

C1.2 Cell Respiration

IB Biology / A Level Exam Preparation Notes

ATP & energy transfer

Anaerobic vs aerobic

Glycolysis

HL: NAD, Krebs, ETC,
chemiosmosis

Guiding questions

- What are the roles of hydrogen and oxygen in the release of energy in cells?
- How is energy distributed and used inside cells?

How to use these notes

1. Learn the **bold key terms** and equations first.
2. Use the tables to compare pathways, locations and products.
3. For HL or A level, prioritise NAD, glycolysis detail, link reaction, Krebs cycle, electron transport chain and chemiosmosis.
4. Practise the data-handling and explanation questions at the end.

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1. One-page overview and essential equations

Big idea

Cells release energy from carbon compounds by controlled oxidation, then store usable energy in ATP. In aerobic respiration, hydrogen carriers transfer high-energy electrons to the electron transport chain, and oxygen acts as the terminal electron acceptor to form water.

Cell respiration in one flow

Organic substrate
(glucose, fatty acids, etc.)

-> Controlled oxidation
by enzyme pathways

-> Hydrogen/electrons transferred
via carriers

-> ATP produced
for cellular work

Essential equations

Process	Word / symbol equation	What it means
Aerobic respiration	Glucose + oxygen -> carbon dioxide + water + ATP $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$	Complete oxidation of glucose. Oxygen is reduced to water. High ATP yield.
Anaerobic respiration in humans	Glucose -> lactate + ATP	Occurs in cytoplasm when oxygen supply is inadequate. Low ATP yield; lactate can be converted later when oxygen is available.
Anaerobic respiration in yeast	Glucose -> ethanol + carbon dioxide + ATP	Alcoholic fermentation. Useful in baking and brewing.
ATP hydrolysis	ATP + H ₂ O -> ADP + Pi + energy	Exergonic reaction that releases usable energy for cellular work.
ATP synthesis	ADP + Pi + energy -> ATP + H ₂ O	Endergonic reaction requiring energy from respiration.

Core sequence of aerobic respiration

Stage	Location	Key event	Main useful products per glucose
Glycolysis	Cytoplasm	Glucose is phosphorylated, split and oxidized to two pyruvate molecules.	Net 2 ATP + 2 NADH
Link reaction	Mitochondrial matrix	Each pyruvate is decarboxylated and oxidized, forming acetyl-CoA.	2 CO ₂ + 2 NADH
Krebs cycle	Mitochondrial matrix	Acetyl groups are oxidized; citrate forms and oxaloacetate is regenerated.	2 ATP + 6 NADH + 2 FADH ₂ + 4 CO ₂
Electron transport + chemiosmosis	Inner mitochondrial membrane / cristae	Electrons move down carriers; protons are pumped; ATP synthase uses proton flow.	Most ATP, usually about 30-34 ATP

Key vocabulary snapshot

Term	Exam meaning
Oxidation	Loss of electrons or hydrogen; in respiration often dehydrogenation of a carbon compound.
Reduction	Gain of electrons or hydrogen; NAD is reduced when it accepts hydrogen/electrons.
Redox reaction	A coupled oxidation and reduction reaction. Oxidation and reduction always occur together.
ATP	Adenosine triphosphate, a nucleotide that distributes energy inside cells.
Pyruvate	Three-carbon product of glycolysis; can enter mitochondria or be converted during fermentation.
Acetyl-CoA	Two-carbon acetyl group carried by coenzyme A into the Krebs cycle.
Chemiosmosis	ATP synthesis powered by diffusion of protons through ATP synthase down a proton gradient.

2. ATP structure, function and the ATP-ADP cycle

C1.2.1 - ATP as the molecule that distributes energy within cells

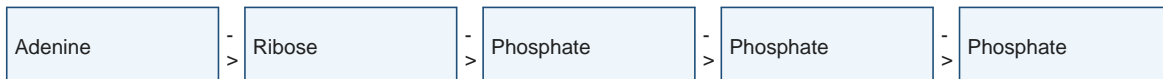
Required statement

ATP stands for adenosine triphosphate. It is a nucleotide made of adenine, ribose and three phosphate groups.

