

S.5 TERM 3

TOPIC 4: RESPIRATION

Competency: The learner appreciates how living organisms generate cellular energy, by analyzing respiratory processes and the chemical breakdown of food within cells, to make informed decisions that promote good health and wellbeing.

SUB TOPIC 1: MITOCHONDRION STRUCTURE AND FUNCTION

Learning Outcome 1

The learner should be able to:

- examine the relationship between the structure of the mitochondrion and the stages of cellular respiration in living organisms. (u, s)

Introduction to Respiration

Respiration is the biochemical process through which cells break down glucose to release energy in the form of ATP, essential for survival.

This process occurs in all living cells, ensuring a continuous energy supply for functions such as muscle contraction, nerve transmission, active transport, and metabolism.

ATP

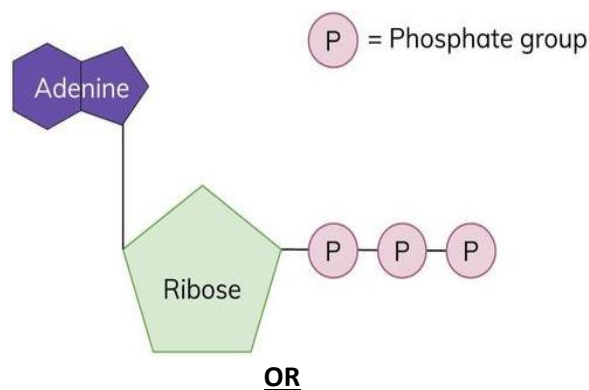
ATP stands for Adenosine Triphosphate.

ATP is a high energy molecule found in the cells of all living organisms.

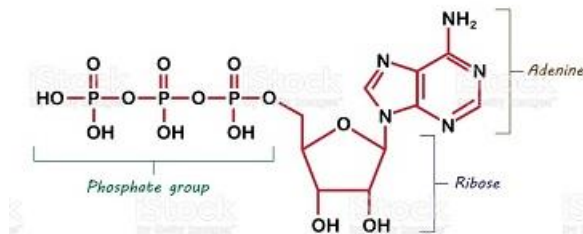
MAIN FUNCTION OF ATP

- To store and provide energy needed for various biological processes like muscle contraction, active transport, and biosynthesis.

Structure of ATP



Adenosine Triphosphate (ATP)



ATP is made up of three main components:

- Adenine – a nitrogen containing base
- Ribose – a five-carbon sugar
- Three phosphate groups – linked together in a chain

These phosphate bonds, especially the bond between the second and third phosphate groups, are high energy bonds.

Energy Release from ATP

Energy is released from ATP by breaking the bond between the second and third phosphate groups.

This process is called hydrolysis.

The reaction is:



Where:

ADP = Adenosine Diphosphate

P_i = Inorganic phosphate

About 30.5 kJ/mol of energy is released.

This energy is used immediately by cells for biological work.

NB:

Phosphorylation is the addition of a phosphate to ADP to form ATP

Importance of Energy Released from ATP

The energy from ATP is essential for many life processes, including:

- Muscle Contraction – for movement
- Active Transport – moving substances against concentration gradients
- Biosynthesis – building proteins, nucleic acids, and other macromolecules
- Cell Division – forming spindle fibers and separating chromosomes
- Nerve Transmission – maintaining resting and action potentials

- Maintaining body temperature – especially in warm blooded animals
- Secretion – aiding vesicle movement during exocytosis

NB:

ATP is the universal energy currency for cells.

TYPES OF RESPIRATION

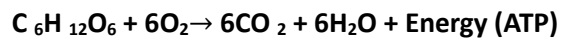
- Aerobic respiration
- Anaerobic respiration

AEROBIC RESPIRATION

Is the process by which cells break down glucose (or other organic molecules) in the presence of oxygen to release energy.

This energy is used to produce ATP (Adenosine Triphosphate), which powers various cellular activities.

Overall Equation



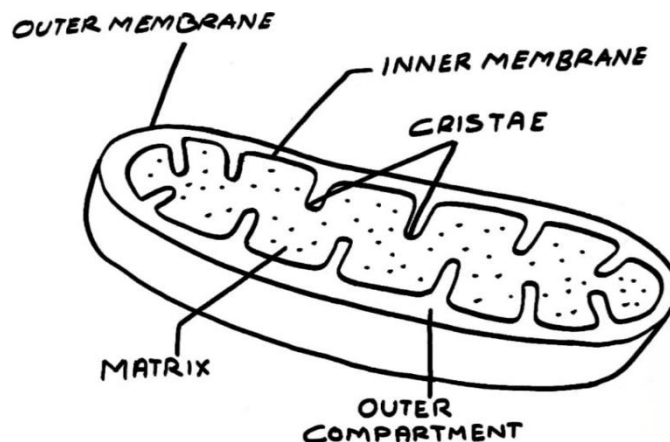
Site of Occurrence of aerobic respiration

- In the mitochondria of cells.
- Initial steps (glycolysis) occur in the cytoplasm.

MITOCHONDRIA

Mitochondria are energy producing double membrane bound organelles found in nearly all eukaryotic cells.

Structure of the mitochondria



Mitochondria are double membrane bound organelles found in nearly all eukaryotic cells,

The outer membrane is smooth and serves as a boundary between the mitochondrion and the cytoplasm,

The inner membrane is highly folded into structures called cristae, which increase the surface area for biochemical reactions,

Inside the inner membrane is the matrix, a gel like substance containing enzymes, ribosomes, and mitochondrial DNA,

The intermembrane space, located between the two membranes, plays a crucial role in energy production,

Mitochondria have their own DNA and ribosomes, allowing them to synthesize some of their own proteins independently.

Summary of functions of Mitochondria

- Produces ATP (adenosine triphosphate) through aerobic respiration.
- Contains its own DNA and ribosomes, allowing it to divide independently.
- Generates heat energy in specialized brown fat cells (thermogenesis).
- Plays a role in apoptosis (programmed cell death) by releasing cytochrome c.

Relationship Between Mitochondrial Structure and Stages of Cellular Respiration

The mitochondrion is often called the "powerhouse of the cell" because of its key role in aerobic respiration, where most of the cell's ATP is produced.

1. Outer Membrane

Structure: Smooth, permeable to small molecules and ions.

Function: Allows entry of substances (like pyruvate and oxygen) needed for respiration and protects the internal environment.

Respiratory Role: Separates the mitochondrion from the cytoplasm and contains enzymes for fatty acid metabolism.

2. Inner Membrane

Structure: Folded into cristae to increase surface area.

Function: Houses the electron transport chain (ETC) and ATP synthase enzymes.

Respiratory Role:

Oxidative phosphorylation (making of ATP using energy from electrons and oxygen) occurs here—electrons from NADH and FADH₂ pass through the ETC, releasing energy to pump protons across the membrane.

The proton gradient drives ATP synthesis as H⁺ ions flow back through ATP synthase.

3. Cristae

Structure: Infoldings of the inner membrane.

Function: Greatly increase surface area for more ETC proteins and ATP synthase molecules.

Respiratory Role: Enhances the efficiency of ATP production by supporting numerous sites for oxidative reactions.

4. Matrix

Structure: Gel-like substance inside the inner membrane.

