Photosynthesis & Cellular Respiration

IB HL Study Guide

How to Use This Guide

- **Photosynthesis** — all light reactions, Calvin cycle, HL detail
- **Cellular Respiration** — glycolysis, Krebs, ETC, chemiosmosis
- **HL / AHL Only** — extra depth required at Higher Level
- **MCQ Practice** — styled like real IB Paper 1 questions
- **Exam Alerts** — the traps and mistakes that cost marks

Aligned to IB Biology 2025 syllabus — C1.2 Cell Respiration — C1.3 Photosynthesis

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Section 1: The Big Picture

Before any detail, you must understand **where** each process happens inside the cell. The single most common source of lost marks in MCQs is **confusing locations**. Fix this first and many questions become easy.

Cell Map — Where Every Reaction Occurs

```
                    <!-- Cell outline -->
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<text x="425" y="132" text-anchor="middle" font-family="JetBrai

      <!-- Arrow from Glycolysis to both organelles -->
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                    <!-- Chloroplast -->
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<text x="225" y="215" text-anchor="middle" font-family="Playfai

      <!-- Thylakoid membrane (inside chloroplast) -->
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<text x="140" y="295" text-anchor="middle" font-family="Source 
```

```
<text x="140" y="310" text-anchor="middle" font-family="Source
<text x="140" y="328" text-anchor="middle" font-family="JetBrai

            <!-- Stroma (inside chloroplast) -->
<rect x="240" y="230" width="150" height="105" rx="12" fill="#A
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<text x="315" y="298" text-anchor="middle" font-family="Source
<text x="315" y="321" text-anchor="middle" font-family="JetBrai

         <!-- Arrow between thylakoid and stroma -->
<line x1="220" y1="275" x2="240" y2="275" stroke="#2E7D32" stro

             <!-- Chloroplast products label -->
<text x="225" y="410" text-anchor="middle" font-family="JetBrai

                   <!-- Mitochondrion -->
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           <!-- Matrix (inside mitochondrion) -->
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        <!-- Inner membrane (inside mitochondrion) -->
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       <!-- Arrow between matrix and inner membrane -->
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                    <!-- Summary box -->
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```

```
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<text x="425" y="490" text-anchor="middle" font-family="Source
```

Cell Map — where every reaction occurs in a plant cell

MEMORISE THIS

Memorise this table:

Process	Location
Glycolysis	Cytoplasm
Link Reaction	Mitochondrial matrix
Krebs Cycle	Mitochondrial matrix
ETC + ATP synthase	Inner mitochondrial membrane
Light reactions	Thylakoid membrane
Calvin cycle	Stroma (inside chloroplast)

EXAM ALERT

Exam Alert: Krebs cycle is in the **MATRIX**, not the inner membrane. ETC is on the **INNER MEMBRANE**. These two are swapped in almost every wrong MCQ answer. The matrix is the fluid; the inner membrane is the physical structure where ETC proteins sit.

Overall Equations

The two processes are the INVERSE of each other.

Photosynthesis:

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

- O_2 comes from splitting H_2O (photolysis) — NOT from CO_2
- CO_2 is FIXED into glucose — it is a REACTANT

Aerobic Cellular Respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \sim 38\ \text{ATP}$$

Anaerobic — animals:

$$\text{Glucose} \rightarrow 2\ \text{Lactate} + 2\ \text{ATP}$$

Anaerobic — yeast:

$$\text{Glucose} \rightarrow 2\ \text{Ethanol} + 2CO_2 + 2\ \text{ATP}$$

IB TIP

The Link: Products of photosynthesis (glucose, O_2) are the reactants of respiration — and vice versa (CO_2, H_2O). These two processes drive the carbon and oxygen cycles on Earth.

MCQ Practice

Which statement is correct about the oxygen released during photosynthesis?

A. It is produced when CO_2 is broken down in the stroma

B. It is a by-product of the Calvin cycle

C. It comes from the photolysis of water in the thylakoid ← CORRECT

D. It is produced when NADPH is oxidised

Why: O_2 is released during PHOTOLYSIS — the splitting of water molecules on the thylakoid membrane using light energy. CO_2 is fixed (incorporated) during the Calvin cycle; it does not release O_2. This is one of the most frequently tested facts in photosynthesis MCQs.

Section 2: Photosynthesis

Photosynthesis converts **light energy into chemical energy** (stored in glucose). Two main stages: **Light-dependent reactions** on the thylakoid membrane, and the **Calvin cycle** in the stroma. Both stages must be understood in detail for HL.

2.1 Chloroplast Structure

```
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                    <!-- Outer membrane -->
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                     <!-- Stroma fill -->
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           <!-- Stroma contents on the right side -->
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<text x="645" y="210" text-anchor="middle" font-family="Source
```

```
<text x="645" y="226" text-anchor="middle" font-family="Source

            <!-- Granum 1 (stack of thylakoids) -->
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<rect x="100" y="280" width="160" height="22" rx="8" fill="#7CB
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                    <!-- Granum 1 label -->
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<text x="180" y="366" text-anchor="middle" font-family="Source

         <!-- Thylakoid lumen label inside one disc -->
<text x="180" y="248" text-anchor="middle" font-family="Source

              <!-- Granum 2 (smaller stack) -->
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              <!-- Lamellae connecting grana -->
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             <!-- Arrow from granum to callout -->
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                 <!-- Thylakoid lumen note -->
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```

```
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                        <!-- Summary box -->
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<text x="425" y="484" text-anchor="middle" font-family="Playfai
<text x="425" y="504" text-anchor="middle" font-family="Source
```

Chloroplast Structure — cross-section with labelled compartments

Chloroplast Adaptations HL

AHL — B2.2.5

Thylakoid membrane — large surface area:

- Gives maximum space for photosystems, electron carriers, and ATP synthase
- Grana (stacked) greatly multiply the surface area per chloroplast

Thylakoid lumen — small volume:

- H^+ ions pumped in by ETC quickly build up a steep concentration gradient
- A steep gradient = strong proton motive force = more efficient ATP synthesis
- Small volume means the same number of H^+ ions creates a higher concentration

Stroma — compartmentalises Calvin cycle:

- Keeps RuBisCO and substrates (RuBP, CO_2) in high concentrations together
- Physically separate from cytoplasm — unique chemical environment maintained
- CO_2 diffuses directly from stomata into the stroma

Double membrane (envelope):

- Maintains a controlled internal environment
- Acts as a selective barrier — regulates what enters/exits the chloroplast

2.2 Photosynthetic Pigments and Light Absorption

Pigments absorb **specific wavelengths** of light. When a photon of the right wavelength hits a pigment, it **excites an electron** to a higher energy level. This energy drives the light reactions. Multiple pigments capture a **broader range** of wavelengths, increasing efficiency.

