion of 1, 3-bisphosphoglycerate to 3-phosphoglycerate and phosphoenolpyruvate to pyruvate)	4 ATP Produced
Oxidation of glyceraldehyde 3-phosphate to 1, 3-bisphosphoglycerate	2 NADH Produced
Total	**2 ATP & 2 NADH**

On oxidation, two molecules of NADH + H^+ produce 6 molecules of ATP. Therefore, during glycolysis, there is a net gain of 8 ATP molecules.

Regulation of Glycolysis

The enzymes catalysing the irreversible reactions, i.e., Hexokinase (catalysing step 1), phosphofructokinase (catalysing step 3), and pyruvate kinase (catalysing step 10) regulate glycolysis.

FATE OF PYRUVATE

- The end product of glycolysis is pyruvate which has three fates depending on the availability of oxygen or cellular needs. The three fates are:
  - **Alcoholic fermentation**
  - **Lactic acid fermentation**
  - **Aerobic respiration**
- In the absence of oxygen, the pyruvate undergoes fermentation or anaerobic respiration while in its presence it undergoes aerobic respiration (complete oxidation).

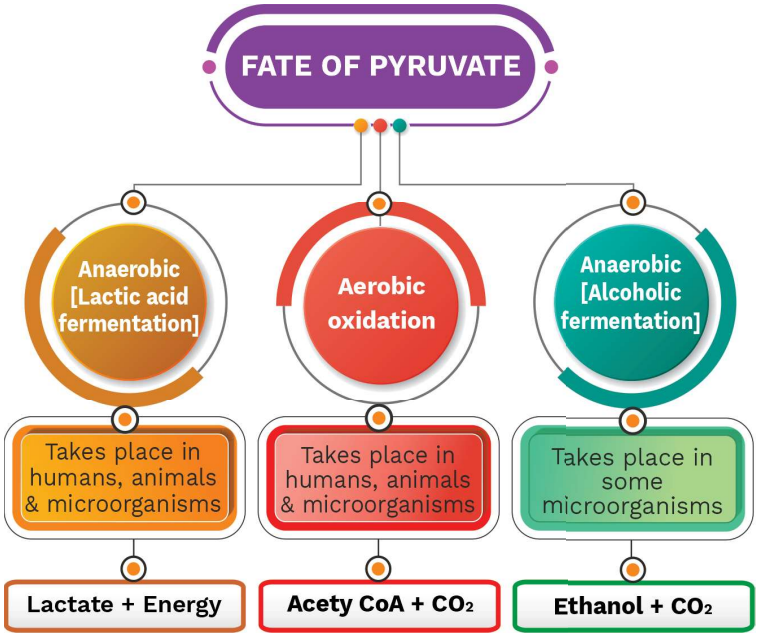
Previous Year's Question

Conversion of glucose to glucose-6-phosphate the first irreversible reaction of glycolysis, is catalysed by

(1) Aldolase
(2) Hexokinase
(3) Enolase
(3) Phosphofructokinase

Gray Matter Alert!!!

Phosphofructokinase is the most important regulatory enzyme in glycolysis that regulates the rate limiting committed step. It is also called as the allosteric pacemaker enzyme of glycolysis which is activated by AMP, ADP and inhibited by ATP and H^+.



FERMENTATION

- It was first time discovered by **Gay Lussac**.
- Fermentation involves the incomplete oxidation of pyruvate to **ethanol and CO_2 or lactic acid**.
- It is an enzyme-controlled **partial breakdown** of **organic compounds** (food) without using oxygen and releasing only a fraction of energy.
- Fermentation is also called as a self-contained process as it doesn't need any electron acceptor from outside.
- The final acceptor of electron is pyruvic acid or acetaldehyde. The end products are lactic acid or ethyl alcohol and not water.
- **Buchner** (1897) realised that fermentation could be caused by mixing sugar solution with yeast extract, instead of living yeast cells. The enzyme complex present in the extract was named as zymase and hence, fermentation is also called zymosis.
- It takes place in **anaerobic conditions**, most commonly found in many **prokaryotes**, unicellular eukaryotes, and germinating seeds.

Rack Your Brain

Which enzyme is known as the pacemaker of glycolysis?

Previous Year's Question

The energy releasing metabolic process in which substrate is oxidised without an external electron acceptor is called

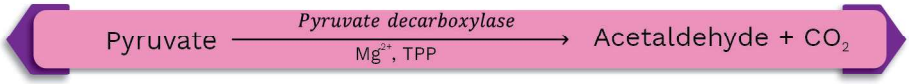
(1) Photorespiration
(2) Glycolysis
(3) Fermentation
(4) Aerobic respiration

- **NADH + H^+** is used as the reducing agent.
- NADH is used to regenerate NAD^+ by transferring electrons to the organic molecules.
- In fermentation (Alcoholic/Lactic) energy released is less than 7% of the energy present in glucose and out of this only a proportion is trapped as high energy bonds of ATP.
- In both types of fermentation, the **net gain 2 ATP.**
- It is a hazardous process.

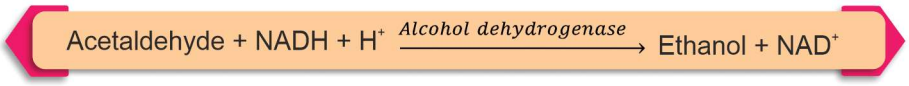
Alcoholic Fermentation

- It takes place in fungi (e.g., *Rhizopus*, yeast) and bacteria.
- It is used for the formation of bread and beverages like alcoholic drinks.
- It is a two-step pathway:

Step 1: Pyruvate first undergoes decarboxylation (removal of carboxyl group in the form of carbon dioxide) with the help of enzyme **pyruvate decarboxylase**, Mg^{2+}, and TPP (thiamine pyrophosphate) to produce acetaldehyde and carbon dioxide.



Step 2: Acetaldehyde is reduced by NADH and H^+ to alcohol by a process that is catalysed by the enzyme **alcohol dehydrogenase**.



- When the concentration of alcohol rises up to 13% or more, yeasts poison themselves to death.

Lactic Acid Fermentation

- It is common in lactic acid bacteria (e.g., *Lactobacillus*) and muscles.
- Pyruvic acid (produced in glycolysis) is reduced by NADH in the presence of enzyme lactate dehydrogenase (LDH) to form lactic acid.

Previous Year's Question

Which one of the following mammalian cells are not capable of metabolizing glucose to carbon dioxide aerobically?
(1) Red blood cells
(2) White blood cells
(3) Unstriated muscle cells
(4) Liver cells

Rack Your Brain

What are the end products of fermentation?

Previous Year's Question

Cytochrome is
(1) Metallo flavo protein
(2) Fe containing porphyrin pigment
(3) Glycoprotein
(4) Lipid

$$\text{Pyruvate} + \text{NADH} + \text{H}^+ \xrightarrow[Zn^{2+}]{\textit{Lactate dehydrogenase}} \text{Lactic acid} + \text{NAD}^+$$

- Skeletal muscles normally derive their energy through anaerobic respiration. After vigorous exercise, oxygen is inadequate for cellular respiration, because of which pyruvate converts into lactic acid in skeletal muscles.
- Lactic acid accumulates that results in muscular fatigue.
- This lactate produced in muscles is sent to the liver where it reconverts into pyruvate during rest.
- Pyruvate converts back into glucose by the process of **gluconeogenesis** in liver and is channelled back to the skeletal muscle for further glycolysis.
- This cycle is known as the **Cori cycle** or **Lactic acid cycle**.

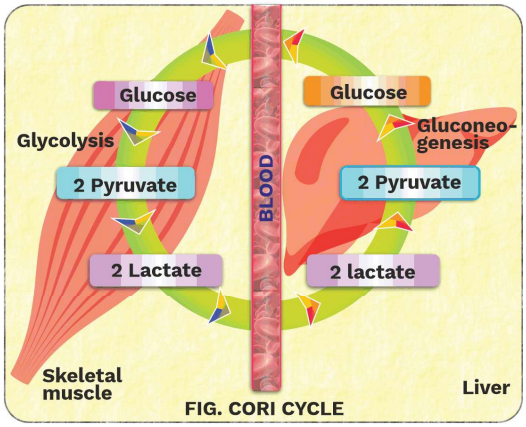


FIG. CORI CYCLE

In both processes, anaerobic respiration yields much less energy than aerobic respiration. The main reasons are:

(i) There is an **incomplete breakdown** of the respiratory substrate.
(ii) One of the end products of anaerobic respiration is organic that still contains energy.
(iii) NADH produced during glycolysis is often reutilised.
(iv) Electron transport chain is not present.
(v) Oxygen is not used for accepting electrons and protons.

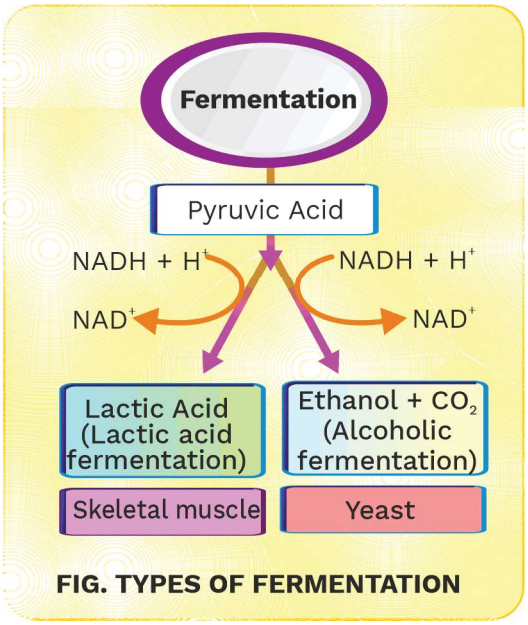


FIG. TYPES OF FERMENTATION

Difference between Glycolysis and Fermentation

GLYCOLYSIS	FERMENTATION
1. It is the first step of respiration which occurs without requirement of oxygen and is common to both aerobic and anaerobic mode of respiration.	1. It is anaerobic respiration which does not require oxygen.
2. It produces pyruvic acid.	2. Fermentation produces different products (ethanol, CO_2 and lactic acid).
3. It produces two molecules of NADH per glucose molecule.	3. It generally utilises NADH produced during glycolysis.
4. Glycolysis forms 2 ATP molecules per glucose molecule.	4. It does not produce ATP.