Function: Contains enzymes, mitochondrial DNA, and ribosomes.

Respiratory Role:

Site of the Link Reaction (conversion of pyruvate to acetyl CoA).

Site of the Krebs Cycle, which produces NADH, FADH₂, and CO₂.

Enzymes here catalyze these reactions and support protein synthesis for mitochondrial function.

SUB TOPIC 2: ATP PRODUCTION PROCESSES

Learning Outcome 2

The learner should be able to;

b) analyse the biochemical processes leading to ATP production in living organisms, and how these processes are affected by physical activities and respiratory poisons (cyanide). (u, s, gs, v/a).
(Details of biochemistry are not required)

STAGES OF AEROBIC RESPIRATION

Aerobic respiration occurs in 3 main stages ie

1. Glycolysis
2. Link Reaction
3. Krebs Cycle
4. Electron Transport Chain and Oxidative

DESCRIPTION OF EACH STAGE

GLYCOLYSIS

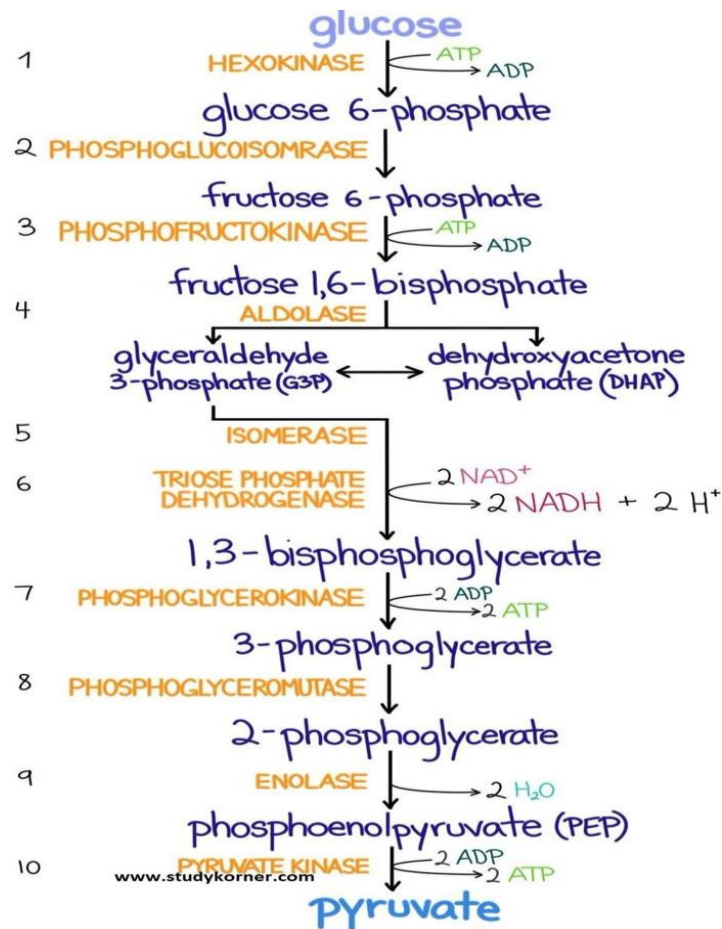
Also called the Embden–Meyerhof–Parnas Pathway

Meaning: Breakdown ("lysis") of glucose to extract energy.

Location: Cytoplasm (fluid part of the cell)

Oxygen required? **✗** No (Anaerobic process)

Illustration;



Starting molecule glucose ($C_6H_{12}O_6$), from digested carbohydrates like bread, rice, or sugar;

Step 1: Phosphorylation of Glucose

Phosphorylation is addition of a phosphate group, which activates glucose

Glucose is given a phosphate group from ATP (from previous cellular respiration or food) to form **Glucose6phosphate (G6P)** in the presence of Hexokinase enzyme

Step 2: Isomerization

Isomerization is the changing structure without changing chemical formula)

G6P is rearranged into **Fructose6phosphate (F6P)** in the presence of

enzyme phosphoglucose isomerase

Step 3: Second Phosphorylation

F6P is phosphorylated again using another ATP to form **P Fructose1,6bisphosphate (F1,6BP)**

In the presence of enzyme phosphofructokinase1 (PFK1).

(This is the ratelimiting step – controls the speed of glycolysis)

Note:

The “p” in p Fructose 1,6bisphosphate stands for “phosphorylated” meaning the, molecule has phosphate group(s) attached to it

Step 4: Splitting (Lysis)

(Lysis = breaking a molecule into smaller parts)

F1,6BP is split into Glyceraldehyde3phosphate (G3P) and Dihydroxyacetone phosphate (DHAP)

in the presence of Aldose enzyme

Step 5: Isomerization of DHAP

DHAP is converted into another G3P in the presence of enzyme triose phosphate isomerase

Now there are two G3P molecules, both continue through the next steps

Energy Payoff Phase

(Each G3P molecule goes through the next steps — so they occur twice per glucose)

Step 6: Oxidation and NADH Formation

G3P is oxidized (loses electrons) to form 1,3bisphosphoglycerate (1,3BPG)

NAD⁺ (Nicotinamide Adenine Dinucleotide, oxidized form) is reduced to NADH in the presence of enzyme G3P dehydrogenase

(Oxidation = loss of electrons; NADH = electron carrier used in later stages)

Note:

NAD⁺ stands for:

Nicotinamide Adenine Dinucleotide (oxidized form)

Function in the Cell:

NAD⁺ is a coenzyme (helper molecule) involved in redox reactions.

It's an electron carrier — it accepts electrons (is reduced) to become NADH.

Reaction:



NAD⁺ gains 2 electrons and 1 proton from G3P to form NADH

NADH then carries these electrons to the Electron Transport Chain (ETC) to help produce ATP

Summary:

NAD ⁺	NADH
Oxidized form (no electrons)	Reduced form (has electrons & energy)
Accepts electrons (e.g., in glycolysis)	Donates electrons (e.g., in ETC)

Step 7: First ATP Formation

A phosphate from 1,3BPG is given to ADP (Adenosine Diphosphate) forming ATP and **3phosphoglycerate (3PG) in the** presence of enzyme phosphoglycerate kinase

Note

Substrate level phosphorylation = direct formation of ATP from a compound

Step 8: Rearrangement

(Rearrangement = changing the position of a functional group in the molecule)

3PG is changed into 2phosphoglycerate (2PG) in the presence of enzyme phosphoglycerate mutase

Step 9: Dehydration

(Dehydration = removal of a water molecule)

Water (H₂O) is removed from 2PG to form phosphoenolpyruvate (PEP) in the presence of enzyme enolase

Step 10: Second ATP Formation and Pyruvate Production

PEP donates a phosphate to ADP, forming ATP and **Pyruvate (C₃H₄O₃)** in the presence of enzyme Pyruvate kinase

Note

Pyruvate is a key molecule that enters the next step if oxygen is present).

Pyruvate is the final Products of Glycolysis (Per Glucose Molecule)

Net Products (per 1 glucose molecule)

Product	Amount	Use
Pyruvate (C ₃ H ₄ O ₃)	2	Used in the Link Reaction
ATP (Adenosine Triphosphate)	4 made, 2 used → Net: 2ATP	Used as energy by the cell
NADH (Reduced Nicotinamide Adenine Dinucleotide)	2	Carries electrons to the Electron Transport Chain
H ⁺	2	
H ₂ O		

Therefore;

Glycolysis is a 10step process that breaks down of glucose molecule into two pyruvate molecules, producing a net gain of 2 ATP and 2 NADH, and it happens in the cytoplasm without oxygen.

