WHAT IS CELLULAR RESPIRATION?

A series of enzyme catalysed reactions in living cells during which complex organic substances are broken down to release energy in form of **adenosine triphosphate (ATP).**

OR A series of enzyme catalysed reactions in living cells during which the chemical-bond energy of complex organic substances is released and converted into the usable form called **adenosine triphosphate (ATP).**

STORAGE OF CHEMICAL ENERGY IN FOOD

The C-H covalent bonds in organic substances (e.g. carbohydrates and lipids) form by sharing pairs of fast-moving energetic electrons, and therefore contain potential energy. The catalytic breakage of the C-H bonds releases energy, some of which powers the formation of ATP – a compound that can readily hydrolyse to provide energy that powers cellular activities. **The higher the C-H bonds, the more the energy yields. This explains why lipids yield twice more energy than carbohydrates of same mass.**

The Fate of High Energy Electrons and Hydrogen ions released from breaking C-H Bonds

To avoid fatality, the electrons lost from compounds are prevented from joining other molecules by joining electron carrier molecules which pass them along the **electron transport chain** until they get attached to oxygen, which becomes negatively charged, O^{2-}. As the electrons are transferred along the transport chain, energy is gradually extracted from them to power ATP formation. To avoid PH becoming acidic, which would be fatal, hydrogen ions, H^{+} combine with O^{2-} to form neutral water.

STRUCTURE OF ADENOSINE TRIPHOSPHATE (ATP)

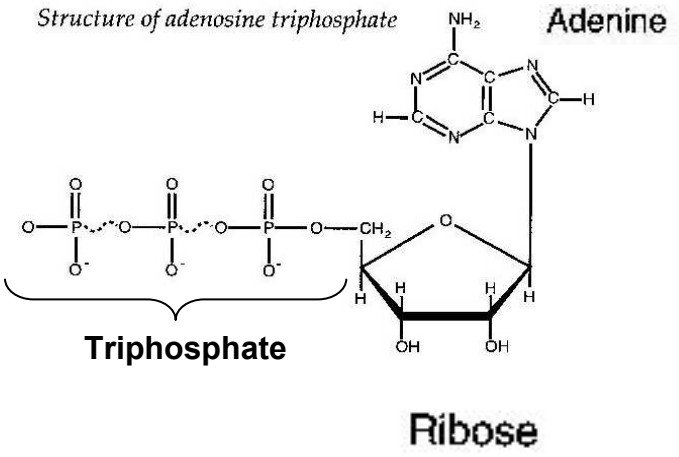
ATP is a compound made up of a molecule of **adenine** – a nitrogenous base, a molecule of **ribose sugar**, and **three phosphate molecules**.

WHY ATP IS CONSIDERED TO BE AN ENERGY CARRIER

ATP is an energy carrier because it stores chemical energy, which is released as free energy on hydrolysis of the covalent phosphate to phosphate bonds. Hydrolysis of ATP to form **adenosine diphosphate (ADP)** releases $30.6kJmol^{-1}$ of free energy, and further hydrolysis of the terminal phosphate bond of ADP to form **adenosine monophosphate (AMP)** yields another $30.6kJmol^{-1}$ of free energy, but hydrolysis of the phosphate-ribose bond in AMP is not feasible because releases very little energy.

WHY THE TWO ATP TERMINAL PHOSPHATE BONDS ARE HIGH-ENERGY BONDS

It is because their hydrolysis proceeds with the release of an unusually large amount of free energy (about 7.3kcal/mol or 30.6kJ per mol from each phosphate bond)



NOTE:

(1) Phosphorylation of AMP (addition of phosphate molecules to AMP) forms ADP, while Phosphorylation of ADP yields ATP.

(2) Addition of each phosphate molecule requires 30.6kJ, and therefore energy released from any chemical reaction if less than 30.6kJ cannot be stored as ATP but is lost as heat.

(3) High-energy bonds are symbolized by the **squiggle (~)** i.e. solid curved line.

(4) Potential energy increases whenever things experiencing a repulsive force are pushed together such as adding the 3rd phosphate to an ADP molecule. Potential energy also increases whenever things that attract each other are pulled apart as in the separating of protons from the electrons.

Dongo Shema F

PHOSPHORYLATION IN CELLS

ATP is formed in cells by three types of phosphorylation:

1. Directly by **substrate-level Phosphorylation *i.e.*** direct transfer of a phosphate group from high energy phosphorylated compounds to ADP to form ATP. Examples of high energy phosphate compounds: **Phosphoenolpyruvate, 1, 3-Bisphosphoglycerate, acetyl phosphate and phosphocreatine.**

2. Indirectly by **oxidative Phosphorylation *i.e.*** use of energy supplied by transmembrane proton gradients across the inner mitochondrial membrane during electron transport system to form ATP.

3. Indirectly by **Photophosphorylation *i.e.*** use of energy supplied by transmembrane proton gradients across thylakoid membranes in chloroplasts during photosynthesis to form ATP.

EXAMPLES OF OTHER HIGH-ENERGY COMPOUND IN CELLS

Phosphoenolpyruvate, 1, 3-Bisphosphoglycerate, acetyl phosphate and phosphocreatine

Apart from ATP, there are other compounds with even higher energy than ATP, but ATP is commonly used because:

(i) ATP releases just the right amount of energy for cellular needs when hydrolysed.

(ii) ATP releases energy at the right time

(iii) ATP and can be moved to any place when need arises.

Example: In muscles and nerve cells where ATP is continually hydrolysed at a rate faster than respiration can provide due to high metabolic activity, **phosphocreatine** provides the phosphate for regeneration of ATP from ADP.

Standard Free Energies of Phosphate hydrolysis of some compounds in cells

Compound	*$\Delta G^{0'}$ (kJ/mol)*
Phosphoenolpyruvate	-61.9
1, 3-Bisphosphoglycerate	-49.4
Acetyl phosphate	-43.1
Phosphocreatine	-43.1
ATP (+ $H_2O \Leftrightarrow$ ADP + P_i)	**-30.6**
Glucose-1-phosphate	-20.9
Fructose-6-phosphate	-13.8
Glucose-6-phosphate	-13.8
Glycerol-3-phosphate	-9.2

1. ATP has an intermediate phosphate-group transfer potential. Under standard conditions, the compounds above ATP in the table on the left can spontaneously transfer a phosphate group to ADP to form ATP, which can in turn spontaneously transfer a phosphate group to the appropriate groups to form the compounds listed below it.

2. The negatives of the values listed in the table are often referred to as **phosphate group-transfer potentials;** compounds with large negative values readily transfer their phosphate group to form compounds with small negative values by first forming ATP

WHY ATP IS REFERRED TO AS "THE UNIVERSAL ENERGY CURRENCY"

It is because the structure and functioning of ATP in providing energy is the same in all living cells.

DURATION OF ATP STORAGE IN CELLS

ATP is continually hydrolysed and regenerated. The metabolic half-life of an ATP molecule varies from seconds to a few minutes depending on the cell type and its metabolic activity.

Examples:

(i) Brain cells have only a few seconds' supply of ATP – which partly explains why brain tissue deteriorates rapidly if deprived of oxygen.

(ii) Muscle cells can store phosphocreatine for some minutes to act as a reservoir of phosphate groups that can be used to produce ATP. **This ATP/PCr store although small, is important in providing instant energy e.g. during sprinting.**

HYDROLYSIS OF ATP TO ADP AND INORGANIC PHOSPHATE (P_i)

Hydrolysis of ATP to ADP + P*i* releases more potential energy than hydrolysis of ADP to AMP + P*i* because:

(1) The three phosphate molecules in ATP have four negative charges with great electrical repulsion, raising the potential energy of the electrons.

(2) The negative charges on ADP and P_i are stablised by much more efficiently by interactions with the partial positive charges on surrounding water molecules. For these and other reasons, ADP and P_i have lower potential energy than does ATP.

USES OF ENERGY OF ATP IN CELLS

(1) Enables transport of materials in phloem of plants.
(2) Enables movement of cilia or flagella and muscle contraction
(3) Allows active transport to be carried out (movement of substances against concentration gradient) e.g. ion pumps
(4) Drives endergonic reactions e.g. assembly of amino acids into proteins, synthesis of polysaccharides from monosaccharides, and DNA replication
(5) Activates chemicals to become more reactive e.g. phosphorylation of sugar during Glycolysis
(6) Enables formation of vesicles during secretion of cell products.
(7) Contraction of microfilaments during cell division

LOCATION OF RESPIRATION IN CELLS

Cell type	**Location of pathway in cell**
All prokaryotic cells	Infoldings of cell membrane (mesosomes) and in cytoplasm
All eukaryotic cells	Cytoplasm ***(Glycolysis)***, Mitochondrial matrix ***(Krebs cycle)*** and inner membrane of mitochondria ***(Electron transport system)***

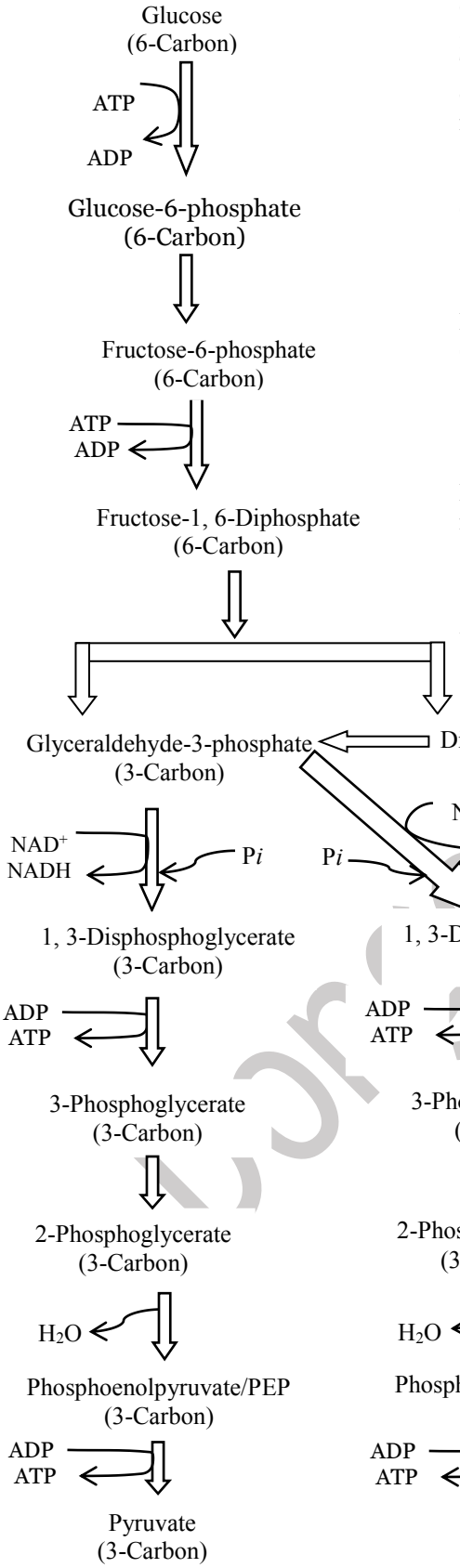
STAGES OF CELLULAR RESPIRATION

(1) Glycolysis **(2)** Krebs cycle **(3)** Electron transfer system
Each step will be discussed individually, but remember that each is part of the whole process.