AEROBIC RESPIRATION (COMPLETE OXIDATION OF PYRUVATE)

- It is the **complete oxidation** of glucose in presence of oxygen and a larger number of ATPs are synthesised with the help of energy-driven from the substrate.
- It is most **common** in **higher organisms** and takes place in the **mitochondria**.
- Pyruvic acid (the final key product of glycolysis) produced in the cytosol, is transported to mitochondria, and thus initiates the second phase of respiration.
- In aerobic respiration, the terminal electron acceptor is **oxygen**, that reduces to form water. The cell utilises the oxygen which is diffused into it from its surroundings.
- Enzymes required for aerobic respiration are located in the matrix and the inner membrane of the mitochondria.
- Carbon dioxide and water produced in the process diffuse out of the cell.

Rack Your Brain

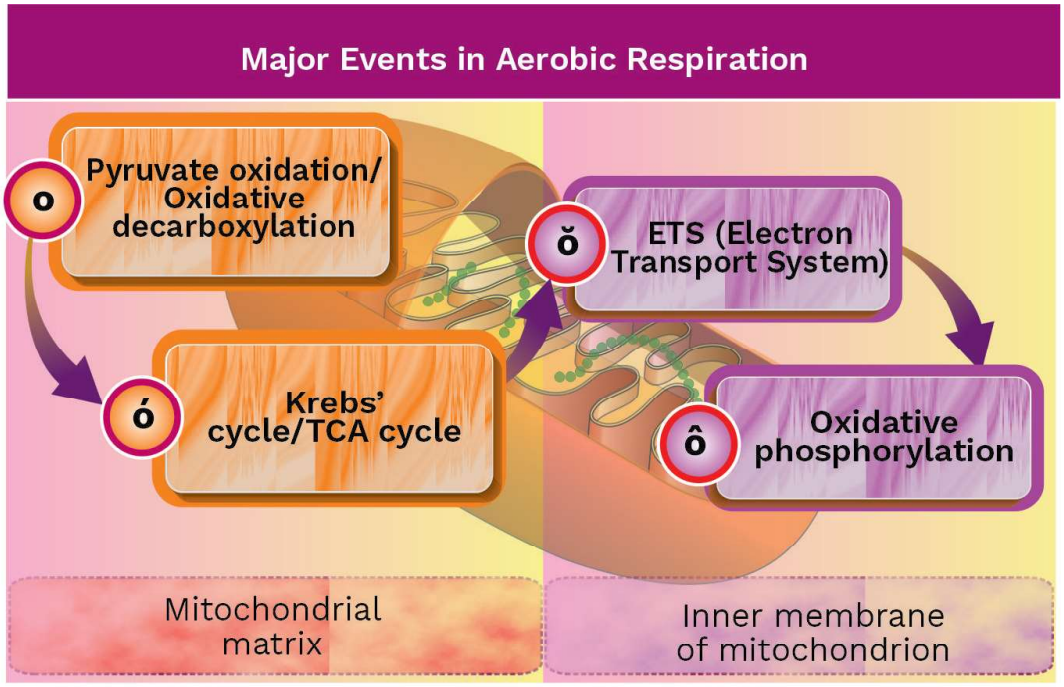
What is the key product of glycolysis?

Gray Matter Alert!!!

NADH produced during the glycolysis cannot pass through the inner mitochondrial membrane. In order to transport electrons to the ETS, NADH is shuttled via two shuttle systems: Malate aspartate shuttle system and Glycerol 3-phosphate shuttle system.

MAJOR PROCESSES IN AEROBIC RESPIRATION

- **Pyruvate oxidation or Oxidative decarboxylation**
- **Krebs' cycle or TCA cycle**
- **ETS and Oxidative phosphorylation**



Pyruvate oxidation or Oxidative decarboxylation

- It is the **first step** of aerobic respiration.
- It is an **intermediate** or **connecting reaction** between glycolysis and Krebs' cycle, thus it is known as **Link reaction** or **transition reaction** or **gateway reaction.**
- It occurs in the **mitochondrial matrix**.
- Pyruvate is first decarboxylated and then oxidised by the enzyme pyruvate dehydrogenase in the presence of cofactors Mg^{++}, TPP, NAD^{+}.
- Out of the three carbon atoms of pyruvic acid, one is oxidised to carbon dioxide.
- **Note:** This is the **first reaction** in **respiration** that leads to **CO_2 production**.
- The remaining 2-carbon forms the acetyl moiety. This acetate unit is readily accepted by a sulphur containing compound, coenzyme A(CoA), to form acetyl CoA.

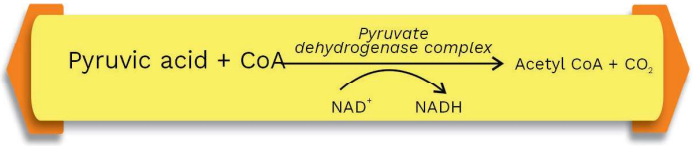
Rack Your Brain

What concentration of alcohol is poisonous to yeast?

Rack Your Brain

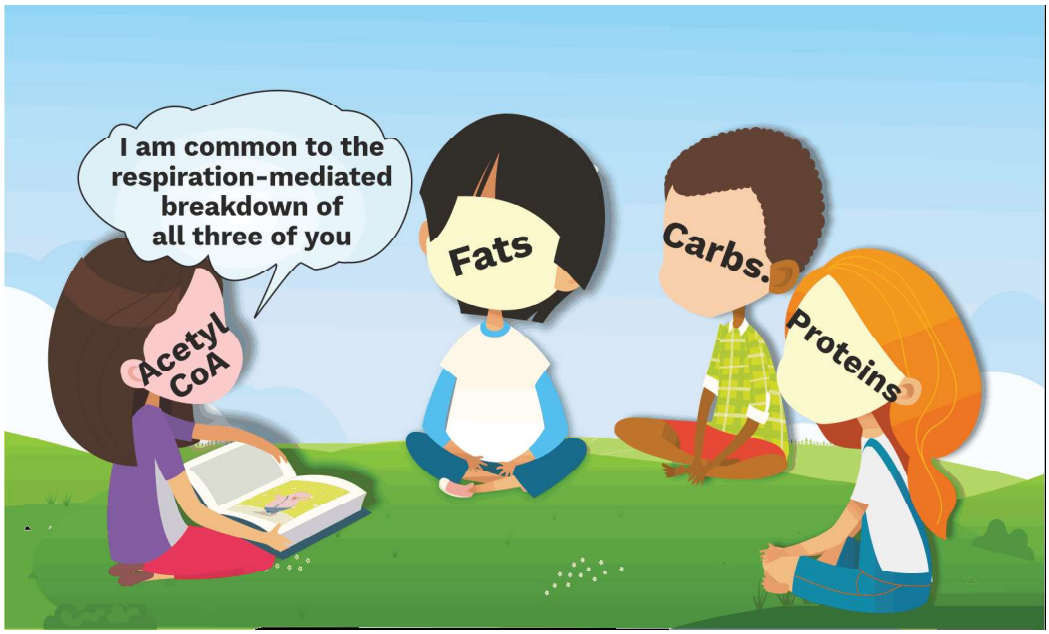
Which reaction is known as the link reaction in aerobic respiration?

- During the process, NAD^+ is reduced to NADH. The reaction is as follows:



Reaction	Product
Conversion of Pyruvate to Acetyl CoA	2 NADH Produced
Total	**2 NADH**

- **Acetyl CoA is the connecting link between glycolysis and the Krebs' cycle.**
- Two molecules of NADH are produced during this process. It results in a net gain of 6 ATP molecules (2 NADH × 3 = 6 ATP).



- Acetyl CoA is the common intermediate to enter Krebs' cycle.

Kreb's Cycle (TCA or Citric Acid Cycle)

- The citric acid cycle or Krebs' cycle was discovered by a German-born British biochemist **H. A. Krebs'** (received Nobel prize in 1953).
- The site for Krebs' cycle is the **mitochondrial matrix** and **all the enzymes** required for it are also **present in the mitochondrial matrix except** for **succinate dehydrogenase** which is located in the **inner mitochondrial membrane**.

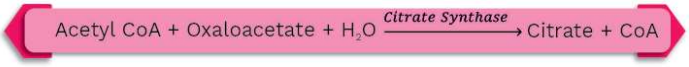
Rack Your Brain

In the respiration-mediated breakdown of fats, carbohydrates and proteins which biomolecule is common?

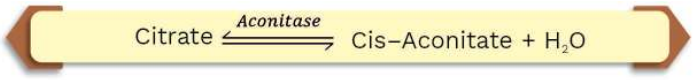
- The Krebs' cycle serves as a **common oxidative pathway for carbohydrates, fat, and proteins.**
- Acetyl-CoA enters this cycle forming citric acid and hence the cycle is named Citric acid cycle.
- Citric acid consists of three carboxylic groups (COOH); hence the cycle is also known as the Tricarboxylic acid (TCA) cycle.
- Krebs' cycle is stepwise oxidative and cyclic degradation of acetyl CoA into CO_2.

The various steps Krebs' cycle are as follows:

- **Condensation:** The first reaction involves the condensation of 2-C compound acetyl CoA with 4-C compound oxaloacetate (OAA) and water in the presence of condensing enzyme citrate synthase to form a tricarboxylic 6-C compound called citric acid and CoA is liberated. The first product of the Krebs' cycle is citric acid.



- **Dehydration:** Citrate undergoes reorganisation in the presence of nonheme iron protein enzyme, aconitase forming 6-carbon cis-aconitate with loss of water.



- **Hydration:** Cis-aconitate is isomerised to 6-carbon isocitrate in the presence of enzyme aconitase with the addition of water.

- **Dehydrogenation:** In the presence of enzyme isocitrate dehydrogenase and Mn^{2+}, isocitrate is dehydrogenated to oxalosuccinate. NAD^+ is converted into NADH + H^+.

Gray Matter Alert!!!

TCA doesn't involve oxygen directly, but it is strictly aerobic because the NAD^+ and FAD required for the cycle are regenerated in ETS only in aerobic conditions.

Rack Your Brain

Why is Krebs' cycle called as the TCA cycle?