Fate of Pyruvate

- With oxygen (aerobic), pyruvate enters the mitochondria matrix and undergoes the **link reaction**.
- Without oxygen (anaerobic), fermentation produces lactase in animals or ethanol in yeast

Significance of Glycolysis

Glycolysis is the first step in cellular respiration, occurring in the cytoplasm of all living cells. It breaks down one glucose molecule (6C) into two molecules of pyruvate (3C).

Major Roles and Importance:

✓ Energy Production:

Produces 2 ATP molecules directly through substrate level phosphorylation (net gain) and 2 NADH that carry electrons to the electron transport chain.

✓ Occurs Without Oxygen:

Glycolysis does not require oxygen, so it can occur in anaerobic conditions (e.g., in muscles during intense exercise, in yeast fermentation).

✓ Gateway to Further Metabolism:

Pyruvate, the end product, can enter:

- Fermentation pathways under anaerobic conditions (e.g., lactic acid or ethanol)
- The link reaction and Krebs cycle under aerobic conditions

THE LINK REACTION aka PYRUVATE DECARBOXYLATION

The link reaction is a short metabolic step that links glycolysis (in the cytoplasm) to the Krebs cycle (in the mitochondria) by converting pyruvate ($C_3H_4O_3$) into acetyl coenzyme A (acetylCoA).

Location:

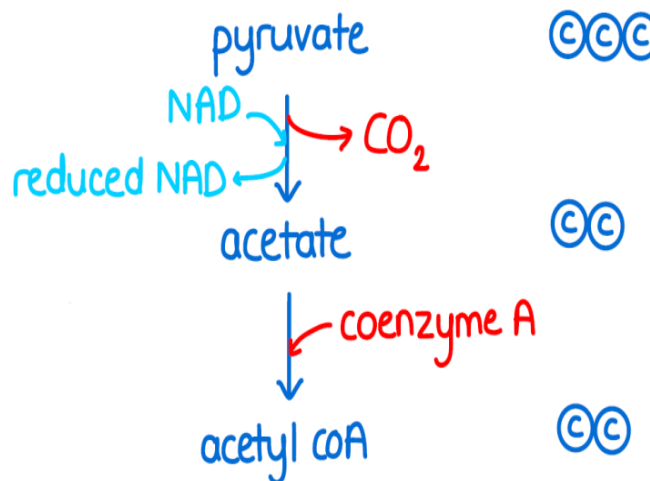
Mitochondrial matrix (inside the mitochondria of eukaryotic cells)

⚠ Occurs only under aerobic conditions (oxygen must be available, although it isn't directly used here).

Step 1: Transport of Pyruvate

Pyruvate, from glycolysis is actively transported from the cytoplasm into the mitochondrial matrix through special carrier proteins in the mitochondrial membrane.

Illustration of link reaction



NAD^+ (Nicotinamide adenine dinucleotide) → comes from the cytoplasm or mitochondria

Coenzyme A (CoA) → a carrier molecule derived from vitamin B₅

Step 2: Decarboxylation (removal of CO_2)

One carbon atom is removed from pyruvate as carbon dioxide (CO_2).

This reduces the molecule from 3 carbons to 2 carbons.

Enzyme involved: Pyruvate dehydrogenase complex

Note

Decarboxylation means removal of a carbon in the form of carbon dioxide.

Step 3: Oxidation of the Remaining 2C Fragment

The 2carbon molecule (now called an acetyl group) is oxidized (loses electrons).

The lost electrons ($2e^-$) and a proton (H^+) are transferred to NAD^+ , forming NADH (reduced NAD^+).

One proton (H^+) is also released into the matrix.

Note:

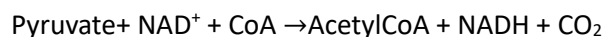
Oxidation means loss of electrons; reduction means gain of electrons.

Step 4: Formation of AcetylCoA

The oxidized 2carbon acetyl group binds to coenzyme A (CoA) to form acetylCoA.

AcetylCoA then enters the Krebs cycle for further energy production.

🚖 Overall Balanced Equation (Per Pyruvate):



Including electrons and protons:



Electrons and protons come from the oxidation of the acetyl group (from pyruvate).

Products (Per Glucose Molecule):

(Since 1 glucose gives 2 pyruvates)

Product	Amount
Acetyl CoA	2
NADH	2
CO_2	2
H^+	2

Summary:

The link reaction converts pyruvate into acetylCoA, releasing CO_2 and producing NADH.

It acts as a bridge between glycolysis and the Krebs cycle, occurring in the mitochondrial matrix, and only in the presence of oxygen.

Note;

The molecular formula of acetylCoA is $C_{23}H_{38}N_7O_{17}P_3S$.

It is a complex molecule formed by attaching a two-carbon acetyl group (CH_3CO-) to coenzyme A through a thioester bond ($-S-COCH_3$).

AcetylCoA plays a key role in cellular respiration by delivering the acetyl group to the Krebs cycle (citric acid cycle) for energy production.

On the other hand, the formula of acetate is $C_2H_3O_2^-$, also written as CH_3COO^- .

Acetate is a much simpler molecule—it is the conjugate base of acetic acid, formed when acetic acid loses a hydrogen ion (H^+).

Acetate can act as a metabolic intermediate and also be converted into acetylCoA under certain cellular conditions.

So, acetylCoA is a large, energy-rich compound involved in metabolism, while acetate is a small ion that can serve as a building block or intermediate.

THE KREBS CYCLE/(Citric Acid Cycle / TCA Cycle)

The Krebs cycle is a cyclic series of chemical reactions used by all aerobic organisms to release energy stored in acetylCoA.

It is also called:

1. Citric Acid Cycle – because citric acid is the first stable compound formed.
2. Tricarboxylic Acid (TCA) Cycle – because citric acid has three carboxyl ($-COOH$) groups.

It was discovered by Sir Hans Krebs in 1937, for which he received a Nobel Prize.

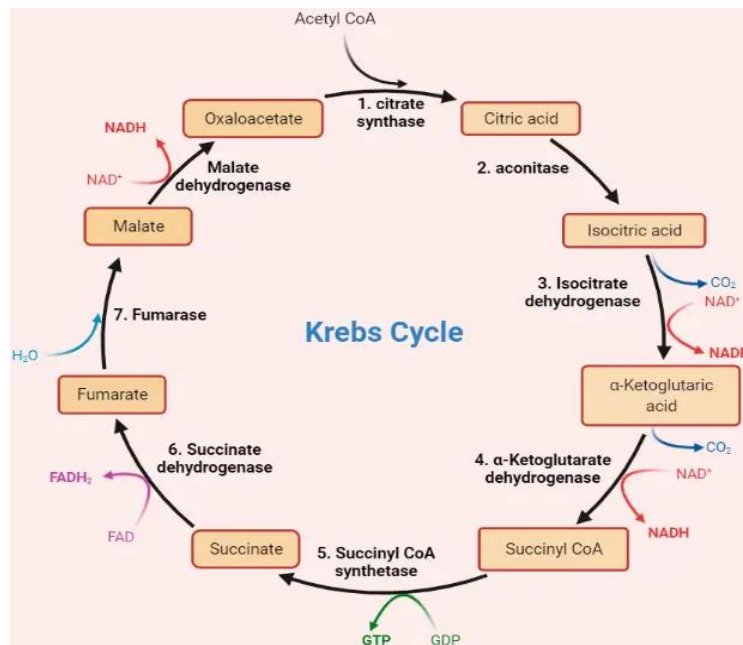
It serves to:

- Break down acetylCoA (derived from carbohydrates, fats, or proteins),
- Produce energy-rich molecules ($NADH$, $FADH_2$, and ATP),
- Release carbon dioxide as a waste product.