Absorption and Action Spectra

{/* DIAGRAM: Absorption spectrum graph showing absorbance (0-100%) vs wavelength (400-700nm). Chlorophyll a peaks at ~430nm (blue-violet) and ~680nm (red). Chlorophyll b peaks at ~450nm (blue) and ~640nm (orange-red). Carotenoids absorb in blue-violet range. Green light (~500-560nm) is poorly absorbed (reflected, making leaves green). Action spectrum graph showing rate of photosynthesis vs wavelength, closely matching the absorption spectrum with peaks at blue (~430nm) and red (~680nm) and a trough at green wavelengths. */}

IB TIP

Key Point: The action spectrum closely **matches** the absorption spectrum. This is evidence that light absorption **causes** photosynthesis. Peaks occur at blue (~430 nm) and red (~680 nm).

Pigment	Wavelengths Absorbed / Role
Chlorophyll a	Red (680 nm) + blue-violet (430 nm). Main reaction-centre pigment. P680 in PS II, P700 in PS I
Chlorophyll b	Blue (450 nm) + orange-red. Accessory pigment — absorbs and transfers energy to Chl a
Carotenoids	Blue-violet (400-500 nm). Accessory pigments. Reflect yellow-orange wavelengths. Also protect chlorophyll from excess light damage
Phycoerythrin / phycocyanin	Green and yellow (in algae/cyanobacteria). Fill the absorption gaps of chlorophylls

Photosystems and Pigment Arrays HL

AHL — C1.3.5

Antenna complex:

- Hundreds of accessory pigment molecules arranged around each reaction centre
- Absorb photons of various wavelengths and pass energy by resonance to the reaction centre
- Acts like a funnel — greatly increases the effective area for light capture
- Accessory pigments can NOT pass electrons directly to the ETC

Reaction centre (one special pair of chlorophyll a):

- **PS II reaction centre = P680** (absorbs 680 nm red light)
  - P680 donates an excited electron to the electron transport chain
  - $P680^{+}$ is the strongest biological oxidising agent (strong enough to split water)
- **PS I reaction centre = P700** (absorbs 700 nm far-red light)
  - Re-energises electrons received from PS II
  - Passes electrons to ferredoxin, which ultimately reduces $NADP^{+}$

EXAM ALERT

Important: PS II comes FIRST in the electron flow (despite the lower number!).

Flow: $H_2O \rightarrow \text{PS II} \rightarrow \text{ETC} \rightarrow \text{PS I} \rightarrow NADP^{+}$

MCQ Practice

Which of the following correctly describes a photosystem's antenna complex?

A. A single chlorophyll a molecule that absorbs red light only

B. An array of accessory pigments that absorb light and pass energy to the reaction centre ← CORRECT

C. The site where water is split to release oxygen

D. A protein complex that pumps H^+ across the thylakoid membrane

Why: The antenna complex is an array of many accessory pigment molecules that absorb light of various wavelengths and transfer the energy by resonance to the reaction centre. Water is split at the reaction centre of PS II (not the antenna). H^+ pumping is done by the cytochrome b6f complex in the ETC.

2.3 Light-Dependent Reactions

The light-dependent reactions occur on the **thylakoid membrane**. They produce ATP, NADPH, and O_2 — the O_2 is a waste product. Two types: **non-cyclic photophosphorylation** (both PS I and PS II) and **cyclic photophosphorylation** (PS I only).

Non-Cyclic Photophosphorylation — The Z-Scheme

```
<!-- Thylakoid membrane -->
<rect x="30" y="195" width="790" height="80" rx="4" fill="#81C7
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<!-- Thylakoid lumen (inside) -->
<text x="420" y="310" text-anchor="middle" font-family="Playfai
<text x="420" y="328" text-anchor="middle" font-family="Source 

<!-- Stroma (outside) -->
<text x="420" y="40" text-anchor="middle" font-family="Playfair
<text x="420" y="58" text-anchor="middle" font-family="Source S

<!-- PSII -->
<rect x="80" y="175" width="120" height="120" rx="10" fill="#15
<text x="140" y="220" text-anchor="middle" font-family="Source 
<text x="140" y="240" text-anchor="middle" font-family="Source 
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<!-- Light hitting PSII -->
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<text x="70" y="125" font-family="JetBrains Mono, monospace" fo

<!-- Photolysis of water -->
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<text x="140" y="385" text-anchor="middle" font-family="Source 
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<!-- Electron carrier chain between PSII and PSI -->
```

```
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               <!-- Electron flow PSII → PQ -->
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                   <!-- Cytochrome b6f -->
<rect x="330" y="175" width="100" height="120" rx="8" fill="#7B
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                    <!-- PQ → Cyt b6f -->
<line x1="310" y1="200" x2="330" y2="220" stroke="#FFB300" stro

                <!-- H+ pumped by Cyt b6f -->
<line x1="380" y1="280" x2="380" y2="340" stroke="#c62828" stro
<text x="380" y="355" text-anchor="middle" font-family="JetBrai

                    <!-- Plastocyanin -->
<rect x="450" y="185" width="80" height="30" rx="4" fill="#A5D6
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                    <!-- Cyt b6f → PC -->
<line x1="430" y1="220" x2="450" y2="200" stroke="#FFB300" stro

                        <!-- PSI -->
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                      <!-- PC → PSI -->
<line x1="530" y1="200" x2="550" y2="230" stroke="#FFB300" stro

                 <!-- Light hitting PSI -->
<line x1="560" y1="130" x2="590" y2="175" stroke="#FFB300" stro
<text x="540" y="125" font-family="JetBrains Mono, monospace" f

                     <!-- Ferredoxin -->
<rect x="690" y="120" width="80" height="28" rx="4" fill="#A5D6
<text x="730" y="139" text-anchor="middle" font-family="Source 

             <!-- PSI → Fd (excited electron) -->
<path d="M670 200 Q700 150 690 134" fill="none" stroke="#FFB300
```

```
               <!-- NADP+ reductase → NADPH -->
<text x="730" y="85" text-anchor="middle" font-family="JetBrair
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                    <!-- ATP Synthase -->
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<text x="745" y="225" text-anchor="middle" font-family="Source
<text x="745" y="243" text-anchor="middle" font-family="Source

             <!-- H+ flow through ATP synthase -->
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<text x="745" y="360" text-anchor="middle" font-family="JetBrai

                    <!-- ATP produced -->
<text x="745" y="155" text-anchor="middle" font-family="JetBrai
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            <!-- Z-Scheme energy level indicator -->
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                      <!-- Summary -->
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<text x="425" y="432" text-anchor="middle" font-family="Playfai
<text x="425" y="452" text-anchor="middle" font-family="JetBrai
```