Previous Year's Question

Which of these statements is incorrect?

(1) Enzymes of TCA cycle are present in mitochondrial matrix
(2) Glycolysis occurs in cytosol
(3) Glycolysis operates as long as it is supplied with NAD that can pick up hydrogen atoms
(4) Oxidative phosphorylation takes place in outer mitochondrial membrane

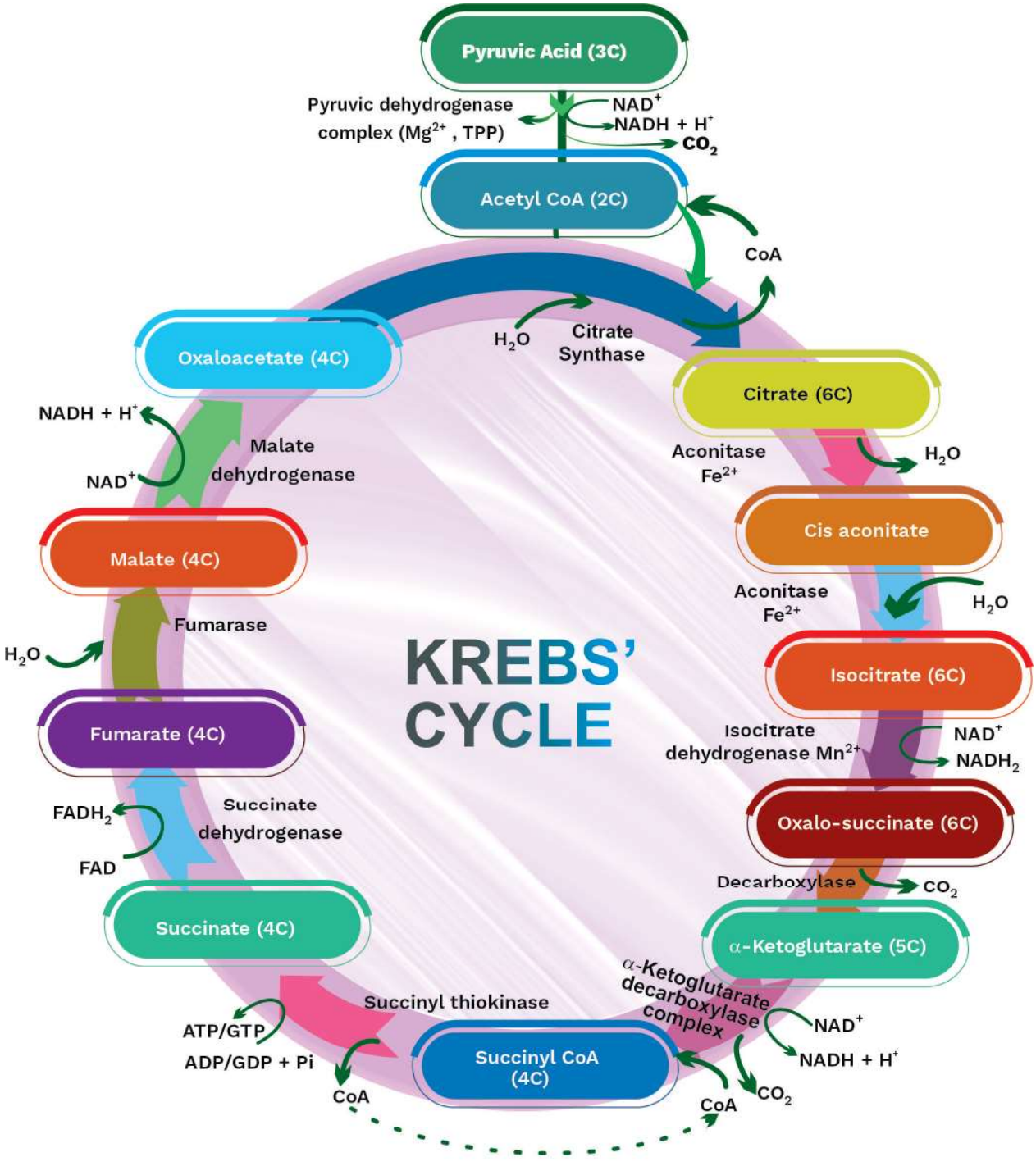
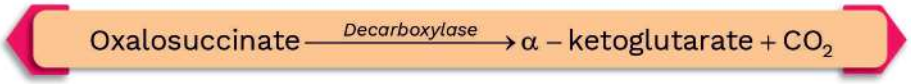
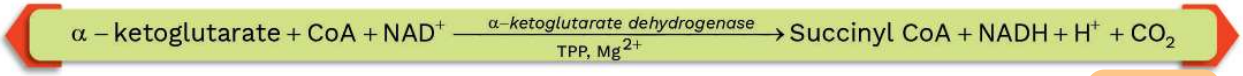


FIG. SCHEMATIC REPRESENTATION OF KREBS' CYCLE

- **Decarboxylation:** Oxalosuccinate in the presence of enzyme decarboxylase, is decarboxylated to form a 5-carbon containing α-ketoglutarate with the production of one molecule of carbon dioxide.



Oxidative decarboxylation: In the presence of enzyme complex α-ketoglutarate dehydrogenase (contains TPP and lipoic acid), α-ketoglutarate is both dehydrogenated (with the help of NAD^+) and decarboxylated to form succinyl CoA.

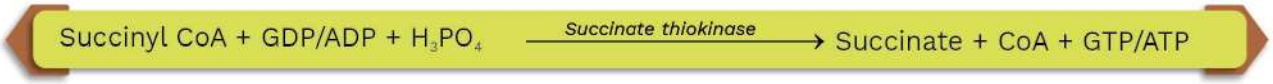


- **Substrate level phosphorylation:** Succinyl CoA is converted into succinate and CoA by the activity of enzyme succinate thiokinase or succinyl-CoA synthetase. Sufficient energy is released in this step to form GTP (in animals) and ATP (in plants).

Note: The GTP produced in this reaction by succinate thiokinase can donate its terminal phosphoryl group to ADP to form ATP, in a reversible reaction with the help of enzyme nucleoside diphosphate kinase.

Definition

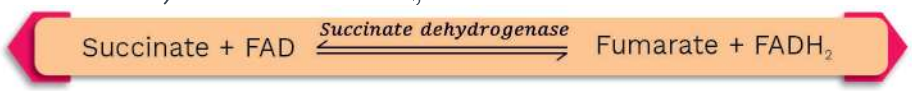
Anaplerotic reactions: TCA cycle includes a lot of intermediates of other biosynthetic pathways. These intermediates are used up in anabolic processes. To replenish these intermediates, anaplerotic reactions are considered (anaplerosis in Greek means to fill up).



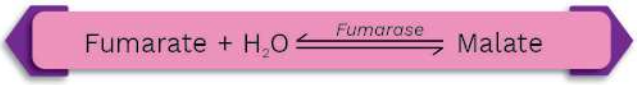
- **Dehydrogenation:** Succinic acid undergoes dehydrogenation in the presence of enzyme succinate dehydrogenase to form a 4-carbon containing fumarate and liberates a pair of hydrogen atom. Here, FAD (Flavin adenine dinucleotide) reduces to $FADH_2$.

Rack Your Brain

How is substrate level phosphorylation different to the oxidative phosphorylation?



- **Hydration:** Fumarate (Fumaric acid) is converted into 4-carbon malate (malic acid) in the presence of enzyme fumarase with the addition of water.

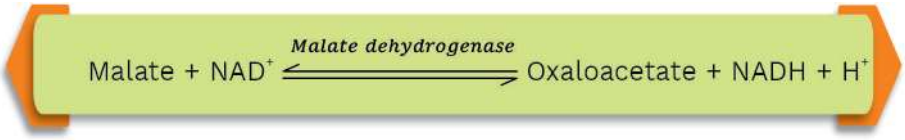


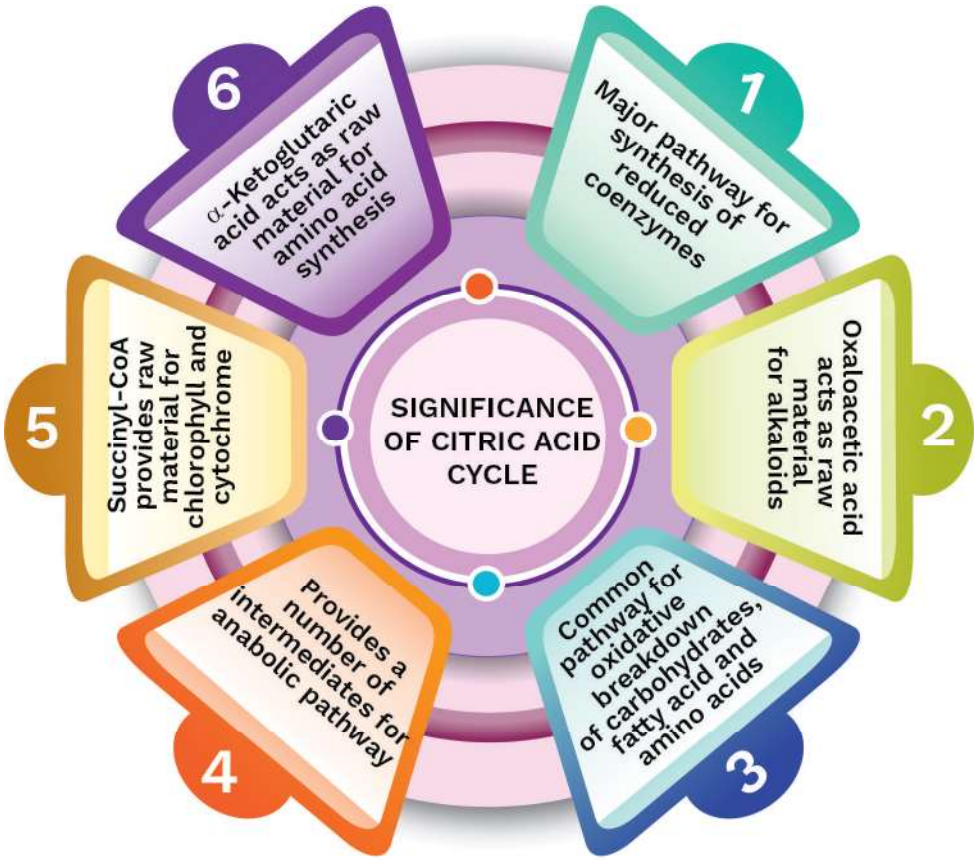
- **Dehydrogenation:** In this step, oxaloacetate is regenerated to react with acetyl CoA. Malate or malic acid in the presence of enzyme malate dehydrogenase is dehydrogenated to produce 4-carbon oxaloacetate. NAD^+ is converted into NADH + H^+.