GLYCOLYSIS (*glyco* = carbohydrate; *lys* = splitting; *sis* = the process of)
Definition:
A series of enzymatically controlled reactions in the cytoplasm of cells during which one molecule of a six-carbon sugar glucose, is split into two molecules of the three-carbon compound Pyruvate, with a net out put of two ATP molecules.

Dongo Shema F

DESCRIPTION OF GLYCOLYSIS



Glycolysis starts with **phosphorylation** of glucose by ATP to form **glucose-6-phosphate**.
This process **(1)** chemically reactivates glucose **(2)** traps glucose in the cell because the phosphate group bears a negative charge yet the cell membrane is impermeable to ions.

Glucose-6-phosphate **isomerizes** to form **fructose-6-phosphate** to ease another Phosphorylation.

Fructose-6-phosphate is **phosphorylated** by ATP to form **fructose-1, 6-bisphosphate** ***(Fructose-1, 6-diphosphate)***

Fructose-1, 6-bisphosphate **splits / cleavages** at once into two molecules each with three-carbons:

- **Glyceraldehyde-3-phosphates** (3-phosphoglyceraldehyde / PGAL)
- **Dihydroxyacetone**, which **isomerizes** into **Glyceraldehyde 3-phosphate**

- Each PGAL is **dehydrogenated** by nicotinamide adenine dinucleotide (NAD^+) to form **reduced nicotinamide adenine dinucleotide** (NADH)
- Each 3-PGAL molecule is **phosphorylated** by phosphates present in the cytoplasm to form **1, 3-diphosphoglycerate**, which later donates the phosphate to ADP to form ATP and **3-phosphoglycerate**, which has 3-carbons.

Each 3-phosphoglycerate **isomerizes** to form **2-phosphoglycerate**

Each 2-phosphoglycerate loses a water molecule (**dehydrated**) to form **3-phosphoenolpyruvate** (PEP).

Each 3-phosphoenolpyruvate (PEP) loses a phosphate to ADP (**dephosphorylated**) to form ATP and **pyruvate** which has three-carbons

SIGNIFICANCE OF GLYCOLYSIS
Glycolysis forms:
(1) ATP which is used to power cell activities
(2) NADH and Pyruvate which may be further oxidized to generate additional ATP.
However in oxygen deficiency, both NADH and pyruvate undergo fermentation to regenerate NAD^+.

NOTE:
The breakdown of Glucose in glycolysis into two molecules of pyruvate yields about 5.2% of the total energy that can be released from glucose by complete oxidation.

EVOLUTIONARY SIGNIFICANCE OF GLYCOLYSIS
The role of glycolysis in both fermentation and respiration suggests that ancient prokaryotes probably used glycolysis to make ATP long before oxygen was present in the atmosphere.
This conclusion is based on the following observations:
(1) The oldest bacterial fossils date back 3.5 billion years, yet oxygen accumulated about 2.7 billion years ago. Therefore early prokaryotes may have generated ATP exclusively from glycolysis, which does not require oxygen.
(2) Glycolysis occurs in all organisms, which suggests that it evolved very early in the history of life.
(3) Glycolysis is located in the cytoplasm where no membrane-bounded organelles are required in eukaryotic cells, which evolved approximately 1 billion years after the prokaryotic cell.

ELECTRON CARRIER MOLECULES
1. NAD^+ (Nicotinamide Adenine Dinucleotide): A coenzyme containing the B-vitamin, **niacin**.
NAD^+ accepts 2 e^- and one H^+ (a hydride) in going to the reduced state, as $\mathbf{NAD^+ + 2\ e^- + H^+ \rightarrow NADH.}$
It may also be written as: $\mathbf{NAD^+ + 2\ e^- + 2H^+ \rightarrow NADH + H^+}$
NAD^+ is a **coenzyme**, that reversibly binds to enzymes.

2. FAD (Flavin Adenine Dinucleotide): is derived from the vitamin riboflavin (B2). The protein to which it is attached is termed a **flavoprotein (FP).**
FAD normally accepts 2 e^- and 2 H^+ in going to its reduced state: $\mathbf{FAD + 2\ e^- + 2\ H^+ \rightarrow FADH_2}$
FAD is an electron-carrier coenzyme like NAD+. However, unlike NAD+, FAD always occurs as a **prosthetic group**, tightly bound at the active site of an enzyme, never as a free carrier.

3. FMN (Flavin Mono Nucleotide): is a prosthetic group of some flavoproteins. It is similar in structure to FAD, but lacking the adenine nucleotide.

ROLE OF VITAMIN B COMPLEX IN CELLULAR RESPIRATION

Vitamin	Role in cellular respiration
B_1 (Thiamine)	Involved in formation of some Krebs cycle enzymes Forms part of acetyl coenzyme A
B_2 (Riboflavin)	Forms part of the hydrogen carrier Flavine Adenine Dinucleotide (FAD)
B_3 (Niacin or Nicotinic acid)	Forms part of coenzymes NAD and NADP Forms part of acetyl coenzyme A
B_5 (Pantothenic acid)	Forms part of acetyl coenzyme A

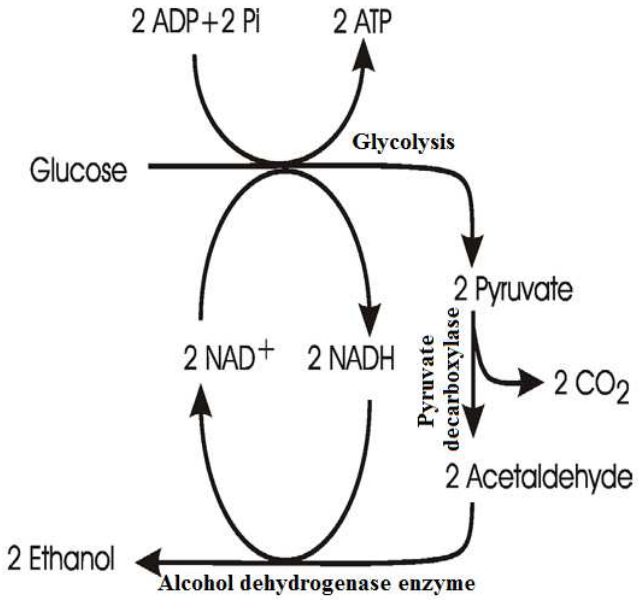
FATE OF THE PRODUCTS OF GLYCOLYSIS
1. ATP: It is hydrolysed to release energy to power the cell's needs.

2. NADH:
Under **aerobic conditions (in the presence of oxygen),** NADH is converted into $FADH_2$ which is then shuttled into the mitochondria where it donates electrons to a series of electron carriers until they reach the final oxidizing agent oxygen in a process called electron transport system. During this process, the free energy of electron transport drives the synthesis of ATP from ADP and NAD+ is regenerated such that it can participate in further catalysis.
Under **anaerobic conditions,** NADH must be re-oxidised by other means to supply glycolysis with NAD+

3. PYRUVATE:
- Under **aerobic conditions**, pyruvate is completely oxidised via the **citric acid cycle** to carbon dioxide and water.
- Under **anaerobic conditions** in the cytoplasm, pyruvate undergoes **fermentation**.

Dongo Shema F

TYPES OF FERMENTATION (ANAEROBIC RESPIRATION)
There are many types of fermentation, but the two common types are given below:

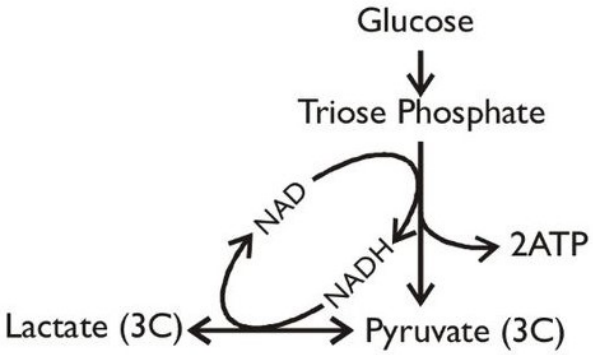


(a) Alcoholic fermentation:
Pyruvate is decarboxylated to form a 2-carbon compound **acetaldehyde** and carbon dioxide

Acetaldehyde is then reduced by NADH to form **ethanol** and NAD^+

NAD^+ enables the continuation of glycolysis.

Alcoholic fermentation occurs in some bacteria and yeasts.



(b) Lactic acid fermentation:
Pyruvate is reduced directly by NADH to form **lactic acid** as the end product. No carbon dioxide is released.
Lactic acid fermentation:
(1) Is carried out by **certain fungi and bacteria** during the formation of **yoghurt** and **cheese**
(2) Occurs during oxygen scarcity in human skeletal muscle cells during sprinting.

The lactic acid is gradually carried away by blood to the liver and converted back to **pyruvate** by **liver cells**. ***If ATP is abundant, pyruvate and lactate can be used as a substrate in the synthesis of glucose.***

EXPERIMENTS ON ALCOHOLIC FERMENTATION IN YEAST
Investigations have been carried out using a Biology gas pressure sensor and Methylene blue dye to determine:
(i) The type of sugar best metabolized by yeast (***Maltose*** or ***glucose*** or ***fructose*** or ***sucrose, galactose*** or ***lactose***)
(ii) The effect of yeast fermentation of polysaccharides.

Using Gas pressure sensor
- A gas pressure sensor is used to monitor anaerobic fermentation of sugar because CO_2 produced causes a change in the pressure of a closed test tube, since no oxygen being consumed.
- Aerobic respiration of yeast consumes oxygen gas at the same rate that CO_2 gas is produced, hence no change in the gas pressure in the test tube. The rate of CO_2 evolution is an indication of the rate of breakdown of sugar.