Light-Dependent Reactions — thylakoid membrane

Non-cyclic products: ATP + NADPH + O_2

Electron source: H_2O (split by photolysis at PS II)

Electron destination: NADPH (electrons carried out of light reactions)

Cyclic Photophosphorylation (PS I Only)

Electron path: PS I → Fd → Cyt b6f → PC → PS I

Product: ATP only (no NADPH, no O_2)

Used when: cell needs more ATP relative to NADPH

Non-Cyclic vs Cyclic Photophosphorylation HL

AHL — C1.3.6 / C1.3.7

Non-cyclic — electrons flow in one direction (linear):

- $H_2O \rightarrow$ PS II $\rightarrow$ plastoquinone $\rightarrow$ cyt b6f $\rightarrow$ plastocyanin $\rightarrow$ PS I $\rightarrow$ Fd $\rightarrow$ $NADP^+$
- Electrons are NOT recycled — they end up stored in NADPH
- Products: ATP + NADPH + O_2 (all three)

Cyclic — electrons loop back (no net products except ATP):

- PS I $\rightarrow$ ferredoxin $\rightarrow$ cyt b6f $\rightarrow$ plastocyanin $\rightarrow$ PS I (loop)
- Products: ATP ONLY
- No O_2 released, no NADPH made, no water split
- Occurs when ATP/NADPH ratio is low — supplements ATP supply

Chemiosmosis in Thylakoids HL

Same principle as mitochondria

H^+ (protons) accumulate in thylakoid lumen from:

1. **Photolysis:** $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (protons released into lumen)
2. **PQ pumping:** PQ carries H^+ from stroma to lumen as electrons pass through

- H^+ concentration in lumen >> stroma → steep proton gradient
- H^+ can ONLY move back into stroma through ATP synthase channels
- Flow of H^+ down the gradient powers rotation of ATP synthase → ATP

NADP Reduction HL

AHL — C1.3.7

- Ferredoxin passes 2 electrons to NADP reductase enzyme
- $NADP^+ + 2e^- + H^+$ (from stroma) $\rightarrow$ NADPH
- H^+ comes from stroma, not from the lumen

Light-Dependent Reactions — Step by Step

1. Photon hits antenna complex of PS II. Energy passes by resonance to P680.
2. P680 absorbs energy — its electron is excited to a higher energy level.
3. Excited electron leaves P680, enters ETC via pheophytin then plastoquinone.
4. **Photolysis:** P680 is now electron-deficient ($P680^+$). It oxidises water: $2H_2O \rightarrow 4H^+ + 4e^- + O_2$. O_2 released as waste gas.
5. Electrons pass through cytochrome b6f complex. H^+ is actively pumped from stroma into the thylakoid lumen. This builds up the proton gradient.
6. Electrons carried by plastocyanin arrive at PS I (P700).
7. Second photon re-energises electrons at PS I. Electrons passed to ferredoxin.
8. Ferredoxin transfers electrons to NADP reductase. $NADP^+ + 2e^- + H^+ \rightarrow$ NADPH.
9. H^+ gradient across thylakoid drives ATP synthase. H^+ flows from lumen to stroma through ATP synthase. $ADP + P_i \rightarrow ATP$ (photophosphorylation).

Chemiosmosis in the Thylakoid

{/* DIAGRAM: Cross-section of thylakoid membrane showing stroma side (low [H+]) and lumen side (high [H+]). H+ enters lumen from: (1) photolysis of H2O and (2) PQ pumping. ATP synthase channel spans the membrane. H+ flows from lumen through ATP synthase back into stroma, driving ADP + Pi to ATP. Proton motive force = concentration gradient + charge difference. H+ can ONLY return to stroma via ATP synthase. This coupling of electron transport to ATP synthesis = chemiosmosis. Same principle operates in BOTH chloroplasts and mitochondria. */}

MCQ Practice

Which combination of products is made by NON-CYCLIC photophosphorylation but NOT by cyclic photophosphorylation?

A. ATP and $\mathrm{CO_2}$

B. NADPH **and** $\mathrm{O_2}$ ← CORRECT

C. ATP and RuBP

D. Glucose and NADPH

Why: Non-cyclic photophosphorylation produces ATP, NADPH, and $\mathrm{O_2}$. Cyclic photophosphorylation produces ATP ONLY — no NADPH and no $\mathrm{O_2}$ (because no photolysis occurs and electrons return to PS I). RuBP and glucose are products of the Calvin cycle, not the light reactions.

2.4 The Calvin Cycle (Light-Independent Reactions)

The Calvin cycle occurs in the **stroma**. It uses ATP and NADPH from the light reactions to **fix** $\mathrm{CO_2}$ into organic molecules. The key enzyme **RuBisCO** attaches $\mathrm{CO_2}$ to RuBP. The cycle regenerates its own substrate — it is truly cyclic. Three turns = one net G3P; six turns = one glucose.