Location

The Krebs cycle occurs in the matrix of mitochondria, the central fluid-filled area surrounded by the inner mitochondrial membrane in eukaryotic cells.

Key steps involved in the Krebs Cycle



Step 1: Formation of Citrate (Citric Acid)

AcetylCoA (2C) combines with oxaloacetate/oxaloacetic acid (4C) to form citrate (6C).

Enzyme: Citrate synthase.

Coenzyme A (CoA) is released.

Step 2: Conversion of Citrate to Isocitrate/ Isocitric acid

Citrate is rearranged into isocitrate (6C).

Enzyme: Aconitase.

This involves removing and readding water (a dehydration–rehydration reaction).

Step 3: Oxidation of Isocitrate to αKetoglutarate/2oxoglutarate

Isocitrate is oxidized (loses electrons) and decarboxylated (loses carbon dioxide) to αketoglutarate (5C).

One NAD⁺ is reduced to NADH.

Enzyme: Isocitrate dehydrogenase.

NAD⁺/NADH = Nicotinamide adenine dinucleotide

Step 4: Oxidation of αKetoglutarate to SuccinylCoA

α Ketoglutarate is oxidized to SuccinylCoA (4C)/ Activated succinate]

One more CO_2 is released.

Another NAD^+ is reduced to NADH.

CoA is added.

Enzyme: α Ketoglutarate dehydrogenase complex.

Step 5: Conversion of SuccinylCoA to Succinate

SuccinylCoA is converted into succinate (4C)/ Succinic acid

One ATP (or GTP) is formed by substrate level phosphorylation.

Coenzyme A is released.

Enzyme: SuccinylCoA synthetase.

GTP = Guanosine triphosphate (sometimes made instead of ATP)

Substrate level phosphorylation is the formation of ATP directly from a reaction, not involving the electron transport chain

Step 6: Oxidation of Succinate to Fumarate/Fumaric acid

Succinate is oxidized to fumarate (4C).

FAD is reduced to FADH_2 .

Enzyme: Succinate dehydrogenase (embedded in inner mitochondrial membrane).

FAD/FADH_2 = Flavin adenine dinucleotide

Step 7: Hydration of Fumarate to Malate/Malic acid

Fumarate is hydrated (water is added) to form malate (4C).

Enzyme: Fumarase.

Step 8: Oxidation of Malate to Oxaloacetate

Malate is oxidized to oxaloacetate (4C).

One NAD^+ is reduced to NADH.

Enzyme: Malate dehydrogenase.

Now Oxaloacetate is ready to combine with another acetyl – CoA, and the cycle continues

Summary of Products from 1 Turn of the Cycle (per 1 AcetylCoA):

- 3 NADH
- 1 FADH₂
- 1 ATP (or GTP)
- 2 CO₂

Since 1 glucose produces 2 acetylCoA, the total per glucose is:

- 6 NADH
- 2 FADH₂
- 2 ATP (or GTP)
- 4 CO₂

Where the Products Go:

- ✓ NADH and FADH₂ carry electrons to the electron transport chain, which uses them to make large amounts of ATP.
- ✓ CO₂ is exhaled as a waste product.
- ✓ ATP is used for energy dependent activities like muscle contraction, nerve impulse transmission, and active transport.

Regulation of the Cycle

The cycle is regulated depending on the cell's energy needs:

High levels of ATP or NADH → the cycle slows down (the cell has enough energy).

High levels of ADP or NAD⁺ → the cycle speeds up (cell needs more energy).

Key regulatory enzymes are

- Citrate synthase
- Isocitrate dehydrogenase
- αKetoglutarate dehydrogenase

These are allosterically regulated, meaning other molecules bind to them to increase or decrease activity.

Connections with Other Pathways

The Krebs cycle is the central metabolic pathway in the body:

- Carbohydrates → glucose → glycolysis → acetylCoA → Krebs cycle
- Fats → fatty acids → acetylCoA → Krebs cycle
- Proteins → amino acids → intermediates like αketoglutarate or oxaloacetate

Significance of the Krebs Cycle

The Krebs cycle (in the mitochondrial matrix) is central to aerobic respiration and has the following roles:

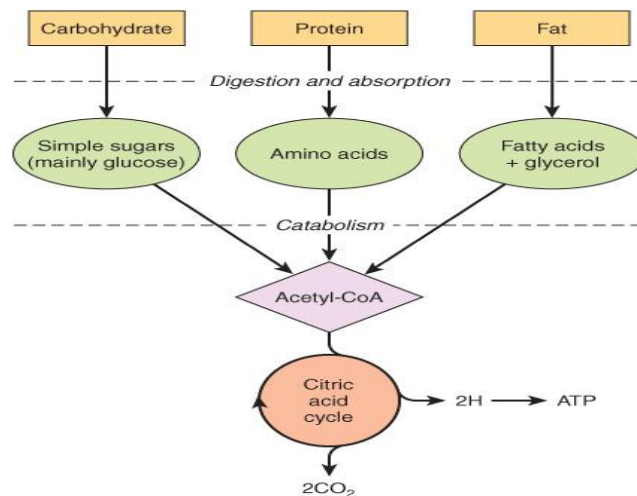
Major Functions:

- ✓ Generates high energy Electron Carriers: Produces: 3 NADH, 1 FADH₂, 1 ATP (or GTP) per cycle (per acetylCoA)
- ✓ Provides Intermediates for Biosynthesis: Cycle intermediates are used to:
 - Make amino acids (e.g., from α ketoglutarate, oxaloacetate)
 - Make heme groups, nucleotides, and fatty acids
- ✓ Carbon Dioxide Release: Releases 2 CO₂ per turn, removing carbon waste from the breakdown of glucose and other nutrients.
- ✓ Integrates with Other Metabolic Pathways: It connects the metabolism of carbohydrates, fats, and proteins.

Role of AcetylCoA in Metabolism of Carbohydrates, Lipids, and Proteins

AcetylCoA is a central metabolic molecule that acts as a common entry point for the Krebs cycle and other biosynthetic pathways.

Illustration



a) In Carbohydrate Metabolism:

Glucose → Glycolysis → Pyruvate → AcetylCoA

AcetylCoA enters the Krebs cycle for aerobic ATP production.

If energy is abundant, acetylCoA can be used to synthesize fatty acids (lipogenesis).

b) In Lipid (Fat) Metabolism:

Fatty acids are broken down via β oxidation in mitochondria to produce multiple molecules of acetylCoA.