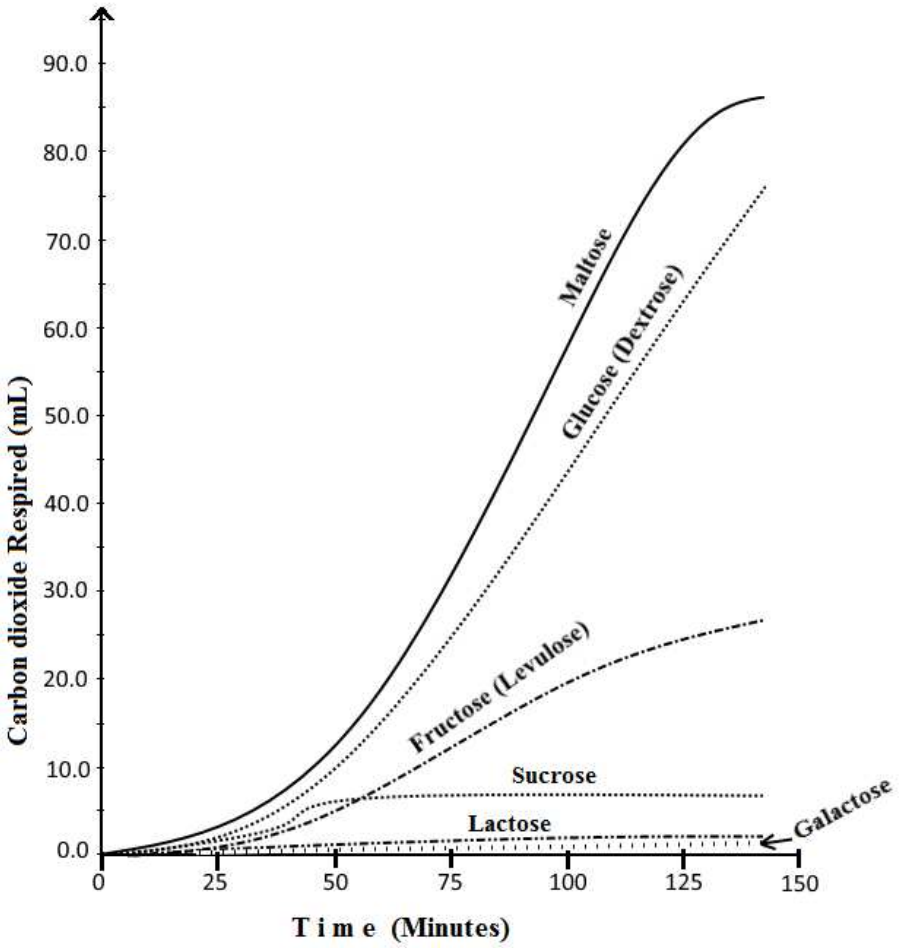
Using Methylene blue or DCPIP dye
- In the **oxidised state**, the colour of indicator / dye is **blue** but on accepting **electrons released by breakdown of sugar** goes into **reduced state** and turns **colourless**. The rate of dye colour change from blue to colourless is an indication of the rate of breakdown of sugar to release electrons.

Donsonal

EXPERIMENT TO DETERMINE THE TYPE OF SUGAR BEST METABOLIZED BY YEAST

Independent variable	Dependent variable	Control variables	Series
Time (minutes)	Carbon Dioxide Production	Sugar concentration, Yeast, Water, Temperature	**Monosaccharides:** Dextrose (Glucose), Levulose (Fructose) and Galactose **Disaccharides:** Sucrose, Maltose, Lactose

Graphs of carbon dioxide evolved with time during anaerobic respiration of yeast in different sugar solutions. A gas pressure sensor was used to monitor anaerobic fermentation of sugar as the CO_2 produced caused a change in the pressure of a closed test tube. The data was collected until no more gas could be detected. All control variables were managed to enable accuracy of results.



EXPLANATION (12 marks)

- From 0 minute to about 38 minutes, CO_2 evolution was slow by almost all sugars**; because** enzyme secretion was still slow / low**;**
- From about 38 minutes to about 148 minutes, CO_2 evolution was rapid in both maltose and glucose**;** but more rapid in maltose**; because** yeast enzymes for maltose and glucose breakdown are rapid**;** but enzymes for maltose breakdown are more rapid**;**
- From about 38 minutes to about 148 minutes, CO_2 evolution was slow in fructose**; because** yeast enzymes for fructose break down are slow**;**
- From about 38 minutes to about 148 minutes, CO_2 evolution was low and constant in sucrose**; because** yeast enzymes for sucrose breakdown are in low concentration**;**
- From about 0 minute to about 148 minutes, CO_2 evolution was very low and remained constant in Lactose and galactose**; because** enzymes for lactose and galactose may be present in very low concentration**;**

How control variables were managed to enable obtaining accurate results **(08 marks)**

- In such experiment involving enzyme work in various substrates, the key control variables that affect results of the experiment include: sugar concentration**;** yeast (enzyme concentration)**;** volume of water**;** temperature**;**
- All the control variables must be kept constant in all the experiments**;**
- Concentrations of sugars and yeast in fixed volume of water must be high enough to generate detectable volume of carbon dioxide**;** for a relatively long period of time**;**
- Temperature should be optimum for enzyme work**;**

Explain the differences in results observed from Maltose and Sucrose, which are both common disaccharides and Glucose and Fructose, which are both common monosaccharides. **(05 marks)**

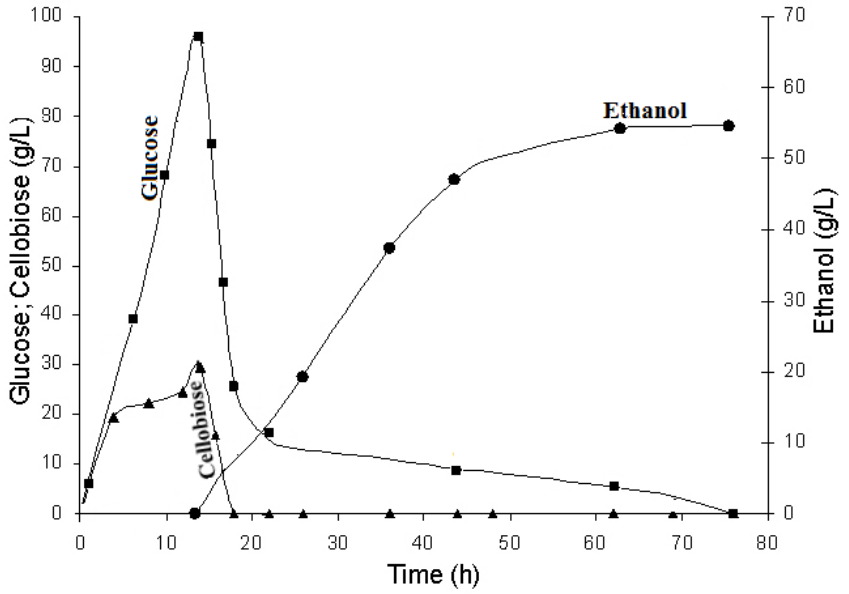
- Yeast breaks down maltose faster than sucrose yet both are disaccharides**;** and also breaks down glucose faster than fructose yet both are monosaccharide**;**
- This is because among monosaccharides and disaccharides are many different configurations of atoms (isomers)**;** requiring different enzymes**;** to be used in utilizing the energy in the different isomers**;**

Briefly describe the essential stages in the anaerobic breakdown of glucose by yeast (08 marks)
Phosphorylation of glucose by ATP**;** second phosphorylation of hexose sugar by ATP**;** cleavage of hexose into two triose molecules**;** dehydrogenation and dephosphorylation of triose molecules to form pyruvate**;** and a net of two ATP molecules**;** decarboxylation of Pyruvate to form acetaldehyde**;** and carbon dioxide**;** reduction of acetaldehyde by NADH to form ethanol**;**

(i) State the commercial applications of fermentation (04 marks)
- In breweries, fermentation of sugars forms alcoholic drinks like wine, beer and spirits.
- In bakeries, fermentation of starch by yeast is used in leavening of bread i.e. production of raised bread
- Applied in the manufacture of milk products like sour milk, yoghurt and cheese
- Applied in food industries for the manufacture of organic acids e.g. citric acid, oxalic acid and butyric acid.
- In sewage treatment, sewage is digested by enzymes secreted by bacteria to reduce the bulk and odour of sewage

(ii) From the results, comment on the suitability of maltose and sucrose in any named commercial application (03 marks)
In breweries in the manufacture of ethanol**;** maltose is a better substrate / raw material than sucrose**;** on the basis of the faster rate of breakdown of maltose to form ethanol than it occurs in glucose**;**

EXPERIMENT TO DETERMINE EFFECT OF YEAST FERMENTATION OF CARBOHYDRATES



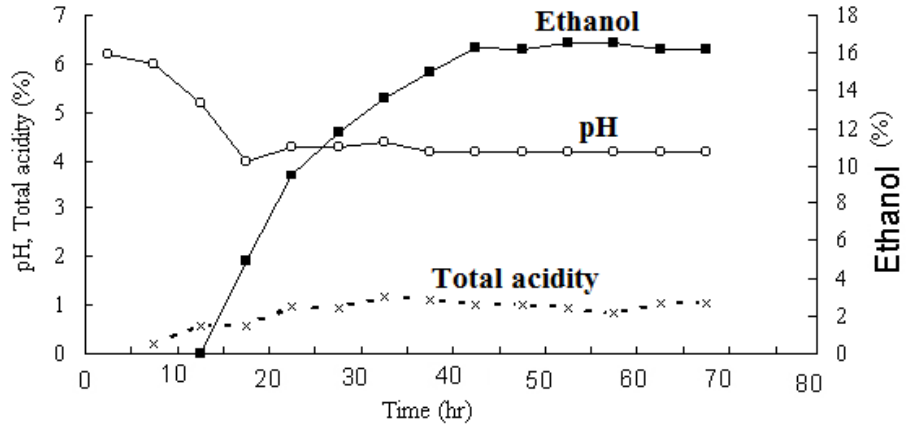


Figure I shows results from the experiment of simultaneous saccharification and fermentation of steam-pretreated sugarcane (*Saccharum officinarum*) bagasse by ***Saccharomyces cerevisiae,*** a strain of yeast.

Bagasse, the fibrous residue obtained after extracting juice from sugar cane consists approximately of 50% cellulose, 25% hemicellulose, and 25% lignin.

During the experiment, temperature of the medium was maintained at 37^0C, and initial pH adjusted to 6.1.
Nitrogen was flushed into the reaction vessels at the beginning of the experiment.

Figure II shows changes in pH and total acidity during the same period of time.