The Calvin Cycle — Complete Annotated Diagram

```
                        <!-- Title -->
<text x="350" y="30" text-anchor="middle" font-family="Playfair
<text x="350" y="50" text-anchor="middle" font-family="Source S

                      <!-- CO2 input -->
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<text x="350" y="88" text-anchor="middle" font-family="JetBrain

                   <!-- Arrow into cycle -->
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               <!-- STAGE 1: Carbon Fixation -->
<rect x="60" y="115" width="170" height="24" rx="4" fill="#2D50
<text x="145" y="132" text-anchor="middle" font-family="Source 

               <!-- RuBP (C5) - top of cycle -->
<rect x="260" y="140" width="180" height="42" rx="8" fill="#A5D
<text x="350" y="157" text-anchor="middle" font-family="Source 
<text x="350" y="174" text-anchor="middle" font-family="Source 
```

```
<!-- RuBisCO enzyme label -->
<rect x="420" y="120" width="100" height="22" rx="4" fill="#FFF
<text x="470" y="136" text-anchor="middle" font-family="Source

<!-- Arrow from RuBP + CO2 → GP -->
<path d="M350 182 Q350 210 350 230" fill="none" stroke="#2D5016

<!-- GP (C3) - 6 molecules -->
<rect x="240" y="235" width="220" height="42" rx="8" fill="#C8E
<text x="350" y="252" text-anchor="middle" font-family="Source
<text x="350" y="269" text-anchor="middle" font-family="Source

<!-- STAGE 2: Reduction -->
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<text x="125" y="312" text-anchor="middle" font-family="Source

<!-- ATP and NADPH input -->
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<text x="530" y="330" font-family="JetBrains Mono, monospace" f
<line x1="490" y1="315" x2="460" y2="300" stroke="#1565C0" stro
<text x="530" y="350" font-family="Source Serif 4, Georgia, ser

<!-- Arrow GP → G3P -->
<path d="M350 277 Q350 320 350 350" fill="none" stroke="#2D5016

<!-- G3P (C3) - 6 molecules -->
<rect x="240" y="355" width="220" height="42" rx="8" fill="#C8E
<text x="350" y="372" text-anchor="middle" font-family="Source
<text x="350" y="389" text-anchor="middle" font-family="Source

<!-- Split: 5 G3P recycled, 1 G3P exits -->
<!-- 1 G3P exits -->
<line x1="350" y1="397" x2="350" y2="440" stroke="#E65100" stro

<!-- Net output: 1 G3P -->
<rect x="260" y="445" width="180" height="42" rx="8" fill="#FFE
<text x="350" y="462" text-anchor="middle" font-family="Source
<text x="350" y="479" text-anchor="middle" font-family="Source

<!-- Note: 2 G3P = 1 Glucose -->
<text x="350" y="510" text-anchor="middle" font-family="Source

<!-- 5 G3P recycled back to RuBP -->
<!-- STAGE 3: Regeneration -->
<rect x="60" y="410" width="150" height="24" rx="4" fill="#2D50
```

```
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<text x="80" y="270" text-anchor="middle" font-family="Source S
<text x="80" y="285" text-anchor="middle" font-family="Source S

                 <!-- ATP for regeneration -->
<text x="100" y="200" font-family="JetBrains Mono, monospace" f

                    <!-- Summary box -->
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<text x="350" y="558" text-anchor="middle" font-family="Playfai
<text x="350" y="578" text-anchor="middle" font-family="JetBrai
<text x="350" y="593" text-anchor="middle" font-family="Source
```

The Calvin Cycle (Light-Independent Reactions) — occurs in the stroma

Per turn (1 CO_2 fixed):

$$\text{Input: } 1\ CO_2 + 3\ ATP + 2\ NADPH \quad \rightarrow \quad \text{Output: } \frac{1}{3}\ G3P \text{ net}$$

To make 1 glucose (6C) from 6 CO_2: need **6 turns** of the cycle.

Total: 18 ATP + 12 NADPH consumed.

MEMORISE THIS

Key Names (must know for HL):

Abbreviation	Full Name	Carbon Atoms	Role
RuBP	Ribulose bisphosphate	5C	CO_2 acceptor
GP	3-phosphoglycerate	3C	First stable product
G3P	Glyceraldehyde-3-phosphate (triose phosphate)	3C	Organic product that exits the cycle

Calvin Cycle — Full HL Mechanism HL

AHL — C1.3.8 / C1.3.9

Step 1: Carbon Fixation

- RuBisCO enzyme catalyses: $CO_2 + RuBP\ (5C) \rightarrow$ unstable 6C intermediate
- 6C immediately splits into $2 \times$ GP (3-phosphoglycerate, 3C)
- GP = the FIRST STABLE PRODUCT of CO_2 fixation

Step 2: Reduction — GP to G3P (triose phosphate)

- ATP phosphorylates GP → 1,3-bisphosphoglycerate (2 ATP per CO_2)

- NADPH reduces 1,3-BPG → G3P (2 NADPH per CO_2)
- G3P is the organic product that exits the cycle (1 of every 6)

Step 3: Regeneration of RuBP

- 5 of every 6 G3P molecules rearranged → ribulose-5-phosphate
- ATP phosphorylates ribulose-5-P → RuBP (3 ATP per 3 CO_2 fixed)

Interdependence of Light and Dark Reactions HL

AHL — C1.3.9

- If **light stops** → ATP and NADPH drop → **GP ACCUMULATES** (cannot be reduced)
- G3P falls, RuBP falls (cannot be regenerated)
- If CO_2 **drops** → RuBisCO slows → **RuBP accumulates**, GP falls
- Both stages are tightly coupled — neither can operate without the other

Calvin's Experiment

- Fed ^{14}C-labelled CO_2 to *Chlorella* algae, used paper chromatography
- GP (3-PGA) was the FIRST labelled product detected
- Proved the C3 pathway — 3-carbon first product

Calvin Cycle — Step by Step

1. CO_2 diffuses from atmosphere into stroma. RuBisCO binds CO_2 to RuBP (5C).
2. Unstable 6C intermediate immediately splits into 2 × GP (3-phosphoglycerate, 3C). This is the first stable carbon fixation product.
3. ATP phosphorylates each GP molecule → 1,3-bisphosphoglycerate. (2 ATP used per CO_2)
4. NADPH reduces 1,3-BPG → G3P (triose phosphate). (2 NADPH used per CO_2)
5. 1 out of every 6 G3P molecules exits the cycle to make glucose, fatty acids, or amino acids.
6. The remaining 5 G3P molecules enter the RuBP regeneration pathway.
7. ATP is used to phosphorylate ribulose-5-phosphate → RuBP. (3 ATP per 3 CO_2 fixed)
8. RuBP is ready to accept another CO_2. The cycle repeats.