Previous Year's Question

In Krebs' cycle, the FAD participates as electron acceptor during the conversion of

(1) Fumaric to Malic acid
(2) Succinic to Fumaric acid
(3) Succinyl CoA to Succinic acid
(4) α-ketoglutarate to Succinyl CoA





The summary equation for this phase of respiration is as follows:

Gray Matter Alert!!!

TCA is amphibolic in nature i.e., it includes both anabolic and catabolic processes.

Net products of Citric acid cycle

Reaction	Product
Conversion of Isocitrate to α-ketoglutarate	2 NADH Produced
Conversion of α-ketoglutarate to Succinyl-CoA	2 NADH Produced
Conversion of Succinyl-CoA to Succinate	2 ATP Produced
Conversion of Succinate to Fumarate	2 $FADH_2$ Produced
Conversion of Malate to Oxaloacetate	2 NADH Produced
Total	**6 NADH, 2 $FADH_2$ & 2ATP**

Note: During citric acid cycle:

- Decarboxylation occurs at two steps releasing two molecules of CO_2.
- 6-molecules of NADH produce 18-molecules of ATP after oxidative phosphorylation (6 NADH × 3 = **18 ATP**).
- 2 $FADH_2$ gives rise to 4-molecules of ATP after oxidative phosphorylation (2 $FADH_2$ × 2 = **4 ATP**).
- Two molecules of ATP are generated during the cycle.
- Thus, a **total of 24 ATP** molecules per molecule of glucose are produced.
- These reduced electron carriers pass on the hydrogen atoms to oxygen through electron transport system yielding ATP molecules.

Previous Year's Question

Plants, but not animals, can convert fatty acids to sugars by a series of reactions called
(1) Photosynthesis
(2) Kreb's cycle
(3) Glycolysis
(4) Glyoxylate cycle

Regulation of Citric Acid Cycle

- Enzymes catalysing the irreversible reactions are the regulators in TCA cycle namely-citrate synthase (inhibited by ATP, NADH and succinyl CoA, isocitrate dehydrogenase (inhibited by ATP and NADH) and α-ketoglutarate dehydrogenase (inhibited by succinyl CoA and NADH.

TERMINAL OXIDATION

- The coenzymes NADH and $FADH_2$ produced during glycolysis and citric acid cycle contain most of the energy in a stored form which is yet to be utilised.
- This is the last step of aerobic respiration which includes the transfer of protons and electrons from reduced coenzymes eventually to oxygen, forming water.
- The standard free energy released from NADH and $FADH_2$ is used for the formation of ATP, which is the ultimate motive.

Terminal oxidation involves two processes

- **ETS (Electron Transport System)**
- **Oxidative Phosphorylation**

Electron Transport System (ETS)

- ETS involves the transfer of electrons from NADH and $FADH_2$ to oxygen via a series of electron carriers, thus this process is named electron transport system.
- It takes place in the **inner mitochondrial membrane** because the electron carriers are present on the inner mitochondrial membrane (plasma membrane in prokaryotes).
- The electron carriers are arranged in an ordered manner in a specific series called electron transport chain (**ETC**) or electron transport system (**ETS**).
- The process commences with the removal of hydride from NADH and its conversion into a proton and two electrons.

Gray Matter Alert!!!

ETS takes place in the inner mitochondrial membrane because the electron carriers are present on the inner mitochondrial membrane (plasma membrane in prokaryotes).

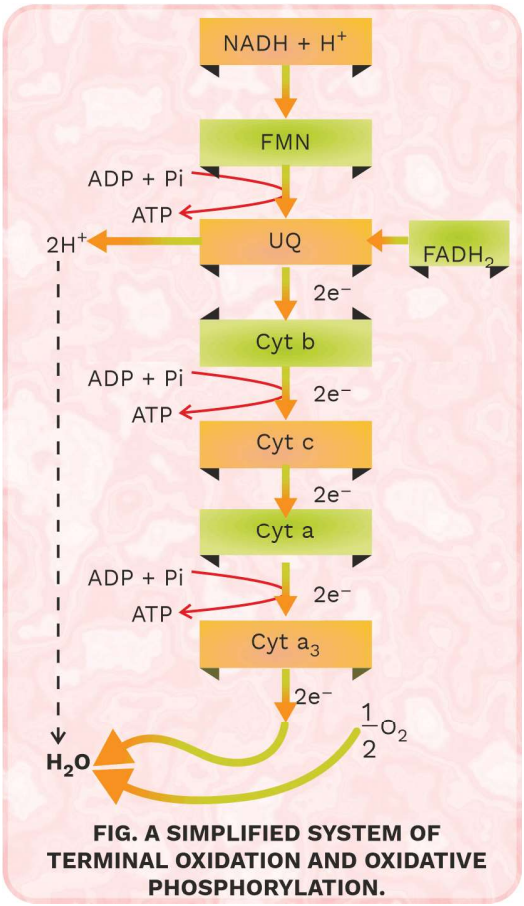


FIG. A SIMPLIFIED SYSTEM OF TERMINAL OXIDATION AND OXIDATIVE PHOSPHORYLATION.

- The electron carriers are grouped into four major respiratory enzyme complexes, each containing transmembrane proteins that hold the complex.
- Each respiratory complex is arranged sequentially in the **increasing order of reduction potential** or affinity for electrons, thus electron passes sequentially from one complex to another up to oxygen (highest affinity for electrons).
- The electron acceptor has a higher electron affinity (than the electron donor) and the energy from such electron transport is utilised in transporting protons (H+) from the matrix across the inner membrane to its outer side (outer chamber).

Rack Your Brain

Which intermediate of TCA cycle acts as a raw material for alkaloids?

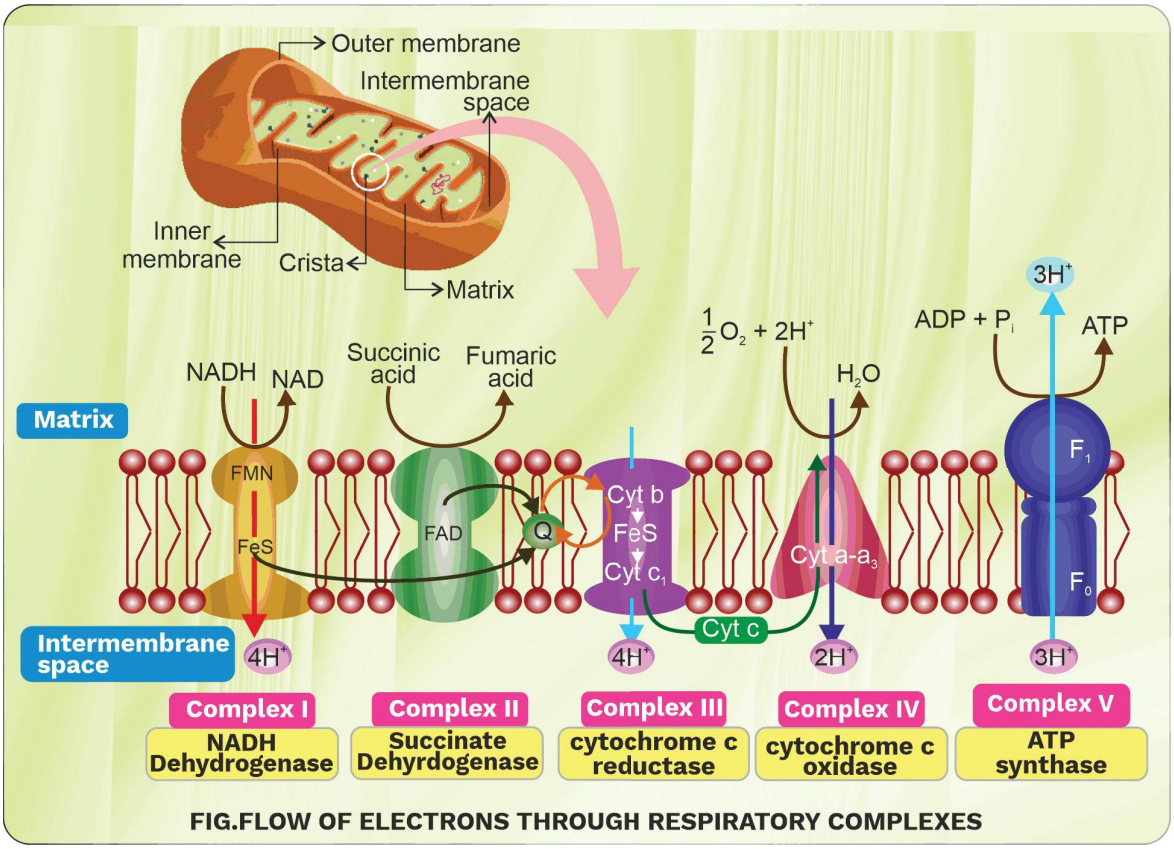


FIG.FLOW OF ELECTRONS THROUGH RESPIRATORY COMPLEXES

The major respiratory enzyme complexes are:

- **Complex I** – NADH Dehydrogenase
- **Complex II** – $FADH_2$ or Succinate Dehydrogenase

- **Complex III** – Cytochrome bc_1 / Cytochrome c reductase
- **Complex IV** – Cytochrome c oxidase
- **Complex V** – ATP synthase/ ATPase

Note: The flow of electrons via these complexes (NADH to O_2) is unidirectional due to the increasing reduction potential of the complexes.

WORKING OF ETS

Complex I– NADH dehydrogenase

- Electrons from NADH (produced during the citric acid cycle in the mitochondrial matrix) are oxidised by an NADH dehydrogenase (Complex I).
- **Complex I** transport **four protons** across the inner mitochondrial membrane per transport of electron pair from NADH to Coenzyme Q.