Feature of ATP	Why it makes ATP a good energy currency
Small and soluble	Can move rapidly around the cell to where energy is needed.
Immediate energy source	Hydrolysis of the terminal phosphate bond releases energy quickly.
Recyclable	ADP and inorganic phosphate can be rejoined to form ATP again.
Couples reactions	Energy from ATP hydrolysis can drive endergonic processes such as active transport and biosynthesis.
Not long-term storage	Cells use ATP as a short-term energy carrier; long-term energy is stored in molecules such as glycogen and lipids.

ATP structure and phosphate bonds

ATP has adenine bonded to ribose, with three phosphate groups attached. Removal of the final phosphate group converts ATP into ADP; removal of two phosphate groups gives AMP. The terminal phosphate bonds are relatively unstable because negatively charged phosphate groups repel each other. Hydrolysis has a low activation energy and releases enough energy for many cellular tasks.



Simplified ATP structure: adenine + ribose + three phosphate groups. The terminal phosphate bond is hydrolysed during energy release.

C1.2.2 - Cell processes that require ATP

- Active transport across membranes, such as pumping ions against concentration gradients.
- Anabolism: synthesis of macromolecules such as proteins, nucleic acids and polysaccharides.
- Movement of whole cells using cilia or flagella.
- Movement within cells, for example chromosome movement in mitosis and meiosis.
- Maintenance of homeostasis through energy-demanding cell processes.

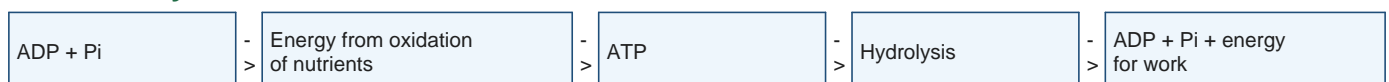
C1.2.3 - Energy transfer in the ATP-ADP cycle

Reaction	Energy change	Biological significance
$\text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{P}_i + \text{energy}$	Exergonic: releases energy	Supplies energy to cell processes.
$\text{ADP} + \text{P}_i + \text{energy} \rightarrow \text{ATP} + \text{H}_2\text{O}$	Endergonic: requires energy	Stores energy from oxidation of nutrients in ATP.

Exam phrase to learn

ATP hydrolysis releases energy; ATP synthesis requires energy. The ATP cycle is continuously turning because most cells do not store large amounts of ATP.

The ATP cycle as a flow



3. Cell respiration overview: aerobic, anaerobic and gas exchange

C1.2.4 - Cell respiration as a system for producing ATP

Cell respiration is the enzyme-controlled metabolic process that releases energy from carbon compounds and uses that energy to synthesize ATP. Glucose and fatty acids are major respiratory substrates, but carbohydrates, proteins and many other organic compounds can also enter respiration pathways.

Cell respiration is not gas exchange

- **Cell respiration:** metabolic reactions inside cells that produce ATP.
 - **Gas exchange:** exchange of oxygen and carbon dioxide between an organism and its environment.
- Do not write that breathing is respiration in an exam unless the question is specifically about ventilation/gas exchange.

C1.2.5 - Anaerobic versus aerobic respiration in humans

Feature	Anaerobic respiration in humans	Aerobic respiration
Oxygen required?	No. Occurs when oxygen supply is inadequate.	Yes. Oxygen is the terminal electron acceptor.
Where it occurs	Cytoplasm only.	Starts in cytoplasm; continues in mitochondria.
Main substrate in this course	Glucose/carbohydrate.	Glucose and fatty acids; other carbon compounds can also enter.
First stage	Glycolysis: glucose → pyruvate.	Glycolysis: glucose → pyruvate.
Fate of pyruvate	Converted to lactate in humans.	Transported into mitochondria, converted to acetyl-CoA, enters Krebs cycle.
ATP yield	Low: net 2 ATP per glucose.	High: many ATP; most from oxidative phosphorylation.
Final products	Lactate + ATP.	Carbon dioxide + water + ATP.
Mitochondria required?	No.	Yes for stages after glycolysis.

Why controlled oxidation matters

A glucose molecule contains energy in covalent bonds. Cells do not release this energy in one uncontrolled step. Instead, enzymes catalyse a series of reactions, breaking and rearranging bonds step by step. This prevents damage and allows much of the released energy to be transferred into ATP or reduced coenzymes such as NADH.