MCQ Practice

If light intensity suddenly drops to zero during active photosynthesis, what immediate change is observed in the Calvin cycle?

A. RuBP levels increase because carbon fixation continues

B. GP levels decrease because it can no longer be made

C. GP **accumulates because it cannot be reduced to** $\mathrm{G3P}$ **without** NADPH ← CORRECT

D. $\mathrm{CO_2}$ levels inside the chloroplast increase

Why: With no light: ATP and NADPH production stops. RuBisCO can still make GP (as long as RuBP and $\mathrm{CO_2}$ are present), but GP CANNOT be reduced to $\mathrm{G3P}$ because NADPH is needed for that step. So GP builds up. $\mathrm{G3P}$ falls. RuBP is gradually used up and not regenerated. This interdependence question is extremely common in HL exams.

MCQ Practice

Which molecule is the DIRECT product of carbon fixation by RuBisCO?

A. $\mathrm{G3P}$ (triose phosphate)

B. Glucose

C. RuBP

D. GP **(3-phosphoglycerate)** ← CORRECT

Why: RuBisCO catalyses $\mathrm{CO_2} + \mathrm{RuBP} \rightarrow \text{unstable } 6\mathrm{C} \rightarrow 2 \times \mathrm{GP}$ (3-phosphoglycerate). GP is the FIRST stable product of carbon fixation. $\mathrm{G3P}$ is made AFTER GP is reduced using ATP and NADPH. Glucose is made after multiple turns of the cycle.

Section 3: Cellular Respiration

Cellular respiration releases energy from organic molecules and stores it as ATP. Four stages: **Glycolysis** (cytoplasm) → **Link Reaction** (matrix) → **Krebs Cycle** (matrix) → **Electron Transport Chain and Chemiosmosis** (inner membrane). Understanding each stage's location, inputs, outputs, and mechanism is essential for HL.

3.1 ATP and NAD — Energy Carriers

ATP Structure and the Energy Cycle

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                     <!-- Adenine base -->
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<text x="105" y="132" text-anchor="middle" font-family="Source
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                     <!-- Ribose sugar -->
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<text x="185" y="188" text-anchor="middle" font-family="Source

                 <!-- Bond to phosphate 1 -->
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              <!-- Phosphate group 1 (alpha) -->
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<text x="420" y="115" text-anchor="middle" font-family="JetBrai
```

```
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              <!-- High-energy bond 1 (wavy) -->
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               <!-- Phosphate group 2 (beta) -->
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              <!-- High-energy bond 2 (wavy) -->
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              <!-- Phosphate group 3 (gamma) -->
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                 <!-- Triphosphate bracket -->
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<text x="560" y="188" text-anchor="middle" font-family="Source

             <!-- Energy label on wavy bonds -->
<text x="560" y="70" text-anchor="middle" font-family="Source S
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<line x1="630" y1="75" x2="630" y2="100" stroke="#c62828" strok

                 <!-- ATP ↔ ADP + Pi cycle -->
                  <!-- ATP label on left -->
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<text x="180" y="275" text-anchor="middle" font-family="Source

                <!-- ADP + Pi label on right -->
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<text x="630" y="255" text-anchor="middle" font-family="JetBrai
<text x="630" y="275" text-anchor="middle" font-family="Source

        <!-- Top arrow: Hydrolysis (ATP → ADP + Pi) -->
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<text x="405" y="234" text-anchor="middle" font-family="Source
```

```
       <!-- Bottom arrow: Synthesis (ADP + Pi → ATP) -->
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<text x="405" y="321" text-anchor="middle" font-family="Source

           <!-- Energy released / stored labels -->
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<text x="405" y="362" text-anchor="middle" font-family="JetBrai

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<text x="425" y="400" text-anchor="middle" font-family="Playfai
<text x="425" y="420" text-anchor="middle" font-family="Source
```

ATP Structure — adenine + ribose + 3 phosphate groups, with the ATP-ADP cycle

- ATP drives: active transport, movement, anabolism (synthesis reactions)
- ATP is NOT stored — it is rapidly recycled (~40 kg ATP cycled per day in humans)

NAD (Nicotinamide Adenine Dinucleotide)

- **Oxidised form:** NAD^+ (empty — can accept electrons)
- **Reduced form:** NADH (loaded — carrying electrons + H)

$$\mathrm{NAD}^+ + 2\mathrm{H} \rightarrow \mathrm{NADH}\ (+\mathrm{H}^+)$$

- Substrate is **oxidised** (loses H)
- NAD^+ is **reduced** (gains H)

FADH_2**:** similar to NADH but carries slightly less energy. Used at one specific step in the Krebs cycle (succinate → fumarate).

MEMORISE THIS

OIL RIG

- **O**xidation = **I**s **L**oss of electrons/hydrogen (substrate → product loses H)
- **R**eduction = **I**s **G**ain of electrons/hydrogen ($\mathrm{NAD}^+ \rightarrow \mathrm{NADH}$ gains H)

Role of NAD as Hydrogen Carrier HL

AHL — C1.2.7

- NAD^+ acts as the hydrogen (electron + proton) ACCEPTOR during substrate oxidation
- Each NADH carries 2 electrons + 1 H^+ to the electron transport chain
- At the ETC, NADH is OXIDISED → NAD^+ is regenerated
- NAD^+ must be regenerated continuously — without it, glycolysis and Krebs stop

- **In aerobic conditions:** NAD^+ regenerated at the ETC (O_2 accepts electrons at end)
- **In anaerobic conditions:** NAD^+ regenerated by fermentation (pyruvate or acetaldehyde accepts electrons)
- $FADH_2$ also donates electrons to the ETC but enters at a later complex → yields slightly less ATP than $NADH$ (~2 vs ~3 ATP per molecule)

3.2 Glycolysis

Location: CYTOPLASM (cytosol). Glycolysis is the ONLY stage shared by aerobic and anaerobic respiration. One glucose (6C) → two pyruvate (3C), with a net yield of 2 ATP and 2 $NADH$. No oxygen required.

Glycolysis — Step-by-Step Flow

```
                     <!-- Title area -->
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<text x="300" y="50" text-anchor="middle" font-family="Source S