These enter the Krebs cycle for energy production.

Excess acetylCoA from fat breakdown may also form ketone bodies (in liver during fasting or diabetes).

c) In Protein Metabolism:

Amino acids are deaminated (removal of amino group), and some are converted into:

- Pyruvate
- AcetylCoA
- Krebs cycle intermediates like α ketoglutarate, succinylCoA, fumarate, or oxaloacetate

This allows amino acids to be used for:

- Energy production
- Glucose synthesis (gluconeogenesis) or fat synthesis

Summary Table

Process	Product Feeding into AcetylCoA	Fate of AcetylCoA
Carbohydrate metabolism	Pyruvate (from glycolysis) $\rightarrow$ AcetylCoA	Enters Krebs cycle for ATP, or converted to fats
Lipid metabolism	Fatty acids $\rightarrow$ AcetylCoA (via β oxidation)	Enters Krebs cycle, or forms ketones
Protein metabolism	Amino acids $\rightarrow$ AcetylCoA or Krebs intermediates	Used for ATP, glucose, or fat synthesis

FATE OF ACETYLCOA, NAD⁺, AND FAD

Fate of AcetylCoA

AcetylCoA (acetyl coenzyme A) is a central molecule in cellular metabolism.

It's the starting point for the Krebs cycle (also called the citric acid cycle or TCA cycle).

It is formed from:

- Pyruvate (from glucose via glycolysis),
- Fatty acids (via beta oxidation),
- And certain amino acids (after deamination).

► In the Krebs Cycle:

Once inside the mitochondrial matrix, acetylCoA (2carbon compound) combines with oxaloacetate (4C) to form citrate (6C). Citrate then undergoes a series of chemical reactions that result in:

- Complete oxidation of the acetyl group,
- The release of two molecules of carbon dioxide (CO_2),
- The transfer of electrons to NAD^+ and FAD, forming NADH and FADH_2 ,
- And the production of one ATP (or GTP) per turn of the cycle.

► Alternative Fates (When Energy Demand Is Low):

If energy demand is low, instead of entering the Krebs cycle, acetylCoA may be:

- Used for fatty acid synthesis (lipogenesis) in the cytoplasm,
- Converted into ketone bodies in the liver (especially during fasting, starvation, or uncontrolled diabetes).

Thus, the fate of acetylCoA depends on the cell's energy needs and nutritional status.

 Fate of NAD^+ (Nicotinamide Adenine Dinucleotide)

NAD^+ is a coenzyme that serves as an electron carrier. It accepts electrons (is reduced) during metabolic reactions and becomes NADH.

► During Metabolism:

In glycolysis, the link reaction, and the Krebs cycle, NAD^+ accepts high energy electrons from fuel molecules, becoming NADH.

► NADH Enters the Electron Transport Chain (ETC):

NADH donates its electrons to Complex I of the electron transport chain, located in the inner mitochondrial membrane.

As electrons pass through the chain, protons (H^+) are pumped into the intermembrane space, creating a proton gradient.

Eventually, electrons combine with oxygen and protons to form water.

The energy from the gradient is used to produce ATP via ATP synthase.

► NAD^+ Is Regenerated:

After NADH donates its electrons, it returns to the oxidized form (NAD^+) and can be reused in the cycle.

 Fate of FAD (Flavin Adenine Dinucleotide)

FAD is another electron carrier similar to NAD^+ , but it has a slightly different structure and function.

► During Metabolism:

In the Krebs cycle, FAD is reduced to FADH_2 during the oxidation of succinate to fumarate.

Unlike NADH, which donates electrons to Complex I, FADH₂ donates its electrons to Complex II of the electron transport chain.

► FADH₂ in the Electron Transport Chain:

FADH₂ contributes electrons that lead to fewer protons being pumped compared to NADH.

As a result, FADH₂ generates slightly less ATP (approximately 1.5 ATP per FADH₂) than NADH (which yields about 2.5 ATP).

► FAD Is Regenerated:

After donating electrons, FADH₂ is oxidized back to FAD, ready to accept electrons again.

Summary:

1. AcetylCoA is oxidized in the Krebs cycle, producing CO₂, NADH, FADH₂, and ATP. It can also be used for fat synthesis or ketone production.
2. NAD⁺ accepts electrons in glycolysis and the Krebs cycle to become NADH, which donates them in the electron transport chain, helping produce ATP. NAD⁺ is then recycled.
3. FAD becomes FADH₂ during the Krebs cycle and donates electrons to the electron transport chain at a later point than NADH, producing a bit less ATP. It is also recycled back to FAD.

THE ELECTRON TRANSPORT CHAIN/ELECTRON TRANSPORT SYSTEM (ETS)

- Is the final stage of aerobic respiration.
- Responsible for generating the majority of ATP used by the cell.
- Process involves the movement of electrons through a series of protein complexes embedded in the inner mitochondrial membrane, resulting in the production of ATP by a process called oxidative phosphorylation.
- ETC takes electrons from NADH and FADH₂, passing them through a chain of proteins (Complexes I–IV), pumps protons to create a gradient, and finally transfers electrons to oxygen to form water. The energy stored in the proton gradient is used by ATP synthase to generate ATP. This process is called oxidative phosphorylation, and it produces the bulk of ATP used by aerobic organisms.

? Location

The ETS occurs in the inner mitochondrial membrane, specifically along the folds known as cristae.

The mitochondrial matrix is the site where the necessary molecules (like NADH and FADH₂) originate.

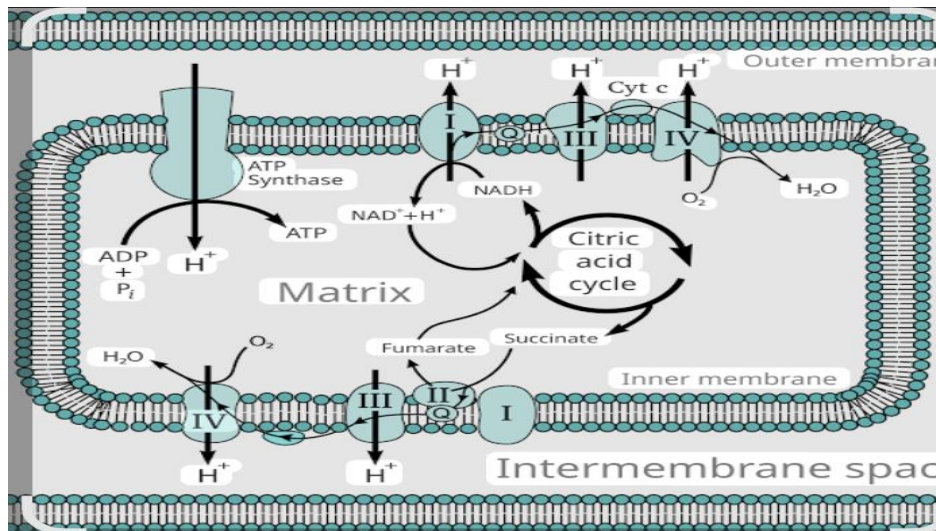
Raw Materials (Inputs)

The system uses:

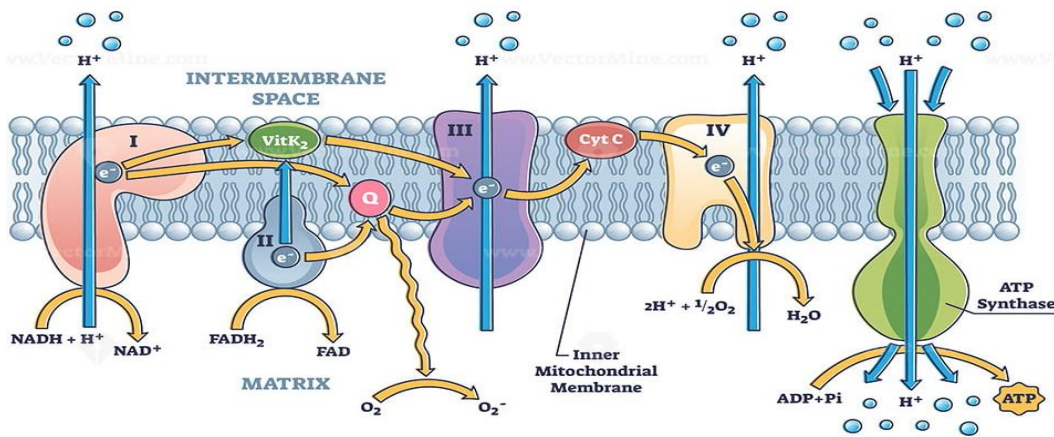
- NADH and FADH₂ (from glycolysis, the link reaction, and the Krebs cycle)
- Oxygen (O₂) — the final electron acceptor
- ADP and inorganic phosphate (Pi) — for ATP formation

StepbyStep Process of the Electron Transport Chain

Illustration;



OR



1. Complex I – NADH Dehydrogenase

NADH donates 2 electrons to Complex I.

As the electrons pass through this complex, 4 protons (H^+) are pumped from the matrix into the intermembrane space.

Electrons are passed to the mobile electron carrier ubiquinone (Coenzyme Q).

NADH becomes NAD^+ , which is recycled to earlier steps of respiration.

2. Complex II – Succinate Dehydrogenase

FADH₂, formed during the Krebs cycle, donates electrons to Complex II.

No protons are pumped by Complex II.

Electrons are passed to ubiquinone just like in Complex I.

FADH₂ becomes FAD, which is also recycled.

> Complex II is also involved in the Krebs cycle, converting succinate to fumarate.

3. Ubiquinone (Coenzyme Q)

A lipid soluble molecule that freely moves within the membrane.

It carries electrons from Complex I and II to Complex III.

4. Complex III – Cytochrome bc₁ Complex

Accepts electrons from ubiquinone.

Passes electrons to another mobile protein called cytochrome c.

4 protons are pumped across the membrane during this step.

5. Cytochrome c

A small, water-soluble protein that shuttles one electron at a time from Complex III to Complex IV.

Found loosely attached to the intermembrane space side of the membrane.

6. Complex IV – Cytochrome c Oxidase

Accepts electrons from cytochrome c and transfers them to oxygen (O₂), the final electron acceptor.

Oxygen combines with electrons and protons to form water (H₂O).

2 protons are pumped across the membrane here.

Without oxygen, this final step cannot occur, causing the chain to stop and energy production to fail.

⚙️ ATP Formation – Oxidative Phosphorylation

As electrons move through the complexes, protons accumulate in the intermembrane space, creating a strong proton gradient and electrical potential (positive outside, negative inside). This is known as the proton motive force.

Protons then flow back into the matrix through an enzyme complex called:

▶️ ATP Synthase

Acts like a molecular turbine.

As protons flow through it, it spins and catalyzes the conversion of ADP + Pi into ATP.

This process of ATP generation using a proton gradient is called chemiosmosis.

Final Products of the ETS

- Water (H_2O) – formed by the reduction of oxygen
- ATP – about 34 ATP molecules per glucose molecule (though actual yield varies)
- NAD^+ and FAD – regenerated for use in glycolysis and the Krebs cycle

Additional Key Points

- ✓ NADH produces more ATP than $FADH_2$ because it starts at Complex I and causes more proton pumping:
Each NADH $\rightarrow$ ~2.5 ATP
Each $FADH_2$ $\rightarrow$ ~1.5 ATP
- ✓ Oxygen is essential. Without it, the entire chain backs up, halting ATP production and leading to cellular death (such as in suffocation or cyanide poisoning).
- ✓ The electron transport chain is tightly regulated and only functions efficiently in the presence of oxygen and sufficient ADP.

MNEMONIC TO REMEMBER THE ORDER AND COMPONENTS

✓ Mnemonic: “Nice Smart Queen Can Cook Our Apple Pie”

Element/Cue	Meaning
Nice	NADH (starts at Complex I)
Smart	Succinate/ $FADH_2$ (starts at Complex II)
Queen	Ubiquinone (Q) (mobile carrier)
Can	Cytochrome c (second mobile carrier)
Cook	Complex I ($NADH \rightarrow Q$)
Our	Complex II ($FADH_2 \rightarrow Q$)
Apple	Complex III ($Q \rightarrow$ cytochrome c)
Pie	Complex IV (cytochrome c $\rightarrow O_2$)

NOTE:

1. Oxidative phosphorylation is a metabolic pathway, occurring in the inner mitochondrial membrane in which cells use enzymes to oxidize nutrients, releasing energy used to form ATP from ADP and inorganic phosphate (P_i). This energy comes from the transfer of electrons from NADH and $FADH_2$ to oxygen (O_2) via the electron transport chain (ETC).

Key Components of Oxidative Phosphorylation:

➤ **a) Electron Transport Chain (ETC) – 4 Main Complexes:**

Complex	Name	Function
I	NADH dehydrogenase	Accepts electrons from NADH and pumps protons
II	Succinate dehydrogenase	Accepts electrons from FADH ₂ (no proton pumping)
III	Cytochrome bc ₁ complex	Transfers electrons and pumps protons
IV	Cytochrome c oxidase	Transfers electrons to oxygen (forms water), pumps protons

Coenzyme Q (Ubiquinone): Mobile carrier between Complex I/II and III.

Cytochrome c: Mobile carrier between Complex III and IV.

➤ **b) Formation of Proton Gradient:**

As electrons move down the chain, energy is used to pump protons (H⁺) from the mitochondrial matrix to the intermembrane space.

This creates a proton motive force (PMF) — an electrochemical gradient.

➤ **c) ATP Synthesis (Chemiosmosis):**

Protons flow back into the matrix via ATP synthase (Complex V).

This process of proton flow drives the conversion of:



✓ **Overall Summary Equation:**



EFFECTS OF CYANIDE ON THE ELECTRON TRANSPORT SYSTEM (ETS)

A highly toxic chemical compound found in certain industrial processes, poisons, and some plants.

Common forms: Hydrogen cyanide (HCN), potassium cyanide (KCN).

Mechanism of Action:

Cyanide binds to the iron (Fe³⁺) center of cytochrome c oxidase (Complex IV).

This prevents electron transfer to molecular oxygen (O₂), the final electron acceptor in the ETC.