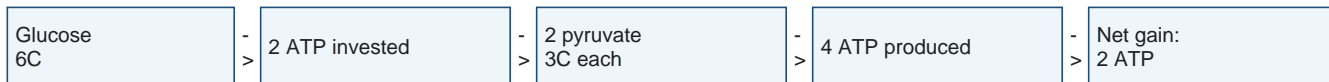
Hydrogen and oxygen in respiration

Molecule / ion	Role
Hydrogen	Hydrogen atoms are removed from substrates during oxidation. Their electrons carry energy to the electron transport chain via reduced carriers such as NADH.
Protons (H ⁺)	Protons are pumped across the inner mitochondrial membrane to create a proton gradient used by ATP synthase.
Oxygen	Oxygen accepts electrons at the end of the electron transport chain and combines with protons to form metabolic water.

4. Glycolysis, fermentation and aerobic respiration overview

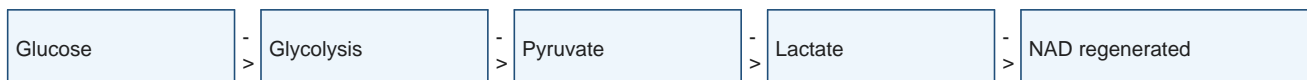
Glycolysis - the shared first stage

Glycolysis occurs in the cytoplasm and does not require oxygen. It converts one six-carbon glucose molecule into two three-carbon pyruvate molecules. Two ATP are used to start the pathway and four ATP are produced later, giving a net gain of two ATP per glucose.



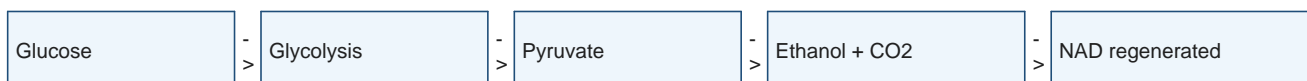
Lactic acid fermentation in humans

When oxygen is unavailable or insufficient, pyruvate does not enter the mitochondria. In human muscle cells, pyruvate is converted to lactate. This regenerates NAD so glycolysis can continue producing a small amount of ATP. The reaction is useful for short bursts of intense activity but cannot be sustained indefinitely.



Alcoholic fermentation in yeast

Yeast cells use glycolysis to generate a net gain of two ATP, then convert pyruvate to ethanol and carbon dioxide under anaerobic conditions. Carbon dioxide makes bread dough rise; ethanol is the alcohol in beer, wine and spirits.



Aerobic respiration overview

Aerobic respiration begins with glycolysis in the cytoplasm. If oxygen is available, pyruvate enters the mitochondrion. The link reaction and Krebs cycle occur in the matrix; the electron transport chain and chemiosmosis occur on the inner mitochondrial membrane and cristae.

Stage	ATP yield highlighted in the supplied section	Comment
Glycolysis	Net 2 ATP	Occurs whether or not oxygen is present.
Krebs cycle	2 ATP per glucose	Also generates reduced NAD and FAD for the electron transport chain.
Electron transport chain / chemiosmosis	About 30-34 ATP	Produces most ATP in aerobic respiration.

Exam caution

Some courses use slightly different total ATP values because estimates depend on shuttle systems and experimental assumptions. For this syllabus section, use the values given by your teacher/exam board when asked for numbers.

5. Variables affecting respiration rate and respirometer skills

C1.2.6 - Variables affecting rate of cell respiration

Factor	Effect on respiration rate	Exam explanation
Temperature	Optimum around 20-30 degrees C in the supplied section; too high or too low decreases rate.	Enzyme-controlled reactions slow at low temperatures; high temperatures can denature enzymes.
Carbon dioxide concentration	Higher CO ₂ can reduce respiration rate.	Accumulation of waste product can affect metabolic reactions and gas gradients.
Oxygen concentration	Lower O ₂ lowers aerobic respiration rate; absence of O ₂ leads to anaerobic respiration.	Oxygen is needed as terminal electron acceptor in aerobic respiration.
Glucose concentration	Low glucose decreases rate.	Less respiratory substrate is available for glycolysis.
Type of cell	Energy-demanding cells respire faster.	Cells such as muscle cells have high ATP demand and many mitochondria.

Respirometer principle

A respirometer estimates respiration rate by measuring oxygen uptake. In many setups, carbon dioxide produced by respiration is absorbed by an alkali such as soda lime or potassium hydroxide. This means the change in gas volume or pressure mainly reflects oxygen consumption.

Data-skill formula

Rate of oxygen consumption = change in oxygen volume / change in time
Units must match the graph or table, for example ml min⁻¹ or cm³ min⁻¹.