               <!-- ENERGY INVESTMENT PHASE -->
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<text x="60" y="85" font-family="Source Serif 4, Georgia, serif
```

```
<!-- Glucose -->
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<text x="300" y="125" text-anchor="middle" font-family="Source

<!-- ATP input -->
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<!-- Arrow down -->
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<!-- Fructose-1,6-bisphosphate -->
<rect x="170" y="185" width="260" height="40" rx="8" fill="#C8E
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<!-- Split arrow -->
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<!-- 2x G3P -->
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<!-- ENERGY PAYOFF PHASE -->
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<!-- Merge arrows -->
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<!-- Oxidation step -->
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<!-- NAD+ reduction -->
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<!-- Arrow -->
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```

```
            <!-- Substrate-level phosphorylation 1 -->
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                             <!-- 3-PG -->
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                            <!-- Arrow -->
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                             <!-- PEP -->
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<text x="300" y="603" text-anchor="middle" font-family="Source 

                            <!-- Arrow -->
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            <!-- Substrate-level phosphorylation 2 -->
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                          <!-- Pyruvate -->
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<text x="300" y="687" text-anchor="middle" font-family="Source 

                        <!-- Summary box -->
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<text x="300" y="790" text-anchor="middle" font-family="Source 
```

Glycolysis: Glucose to Pyruvate (occurs in the cytoplasm)

	Per glucose
ATP used	2 (phosphorylation)
ATP made	4 (substrate-level phosphorylation)
Net ATP	**+2**
NADH produced	2
Pyruvate made	2 x 3C

Glycolysis — HL Mechanism HL

AHL — C1.2.8

Stage 1 — Phosphorylation:

- 2 ATP hydrolysed → glucose receives 2 phosphate groups
- Forms fructose-1,6-bisphosphate (6C, 2 phosphates)
- **Why:** Adding phosphates destabilises the molecule, making it easy to split AND traps glucose inside the cell (phosphorylated glucose cannot cross membranes)

Stage 2 — Lysis:

- Fructose-1,6-bisphosphate → 2× triose phosphate (G3P, 3C each)
- Each G3P retains 1 phosphate group from the phosphorylation step

Stage 3 — Oxidation:

- Each G3P oxidised — removes 2H (electrons + protons)
- NAD^+ accepts the hydrogen → NADH formed (2 total)
- A second inorganic phosphate (P_i) is added to each G3P
- Molecule now has 2 phosphate groups and is highly energised

Stage 4 — ATP Formation (substrate-level phosphorylation):

- Each of the 2 phosphate groups is transferred directly to ADP
- 4 ATP produced in total (2 phosphates transferred per pyruvate x 2 G3P)
- Net: 4 made - 2 used = **2 ATP net**

IB TIP

Note: Specific intermediate names are NOT required by the IB 2025 syllabus, but you MUST know the 4 stages and their inputs/outputs.

MCQ Practice

A cell is fed glucose labelled with ^{14}C at every carbon atom. After glycolysis only (no further reactions), in which molecule(s) would ALL the ^{14}C be found?

A. CO_2 only

B. ATP and NADH

C. Pyruvate ← CORRECT

D. CO_2 and pyruvate equally

Why: Glycolysis converts glucose to pyruvate — NO CO_2 is released in glycolysis. All 6 carbons end up in the 2 pyruvate molecules (3C each). CO_2 is released in the LINK REACTION (1 CO_2 per pyruvate) and KREBS CYCLE. ATP and NADH carry no carbon atoms from glucose.

3.3 Anaerobic Respiration

When O_2 is absent, cells must **regenerate** NAD^+ without using the ETC. The ONLY purpose of fermentation is to recycle NAD^+ so glycolysis can continue. Two pathways exist — one in animals, one in yeast.

Lactate Fermentation (Animals / Humans)

$$\text{Pyruvate (3C)} + \text{NADH} \xrightarrow{\text{lactate dehydrogenase}} \text{Lactate (3C)} + \text{NAD}^+$$

- Pyruvate is REDUCED to lactate
- NADH is OXIDISED back to NAD^+ — **this is the WHOLE POINT**
- NAD^+ recycled → glycolysis can continue producing ATP
- Lactate accumulates in muscle → transported to liver (Cori cycle)
- When O_2 returns: lactate → pyruvate → aerobic pathway (oxygen debt)
- **Net ATP:** 2 per glucose (glycolysis only)
- **REVERSIBLE** reaction

Ethanol Fermentation (Yeast)

$$\text{Pyruvate (3C)} \xrightarrow{\text{pyruvate decarboxylase}} \text{Acetaldehyde (2C)} + \text{CO}_2$$

$$\text{Acetaldehyde} + \text{NADH} \xrightarrow{\text{alcohol dehydrogenase}} \text{Ethanol (2C)} + \text{NAD}^+$$

- CO_2 is released (used in baking = bread rises; fermentation = carbonation)
- Ethanol accumulates — toxic to yeast at concentrations $> \sim 15\%$
- **IRREVERSIBLE** — yeast cannot convert ethanol back to pyruvate
- **Net ATP:** 2 per glucose (glycolysis only)

Comparison

	Both pathways	Animals	Yeast
Purpose	Regenerate NAD^+	Lactate (3C)	Ethanol (2C) + CO_2
ATP yield	2 only	2 only	2 only
Location	Cytoplasm	Cytoplasm	Cytoplasm
Reversibility	—	Reversible	Irreversible

Anaerobic Respiration — HL Points HL

AHL — C1.2.9 / C1.2.10 / C1.2.17

> **EXAM ALERT**
>
> **Key Concept:** The purpose of fermentation is NOT to produce energy — it is to regenerate NAD^+ so glycolysis can KEEP producing ATP. Without NAD^+, glycolysis stops at the oxidation step and no ATP is made.

Lipids vs Carbohydrates as Respiratory Substrates HL

AHL — C1.2.17

- Lipids yield ~2x more energy per gram than carbohydrates
- **Why:** Lipids are more reduced — they contain more C-H bonds per carbon (more hydrogen to be oxidised → more NADH → more ATP from ETC)

- Lipids contain very little oxygen already bound → more oxidation can occur
- Glycerol component → enters glycolysis
- Fatty acids → beta-oxidation in mitochondrial matrix → Acetyl-CoA → Krebs

EXAM ALERT

Important: Glycolysis and anaerobic respiration can ONLY use carbohydrates. Lipids BYPASS glycolysis entirely — they enter as Acetyl-CoA at the link reaction level.