Ubiquinone/ Coenzyme Q

- Electrons are then transferred to Coenzyme Q (also known as ubiquinone) located within the inner membrane. 'Q' refers to the quinone chemical group. Ubiquinone is in its oxidised state (UQ) that accepts electron and converts into reduced state Ubiquinol (UQH_2).
- **Complex II – $FADH_2$ or Succinate dehydrogenase**
- Succinate dehydrogenase converts succinic acid to fumaric acid, releasing two electrons that are transferred first to FAD, then to iron-sulphur center (Fe-S), and finally to coenzyme Q/ ubiquinone.

Note: Complex II **does not pump protons** to the inner mitochondrial membrane during electron transfer.

The Coenzyme Q/ ubiquinone receives electrons from both complex-I and complex-II.

- **Complex III – Cytochrome bc_1 / Cytochrome c reductase**
- The Coenzyme Q/ ubiquinol (UQH_2) transfers the electrons received from both complex-I and

Name of enzyme complex and their prosthetic groups

Enzyme complex	Prosthetic groups
Complex I (46 subunits)	**FMN, Fe-S**
Complex II (4 subunits)	**FAD, Fe-S**
Complex III (11 subunits)	**Heme, Fe-S**
Complex IV (13 subunits)	**Heme, Cu^+**

Definition

Q-cycle: Peter Mitchell explained the mechanism of participation of ubiquinone in the ETS and named it proton motive Q-cycle.

Gray Matter Alert!!!

Mitochondria contain three classes of cytochromes – *a,b,c* based on the spectral absorption peaks. In the respiratory electron complexes, two a-type cytochromes (*a* and a_3), two b-type cytochromes (b_{566} and b_{562}), two c-type cytochromes (c and c_1) are present.

complex-II to the complex-III and oxidises to ubiquinone (UQ).

- The electrons are transported from cytochrome b to Cyt C_1 via Rieske iron-sulphur center (Fe-S).
- While the electron pair transfer, the complex-III pumps **four protons** across the inner mitochondrial membrane.

Note: Cytochrome c is a **peripheral protein** of the inner mitochondrial membrane found in all aerobic organisms. It binds via electrostatic interactions in intermembrane space.

- **Complex IV – Cytochrome c oxidase**
- The electrons are transferred from reduced cytochrome *c* to molecular oxygen with the help of the enzyme cytochrome c oxidase.
- There are two types of cytochrome-*a* and a_3 and two copper centers- Cu_a and Cu_b.
- Cytochrome *c* transfers the electron first to Cu_a, followed by cytochrome-*a* (Cyt *a*), Cyt a_3, Cu_b in sequential order and then to the final electron acceptor oxygen.
- Cu_b and Cyt a_3 form the active center at which the oxygen reduces to water.
- **Two protons** are transferred by the complex-IV across the inner mitochondrial membrane for two-electron transfer.
- While the electrons are transferred from the carrier complexes (I to IV), they are coupled to complex V (ATP synthase) for oxidative phosphorylation.

Note: Complex IV hosts the only step in the whole respiration process where oxygen is required. Oxygen is the final hydrogen acceptor and drives the whole process by removing hydrogen from the system.

- **The complex V (ATP synthase/ ATPase)** is involved in oxidative phosphorylation.
- The first four complexes are involved in the proton pump across the inner mitochondrial membrane

Definition

Uncouplers: Substances that uncouples oxidation from ATP formation i.e., allows oxidation of substrates without the formation of ATP, for e.g., 2,4-dinitrophenol.

Previous Year's Question

Out of 38 ATP molecules produced per glucose, 32 ATP molecules are formed from $NADH/FADH_2$ in
(1) Respiratory chain
(2) Kreb's cycle
(3) Oxidative decarboxylation
(d) EMP

Gray Matter Alert!!!

Inhibitors of ETS complexes:
Rotenone, Amobarbital and Piericidin are inhibitors of Complex I.
Malonate is a competitive inhibitor of complex II.
Antimycin A, an antibiotic, blocks complex III.
Cyanide, azide and carbon monoxide are inhibitors of complex IV.

that creates a higher proton concentration outside the inner membrane (i.e., in the inter membrane space or inter mitochondrial space) than in the matrix leading to a proton gradient or proton motive force (pmf).

- The difference in proton concentration on the outer and inner sides of the inner mitochondrial membrane is known as the proton gradient.

Oxidative phosphorylation

- ETS involves redox reactions (reduction and oxidation) and liberation of energy at each step, this energy is utilised for the maintenance of the **proton gradient**.
- This proton gradient is used for ATP synthesis by the complex V (oxidative phosphorylation
- For the synthesis of ATP, the energy is derived from oxidation of NADH or $FADH_2$ in ETS, or it takes place in the presence of oxygen and thus this process is called oxidative phosphorylation.
- The enzyme complex used for oxidative phosphorylation is Complex V-ATP synthase.

Complex V – ATP synthase

- It is also known as **F_0F_1 complex** as it contains two components - F_0 and F_1.
- **F_0 subunit** is embedded in the **inner mitochondrial membrane** and consists of one 'a' subunit, two 'b' subunits, and 9-12 'c' subunits. The F_0 subunit creates the channel through which the protons cross the inner membrane.
- F_1 subunit is tightly bound to F_0 and protrudes into the matrix consists of three sets of **each** α **and** β **and separate** γ, δ, ε, subunits.
- The γ subunit interacts with F_0 subunit. **The** γ, ε, **and** c acts together as a rotor.

Note: Three β units (a component of F_1) are exactly the sites for ATP production.

- The proton motive force generated during ETS is harnessed by ATP synthase to synthesise ATP.

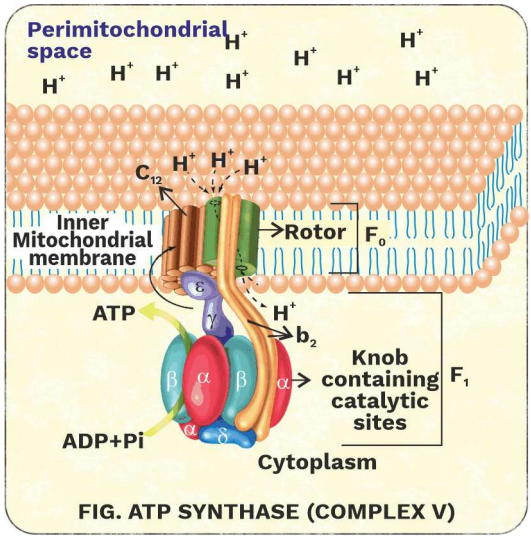


FIG. ATP SYNTHASE (COMPLEX V)

Previous Year's Question

When one glucose molecule is completely oxidised, it changes

(1) 36 ADP molecules into 36 ATP molecules
(2) 38 ADP molecules into 38 ATP molecules
(3) 30 ADP molecules into 30 ATP molecules
(4) 32 ADP molecules into 32 ATP molecules

Rack Your Brain

Which molecule is the final acceptor of hydrogen in the ETS?

Mechanism of Oxidative Phosphorylation

- Proton gradient developed across the membranes (higher proton concentration on F_0 side i.e. intermembrane space than F_1 i.e. inner side or matrix) activates ATP synthase.
- The enzyme ATP synthase uses the energy from the **proton gradient** and synthesises ATP from ADP and inorganic phosphate.
- The protons have a thermodynamic tendency to return to the matrix, while doing so, the energy is dissipated which is used to synthesise ATP in the matrix.
- ATP synthesis is coupled with a conformational change in the complex V (ATP synthase) generated by the rotor.
- The transfer of proton across the F_0 subunit results in the rotation of subunit of F_1 and conformation change in nucleotide-binding sites in the three beta subunits.
- ATP is formed and released simultaneously with each rotation driven by the proton transfer.
- The number of ATP molecules synthesised is related to the nature of the electron's donor.
- Transport of two electrons from NADH + H^+ by the electron transport chain simultaneously transfers three pairs of protons to the outer compartment. A high- energy ATP bond is produced per pair of protons returning to the matrix through the inner membrane particles.
- Thus, **oxidation of one molecule of NADH gives rise to 3 molecules of ATP**
- **Oxidation of one molecule of $FADH_2$, yields 2 molecules of ATP as it donates its electron further down the chain.**

The Respiratory Balance Sheet

- The net gain of ATP per glucose molecule can be calculated but it is just a matter of theoretical exercise.
- Though it is calculated based on the following assumptions:

Rack Your Brain

Which complex in the ETS requires oxygen?

Previous Year's Question

Terminal cytochrome of respiratory chain which donates electrons to oxygen is

(1) Cyt b
(2) Cyt c
(3) Cyt a_1
(4) Cyt a_3

Rack Your Brain

Which complex doesn't transfer proton across the inner mitochondrial membrane?

(a) The glycolysis, TCA cycle, and ETS pathways function in sequential order, one after another with one substrate forming the next.
(b) The NADH produced in glycolysis is transferred to mitochondria where it undergoes oxidative phosphorylation.
(c) No intermediate produced in the pathway is utilised to synthesise any other compound.
(d) Glucose is the sole respiratory substrate; no other alternative substrate is used in the pathway.

- The above-mentioned assumptions are not really valid as they are contradictory to the following facts:
  - All the pathways work simultaneously, not one after another.
  - Whenever necessary, the substrates can be withdrawn from the pathway.
  - ATP is utilised according to the need.

Note: Shuttle system

In eukaryotes, the **NADH produced** during the glycolysis **cannot pass** through the inner mitochondrial membrane. In order to transport electrons to the ETS, NADH is shuttled via two shuttle systems:

- **Malate aspartate shuttle system**
- **Glycerol 3-phosphate shuttle system**

Malate aspartate shuttle system

The electrons are carried to the mitochondrial matrix in form of malate. On entering the mitochondrial matrix, malate converts back to oxaloacetate and then to aspartate by reducing NAD^+.

Glycerol 3-phosphate shuttle system

Electrons from NADH enters the mitochondrial matrix by reducing dihydroxyacetone phosphate to glycerol-3 phosphate.