How to answer respiration-rate graph questions

- Identify which line has the steepest gradient; this shows the fastest oxygen uptake and therefore the highest aerobic respiration rate.
- Use evidence: mention oxygen consumption if asked whether aerobic respiration is occurring.
- Compare temperature treatments carefully: higher temperature often increases enzyme activity up to an optimum.
- For dormant or non-germinating seeds, expect a much lower metabolic rate and therefore much lower oxygen uptake.
- When predicting a new line, justify its position relative to existing lines.

Worked example template

Question type	Model answer pattern
What type of respiration is occurring?	Aerobic, because oxygen is being consumed.
Why is a treatment lower?	Lower metabolic activity, fewer enzyme reactions, lower ATP demand, or less substrate/oxygen available.
Why is rate higher at 22 degrees C than 12 degrees C?	Higher temperature increases kinetic energy and enzyme-substrate collision frequency until the optimum is reached.
Predict a line	Draw or describe a line with a justified gradient and final value.

Ethics note

Practical work involving animals requires ethical review, risk assessment and attention to welfare. Use non-animal models such as seeds or yeast whenever possible.

6. HL extension: NAD, glycolysis detail, link reaction and Krebs cycle

C1.2.7 - NAD as a hydrogen carrier

Nicotinamide adenine dinucleotide (NAD) is a coenzyme used in respiration. NAD accepts hydrogen/electrons during oxidation of substrates and becomes reduced NAD (NADH). Later, NADH donates high-energy electrons to the electron transport chain and is converted back to NAD.

Oxidation	Reduction
Loss of electrons	Gain of electrons
Loss of hydrogen	Gain of hydrogen
Gain of oxygen	Loss of oxygen
More C-O bonds; lower potential energy	More C-H bonds; higher potential energy
Example: glucose is oxidized as hydrogen is removed	Example: NAD is reduced to NADH when it accepts hydrogen/electrons

Memory aid

OIL RIG: Oxidation Is Loss; Reduction Is Gain. In respiration, focus especially on loss or gain of electrons and hydrogen.

C1.2.8 - Glycolysis in more detail

Stage	What happens	Why it matters
1. Phosphorylation	Two ATP molecules donate phosphate groups to glucose, forming a less stable phosphorylated hexose.	Makes the molecule more reactive and prepares it for splitting.
2. Lysis	The six-carbon phosphorylated sugar splits into two three-carbon triose phosphate molecules.	Creates two molecules that can each be oxidized and converted to pyruvate.
3. Oxidation and ATP formation	Each triose phosphate is oxidized; NAD is reduced to NADH. Inorganic phosphate is added, then phosphate groups are transferred to ADP.	Produces four ATP, two NADH and two pyruvate. Net ATP gain is two because two ATP were used at the start.

Glucose	-	2 ATP used phosphorylation	-	2 triose phosphate lysis	-	2 NADH made oxidation	-	2 pyruvate + net 2 ATP
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C1.2.9 - Fate of pyruvate in anaerobic conditions

Without oxygen, reduced NAD must be oxidized back to NAD so that glycolysis can continue. In humans, NADH donates hydrogen/electrons to pyruvate, reducing it to lactate. The cell gains only the net two ATP from glycolysis, but this can sustain ATP supply briefly.

Condition	Fate of pyruvate	Purpose
Oxygen present	Pyruvate enters mitochondria and is converted to acetyl-CoA.	Allows aerobic respiration and high ATP yield.
Oxygen absent in humans	Pyruvate is reduced to lactate in the cytoplasm.	Regenerates NAD so glycolysis can continue.
Oxygen absent in yeast	Pyruvate is converted to ethanol and CO ₂ .	Regenerates NAD; produces products used in brewing and baking.

C1.2.11 - The link reaction

If oxygen is present, pyruvate is transported into the mitochondrial matrix. In the link reaction, pyruvate is decarboxylated to remove CO₂, oxidized to reduce NAD to NADH, and joined to coenzyme A to form acetyl-CoA.

For each pyruvate	For each glucose
1 CO ₂ released	2 CO ₂ released
1 NADH produced	2 NADH produced
1 acetyl-CoA formed	2 acetyl-CoA formed

Pyruvate 3C	-	CO ₂ removed	-	NAD → NADH	-	CoA added	-	Acetyl-CoA 2C
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C1.2.12 - Krebs cycle

The Krebs cycle occurs in the mitochondrial matrix. Acetyl-CoA transfers a two-carbon acetyl group to four-carbon oxaloacetate, forming six-carbon citrate. Through enzyme-controlled reactions, citrate is decarboxylated and oxidized, and oxaloacetate is regenerated so the cycle can continue.