MCQ Practice

Why must NAD^+ be regenerated during anaerobic respiration?

A. NAD^+ is needed to drive the electron transport chain

B. NAD^+ is required for oxidation of glucose in the Krebs cycle

C. Without NAD^+, glycolysis cannot oxidise triose phosphate, so ATP production stops ← CORRECT

D. NAD^+ is needed to split water during photolysis

Why: Glycolysis REQUIRES NAD^+ in the oxidation step to accept hydrogen from triose phosphate. Without NAD^+, this step stalls, glycolysis cannot proceed, and no ATP is produced. Fermentation regenerates NAD^+ by using pyruvate (or acetaldehyde) as an electron acceptor instead. The ETC is not available in anaerobic conditions.

3.4 The Link Reaction

Location: mitochondrial matrix. Pyruvate (3C) from glycolysis is converted to Acetyl-CoA (2C), releasing CO_2. This connects glycolysis to the Krebs cycle. Two link reactions occur per glucose (two pyruvate molecules).

Link Reaction — Full Diagram

```
                        <!-- Title -->
<text x="425" y="30" text-anchor="middle" font-family="Playfair
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                   <!-- Cytoplasm zone -->
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                    <!-- Pyruvate box -->
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<text x="120" y="117" text-anchor="middle" font-family="Source
<text x="120" y="135" text-anchor="middle" font-family="JetBrai

                  <!-- Arrow into matrix -->
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               <!-- Mitochondrial matrix box -->
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               <!-- Step 1: Decarboxylation -->
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<text x="380" y="140" text-anchor="middle" font-family="Source
<text x="380" y="158" text-anchor="middle" font-family="JetBrai

                    <!-- CO2 released -->
```

```
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                <!-- Arrow Step 1 → Step 2 -->
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                  <!-- Step 2: Oxidation -->
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                    <!-- NADH produced -->
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                <!-- Arrow Step 2 → Step 3 -->
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                 <!-- Step 3: CoA addition -->
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                  <!-- Acetyl-CoA output -->
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                     <!-- Summary box -->
```

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```

Link Reaction — pyruvate to Acetyl-CoA in the mitochondrial matrix

	Per pyruvate	Per glucose
CO_2 released	1	2
$NADH$ produced	1	2
Acetyl-CoA formed	1	2

- CoA = Coenzyme A (acts as a carrier/handle for the acetyl group)
- CoA is released when Acetyl-CoA enters Krebs, and is recycled

3.5 The Krebs Cycle

Location: mitochondrial matrix. The Krebs cycle fully oxidises Acetyl-CoA, releasing CO_2 and producing large amounts of $NADH$ and $FADH_2$. These electron carriers deliver energy to the ETC. The 4C oxaloacetate starting molecule is regenerated each turn — making it truly cyclic.

The Krebs Cycle — Complete Annotated Diagram

```
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<!-- Pyruvate input (top) -->
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<!-- Link reaction arrow -->
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<!-- Acetyl CoA -->
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```
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<!-- Cycle compounds arranged in a circle -->
<!-- Citrate (top, C6) -->
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<!-- OAA feeds into citrate -->
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<!-- Arrow: Citrate → Isocitrate (right) -->
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<!-- Outputs: CO2, NADH -->
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<!-- Alpha-ketoglutarate (right, C5) -->
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<!-- Outputs: CO2, NADH -->
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<!-- Succinyl CoA (bottom-right, C4) -->
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<!-- Output: GTP/ATP -->
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<!-- Succinate (bottom, C4) -->
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```

```
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                    <!-- Output: NADH -->
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         <!-- Malate → Oxaloacetate (left-top, C4) -->
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```

The Krebs Cycle (Citric Acid Cycle) — occurs in the mitochondrial matrix

Per turn (per Acetyl-CoA = per 1/2 glucose):

Product	Amount
CO_2 released	2
NADH produced	3
$FADH_2$ produced	1
ATP (substrate-level phosphorylation)	1

Per glucose (2 turns):

$$4\ CO_2 + 6\ NADH + 2\ FADH_2 + 2\ ATP$$

MEMORISE THIS

Must-know intermediates: Citrate (6C) and Oxaloacetate (4C)

Krebs Cycle — HL Detail HL

AHL — C1.2.12

Condensation: Acetyl-CoA (2C) + Oxaloacetate (4C) → Citrate (6C) + CoA released. CoA is recycled to pick up another acetyl group from the link reaction.

1st Decarboxylation: Isocitrate → alpha-ketoglutarate. CO_2 released + NAD^+ reduced to $NADH$.

2nd Decarboxylation: alpha-ketoglutarate → Succinyl-CoA. CO_2 released + NAD^+ reduced to $NADH$.

Substrate-level Phosphorylation: Succinyl-CoA → Succinate. 1 ATP produced directly (not via ETC). CoA released.

FAD Reduction: Succinate → Fumarate. FAD reduced to $FADH_2$ (not NAD^+).

- **Why FAD here?** This oxidation step has insufficient energy to reduce NAD^+. Succinate dehydrogenase enzyme is embedded in the inner mitochondrial membrane.

Malate Oxidation: Malate → Oxaloacetate. NAD^+ reduced to $NADH$. Oxaloacetate regenerated → cycle continues.

Products summary (per turn): 3 $NADH$ + 1 $FADH_2$ + 1 ATP + 2 CO_2 (+ regenerated oxaloacetate)

Krebs Cycle — Step by Step

1. Acetyl-CoA (2C) enters the matrix. CoA is released and recycled to the link reaction.
2. Condensation: acetyl group (2C) combines with oxaloacetate (4C) → citrate (6C).
3. Citrate rearranged → isocitrate (same formula, different structure).
4. 1st decarboxylation: isocitrate → alpha-ketoglutarate (5C) + CO_2. $NAD^+ \rightarrow NADH$.
5. 2nd decarboxylation: alpha-ketoglutarate → succinyl-CoA (4C) + CO_2. $NAD^+ \rightarrow NADH$.
6. Substrate-level phosphorylation: succinyl-CoA → succinate + 1 ATP. CoA released.
7. Oxidation: succinate → fumarate. $FAD \rightarrow FADH_2$.
8. Hydration: fumarate + H_2O → malate.
9. Oxidation: malate → oxaloacetate. $NAD^+ \rightarrow NADH$. Oxaloacetate ready for next turn.