Previous Year's Question

During which stage in the complete oxidation of glucose are the greatest number of ATP molecules formed from ADP?
(1) Glycolysis
(2) Krebs' cycle
(3) Conversion of pyruvic acid to acetyl CoA
(4) ETS

Previous Year's Question

Out of 36 ATP molecules produced per glucose molecule during respiration
(1) 2 are produced outside glycolysis and 34 during respiratory chain
(2) 2 are produced outside mitochondria and 34 inside mitochondria
(3) 2 during glycolysis and 34 during Krebs cycle
(4) All are formed inside mitochondria

Previous Year's Question

Aerobic respiratory pathway is appropriately termed
(1) parabolic
(2) amphibolic
(3) anabolic
(4) catabolic

Glycerol-3 phosphate is reoxidised by transferring the electron to FAD.

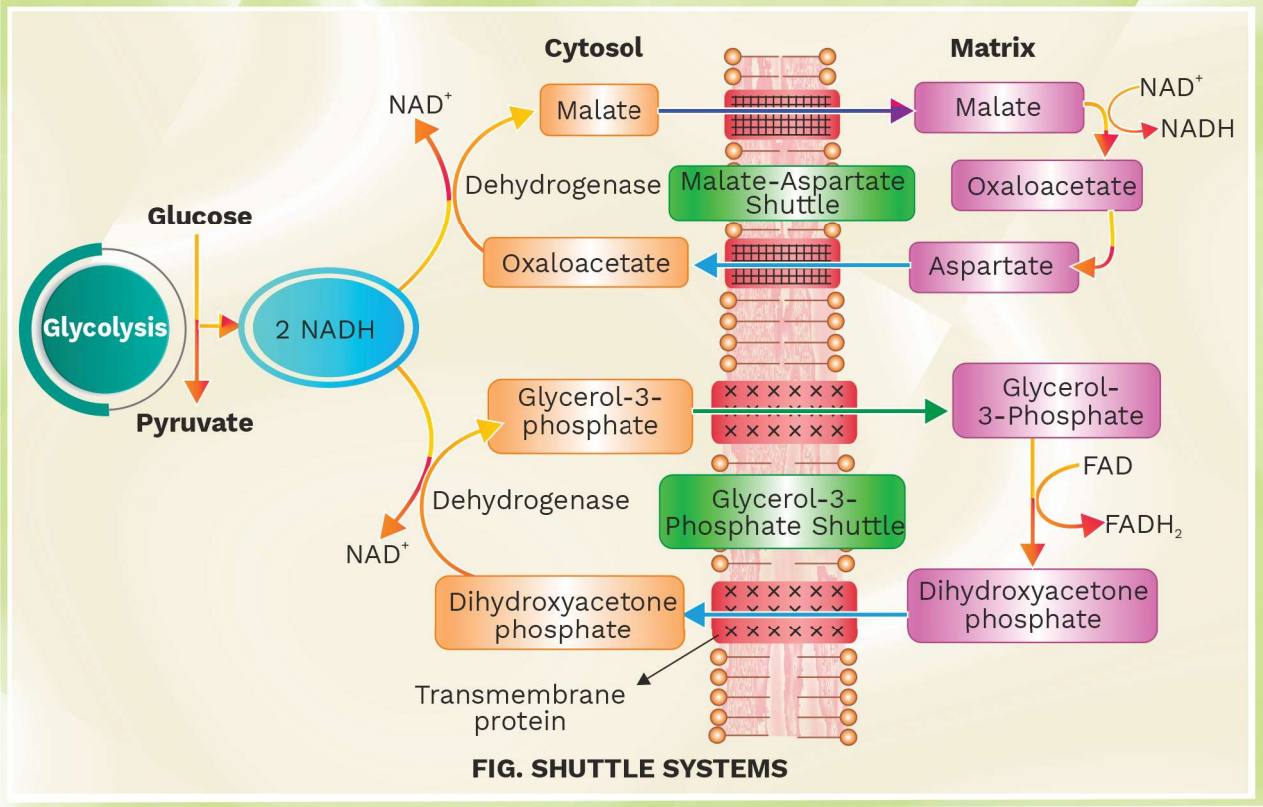


FIG. SHUTTLE SYSTEMS

ATP FORMATION ANALYSIS

- The **10 NADH molecules produce 30 molecules of ATP (3 ATP each).**
- The **2 $FADH_2$ molecules produce 4 molecules of ATP (2 ATP each).**
- There is a net gain of **38 ATP** molecules during aerobic respiration for one molecule of glucose.
- Whereas the net gain in most of the eukaryotic cells (i.e., muscles and nerve cells) is **36 ATP** molecules.
- ATP molecules are transported out of mitochondria to the cytoplasm through facilitated diffusion.

Rack Your Brain

Why the net gain of ATP molecules produced is 36 in muscles and nerve cells and not 38?

ANALYSIS OF ATP FORMATION PER MOLECULE OF GLUCOSE

Glycolysis (cytosol)	NADH	$FADH_2$	ATP
Glucose → Glucose-6-phosphate			–1
Fructose-6-phosphate → Fructose-1, 6- bisphosphate			–1
2 Glyceraldehyde-3-phosphate → 2 Glycerate-1,3-bisphosphate	+2		+2
2 Glycerate-1,3-bisphosphate → 2 Glycerate-3-phosphate			+2
2 Phosphoenolpyruvate → 2 Pyruvate			+2
Pyruvate Oxidation			
2 Pyruvate → 2 Acetyl CoA	+2		
Citric Acid Cycle			
2 Isocitrate → 2 α-ketoglutarate	+2		
2 α-ketoglutarate → 2 Succinyl-CoA			
2 Succinyl-CoA → 2 Succinate			+2
2 Succinate → 2 Fumarate		+2	
2 Malate → 2 Oxaloacetate	+2		
Total yield of ATP on complete oxidation of one glucose molecule	10 NADH (10 × 3 = 30 ATP)	2 $FADH_2$ (2×2= 4 ATP)	4 ATP

Efficiency of Aerobic Respiration

- **One molecule of ATP** yields **34 kJ of energy.**
- The energy yield from 38 ATP molecules comes to 1292 kJ.
- The energy yield from the complete oxidation of glucose is 2870 kJ. Thus, the efficiency of respiration is:

$$\frac{1292}{2870} \times 100 = 45 \text{ per cent}$$

Rack Your Brain

Which product of glycolysis needs shuttle system for the electron transport into the mitochondrial matrix?

- It indicates that only a part of this energy is used to make ATP and much of the energy generated during respiration is released in the form of heat.

AMPHIBOLIC PATHWAY

- Amphibolic pathways are neither completely catabolic nor completely anabolic, rather they act as links between them.
- They occur at the **'crossroads' of metabolism**.
- **Glucose** is the **most favourable** respiratory substrate. Carbohydrates are broken down into glucose to be utilised as a respiratory substrate.
- Fats are broken down to fatty acids and glycerol, then the fatty acid will be broken down then to acetyl CoA and Glycerol into PGAL to enter the pathway.
- Proteins are broken down by protease enzymes and amino acids enter the pathway (Krebs' cycle or acetyl CoA or even as pyruvate) according to their structure.

Note: All the processes mentioned above for the breakdown of fats and proteins would need to be reversed whenever there is a requirement for their own synthesis.

Acetyl CoA is required for the synthesis of fatty acid, so it is driven out from the respiratory pathway whenever fatty acids need to be synthesised.

- Thus, the **respiratory pathway** shares a **common stage** for both **synthesis and breakdown** of fatty acids and similarly for proteins too.
- As respiratory pathway is involved both in anabolic and catabolic pathways, it is considered as an **amphibolic pathway**.

Note: Acetyl CoA is a common stage for the respiration-mediated breakdown of different organic molecules to CO_2 and H_2O.

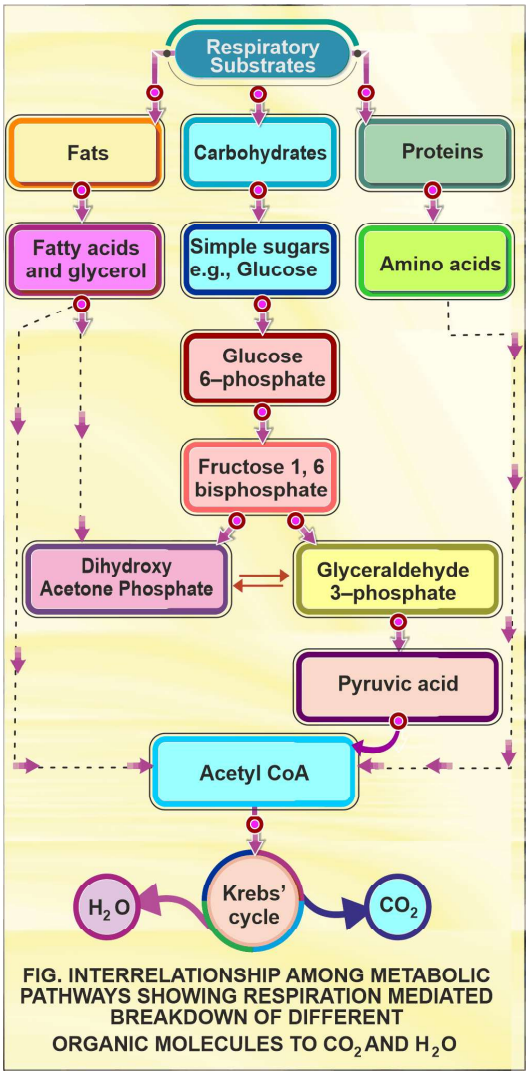


FIG. INTERRELATIONSHIP AMONG METABOLIC PATHWAYS SHOWING RESPIRATION MEDIATED BREAKDOWN OF DIFFERENT ORGANIC MOLECULES TO CO_2 AND H_2O

Rack Your Brain

Why respiration is called as an amphibolic pathway?

RESPIRATORY QUOTIENT (RQ)

- During respiration, oxidation of a respiratory substrates leads to the production of CO_2 and energy.
- Respirometer is the apparatus used to determine RQ.
- The respiratory quotient or respiratory ratio or respiratory coefficient can be defined as the **ratio** of the **volume of carbon dioxide produced** to the **volume of oxygen consumed** during the complete oxidation of metabolic fuel to CO_2 and H_2O.