Consequences of Cyanide Inhibition:

Effect	Explanation
✗ ETC stops	Electrons can no longer flow beyond Complex IV.
✗ Proton gradient collapses	No pumping of protons → No ATP production.
✗ Oxidative phosphorylation halts	ATP synthase cannot function.
✓ Anaerobic respiration increases	Cells rely on glycolysis for ATP → produces lactic acid.
⚠ Cellular hypoxia	Tissues lack usable oxygen even when it is present.
Severe organ damage	Brain and heart are most affected due to high ATP demand.
💀 Rapid death	Without energy, essential cellular functions fail.

COMMON LOCAL SOURCES OF CYANIDE:

1. Plants (Cyanogenic Plants)

These plants produce cyanogenic glycosides, which release hydrogen cyanide (HCN) when the plant is chewed, crushed, or digested e.g.

Cassava (*Manihot esculenta*) especially the bitter varieties.

- The roots and leaves contain linamarin and lotaustralin, which release cyanide during improper processing or proper soaking, drying, or cooking can lead to cyanide poisoning.

Sorghum (especially young plants)

- Contains cyanogenic compounds in early growth stages.
- When drought stressed or poorly managed, cyanide levels rise.

Lima Beans

- Contain cyanogenic compounds if not well cooked.

Bamboo shoots

- Young shoots have cyanide and must be properly boiled.

Stone fruits (less common locally)

- Seeds/pits of apricots, peaches, plums, and cherries contain amygdalin, a cyanogenic compound.

2. Household and Industrial Sources

Not common in rural households but possible in urban or school labs

Pesticides and Rodenticides

- Some contain cyanide or cyanide releasing compounds (e.g., sodium cyanide, potassium cyanide).

Fumigants

- Cyanide based fumigants may be used in stored grain pest control (rare and regulated).

Mining and Metal Processing

- In gold mining, cyanide solutions are used to extract gold from ore.
- Spillage or improper handling can expose communities.

Important Notes on Cyanide Poisoning:

Symptoms:

- | | |
|------------------------|------------------------|
| • Headache, | • Convulsions, and |
| • Dizziness, | • Death in severe case |
| • Shortness of breath, | |

Prevention (especially for cassava):

- | | |
|--|-----------------------|
| • Peel thoroughly. | • Ferment or sundry. |
| • Soak in water for several hours or days. | • Boil before eating. |

Medical Note:

Antidotes like hydroxocobalamin can bind cyanide and form cyanocobalamin (vitamin B₁₂), reducing its toxicity.

ATP PRODUCTION DURING VARIOUS VIGOROUS EXERCISE INTENSITIES

We shall consider 3 situations ie

1. Very high intensity, short duration (e.g. sprinting for 0–10 seconds)
2. High intensity, medium duration (10 seconds – 2 minutes)
3. Moderate intensity, long duration (over 2 minutes, like distance running)

1. VERY HIGH INTENSITY, SHORT DURATION (E.G. SPRINTING FOR 0–10 SECONDS)

System Used: ATP–PC (Phosphagen) System

How ATP is Produced:

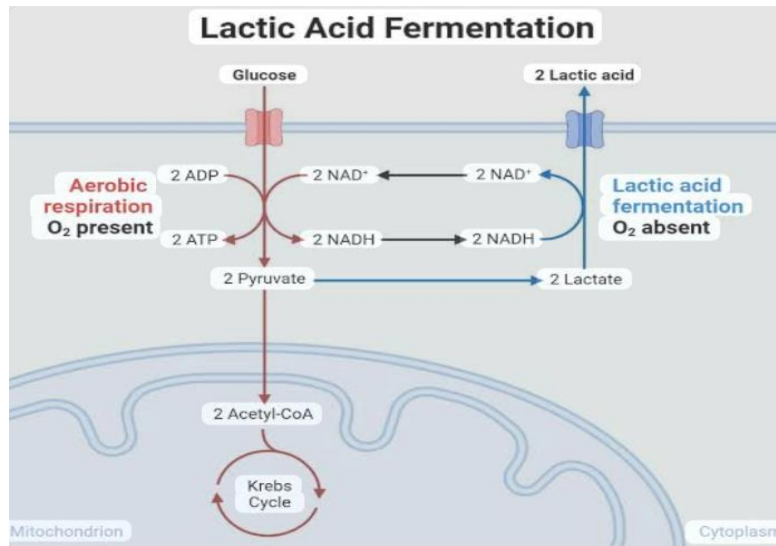
Muscles use stored ATP immediately. As it depletes, phosphocreatine (PCr) donates a phosphate to ADP to regenerate ATP very rapidly.

Oxygen Required: No

ATP Yield: Small but immediate (enough for a few seconds of effort)

2. HIGH INTENSITY, MEDIUM DURATION (10 SECONDS – 2 MINUTES)

System Used: Anaerobic Glycolysis (Lactic Acid System)



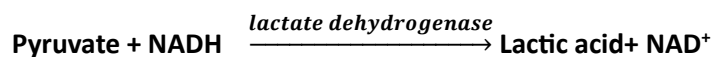
Normally, in the presence of oxygen, pyruvate enters the mitochondria and is used in aerobic respiration.

But when oxygen is not available, the electron transport chain (ETC) stops, and NADH cannot be oxidized to NAD⁺.

The cell must regenerate NAD⁺ to keep glycolysis going (since glycolysis depends on NAD⁺).

To do this, pyruvate is reduced to lactic acid (C₃H₆O₃) by lactate dehydrogenase enzyme.

This uses NADH and releases NAD⁺. This process is called **Fermentation**



Signs of Lactic Acid Build-Up in the Body (Not required)

When lactic acid accumulates in the muscles and bloodstream (especially during intense exercise or oxygen-deficient conditions), it can lead to a condition known as lactic acidosis or temporary muscle fatigue. Here are the common signs and symptoms:

- ✓ Muscle Fatigue
- ✓ Muscle Pain or Cramping
- ✓ Rapid Breathing (Hyperventilation), body tries to compensate for acidosis by blowing off CO₂
- ✓ Nausea and Vomiting, in cases of severe lactic acidosis (not common in regular exercise)

- ✓ Sweating and Dizziness, due to stress response and acid imbalance
- ✓ Low Blood pH (Acidosis), detected through blood tests (usually seen in medical settings)
- ✓ Decreased Exercise Performance
- ✓ Severe Cases of Lactic Acidosis (medical emergency) may lead to confusion or drowsiness, rapid heartbeat, low blood pressure, cold or bluish skin

 Important Note:

During normal exercise, lactic acid build-up is temporary and clears when oxygen becomes available again.

Serious lactic acidosis usually happens due to underlying conditions like diabetes, kidney failure, liver disease, or certain medications.

Fate of lactic acid(Not required)

1. Transport to the Liver (Cori Cycle)

Lactic acid is converted to lactate, which diffuses from the muscles into the bloodstream, then transported to the liver.

In the liver, lactate is converted back into glucose through a process called gluconeogenesis.

This newly formed glucose can then be sent back to the muscles for energy, or be stored as glycogen. This whole process is known as the **Cori cycle**.

2. Oxidation in Muscle Cells

When oxygen becomes available again (e.g., after exercise), lactic acid is converted back to pyruvate.

Pyruvate enters the Krebs cycle (in mitochondria) for full aerobic respiration to produce more ATP.

3. Buffering and Neutralization

Excess lactic acid lowers the pH of muscles and blood (increases acidity).