Required name / idea	What to remember
Citrate (6C)	Formed when acetyl group (2C) combines with oxaloacetate (4C).
Oxaloacetate (4C)	Regenerated at the end of the cycle, allowing another acetyl group to enter.
Decarboxylation	Two CO ₂ molecules are released per acetyl group in the Krebs cycle.
Oxidation / dehydrogenation	Hydrogen/electrons are removed, reducing NAD and FAD.
ATP	One ATP per cycle, so two ATP per glucose.

Krebs products per glucose

Product	Amount per glucose	Why
ATP	2	Cycle runs twice per glucose because glycolysis produces two pyruvate.
Reduced NAD (NADH)	6	Three NADH per turn x two turns.
Reduced FAD (FADH ₂)	2	One FADH ₂ per turn x two turns.
CO ₂	4	Two CO ₂ per turn x two turns; combined with link reaction CO ₂ accounts for all six glucose carbons.

7. HL extension: electron transport chain, chemiosmosis, oxygen and substrates

C1.2.13 - Reduced NAD transfers energy to the ETC

Reduced NAD from glycolysis, the link reaction and the Krebs cycle carries high-energy electrons. In the mitochondrion, NADH donates a pair of electrons to the first carrier in the electron transport chain and is oxidized back to NAD. This allows NAD to be reused in earlier stages.

C1.2.14 - Proton gradient generation

The electron transport chain is located on the inner mitochondrial membrane and cristae. Electron carriers are repeatedly reduced and oxidized. As electrons pass along the chain, energy is released in small amounts. This energy pumps protons from the matrix to the intermembrane space, creating a proton gradient.



C1.2.15 - Chemiosmosis and ATP synthase

Step	Description
1	Protons accumulate in the intermembrane space, making their concentration higher than in the matrix.
2	The inner mitochondrial membrane is not freely permeable to protons.
3	Protons diffuse back into the matrix through ATP synthase.
4	ATP synthase couples proton flow to phosphorylation of ADP, forming ATP.

Precise exam wording

The electron transport chain does not directly make ATP. It generates a proton gradient. ATP is synthesized by ATP synthase during chemiosmosis.

C1.2.16 - Oxygen as terminal electron acceptor

Oxygen accepts electrons at the end of the electron transport chain and combines with protons from the matrix to form water. This removal of electrons allows electron flow to continue. Without oxygen, the chain backs up, NADH cannot be reoxidized efficiently, and aerobic ATP production stops.



C1.2.17 - Respiratory substrates: carbohydrates versus lipids

Feature	Carbohydrates such as glucose	Lipids / fatty acids
Energy yield per gram	Lower than lipids.	Higher because lipids contain less oxygen and more oxidizable C-H bonds.
Anaerobic respiration possible?	Yes, glycolysis and fermentation can occur using carbohydrate substrate.	No full glycolysis/anaerobic pathway for fatty acids in this syllabus context.
Entry point	Glucose enters glycolysis; pyruvate forms acetyl-CoA.	Fatty acids are broken down into two-carbon acetyl groups that combine with CoA to form acetyl-CoA.
Oxygen requirement	Can begin without oxygen; complete oxidation requires oxygen.	Use as respiratory substrate is aerobic; acetyl-CoA enters Krebs cycle.
Storage role	Glycogen/starch are accessible carbohydrate stores.	Triglycerides store dense energy reserves.

Where other molecules enter respiration

Molecule type	Likely entry route
Sugars / carbohydrates	Converted to glucose or glycolysis intermediates.
Glycerol from fats	Can enter around glycolysis.
Fatty acids	Broken into acetyl groups that form acetyl-CoA and enter the Krebs cycle.
Amino acids	Can enter as pyruvate, acetyl groups or other intermediates after removal of nitrogen-containing groups.