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

- RQ depends on the **nature of the respiratory substrate** that is being used during respiration.
- Its value can be **1, 0, more than 1 or less than 1**.
- RQ value for different respiratory substrates is given below:
- **Carbohydrates**
  - The value of RQ is **equal to 1 or unity**, when carbohydrates are respiratory substrate and are completely oxidised.

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

$$RQ = \frac{6CO_2}{6O_2} = 1.0$$

- **Fats**
  - The value of RQ is **less than 1**, when the respiratory substrate is fat, and the respiration is aerobic.

RQ value is about **0.7** for fatty acid, **tripalmitin**:

$$\underset{\text{Tripalmitin}}{2C_{51}H_{98}O_6} + 145O_2 \longrightarrow 102CO_2 + 98H_2O + \text{Energy}$$

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

Definition

Respiratory quotient (RQ): the ratio of the volume of carbon dioxide produced to the volume of oxygen consumed during the complete oxidation of metabolic fuel to CO_2 and H_2O.

Previous Year's Question

What is RQ of the reaction?

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

(1) 0.7
(2) 1.0
(3) 1.45
(4) 1.62

Rack Your Brain

Which respiratory substrate is commonly used in respiration-mediated breakdown and why?

- **Proteins**
  - When proteins are used as respiratory substrates, RQ is about **0.9.**
  - The value of RQ is **zero** in the case of **succulent plants** at night, when their stomata are open. The carbohydrates are broken down into organic acids. Oxygen is utilised in the process, but carbon dioxide is not produced.

$$\underset{\text{Glucose}}{2C_6H_{12}O_6} + 3O_2 \longrightarrow \underset{\text{Malic acid}}{3C_4H_6O_5} + 3H_2O$$

$$RQ = \frac{CO_2}{3O_2} = \frac{\text{Zero}}{3O_2} = \text{Zero}$$

- **Organic acids**
  - The value of RQ is **more than one** when organic acids like malic acid, oxalic acid are broken down as respiratory substrates under aerobic conditions.

$$\underset{\text{Malic acid}}{C_4H_6O_5} + 3O_2 \longrightarrow 4CO_2 + 3H_2O$$

$$RQ = \frac{4CO_2}{3O_2} = 1.33$$

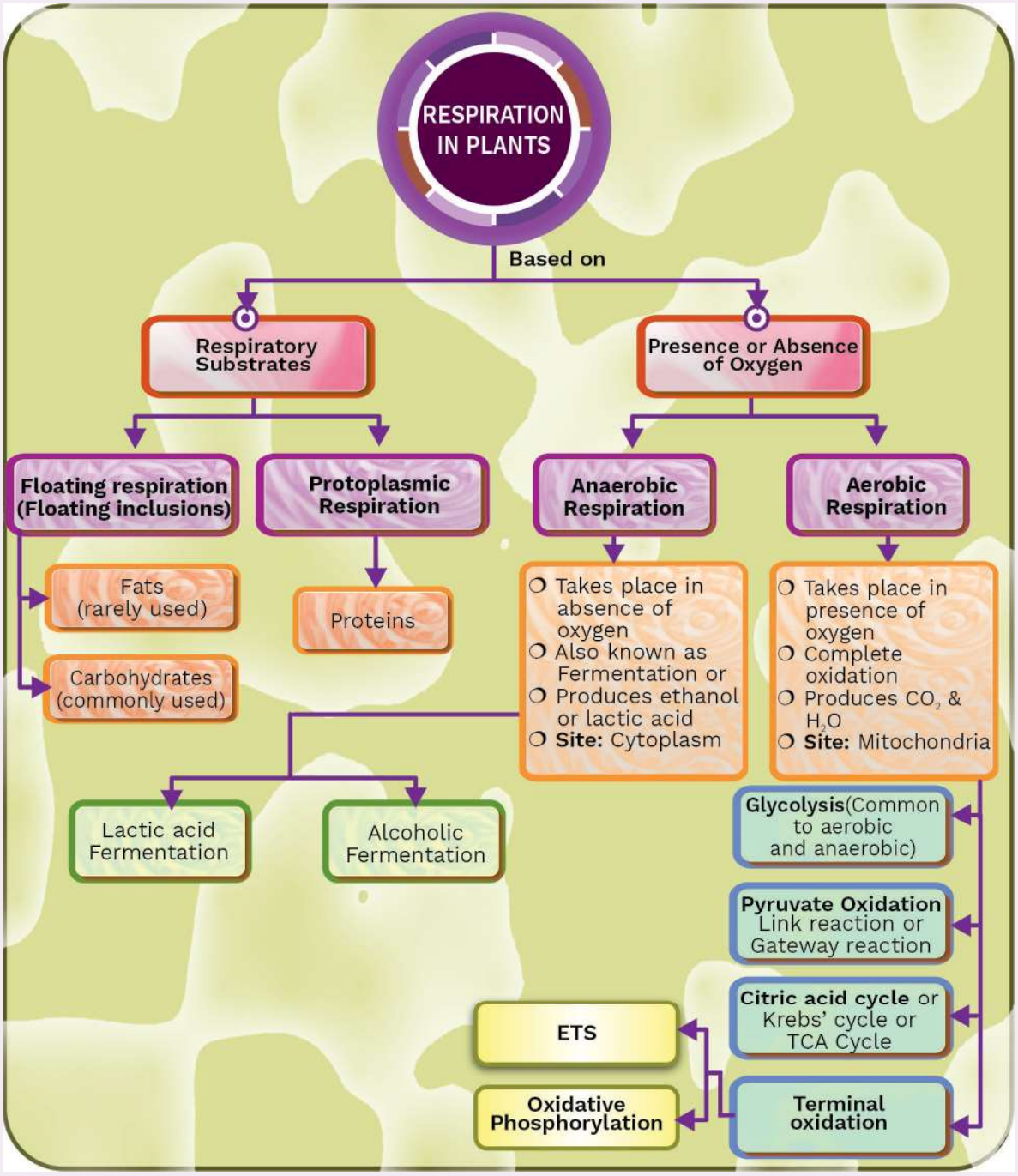
- **Anaerobic respiration**
  - The value of RQ is **infinity during anaerobic respiration**, where carbon dioxide is produced, but oxygen is not utilised.

Substrates	RQ
Carbohydrates	1
Maturing fatty seed	> 1
Mixed diet	0.85
Oxalic acid	4.0
Starved leaves	< 1
Proteins	0.8 – 0.9
Oleic acid (Lipid)	0.71
Malic acid	1.33
Coloured petals	< 1

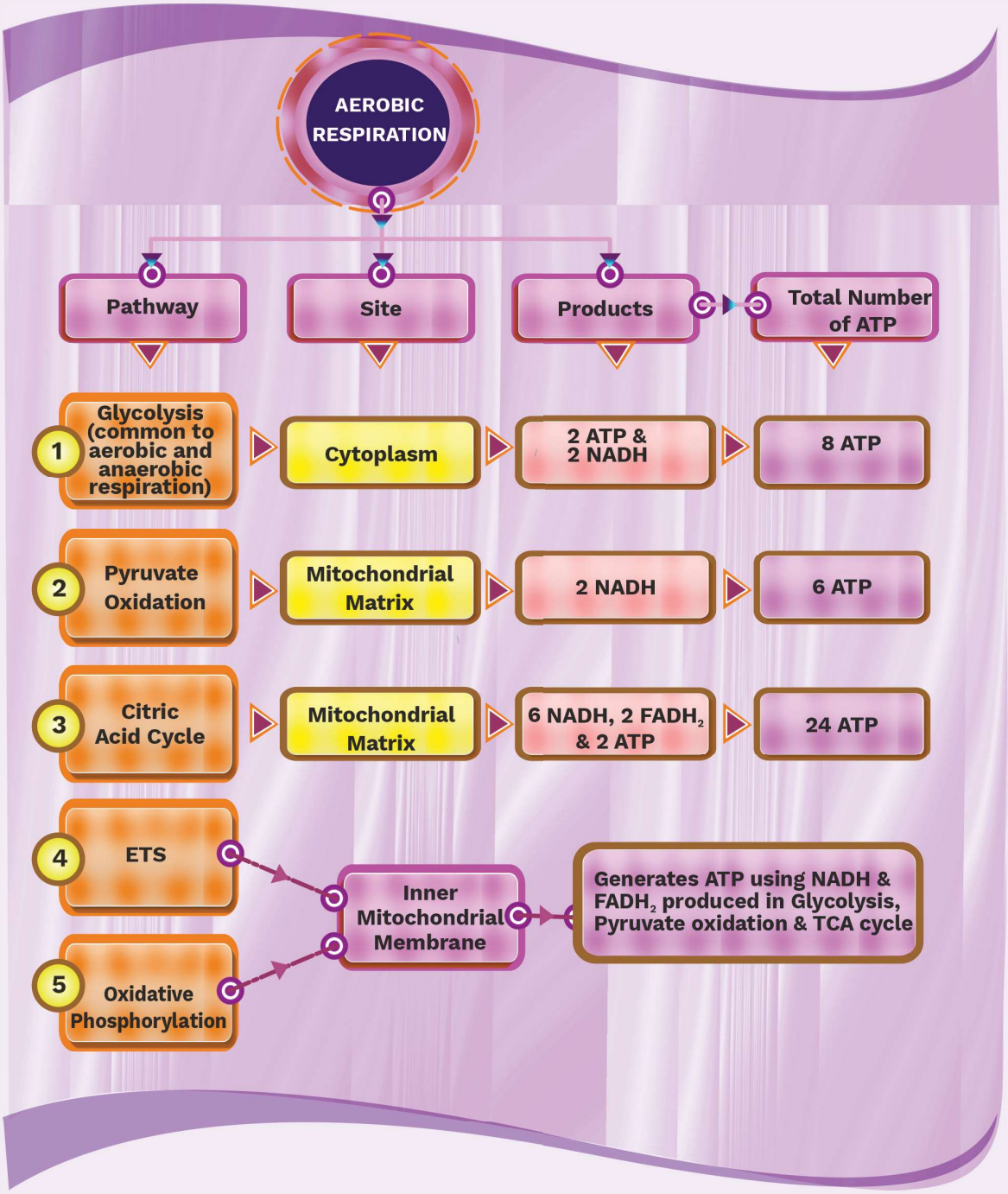
Previous Year's Question

Apparatus to measure rate of respiration and RQ is
(a) Auxanometer
(b) Potometer
(c) Respirometer
(d) Manometer