(a) From figure I:

(i) Describe the changes in the concentration of sugars and ethanol. **(10 marks)**

From 0 hour to about 15 hours, the concentration of glucose increased rapidly**;**
From about 15 hours to about 19 hours the concentration of glucose decreased rapidly**;**
From about 19 hours to about 76 hours the concentration of glucose decreased gradually to complete disappearance**;**

From 0 hour to about 4 hours the concentration of Cellobiose increased rapidly**;**
From about 4 hours to about 15 hours, the concentration of Cellobiose increased gradually**;**
From about 13 hours to about 15 hours the concentration of Cellobiose increased rapidly**;**
From about 15 hours to about 18 hours the concentration of Cellobiose decreased rapidly to complete disappearance**;**

From 13 hours to about 45 hours the concentration of ethanol increased rapidly**;**
From about 45 hours to about 62 hours, the concentration of ethanol increased gradually**;**
From about 62 hours to about 76 hours the concentration of ethanol was relatively constant**;**

(ii) Explain the changes in the concentration of sugars and ethanol. **(10 marks)**

From about 0 hour to about 15 hours cellulosic hydrolyzing enzymes secreted by yeast rapidly hydrolysed cellulose to form glucose and Cellobiose / **there was rapid saccharification;**
From about 15 hours to about 19 hours yeast respired the sugars glucose and Cellobiose rapidly under anaerobic conditions to form ethanol**;**
From about 19 hours to about 76 hours there was gradual breakdown of cellulosic material to form glucose**;** yet there was rapid anaerobic respiration to form ethanol**;**
From 13 hours to about 45 hours rapid alcoholic fermentation of sugars formed ethanol rapidly**;**
From about 45 hours to about 62 hours gradual alcoholic fermentation of sugars formed ethanol gradually due to little inhibition of enzymes**;** by some of the products of saccharification and fermentation**;**
From about 62 hours to about 76 hours alcoholic fermentation of sugars had ceased / stopped due to much inhibition of enzymes by some of the products of saccharification and fermentation**;**

(b) Explain the necessity of the following in the experiment:

(i) Steam-pretreatment of sugarcane bagasse **(05 marks)**

Steam-pretreatment **separates / loosens / disentangles** lignin from cellulose in the sugarcane residue (bagasse)**;** which exposes cellulose molecules to yeast's hydrolytic enzymes / cellulase and hemicellulase**;** for conversion into glucose and Cellobiose sugars**;**
Steam-pretreatment also sterilizes the bagasse**;** to avoid interference by any other microorganisms except yeast**;**

(ii) Adjustment of pH to 6.1 **(02 marks)**

Creates an optimum weakly acidic medium**;** in which yeast's hydrolytic enzymes work best**;**

(iii) Flushing nitrogen into the reaction vessel. **(02 marks)**

To reduce the partial pressure of oxygen within the vessel**;** so as to create anaerobic conditions for fermentation to occur**;**

(c) Explain the observed changes in pH and total acidity of the medium during the experiment. **(07 marks)**

From about 1 hour to about 15 hours the pH of the medium decreased gradually to become more acidic**;** and thereafter remained relatively constant**; because** anaerobic respiration of glucose produced carbon dioxide**;** which reacted with water in the solution to form a weakly acidic medium**;**
From about 1 hour to about 15 hours glucose was still much in the medium**;** hence providing much substrate for anaerobic respiration of yeast**;**
After 15 hours to 70 hours the concentration of glucose in the medium decreased gradually**;** hence little carbon dioxide was generated from anaerobic respiration**;** whose effect on pH was minimal**;**

(d) From figure II, suggest one reason for the observed efficiency of the experiment. **(04 marks)**

Experiment was inefficient**;** since only about 16% of the total yielded of ethanol was realised**;** probably because cellulose and hemicellulose in bagasse could not be easily hydrolysed / digested into sugars**;** by enzymes in yeast**;**

Dongo Shema F

COMPARISON OF CELLULAR RESPIRATION AND FERMENTATION

Similarities: Both

(i) Form ATP

(ii) Use glycolysis to oxidise glucose to pyruvate

(iii) Use NAD+ as the oxidizing agent that accepts electrons from food during glycolysis

(iv) May be carried out by same cells (e.g. muscle cells) or same organisms (e.g. yeasts and bacteria).

Differences:

Cellular respiration / Aerobic respiration	**Fermentation / Anaerobic respiration**
● Uses oxygen for releasing energy	● Occurs in absence of oxygen
● Efficient i.e. up to **38 ATPs** formed per glucose molecule.	● Inefficient i.e. **2 ATPs** formed per glucose molecule
● Occurs in cytosol and mitochondria.	● Occurs in cytoplasm (cytosol) only.
● End products are CO_2 and water	● End products are Ethanol or 2 Lactate and CO_2
● Complete oxidation of respiratory substrate occurs	● Incomplete oxidation of respiratory substrate occurs

FATE OF PYRUVATE UNDER AEROBIC CONDITIONS

In the presence of oxygen, each pyruvate molecule produced by glycolysis in the cell cytoplasm is **actively transported** across the mitochondrial envelope (since it is a charged molecule) into the matrix, where it is transformed in what is called **link reaction** as follows:

First, pyruvate is decarboxylated, then oxidised (dehydrogenated) to form a **2-C compound called acetate**, **carbon dioxide** and **NADH**.

Carbon dioxide, a waste product is eventually excreted while NAD+ serves as a hydrogen carrier.

Finally, **Acetate** is attached to **Coenzyme A** to form **acetyl coenzyme A**, making the **acetyl group very reactive**.

Acetyl coenzyme A now enters citric acid cycle for further oxidation. (A–stands for acetylation)

Note: the transition from pyruvate to acetyl coenzyme A is not usually considered as a separate phase and is included with the first step of Krebs cycle.

THE ROLE OF CoA IN RESPIRATION

(1) Within the active centre of the enzyme **citrate synthetase,** CoA transfers the 2-carbon **acetyl group** to a 4-carbon molecule of **oxalocetate** to make a molecule of **citrate** which enters the Krebs cycle.

(2) It serves as a link between many different pathways of metabolism to provide a wide range of carbon compounds needed in the cell

(3) During energy deficiency, amino acids from proteins and fatty acids from lipids can be broken down to provide acetyl CoA for use in respiration.

Acetyl- Coenzyme A: *a central metabolic intermediate*

All proteins, lipids, and carbohydrates must be converted to **Acetyl- Coenzyme A** prior to participation in cellular respiration.

The fate of *acetyl-CoA* is dependent upon ATP needs. When ATP is prevalent, *acetyl-CoA* serves as the basis for fatty acid synthesis, which forms the basis of your body's long-term energy storage: triglycerides (i.e., fat). ***Acetyl-CoA* is the starting point for anabolic pathways that result in the synthesis of fatty acids.**

Alternatively, *acetyl-CoA* may enter the Kreb's citric acid cycle.

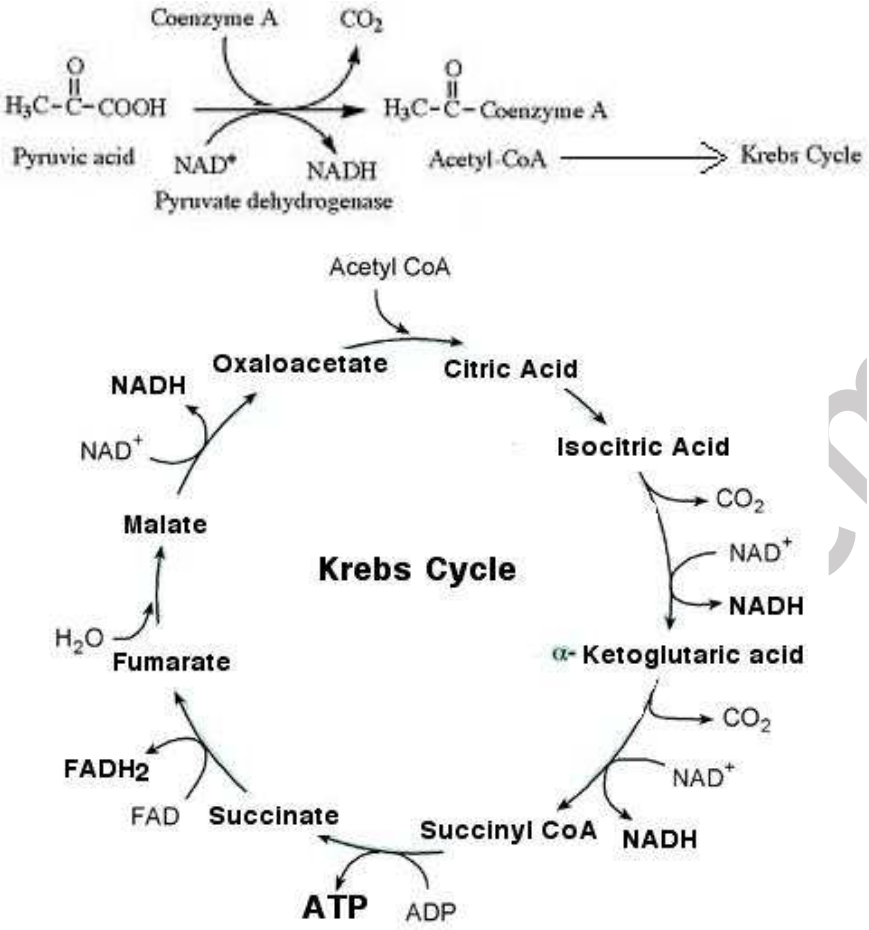
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KREBS CYCLE/ TRICARBOXYLIC ACID CYCLE / CITRIC ACID CYCLE

It is a multi-step reaction in the mitochondrial matrix during which an acetyl group is completely oxidized to CO_2 with the generation of ATP and reducing hydrogens in the form of NADH and $FADH_2$.

It is named:

1. Krebs cycle after the formulator Hans Krebs
2. Citric acid because citric acid is the first compound formed.
3. Tricarboxylic acid because citric acid which is the first compound formed has 3 carboxyl (-COOH) groups



1st Reaction: Prior to entering the Krebs cycle, pyruvate must be converted into acetyl CoA. Acetyl CoA adds its 2-C acetyl group to a 4-C oxaloacetate to form a 6-C citrate molecule.

2nd reaction: citrate isomerizes to a more reactive isocitrate by both removal and addition of one water molecule.

3rd reaction: isocitrate is decarboxylated (loses a carbon dioxide) and then oxidized (loses hydrogen to NAD+ to form NADH) to form α-ketoglutarate.

4th reaction: α-ketoglutarate loses a carbon dioxide (is decarboxylated) and is oxidised (loses hydrogen to NAD+ to form NADH) and attached to coenzyme A to form succinyl-CoA.

5th step: succinyl-CoA causes phosphorylation of ADP to ATP and the formation of succinate.

6th reaction: a 4-C succinate loses two hydrogens to FAD (is dehydrogenated), forming $FADH_2$ and a 4-C fumarate.

7th reaction: fumarate is hydrated (a water molecule is added) and rearranged to form malate.

8th reaction: finally, malate loses hydrogen to NAD+ to form NADH (is oxidised) regenerating oxaloacetate.

NOTE:

(1) Carboxylic acids are represented in their ionized forms as $-COO^-$ because the ionized forms prevail at the PH within the mitochondrion. E.g. **citrate** is the ionized form of **citric acid**.

(2) The regeneration of oxalocetate makes the process a cycle

(3) For each acetyl group that enters the cycle, 3 NAD+ are reduced to NADH (reactions 3, 4, and 8)

(4) Most of the ATP output of respiration results from oxidative phosphorylation, when the NADH and FADH2 produced by the citric acid cycle relay the electrons extracted from food to the electron transport chain.

COMPARISON OF KREBS CYCLE AND GLYCOLYSIS

Similarities: In both:

(1) NADH forms

(2) ATP is generated

(3) There is a reduction in number of carbon atoms of organic compounds

(4) Pyruvate participates

(5) Both occur in living cells

***Differences*:**

Glycolysis	**Krebs cycle**
• The electron acceptor FAD is **not** involved	• The electron acceptor FAD is involved
• Carbon dioxide doesn't form	• Carbon dioxide is liberated
• Occurs in cell cytoplasm	• Occurs in mitochondrial matrix
• Doesn't necessarily depend on oxygen	• Depends on oxygen availability to occur

ELECTRON TRANSPORT SYSTEM, CHEMIOSMOSIS AND OXIDATIVE PHOSPHORYLATION

●***Electron transport system:***

A sequence of oxidation-reduction (redox) reactions whereby the transfer of electrons between protein complexes in inner mitochondrial membrane is coupled with the transport of protons into intermembrane space to create a proton gradient that drives synthesis of about 34 ATP molecules.