8. High-yield comparison tables and common exam traps

Locations and products

Stage	Location	Requires O ₂ directly?	Main products / outputs
Glycolysis	Cytoplasm	No	2 pyruvate, net 2 ATP, 2 NADH
Lactate fermentation	Cytoplasm	No	Lactate; NAD regenerated
Alcoholic fermentation	Cytoplasm in yeast	No	Ethanol, CO ₂ ; NAD regenerated
Link reaction	Mitochondrial matrix	Indirectly, because ETC must keep NAD available	Acetyl-CoA, CO ₂ , NADH
Krebs cycle	Mitochondrial matrix	Indirectly	CO ₂ , ATP, NADH, FADH ₂
Electron transport chain	Inner mitochondrial membrane / cristae	Yes, at final electron acceptor step	Proton gradient; water
Chemiosmosis	ATP synthase in inner mitochondrial membrane	Depends on ETC and oxygen	Most ATP

Hydrogen, electrons and oxygen

Idea	Correct exam statement
Hydrogen removed from substrates	This is oxidation/dehydrogenation; the substrate loses electrons and potential energy.
NAD accepts hydrogen/electrons	NAD is reduced to NADH and carries energy to the ETC.
Electron transport chain	Electrons lose energy as they pass between carriers; released energy pumps protons.
Proton gradient	Potential energy stored in the gradient drives ATP synthase.
Oxygen	Final electron acceptor; combines with protons and electrons to form water.

Common exam traps

Trap	Avoid it by writing...
Saying ATP stores all cell energy long-term	ATP is a short-term energy currency; long-term stores include lipids and carbohydrates.
Confusing respiration with gas exchange	Cell respiration is a metabolic pathway; gas exchange supplies O ₂ and removes CO ₂ .
Claiming glycolysis needs oxygen	Glycolysis is anaerobic and occurs in the cytoplasm.
Claiming anaerobic respiration in humans makes ethanol	Humans convert pyruvate to lactate; yeast produces ethanol and CO ₂ .
Forgetting NAD regeneration	Fermentation regenerates NAD so glycolysis can continue.
Writing that ETC directly makes ATP	ETC makes a proton gradient; chemiosmosis through ATP synthase makes ATP.
Forgetting that glucose has two pyruvate	Link reaction and Krebs cycle occur twice per glucose.
Ignoring oxygen's final role	Oxygen accepts electrons and protons to form water, keeping electron flow going.

Exam command terms - what to include

Command	How to answer
State	Give a precise fact, e.g. 'Glycolysis occurs in the cytoplasm.'
Outline	Give the sequence with minimal detail, e.g. glucose → pyruvate → lactate.
Explain	Use causes and consequences, e.g. why oxygen enables ATP production.
Compare	Give similarities and differences, ideally in a table.
Calculate	Show rate formula, substitution and units.
Suggest / predict	Use the data trend and biological reasoning.

Rapid recall checklist

- Define ATP and identify it as a nucleotide.
- Explain ATP hydrolysis and ATP synthesis with ADP and Pi.
- Name at least three ATP-requiring cellular processes.
- Distinguish cell respiration from gas exchange.
- Compare aerobic and anaerobic respiration in humans.
- Write word equations for aerobic respiration, lactate fermentation and alcoholic fermentation.

- [] Describe glycolysis location, products and net ATP yield.
- [] Explain how lactate fermentation regenerates NAD.
- [] Explain why yeast fermentation is useful in baking and brewing.
- [] Calculate respiration rate from oxygen consumption data.
- [] HL: explain NAD as a hydrogen/electron carrier.
- [] HL: outline phosphorylation, lysis, oxidation and ATP formation in glycolysis.
- [] HL: describe pyruvate oxidation and decarboxylation in the link reaction.
- [] HL: describe citrate formation and oxaloacetate regeneration in Krebs.
- [] HL: explain how ETC produces a proton gradient and how chemiosmosis makes ATP.
- [] HL: explain oxygen as terminal electron acceptor.
- [] HL: compare lipid and carbohydrate respiratory substrates.

9. Practice questions

How to use the questions

Answer on paper first. Then check the concise mark scheme. For extended answers, practise using the exact technical terms in the mark scheme.

1. Define ATP and explain why it is described as the energy currency of the cell. (4 marks)

Mark scheme: ATP is adenosine triphosphate; it is a nucleotide. Hydrolysis of the terminal phosphate bond releases usable energy. It can transfer energy to processes such as active transport, biosynthesis and movement. It is rapidly regenerated from ADP and Pi, so it links energy-releasing and energy-requiring reactions.