The body has buffer systems (like bicarbonate) that neutralize the acid to maintain a stable pH.

4. Elimination (in small amounts)

A small portion of lactic acid may be excreted in urine or sweat.

3. MODERATE INTENSITY, LONG DURATION (OVER 2 MINUTES, LIKE DISTANCE RUNNING)

System Used: Aerobic Respiration

How ATP is Produced:

In the presence of oxygen, glucose (and sometimes fatty acids) is fully broken down in the mitochondria via glycolysis, the Krebs cycle, and oxidative phosphorylation.

This releases large amounts of energy used to generate up to 36–38 ATP per glucose.

Oxygen Required: Yes

ATP Yield: High, but slower to supply

Sample AOI 1

In Magale TC, many people—including farmers, boda-boda riders, bricklayers, and students—regularly complain of persistent tiredness, low energy, and poor performance during physical work and daily activities. The local health center has noted that most residents rely heavily on starchy foods such as cassava, maize, and rice, but consume very little protein, fruits, or vegetables. Many youths use sugary drinks and snacks to boost energy, but still become fatigued quickly and recover slowly. This has caused reduced productivity, frequent absenteeism from school and work, and poor participation in sports. Health workers believe that inefficient energy production in the body, due to poor diet and lack of understanding about how energy is produced from food, is a major cause.

Concerned about the situation, community leaders have organized a radio talk show on Elgon Fm about the issues affecting the community and you are one of the keynote speakers invited.

Task

Prepare a speech that you will present.

Model Student Response

To help solve the problem of persistent fatigue and low energy in our community, I would like to explain how the human body produces energy from the food we eat and suggest practical ways to improve this process through diet and lifestyle.

The body gets energy by breaking down glucose, which mainly comes from starchy foods like cassava, maize, and rice. This glucose is broken down during a process called cellular respiration to produce ATP (adenosine triphosphate)—the energy currency used by our muscles and body organs. However, for this process to be efficient, the body needs not only glucose but also enzymes and coenzymes, which are made from nutrients found in a balanced diet.

Many people in our community eat only carbohydrates without enough proteins, which are needed to build enzymes that control the steps of respiration such as glycolysis, the Krebs cycle, and the electron transport chain. Without these enzymes, glucose cannot be properly converted into energy, and this results in tiredness and weakness even after eating.

Additionally, the body needs coenzymes such as NAD⁺ and FAD, which are involved in carrying electrons during respiration. These coenzymes are formed from B-vitamins like B2 (riboflavin) and B3 (niacin), which are found in foods like bananas, groundnuts, leafy vegetables, eggs, and fish. Unfortunately, these are missing in the diets of many people in the community, which reduces the body's ability to produce ATP.

When oxygen is available, aerobic respiration occurs, and each glucose molecule produces up to 38 ATP. But when oxygen is limited—for example, during intense work or due to poor breathing—anaerobic

respiration takes over, producing only 2 ATP per glucose and causing lactic acid to build up. This leads to muscle fatigue and pain.

To solve this problem, I recommend that people in the community:

- Eat more balanced meals that include affordable protein sources like beans, groundnuts, and silverfish.
- Add fruits and vegetables to their daily diet to provide the vitamins needed for coenzyme formation.
- Drink plenty of clean water and reduce consumption of sugary drinks, which give short bursts of energy but no lasting benefit.
- Engage in light regular exercise and work in well-ventilated areas to increase oxygen intake, which supports aerobic respiration.

If we apply these practices, our bodies will produce more ATP, we will have more energy for work and school, recover faster after physical activity, and reduce the fatigue that affects our daily life.

Sample Scoring Scheme (Out of 10)

Criteria	Scores	Description
Clear explanation of ATP production	2	Explains that ATP is produced from glucose through cellular respiration.
Mention of enzymes and proteins	2	Recognizes the need for enzymes (made from proteins) in the respiration process.
Role of coenzymes and vitamins	2	Explains the role of coenzymes like NAD ⁺ and FAD, and their vitamin origins (B2, B3).
Difference between aerobic and anaerobic respiration	1	Explains aerobic respiration yields more ATP; anaerobic yields less and produces lactic acid.
Identification of poor diet effects	1	Connects poor diet (lack of protein, vitamins) to inefficient energy production and fatigue.
Practical, relevant recommendations	2	Suggests realistic diet improvements, lifestyle changes, and community actions.
Total scores:10		

Sample AOI 2

In a community near your school, several people working in industrial sites and agricultural farms have reported symptoms such as headache, dizziness, difficulty breathing, and sudden collapse. Some residents near cassava-processing centers also complain of similar symptoms after eating poorly processed cassava. Health workers suspect cyanide poisoning due to exposure to industrial waste and consumption of improperly prepared cassava. The community leaders are concerned and, in a sensitization, campaign have invited your school to participate.

Task

Write an article that your school will use.

Model Student Response

Cyanide is a poisonous chemical that affects the body by stopping cells from producing energy. Normally, the body's cells use oxygen to convert glucose into energy (ATP) through a process called aerobic respiration. This process depends on an enzyme called cytochrome c oxidase in the mitochondria, which helps transfer electrons to oxygen in the electron transport chain.

Cyanide works by binding to cytochrome c oxidase and blocking this enzyme, which prevents the cells from using oxygen to produce ATP. Without ATP, cells cannot perform vital functions and begin to die, especially in organs that need a lot of energy like the brain and heart. This leads to symptoms such as headache, dizziness, confusion, difficulty breathing, rapid heartbeat, and in severe cases, loss of consciousness and death.

Common sources of cyanide exposure in this community include:

- Industrial waste from chemical factories and mining.
- Consumption of improperly processed cassava, which contains cyanogenic glycosides that release cyanide when eaten raw or poorly prepared.
- Smoke inhalation from fires involving certain plastics or synthetic materials

To prevent cyanide poisoning, the community should:

- Avoid eating raw or improperly processed cassava by soaking and thoroughly cooking it to remove cyanide compounds.
- Wear protective gear when working in industries where cyanide exposure is possible.
- Ensure proper disposal of industrial waste to prevent environmental contamination.
- Educate people about the dangers of cyanide and early symptoms to seek immediate medical help.

If poisoning occurs, immediate treatment includes removing the person from the source, providing oxygen to improve breathing, and administering antidotes like amyl nitrite or hydroxocobalamin at health facilities.

By understanding how cyanide affects the body and taking these preventive and management steps, the community can reduce the risks of poisoning and protect their health.

Sample Scoring Scheme (Out of 10)

Criteria	Scores	Description
1. Explanation of cyanide's effect on respiration	3	Describes cyanide binding to cytochrome c oxidase and blocking electron transport/ATP production
2. Identification of common cyanide sources	2	Lists at least two sources such as industrial waste and improperly processed cassava
3. Description of symptoms	2	Mentions symptoms like headache, dizziness, breathing difficulty, confusion, collapse
4. Practical prevention measures	2	Suggests measures such as proper cassava processing, protective gear, and safe waste disposal
5. Mention of management/treatment	1	Describes immediate actions like removing exposure, oxygen, antidotes

THE END

To God Be the Glory

For such wonderful master pieces, feel free to;

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“FOCUS BIOLOGY DECODING BIOLOGY MYSTERIES. UNLOOKING BIOLOGY CONUNDRUMS”