●***Chemiosmosis:***

The process by which chemical ions e.g. H^+ move from an area of high concentration to an area of low concentration through transport proteins on the selectively permeable membrane as a result of proton gradient that forms across the membrane that is not readily permeable to ions.

●***Oxidative Phosphorylation:***

Use of energy supplied by transmembrane proton gradients across the inner mitochondrial membrane during electron transport system to form ATP.

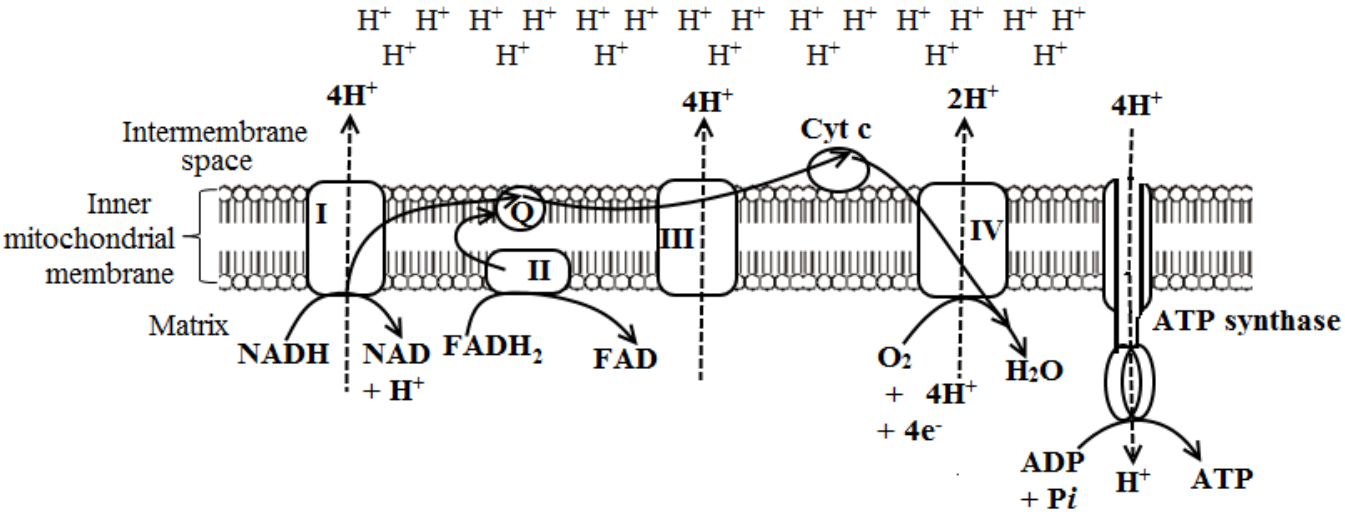
Components of electron transport chain

Complex	**Name**	**Prosthetic Groups**
Complex I	NADH Dehydrogenase	FMN, 9 Iron-Sulphur (Fe-S) centres
Complex II	Succinate-Coenzyme Q Reductase	FAD, cyt b_{560}, 3 Fe-S centers
	Coenzyme Q (CoQ) (also called ubiquinone)	cyt b_H, cyt b_L, cyt c_1, Fe-S
Complex III	Cytochrome bc1 complex	Cytochrome b_1 heme, b_2 heme
	Cytochrome c	cyt c
Complex IV	Cytochrome Oxidase	cyt a, cyt a_3, copper (Cu_A)and (Cu_B)

Cytochromes: are proteins with **haem** prosthetic groups. **Haem** contains an iron atom embedded in a porphyrin ring system. They absorb light at characteristic wavelengths.

Iron-sulfur centers (Fe-S): are prosthetic groups containing **2, 3, 4, or 8 iron atoms**, complexed to a combination of elemental and cysteine **sulfur atoms**.

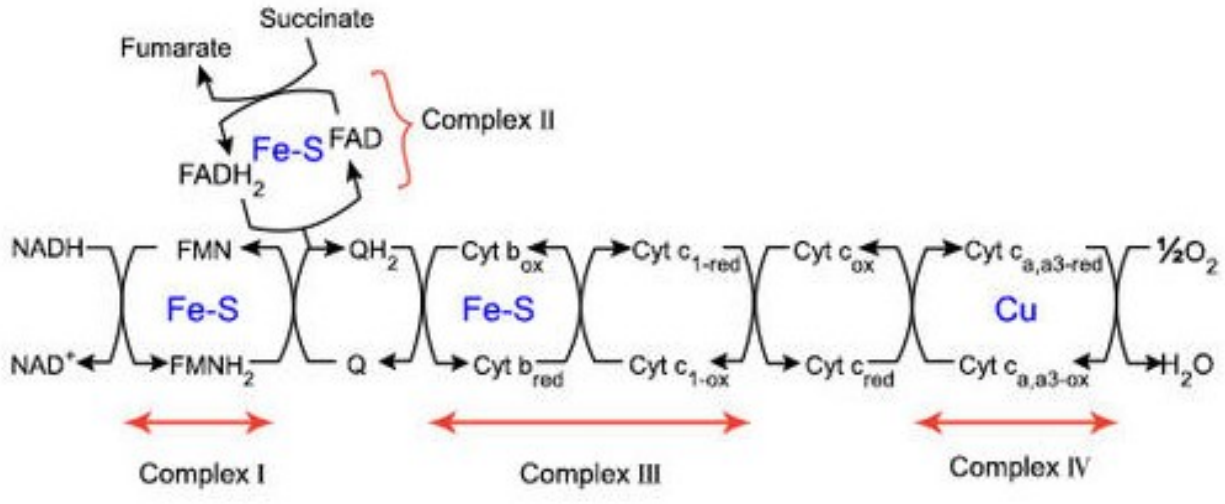
LOCATION OF CONSTITUENTS OF ELECTRON TRANSPORT CHAIN



The production of ATP during electron transport involves two separate but connected processes i.e. Chemiosmosis and oxidative phosphorylation

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DESCRIPTION OF ELECTRON TRANSPORT SYSTEM



The electrons released during glycolysis and carried by NADH are converted to $FADH_2$ in order to shuttle them from the cytoplasm into the mitochondrial matrix.

In Complex I (also called **NADH reductase)**, reduced nicotinamide adenine dinucleotide **(**NADH) donates electrons to the coenzyme Flavin mononucleotide (FMN) which then passes electrons to an iron-sulphur (Fe-S) protein and the electrons lose some energy. **NADH** is oxidized to **NAD^+,** while **FMN and Fe^{3+}** are **reduced to $FMNH_2$ and Fe^{2+}** respectively. Each electron is transferred with a proton. Electrons from the reduced Fe-S proteins are then passed to Coenzyme Q along with protons. Coenzyme Q is thus reduced while the Fe-S proteins are oxidised back to Fe^{3+} state.

In **complex II (succinate dehydrogenase),** electrons from $FADH_2$ are passed on to Fe-S proteins then to Coenzyme Q which transfers them to **complex III**. **$FADH_2$** becomes oxidised to **FAD+.** During this process, four protons (H^+) are translocated across the inner mitochondrial membrane, from the matrix to the intermembrane space. This creates a proton gradient that will be later used to generate ATP through oxidative phosphorylation. During oxidation of $FADH_2$ complex I is bypassed because complex II has only enough reducing potential to pass electrons to Coenzyme Q.

Reduced coenzyme Q ($CoQH_2$) transfers electrons to **Complex III** where they pass through several cytochromes and Fe-S proteins and during the process Fe^{3+} is reduced to Fe^{2+}. The electrons lose additional energy and are passed on to cytochrome *c* which passes electrons to **Complex IV (cytochrome *c* oxidase**), which finally transfers the electrons to reduce molecular oxygen to form **water.** $O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$. At the same time, complex IV moves protons (H+) across the membrane into the intermembrane space, producing a proton gradient.

Energy lost by electrons in complex I, III and IV, is used to pump protons into the intermembrane space producing a proton gradient.
Complex II (succinate dehydrogenase) is not a proton pump. It only serves to funnel additional electrons into coenzyme Q. Electron transfers involving Coenzyme Q and Cytochrome c do not release enough free energy to pump any protons.
When the protons flow down the concentration gradient through the channels in the stalked particles, ATP synthase enzymes are able to use the energy to generate ATP.

Note: If the oxygen supply is cut off, the electrons and hydrogen protons cease to flow through the electron transport system. If this happens, the proton concentration gradient will not be sufficient to power the synthesis of ATP. This is why we, and other species, are not able to survive for long without oxygen!

IS THE E.T.S A SEQUENCE?
No! The complexes move in the fluid membrane independently of one another, and exchange electrons when they are in mutual proximity. Although textbooks show the ETS as a physical sequence, the complexes and carriers are not locked in place.

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CHEMIOSMOTIC COUPLING HYPOTHESIS AND OXIDATIVE PHOSPHORYLATION

As proposed by Peter D. Mitchell, the chemiosmotic coupling hypothesis explains that the electron transport chain and oxidative phosphorylation are coupled by a proton gradient across the inner mitochondrial membrane.

The efflux of protons into the intermembrane space creates both a **pH gradient** and an **electrochemical gradient**. This proton gradient is used by the ATP synthase complex to make ATP via **oxidative phosphorylation**. The stalk component of ATP synthase complex works as an ion channel for return of protons back to mitochondrial matrix during which the free energy produced during the generation of the oxidized forms of the electron carriers (NAD^+) is released and used to drive ATP synthesis, catalyzed by the head component of the ATP synthase complex.

ACCOUNTING FOR ELECTRONS IN EUKARYOTIC ORGANISMS

Oxidation of NADH to NAD^+ pumps 3 protons from the mitochondrial matrix into the intermembrane space, which charges the electrochemical gradient with enough potential to generate 3 ATP. Oxidation of $FADH_2$ to FAD^+ pumps 2 protons into the intermembrane space, which charges the electrochemical gradient with enough potential to generate 2 ATP.

However, information from recent sources suggests that 1NADH generates 2.5 ATP and 1$FADH_2$ generates 1.5 ATP. The reason for this is that not all of the energy stored in the proton gradient is used to generate ATP. Some of the energy is used to power transport of ions in and out of the mitochondria.