2. State three cell processes that require ATP. (3 marks)

Mark scheme: Any three: active transport; synthesis of macromolecules/anabolism; movement by cilia/flagella; chromosome movement during cell division; other valid cell movement or maintenance processes.

3. Distinguish cell respiration from gas exchange. (3 marks)

Mark scheme: Cell respiration is an enzyme-controlled metabolic pathway inside cells that produces ATP. Gas exchange is the uptake of oxygen and removal of carbon dioxide between an organism and its environment. Gas exchange supports aerobic respiration but is not the same process.

4. Write word equations for aerobic respiration in humans and anaerobic respiration in humans. (2 marks)

Mark scheme: Aerobic: glucose + oxygen → carbon dioxide + water + ATP. Anaerobic in humans: glucose → lactate + ATP.

5. Compare anaerobic and aerobic respiration in humans. (6 marks)

Mark scheme: Both start with glycolysis in the cytoplasm and convert glucose to pyruvate. Anaerobic respiration does not require oxygen, occurs in the cytoplasm only, produces lactate and has a low ATP yield of net 2 ATP. Aerobic respiration requires oxygen, continues in mitochondria, produces CO₂ and water and has a much higher ATP yield.

6. Explain why glycolysis has a net yield of two ATP per glucose. (3 marks)

Mark scheme: Two ATP are used to phosphorylate glucose at the start. Four ATP are produced later when phosphate groups are transferred to ADP. Net gain = 4 - 2 = 2 ATP.

7. Explain why lactate fermentation allows glycolysis to continue in human muscle cells. (4 marks)

Mark scheme: Without oxygen, reduced NAD cannot be efficiently reoxidized by the electron transport chain. NAD is needed to accept hydrogen/electrons during glycolysis. Pyruvate accepts hydrogen/electrons from NADH and is reduced to lactate. This regenerates NAD, allowing glycolysis to continue producing ATP.

8. Yeast is added to bread dough. Explain how anaerobic respiration in yeast helps bread rise. (3 marks)

Mark scheme: Yeast carries out glycolysis and alcoholic fermentation under anaerobic conditions. Pyruvate is converted to ethanol and carbon dioxide. Carbon dioxide bubbles expand the dough, causing it to rise.

9. A student measures oxygen consumption by germinating seeds. Explain why oxygen consumption is evidence for aerobic respiration. (2 marks)

Mark scheme: Oxygen is required as the final electron acceptor in aerobic respiration. If oxygen is being consumed, the seeds are using oxygen to support aerobic ATP production.

10. Calculate the respiration rate if oxygen consumption increases from 0.2 ml to 1.4 ml in 6 minutes. (2 marks)

Mark scheme: Change in oxygen = 1.4 - 0.2 = 1.2 ml. Rate = 1.2 / 6 = 0.20 ml min⁻¹.

10. HL practice questions

11. Explain the role of NAD in aerobic respiration. (5 marks)

Mark scheme: NAD is a coenzyme and hydrogen/electron carrier. It accepts hydrogen/electrons during oxidation of substrates and becomes reduced NAD (NADH). NADH carries high-energy electrons from glycolysis, link reaction and Krebs cycle to the electron transport chain. NADH is oxidized back to NAD when it donates electrons, allowing NAD to be reused. Electron energy ultimately contributes to proton pumping and ATP synthesis.

12. Describe the main stages of glycolysis, including phosphorylation, lysis, oxidation and ATP formation. (6 marks)

Mark scheme: Glucose is phosphorylated using two ATP, forming a less stable hexose phosphate. The six-carbon molecule is split by lysis into two triose phosphate molecules. Each triose phosphate is oxidized, reducing NAD to NADH. Inorganic phosphate is added and phosphate groups are transferred to ADP. Four ATP are produced and two were used, giving a net gain of two ATP. Two pyruvate molecules are formed.

13. Outline the link reaction. (4 marks)

Mark scheme: Pyruvate enters the mitochondrial matrix. It is decarboxylated, releasing CO₂. It is oxidized, reducing NAD to NADH. The two-carbon acetyl group combines with coenzyme A to form acetyl-CoA.

14. Explain why the Krebs cycle runs twice per glucose molecule. (2 marks)

Mark scheme: One glucose molecule is split into two pyruvate molecules during glycolysis. Each pyruvate forms one acetyl-CoA, so two acetyl groups enter the Krebs cycle per glucose.