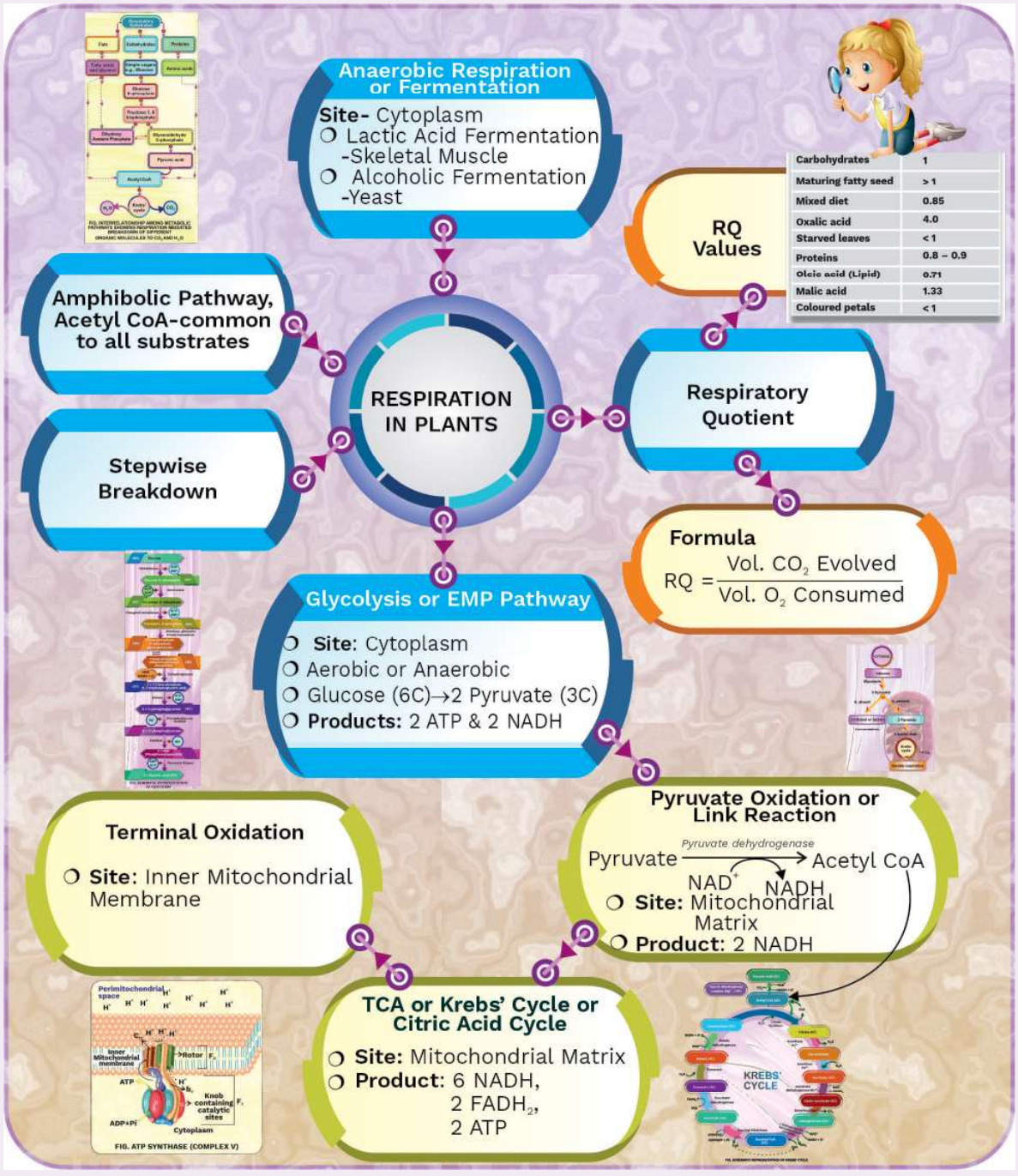
Summary


RESPIRATION IN PLANTS
Based on
Respiratory Substrates
Presence or Absence of Oxygen
Floating respiration (Floating inclusions)
Protoplasmic Respiration
Anaerobic Respiration
Aerobic Respiration
Fats (rarely used)
Carbohydrates (commonly used)
Proteins
❍ Takes place in absence of oxygen
❍ Also known as Fermentation or
❍ Produces ethanol or lactic acid
❍ Site: Cytoplasm
❍ Takes place in presence of oxygen
❍ Complete oxidation
❍ Produces CO_2 & H_2O
❍ Site: Mitochondria
Lactic acid Fermentation
Alcoholic Fermentation
Glycolysis(Common to aerobic and anaerobic)
Pyruvate Oxidation Link reaction or Gateway reaction
Citric acid cycle or Krebs' cycle or TCA Cycle
ETS
Oxidative Phosphorylation
Terminal oxidation

Summary


AEROBIC RESPIRATION
Pathway
Site
Products
Total Number of ATP
1 Glycolysis (common to aerobic and anaerobic respiration)
Cytoplasm
2 ATP & 2 NADH
8 ATP
2 Pyruvate Oxidation
Mitochondrial Matrix
2 NADH
6 ATP
3 Citric Acid Cycle
Mitochondrial Matrix
6 NADH, 2 FADH2 & 2 ATP
24 ATP
4 ETS
5 Oxidative Phosphorylation
Inner Mitochondrial Membrane
Generates ATP using NADH & FADH2 produced in Glycolysis, Pyruvate oxidation & TCA cycle

Summary


Anaerobic Respiration or Fermentation
Site- Cytoplasm
Lactic Acid Fermentation -Skeletal Muscle
Alcoholic Fermentation -Yeast
RQ Values
Carbohydrates 1
Maturing fatty seed > 1
Mixed diet 0.85
Oxalic acid 4.0
Starved leaves < 1
Proteins 0.8 – 0.9
Oleic acid (Lipid) 0.71
Malic acid 1.33
Coloured petals < 1
Amphibolic Pathway, Acetyl CoA-common to all substrates
RESPIRATION IN PLANTS
Respiratory Quotient
Stepwise Breakdown
Formula
RQ = Vol. CO2 Evolved / Vol. O2 Consumed
Glycolysis or EMP Pathway
Site: Cytoplasm
Aerobic or Anaerobic
Glucose (6C)→2 Pyruvate (3C)
Products: 2 ATP & 2 NADH
Pyruvate Oxidation or Link Reaction
Pyruvate dehydrogenase
Pyruvate → Acetyl CoA
NAD+ NADH
Site: Mitochondrial Matrix
Product: 2 NADH
Terminal Oxidation
Site: Inner Mitochondrial Membrane
TCA or Krebs' Cycle or Citric Acid Cycle
Site: Mitochondrial Matrix
Product: 6 NADH, 2 FADH2, 2 ATP
KREBS' CYCLE
FIG. ATP SYNTHASE (COMPLEX V)

Solved Questions

1. **RQ is**

(a) C/N **(b) N/C**

(c) CO_2/O_2 **(d) O_2/CO_2**

Sol. **(c)**

The respiratory quotient (RQ) or respiratory ratio can be defined as the ratio of the volume of carbon dioxide produced to the volume of oxygen consumed during the complete oxidation of metabolic fuel to CO_2 and H_2O.

2. **EMP can produce a total of**

(a) 6 ATP **(b) 8 ATP**

(c) 24 ATP **(d) 38 ATP**

Sol. **(b)**

Glycolysis produces 2 ATP and 2 NADH which after oxidative phosphorylation produces 6 ATP (3 ATP each). Thus, total 8 ATP molecules are formed.

3. **All enzymes of TCA cycle are located in the Mitochondrial matrix except one which is located in inner mitochondrial membranes in eukaryotes and in cytosol in prokaryotes. This enzyme is**

(a) Isocitrate dehydrogenase **(b) Malate dehydrogenase**

(c) Succinate dehydrogenase **(d) Lactate dehydrogenase**

Sol. **(c)**

Succinate dehydrogenase is located in the inner mitochondrial membrane.

4. **Organisms which obtain energy by the oxidation of reduced inorganic compounds are called**

(a) Photoautotrophs

(b) Chemoautotrophs

(c) Saprozoic

(d) Coproheterotrophs

Sol. **(b)**
Chemoautotrophs obtain energy by the oxidation of reduced inorganic compounds.

5. **Net gain of ATP molecules, during aerobic respiration, is**
(a) 40 molecules **(b) 48 molecules**
(c) 36 molecules **(d) 38 molecules**

Sol. **(c)**
Net 36 molecules of ATP are obtained during aerobic respiration.

6. **The end products of fermentation are:**
(a) O_2 and C_2H_5OH
(b) CO_2 and acetaldehyde
(c) CO_2 and O_2
(d) CO_2 and C_2H_5OH

Sol. **(d)**
The end products of fermentation are CO_2 and C_2H_5OH (ethyl alcohol).

7. **The correct sequence of electron acceptor in ATP synthesis is**
(a) Cyt. b, c, a_3, a **(b) Cyt. c, b, a, a_3**
(c) Cyt. a, a, b, c **(d) Cyt. b, c, a, a_3**

Sol. **(d)**
The correct sequence of electron acceptors in ATP synthesis is Cyt. b→c→a→a_3.

8. **At the end of glycolysis, six carbon compounds ultimately change into**
(a) Ethyl alcohol **(b) Acetyl CoA**
(c) Pyruvic acid **(d) ATP**

Sol. **(c)**
In glycolysis, six carbon compounds (glucose) ultimately change into three carbon compound pyruvic acid.

9. **The first phase in the breakdown of glucose, in animal cell, is**

(a) Fermentation **(b) Krebs' cycle**

(c) Glycolysis **(d) ETS**

Sol. **(c)**

Glycolysis is the first phase in the breakdown of glucose in animal cell.

10. **End product of citric acid cycle or Krebs' cycle is**

(a) Citric acid **(b) Lactic acid**

(c) Pyruvic acid **(d) $CO_2 + H_2O$**

Sol. **(d)**

End product of citric acid cycle or Krebs' cycle is CO_2 and H_2O.