A total of 12 pairs of electrons and hydrogens are transported to the electron transport system from glycolysis and Krebs cycle for each glucose molecule that enters the process:

- 4 pairs are carried by NADH and were generated during glycolysis in the cytoplasm, 8 pairs are carried as NADH and were generated within the mitochondrial matrix and 2 pairs are carried by $FADH_2$ and were generated within the mitochondrial matrix.
- For each of the 8 NADHs generated within the mitochondrial matrix, enough energy is released to produce 3 ATP molecules; therefore, 24 ATP molecules are released from these electrons carried by NADH.
- The electrons carried by FADH2 are lower in energy, so during the oxidation-reduction reactions, they release energy to produce only 8 ATP molecules.
- Therefore, a grand total of 32 ATP molecules are produced from hydrogen electrons that enter the electron transport system.

WHAT QUANTITY OF ATP IS GENERATED BY CHEMIOSMOSIS FROM ONE MOLECULE OF GLUCOSE DURING THE ELECTRON TRANSPORT CHAIN?

The chemiosmotic model suggests that one ATP molecule is generated for each H^+ pump activated by the electron transport chain. Since the electrons from NADH activate **three pumps** and those from $FADH_2$ activate **two**, it would be expected that the numbers of ATP molecules generated by each molecule of NADH and $FADH_2$ are t**hree** and **two** respectively.

However, since the transportation of the **two** molecules of NADH produced during Glycolysis into the mitochondrion requires **two ATPs**, the theoretical yield from aerobic respiration = 36 molecules of ATP i.e. 4 (from substrate-level Phosphorylation) + 30 (3 from each of 10 molecules of NADH) + 4 (2 from each of 2 molecules of $FADH_2$) – 2 (for transport of glycolytic NADH).

The actual yield is less than 36 because:

(1) The inner mitochondrial membrane allows some H^+ to re-enter the matrix without passing though ATP-generating channels

(2) Mitochondria often use the proton gradient generated by chemiosmosis for purposes other than ATP synthesis e.g. transporting Pyruvate into the matrix. As a result, the measured values of ATP generated are closer to 2.5 for each NADH and 1.5 for each $FADH_2$.

The molecules of ATPs formed from one molecule of glucose = 30 i.e. 4 (from substrate-level Phosphorylation) + 25 (2.5 from each of 10 molecules of NADH) + 3 (2 from each of 2 molecules of $FADH_2$) – 2 (for transport of glycolytic NADH)

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SUMMARY OF ENERGY YIELD DURING AEROBIC RESPIRATION OF ONE GLUCOSE MOLECULE

Pyruvate ⟶ **Acetyl CoA** = 6 ATP (2 Molecules of reduced NAD each yielding 3 ATP)

Krebs cycle = 24 ATP (6 Molecules of reduced NAD each yielding:

3 ATP + 2 Molecules of reduced FAD yielding

2 ATP + 2 Molecules of ATP formed directly)

Total ATP yield = 38 Molecules of ATP

INHIBITORS OF ELECTRON TRANSPORT

• **Inhibitors**	• **Action**
• Cyanide and Carbon monoxide	• Block cytochrome oxidase enzyme in complex IV
• Rotenone	• Blocks complex I. It's a common rat poison
• Antimycin	• Blocks electron transfer in complex III
• Oligomycin	• Blocks the proton channel in ATP synthase

Inhibitors bind to the components of the electron transport chain and block electron transfer. All components before the block are stuck in a reduced state and all components after in an oxidised state. No electron transfer is possible and proton pumping stops. The proton gradient is quickly run down and ATP synthesis stops. Inhibitors may also block the proton channel of ATP synthase.

EFFICIENCY OF RESPIRATION

Not all the energy present in the high-energy hydrogen atoms is conserved as ATP. Part of the energy is released as heat used for the maintenance of body temperature, but if it is in excess then it can be dissipated to the external environment. The efficiency of energy conserved in aerobic respiration, alcoholic fermentation and lactic acid fermentation are thus as follows:

Aerobic respiration	**Alcoholic fermentation**	**Lactic acid fermentation**
A total of 38 molecules of ATP are formed while the amount of energy released is 2880KJ. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 38 molecules of ATP is equal to 38 x 30.6 = 1162.8KJ.	Alcohol fermentation releases 210KJ with the formation of 2ATP. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 2 molecules of ATP is equal to 2 x 30.6 = 61.2KJ.	Lactic acid fermentation releases 150KJ with the formation of 2ATP. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 2 molecules of ATP is equal to 2 x 30.6 = 61.2KJ.
Efficiency of energy conserved = $\frac{(38ATP \times 30.6KJ)}{2880} \times 100$ = 40.375 ≈ 40.4%	*Efficiency of energy conserved* = $\frac{(2ATP \times 30.6KJ)}{210} \times 100$ = 29.1%	*Efficiency of energy conserved* = $\frac{(2ATP \times 30.6KJ)}{150} \times 100$ = 40.8%
The remaining 1717.2KJ (59.6%) is released as heat	The remaining 148.8KJ (70.9%) is released as heat	The remaining 88.8KJ (59.2%) is released as heat
However, considering that glucose on complete oxidation releases 2880KJ of energy, the yield from anaerobic respiration is given by: $\frac{(2ATP \times 30.6KJ)}{2880} \times 100 = 2.1\%$ Therefore, on a whole anaerobic respiration is 2% efficient.		

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ENERGY FROM NON-GLUCOSE SUBSTRATES

1. ENERGY FROM LIPIDS (FAT AND OIL)
In the gut, the enzyme lipase catalyses the hydrolysis of lipids into **fatty acids** and **glycerol** which enter the **lacteal** and finally gain entry into **liver cells**.

Glycerol is phosphorylated with ATP, dehydrogenated with NAD and converted to triose phosphate (glyceldehyde-3-phosphate) which is fed into the glycolysis pathway. There is a net yield of **19 molecules of ATP** from the oxidation of triose phosphate and of the NADH formed.

The fatty acid component is progressively broken in the matrix of the mitochondria into fragments of 2 carbons each which are converted to acetyl coenzyme A. This then enters the Krebs cycle with subsequent release of energy.

Carbohydrates versus Fats in energy release

Aspect	Explanation
Amount of energy released	Gram for gram, fats provide more energy than carbohydrates. The reason for this is the amount of oxidation that takes place as these compounds are converted to carbon dioxide and water. Carbon for carbon, fats require more oxidation to become CO2 and H2O than do carbohydrates. Roughly, carbohydrates already have one oxygen for every carbon atom, thus each carbon atom needs only one more oxygen and each pair of hydrogen atoms needs one more oxygen. However, almost every carbon atom in a fat molecule needs two oxygens instead of just one additional one, and each pair of hydrogen atoms still needs one more oxygen. So, just from counting the number of oxygens needed to be added, fats require about half again as much oxygen for the same number of carbon atoms. Because of this, the oxidation of fats takes longer, but it also gives off more energy. When comparing gram to gram, instead of carbon to carbon, the effect is exaggerated. When you weigh a carbohydrate, more oxygen is included in that weight. When you weigh a fat, you get more carbon atoms per gram and therefore, gram for gram, the fats will give even more energy (over twice as much) than will the carbohydrates.
Time spent	**Carbohydrates** enter into the oxidation process much more quickly and **provide energy more rapidly than fats.** This is because **fats** go through several more steps than do carbohydrates to become acetyl CoA and enter the citric acid cycle.

ENERGY FROM OTHER HEXOSES
In most organisms, hexoses other than glucose can undergo glycolysis after conversion to a phosphorylated derivative.

1. FRUCTOSE: is present in free form in many fruits and is also formed by hydrolysis of sucrose in the ileum of vertebrates.
In the muscles and kidney fructose is phosphorylated to fructose-6-phosphate by hexokinase enzyme while in the liver fructokinase enzyme catalyses the phosphorylation of fructose to fructose-1-phosphate which then splits into glyceraldehyde and dihydroxyacetone phosphate.
Dihydroxyacetone phosphate converts to glyceraldehyde 3-phosphate while glyceraldehyde is phosphorylated by ATP to glyceraldehyde 3-phosphate. Thus both products of fructose 1-phosphate hydrolysis enter the glycolytic pathway as glyceraldehyde 3-phosphate.

2. GALACTOSE: is a product of hydrolysis of the disaccharide lactose (milk sugar). Galactose is first phosphorylated by ATP to galactose-1-phosphate and then converted to glucose-1-phosphate through a series of reactions.
Galactosemia is a human genetic disease that results from disordered galactose metabolism in which the overall conversion of galactose to glucose prevented.

3. MANNOSE, which is released in the digestion of various polysaccharides and glycoproteins of foods, can be phosphorylated at C-6 by hexokinase:
Mannose + ATP → mannose 6-phosphate + ADP
Mannose 6-phosphate then isomerizes to fructose 6-phosphate, an intermediate of glycolysis.

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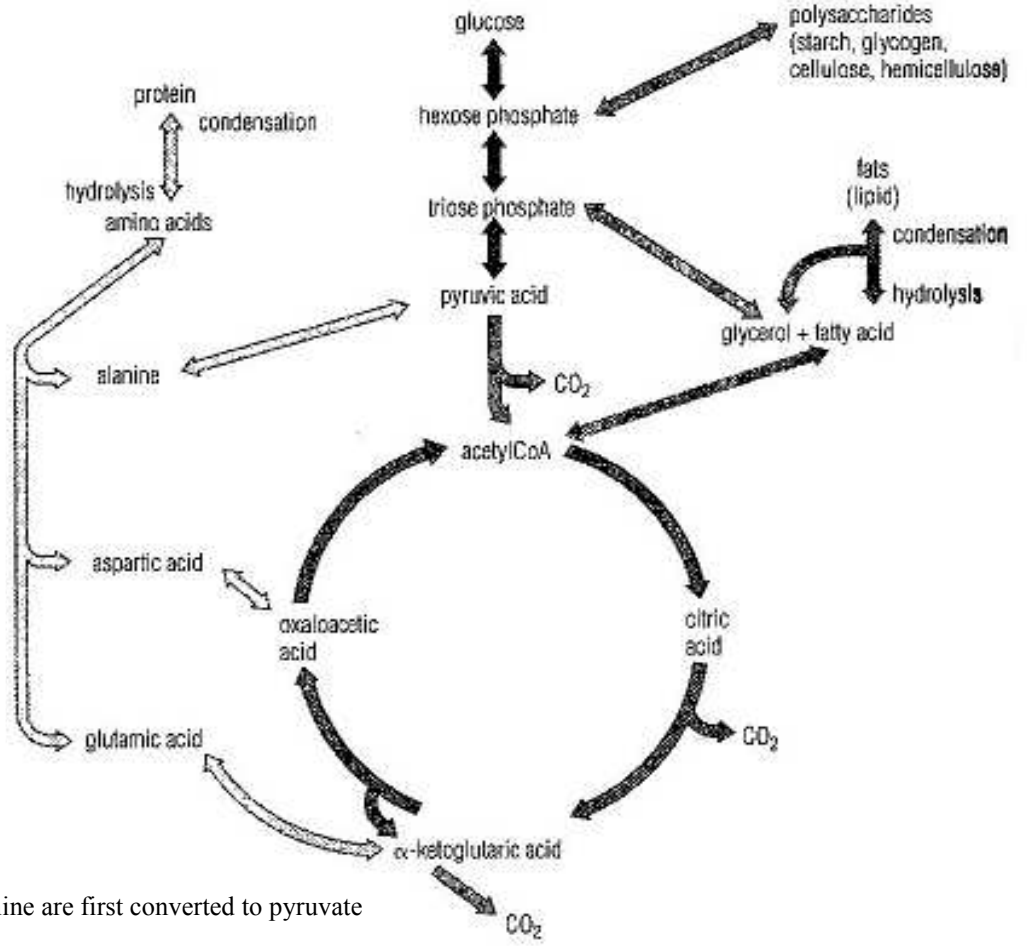
Tissue respiration and its connections with the rest of metabolism

ENERGY FROM PROTEIN

- The body resorts to protein as an energy source only during starvation.
- Protein is first hydrolysed to amino acids which are then individually deaminated i.e. amino groups (-NH2) are removed and converted to ammonia, urea or uric acid for excretion. The residual carbon compound (a keto acid) then enters the respiratory pathway at a number of points depending on their number of carbon atoms:

(i) 5-C amino acids like glutamate are converted to α-ketoglutarate,

(ii) 4-C amino acid like aspartate are converted to oxaloacetate. α-ketoglutarate and oxaloacetate enter Krebs cycle.