15. Describe how citrate and oxaloacetate are involved in the Krebs cycle. (4 marks)

Mark scheme: A two-carbon acetyl group from acetyl-CoA combines with four-carbon oxaloacetate to form six-carbon citrate. Citrate is then converted through several reactions involving decarboxylation and oxidation. Oxaloacetate is regenerated at the end of the cycle. This allows the cycle to accept another acetyl group.

16. Explain how the electron transport chain generates a proton gradient. (5 marks)

Mark scheme: Reduced NAD and FAD donate high-energy electrons to the chain. Electrons pass between carrier proteins in the inner mitochondrial membrane through redox reactions. Energy is released in small amounts as electrons move down the chain. This energy pumps protons from the matrix into the intermembrane space. A higher proton concentration builds up in the intermembrane space than in the matrix.

17. Explain chemiosmosis in mitochondria. (5 marks)

Mark scheme: A proton gradient exists across the inner mitochondrial membrane. Protons cannot freely cross the hydrophobic membrane. They diffuse down their concentration gradient through ATP synthase. ATP synthase uses the energy of proton flow to phosphorylate ADP with Pi. This forms ATP in oxidative phosphorylation.

18. Explain the role of oxygen in aerobic respiration. (4 marks)

Mark scheme: Oxygen is the terminal electron acceptor at the end of the electron transport chain. It accepts electrons and combines with protons from the matrix to form water. This prevents electron carriers from remaining reduced. Therefore electron flow, NAD regeneration and ATP production can continue.

19. Compare lipids and carbohydrates as respiratory substrates. (5 marks)

Mark scheme: Lipids have more oxidizable C-H bonds and less oxygen than carbohydrates, so they release more energy per gram. Carbohydrates such as glucose enter glycolysis and can be used in anaerobic respiration. Fatty acids are broken down into two-carbon acetyl groups that enter as acetyl-CoA. Lipid respiration requires aerobic pathways through Krebs cycle/ETC. Carbohydrate stores are more accessible for rapid ATP supply, while triglycerides are dense long-term stores.

20. A poison makes the inner mitochondrial membrane leaky to protons. Predict the effect on ATP production and explain why. (4 marks)

Mark scheme: ATP production by oxidative phosphorylation would decrease or stop. The proton gradient would be dissipated because protons could cross the membrane without ATP synthase. ATP synthase would have less proton flow through it. The electron transport chain might still pass electrons, but the released energy would not be effectively coupled to ATP synthesis.

11. Final two-minute revision sheet

Core answer to the two guiding questions

Hydrogen and oxygen: Hydrogen/electrons are removed from respiratory substrates during oxidation. NAD carries these high-energy electrons. In aerobic respiration, oxygen accepts electrons and protons at the end of the electron transport chain, forming water and allowing electron flow to continue.

Energy distribution: ATP distributes energy inside cells. ATP hydrolysis releases energy for active transport, biosynthesis and movement. ATP is regenerated from ADP and Pi using energy released from respiration.

Must-know fact	One-sentence version
ATP	Adenosine triphosphate; nucleotide; immediate energy currency.
ATP cycle	ATP hydrolysis releases energy; ATP synthesis requires energy.
Glycolysis	Cytoplasm; no oxygen needed; glucose → 2 pyruvate; net 2 ATP + 2 NADH.
Anaerobic in humans	Pyruvate → lactate; regenerates NAD; net 2 ATP.
Anaerobic in yeast	Pyruvate → ethanol + CO ₂ ; regenerates NAD; used in brewing and baking.
Aerobic locations	Glycolysis in cytoplasm; link and Krebs in matrix; ETC/chemiosmosis on inner membrane.
Link reaction	Pyruvate → acetyl-CoA + CO ₂ + NADH.
Krebs cycle	Acetyl group + oxaloacetate → citrate; CO ₂ , ATP, NADH and FADH ₂ produced; oxaloacetate regenerated.
ETC	Electrons from NADH/FADH ₂ pass along carriers; energy pumps protons.
Chemiosmosis	Protons flow through ATP synthase to make ATP.
Oxygen	Terminal electron acceptor; forms water.
Lipids	Higher energy per gram; fatty acids enter as acetyl-CoA.

Last-minute priority list

1. Memorise locations and products for each stage.
2. Practise explaining NAD regeneration in fermentation.
3. Practise explaining ETC → proton gradient → ATP synthase → ATP.
4. In data questions, use gradients, units and biological explanations.