(iii) 3-C amino acids like alanine are first converted to pyruvate and then acetyl coenzyme A.

- Amino acids with many carbon atoms are converted by transamination reactions into 3, 4 or 5-carbon amino acids.

CONTROL OF RESPIRATION

Because the main function of respiration is to produce ATP, it must be regulated so that ATP is generated only when needed. This occurs in a number of ways:

1. At cellular level, the rate at which respiration occurs is regulated mainly by the energy state of the cell (i.e. the ratio of ATP to ADP), acting via regulatory enzymes.

High levels of ATP (high energy level of the cell) inhibit the enzyme **hexokinase** that catalyses phosphorylation of glucose at the start of glycolysis while low energy levels (high ADP levels) stimulate **hexokinase** enzyme. Highly active cells utilize ATP very fast breaking it to ADP. This has the effect of enhancing the rate of respiration. Such cells include **liver cells, striated muscle cells, spermatozoa** and **nerve cells**. They are characterized by presence of numerous mitochondria. Less active cells utilize ATP slowly and hence respiration in them is slow e.g. **fat cells**.

2. At the level of the whole organism, the respiratory rate is influenced by **environmental factors** e.g. temperature, **structural factors** e.g. body size and **physiological factors** such as level of activity, growth and dormancy.

***(a) Temperature*:**

Generally, very low temperature slows down respiration in both homoiotherms and poikilotherms, although it can be observed that homoiotherms need increased respiration rate to generate much heat for maintaining body temperature. In poikilotherms temperature near to that of the body increases the respiration rate. *This partly explains why mosquitoes and tsetse flies are only found in the tropics where environmental temperature is close to their optimal temperature.* High temperature slows down the respiration rate in homoiotherms. This explains why such animals tend to be sluggish during hot weather. However, excessively high temperatures trigger increased respiration rate and finally stop as a response by enzymes to temperature.

(b) Body size:
Small organisms with a large surface area to volume ratio lose heat faster and therefore respire faster than large organisms.
(c) Level of activity:
Animals engaging in vigorous physical exercise require much energy and so experience faster respiration rate e.g. sprinting, flying, etc
(d) Growth:
Actively growing organisms e.g. young animals and germinating seeds respire faster to generate much energy required to drive metabolic processes involved in cell division.
(e) Dormancy during extreme cold and hot seasons:
Respiration rate is always slow to avoid depleting food reserves before the unfavourable season ends.

RESPIRATORY QUOTIENT (RQ)
RQ is the ratio of the volume of Carbon dioxide produced to the volume of oxygen used in respiration during the same period of time

$$RQ = \frac{\text{Volume of Carbon dioxide given out}}{\text{Volume of oxygen taken in}}$$

Importance of RQ values
(1) Can indicate the kind of substrate being respired by the cell or organism
(2) Can indicate whether the respiration is aerobic or anaerobic.

RQ can be measured using a **spirometer** or **respirometer.**

RQ FOR HEXOSE SUGAR
Like glucose, the equation for its complete oxidation is:

$$C_6H12O_6 + 6O2 \longrightarrow 6CO_2 + 6H_2O$$

Hence RQ is: $\frac{6CO_2}{6O_2} = 1.0$ (one)

R.Q FOR FATS
For lipids like tripalmitin and tristearin, the equation for its complete oxidation is:

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

RQ is: $\frac{102CO_2}{145O_2} = 0.7$ (less than one)

$2\ C_{57}H_{110}O_6 + 163\ O_2 \rightarrow 110\ H_2O + 114\ CO_2$
RQ is: $\frac{114CO_2}{145O_2} = 0.69$ (less than one)

NB: The R.Qs for different fats show slight variations because of differences in molecular composition.

R.Q FOR PROTEINS
No concrete value can be calculated since:
(i) Proteins vary so much in composition
(ii) Proteins are difficult to separate in the pure state.
RQ estimates for protein vary between 0.5 and 0.8 on complete oxidation.

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SUMMARY OF THE POSSIBLE INTERPRETATIONS OF R.Q VALUES:

Subject	R.Q.	Possible interpretations
Germinating starchy seeds Leaves rich in carbohydrate	1.0 1.0	Complete oxidation of a carbohydrate substrate
Wheat seedlings in nitrogen	∞	Anaerobic respiration
Germinating seeds	0.64	Oxidation of a fatty substance
Germinating peas (testa intact)	3.0 to 4.0	Slow entry oxygen causing some anaerobic respiration
Germinating peas (testa removed)	1.5 to 2.5	More rapid entry of oxygen, but some anaerobic respiration
Man (average)	0.8 to 0.85	Mixed fat and carbohydrates substrate
Lumbricus terrestris	0.75	Mainly fat substrate
Drosophila (at rest)	1.23	Conversion of carbohydrate to fat / organic acids : excess CO_2 produced by decarboxylation
Drosophila (flying)	1.0	Complete oxidation carbohydrate
Nerve tissue (resting)	0.77	Possibly mainly fat substrate
Nerve tissue (active)	0.97	Almost entirely carbohydrate substrate

COMPARISON OF RESPIRATION WITH PHOTOSYNTHESIS

Similarities Both:

(i) Involve converting energy from one form to another
(ii) Occur in living cells
(iii) Form adenosine triphosphate (ATP)
(iv) Require energy to occur
(v) Involve a series of multi-enzyme catalysed reactions
(vi) Involve flow of electrons along electron carriers.

Differences

Photosynthesis	Respiration
Occurs in cells with chlorophyll	Occurs in all cells
Occurs in the presence of light	Occurs all the time
Raw materials are Carbon dioxide and water	Raw materials are reduced carbon compounds and oxygen
Forms Reduced carbon compounds, oxygen, and water	Forms Carbon dioxide and water
Light is a source of energy	Chemical bonds are the source of
Energy stored	Energy released
Reactions involve reduction of carbon compounds	Reactions involve oxidation of carbon compounds
Energy carrier is NADP	Energy carriers are NAD and FAD

ECONOMIC / COMMERCIAL IMPORTANCE OF ANAEROBIC RESPIRATION

(i) In breweries, fermentation of sugars forms alcoholic drinks like wine, beer and spirits.
(ii) In bakeries, fermentation of starch by yeast is used in leavening of bread i.e. production of raised bread
(iii) Applied in the manufacture of milk products like sour milk, yoghurt and cheese
(iv) Applied in food industries for the manufacture of organic acids e.g. citric acid, oxalic acid and butyric acid.

CIRCUMSTANCES THAT MAY LEAD TO ANAEROBIC RESPIRATION

In Yeast	In flowering plant	In a mammal
● Stagnant solutions ● Centre of decomposing fruits and other organic matter	● Young seeds ● Seeds at centre of fruits and other organic matter ● In roots growing in water logged soils ● In aquatic plants growing in stagnant ponds	● Inefficiency of lungs e.g. emphysema ● Decrease in blood pressure e.g. haemorrhage, pressure on artery ● Low oxygen carrying capacity of blood e.g. anaemia, bone marrow disease. ● Low cardiac output e.g. slow heart rate, coronary thrombosis. ● Capillary network inadequate e.g. angina. ● High oxygen demands e.g. strenuous exercise, pregnancy. ● **Others:** Hibernation, Sperm in oviduct, High altitude

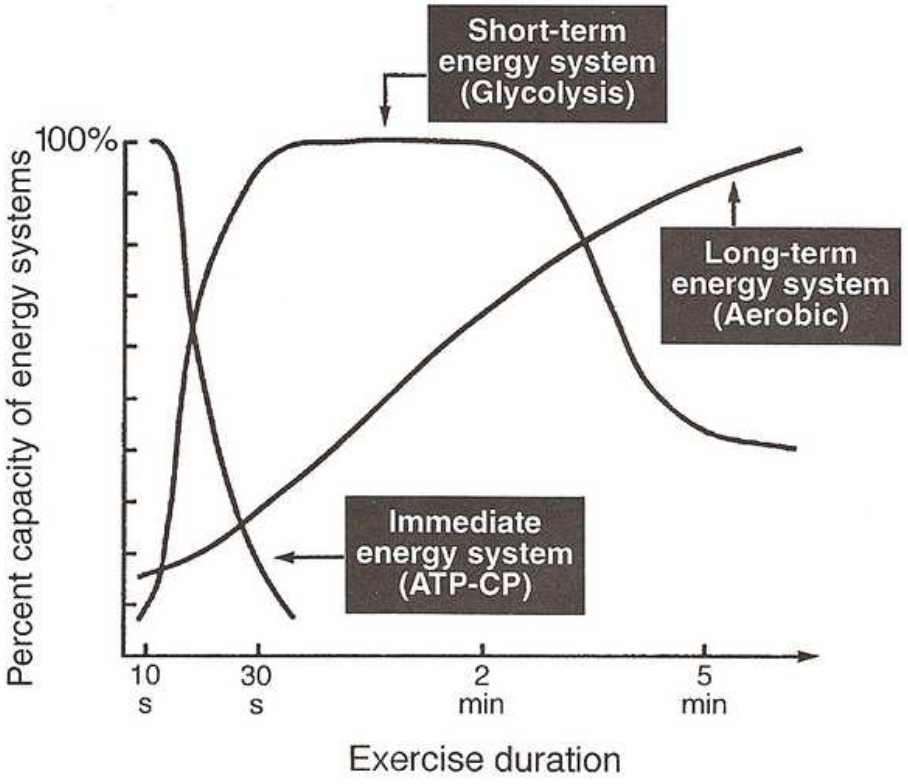
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ATP PRODUCTION DURING EXERCISE

- On average, a muscle contains only enough ATP to sustain about 15 seconds of intense exercise. For muscle contractions to continue, massive amounts of ATP are required.
- Depending on intensity and duration of activity, exercising muscles may produce the ATP aerobically or anaerobically.
- Sustained periods of sub-maximal activity like jogging are powered by aerobic respiration, but in contrast short periods of intense activity like sprinting are powered by a combination of aerobic and anaerobic respiration.

"Anaerobic" here means a combination of glycolysis and stored ATP/Phosphocreatine release.

The graph below shows the three systems of energy transfer and their percentage contribution to total energy output during all-out exercise of different durations.



Observations / Description:

(1) From 10 seconds to about 35 seconds, % capacity of energy from **ATP / Phosphocreatine** decreases rapidly and stops.

(2) From 10 seconds to about 15 seconds, % capacity of energy from **Glycolysis** increases gradually, then increases rapidly to the maximum at 32 seconds, then remains constant from about 32 seconds to about 2 minutes, then decreases rapidly to about 3 minutes and finally decreases gradually.

(3) From 10 seconds to about 30 seconds, % capacity of energy from **Aerobic respiration** increases gradually, then increases rapidly thereafter.

Explanation:

During the first 30 seconds, the small amounts of ATP and phosphocreatine stored in cells provide instant energy for muscle contraction and get depleted.

During the first 15 seconds, glycolysis provides a proportionally smaller contribution, and a smaller contribution yet comes from aerobic respiration.

From about 15 seconds to about 2 minutes, muscles largely rely on glycolysis to generate ATP for contraction.

From about 30 seconds to 2 minutes, aerobic respiration supplements glycolysis in providing ATP, but after 2 minutes, muscle contraction mainly relies on aerobic respiration for ATP.

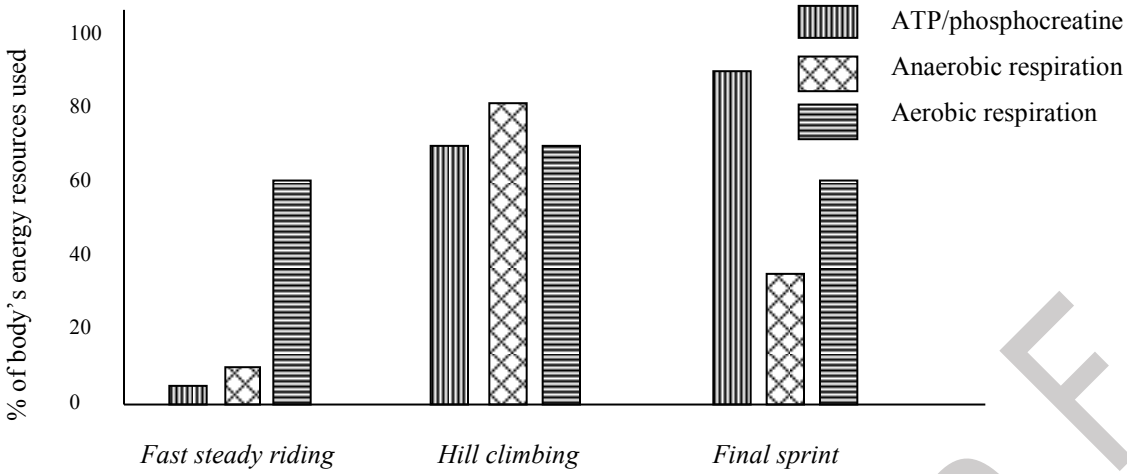
NOTE:

- Phosphocreatine (also called creatine phosphate), **stores ~P bonds in** nerve and muscle cells.
- Creatine Kinase catalyzes: **phosphocreatine + ADP ⇔ ATP + creatine**
- This is a reversible reaction, though the equilibrium constant slightly favors phosphocreatine formation.

Phosphocreatine is produced when ATP levels are high. When ATP is depleted during exercise in muscle, phosphate is transferred from phosphocreatine to ADP, to replenish ATP.

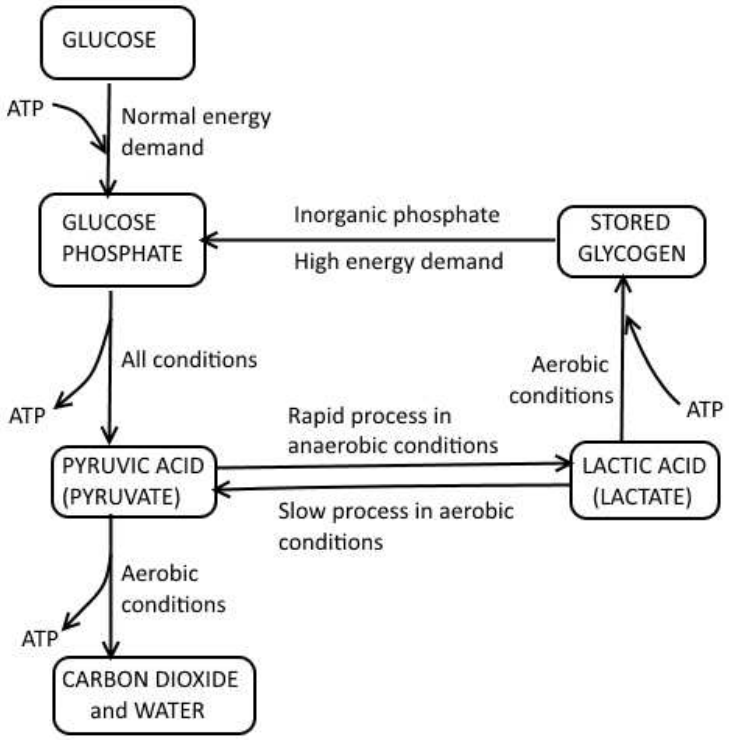
Dons

The figure below shows how the different energy sources are used at different stages in a bicycle race.



Observations:
(1) During the fast steady riding, there is an overriding contribution of aerobic respiration, but very little from ATP/phosphocreatine and anaerobic respiration.
(2) In the stretches of hill climbing, glycolysis predominates over ATP/phosphocreatine and aerobic respiration in providing energy. The latter two make equal contribution, which follows closely.
(3) In the final sprint, ATP/phosphocreatine takes the leading role in providing energy, followed by aerobic respiration and leastly by anaerobic respiration. This is because during the steady riding, ATP/phosphocreatine reservoirs replenished and therefore provides energy fast to the cells.

TYPICAL EXAMINATION QUESTION
The figure below summarises the metabolic processes involved in the release of energy in the muscles during and after running in a 200-metre sprint. During the race, the rate of oxygen consumption rose above the resting level while after the race, oxygen consumption did not drop to the resting level for some time. Blood sample tests after the race revealed a significant increase in lactic acid (lactate).



(a) (i) Explain why, although oxygen consumption rises during the race, more lactic acid (lactate) is present in the blood at the end of the race.
(ii) Why is the athlete's oxygen consumption still higher than normal sometime after the race.
(iii) After the race ATP is used to convert most lactic acid (lactate) to glycogen. With the help of information in the diagram, explain why this is efficient use of lactic acid.
(iv) For every molecule of glucose, 38 molecules of ATP are produced during aerobic respiration but only 2 molecules of ATP are produced during anaerobic respiration. Explain how this difference occurs.
(v) From the information in the figure above, explain why it is advantageous to respire glycogen rather than glucose during strenuous exercise.
(b) Suggest three ways in which exercise may improve an athlete's subsequent performance.

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SUGGESTED ANSWERS

(i) During the race, oxygen supplied by ventilation and gaseous exchange is not sufficient to meet the ATP demands of the body, causing muscles to resort to anaerobic for ATP generation, with formation of lactic acid.

(ii) All the lactic acid formed during the race is transported to the liver for degradation, which requires oxygen uptake shortly after the race. This is what is called paying the **"Oxygen debt".**

(iii) Immediately after the race, skeletal muscles have low ATP requirements. Since lactic acid can later be converted to pyruvate, conversion of lactic acid to glycogen therefore stores energy for later use rather than oxidise all the lactic acid to form ATP which has no immediate use.

(iv) In the absence of oxygen, Krebs cycle and electron transport system are inhibited, so glucose is only partially broken down by glycolysis to yield a net of 2 ATP molecules. Under aerobic conditions, Glycolysis, Krebs cycle and electron transport system all occur to yield about 38 ATP molecules.

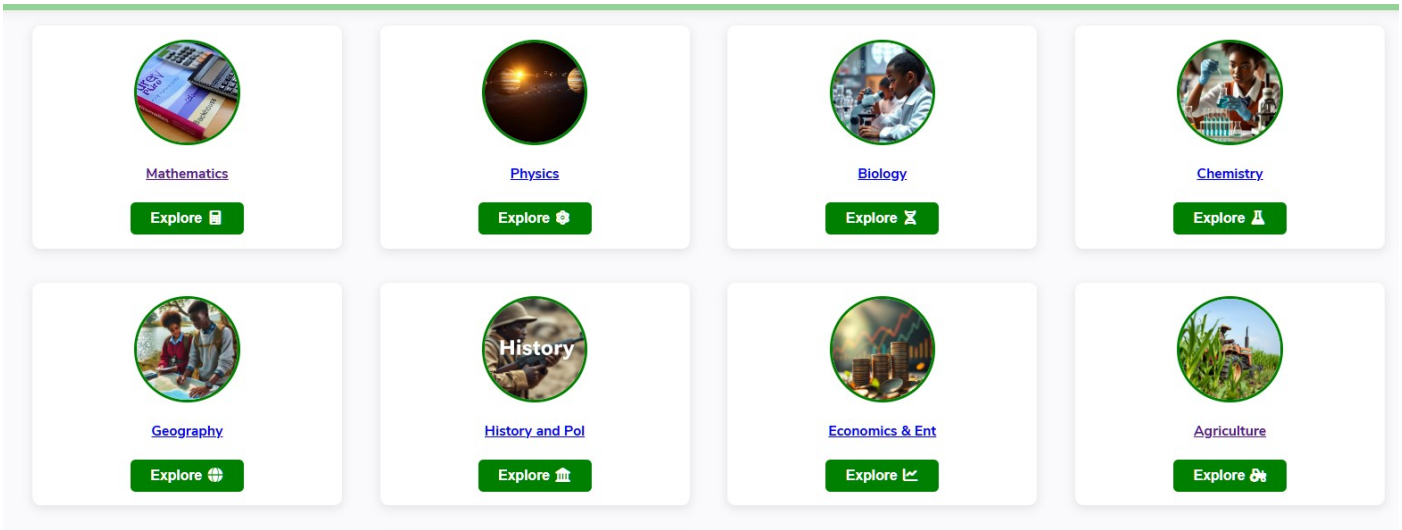
(v) Conversion of glucose to glucose phosphate requires ATP, which reduces the total ATP produced. Conversion of glycogen to glucose phosphate does not require ATP, therefore more ATP is available to the organism to power muscle contraction during exercise.

(b)

- Build up and improved functioning of the muscles.
- Improvements in blood circulation, efficient cardiac output (more blood pumped per unit time)
- Improved oxygen carrying capacity of the body e.g. through a greater concentration of red blood cells with more haemoglobin in each one.
- Greater lung capacity permitting more air and therefore oxygen to be inspired per unit time.

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