MCQ Practice

How many molecules of CO_2 are produced per turn of the Krebs cycle (per acetyl-CoA)?

A. 1

B. 2 ← CORRECT

C. 3

D. 4

Why: Two CO_2 molecules are released per turn of the Krebs cycle — one at each of the two decarboxylation steps (isocitrate → alpha-KG and alpha-KG → succinyl-CoA). Per glucose (2 turns): 4 CO_2 from Krebs + 2 CO_2 from the link reaction = 6 CO_2 total from Krebs + link (matching the 6 CO_2 in the overall equation).

MCQ Practice

Which is the only Krebs cycle step that produces $FADH_2$ rather than $NADH$?

A. Isocitrate → alpha-ketoglutarate

B. alpha-ketoglutarate → succinyl-CoA

C. Succinate → fumarate ← CORRECT

D. Malate → oxaloacetate

Why: FAD (rather than NAD^+) is the hydrogen acceptor at the succinate → fumarate step. This is because the oxidation of succinate releases insufficient energy to reduce NAD^+. Succinate dehydrogenase is the enzyme, and it is embedded in the inner mitochondrial membrane. All other oxidative steps use NAD^+.

3.6 Electron Transport Chain and Chemiosmosis

Location: INNER MITOCHONDRIAL MEMBRANE. $NADH$ and $FADH_2$ from glycolysis, the link reaction, and the Krebs cycle deliver electrons to protein complexes embedded in the inner membrane. As electrons flow down the chain, H^+ is pumped into the intermembrane space. The proton gradient drives ATP synthesis through chemiosmosis. O_2 is the FINAL electron acceptor.

Electron Transport Chain and Chemiosmosis — Diagram

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```

```
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               <!-- H+ pump from Complex III -->
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               <!-- H+ pump from Complex IV -->
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            <!-- O2 as final electron acceptor -->
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```

Electron Transport Chain & Oxidative Phosphorylation — inner mitochondrial membrane

- NADH → ~3 ATP
- $\mathrm{FADH_2}$ → ~2 ATP (enters at ubiquinone, skips Complex I)
- O_2 is ESSENTIAL — without it, ETC stops, H^+ not pumped, no ATP
- Water is produced at Complex IV (matrix side of inner membrane)
- ATP yield from ETC per glucose: ~34 ATP

ETC and Chemiosmosis — HL Mechanisms HL

AHL — C1.2.13 to C1.2.16

Energy Transfer to ETC (AHL C1.2.13):

- NADH delivers electrons to Complex I (NADH dehydrogenase)
- $\mathrm{FADH_2}$ delivers electrons to Complex II (succinate dehydrogenase) via ubiquinone
- As electrons pass through each complex, energy released pumps H^+ into IMS
- $\mathrm{FADH_2}$ yields LESS ATP than NADH because it bypasses Complex I (less H^+ pumped)

Proton Gradient Generation (AHL C1.2.14):

- Complexes I, III, and IV all pump H^+ from matrix into intermembrane space (IMS)
- IMS has small volume → H^+ accumulates quickly → steep concentration gradient
- Electrochemical gradient = proton motive force (concentration + charge difference)

Chemiosmosis and ATP Synthesis (AHL C1.2.15):

- H^+ can ONLY re-enter the matrix through ATP synthase (Complex V)
- Flow of H^+ down the gradient causes mechanical rotation of ATP synthase
- Rotation drives conformational changes in ATP synthase → $ADP + P_i \rightarrow ATP$
- ~3 H^+ needed per ATP molecule (approximate, accepted by IB)

Role of O_2 (AHL C1.2.16):

- O_2 is the TERMINAL (final) electron acceptor at Complex IV
- $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$ (water produced in the matrix)
- WITHOUT O_2: electrons cannot leave Complex IV → ETC completely blocks
- Blocked ETC → H^+ not pumped → no gradient → no ATP synthesis
- $NADH/FADH_2$ cannot be oxidised → NAD^+ runs out → Krebs and link reaction stop
- ONLY glycolysis (with fermentation for NAD^+ regeneration) continues without O_2

ETC and Chemiosmosis — Step by Step

1. $NADH$ (from glycolysis, link reaction, Krebs) passes electrons to Complex I. $FADH_2$ passes electrons to ubiquinone (bypassing Complex I).
2. Electrons flow from Complex I → ubiquinone → Complex III → cytochrome c → Complex IV.
3. At each complex (I, III, IV), energy from electron flow pumps H^+ from matrix into the intermembrane space.
4. H^+ accumulates in the intermembrane space — builds up a steep concentration gradient (proton motive force).
5. H^+ can ONLY flow back into the matrix through ATP synthase channels.
6. H^+ flowing through ATP synthase causes it to rotate — this mechanical energy drives synthesis of ATP from $ADP + P_i$ (oxidative phosphorylation).
7. At Complex IV: electrons are transferred to O_2. O_2 + electrons + H^+ → H_2O. Water is the final product of the ETC.
8. NAD^+ and FAD are regenerated and return to the Krebs cycle and link reaction to pick up more electrons.

MCQ Practice

Why does aerobic respiration stop if oxygen is removed, even though glycolysis does not require oxygen?

A. Oxygen is needed to activate RuBisCO in the matrix

B. Without oxygen the ETC stops, $NADH$ cannot be oxidised, NAD^+ runs out, and the Krebs cycle stops ← CORRECT

C. Oxygen is required for the condensation reaction in the Krebs cycle

D. Without oxygen, pyruvate cannot enter the mitochondrial matrix

Why: Oxygen is the terminal electron acceptor at the end of the ETC. Without it, electrons cannot leave Complex IV, the ETC backs up, $NADH$ cannot be oxidised to NAD^+, and NAD^+ runs out. Without NAD^+, the Krebs cycle and link reaction cannot proceed. Only glycolysis continues, using fermentation to regenerate NAD^+. This is a classic chain-of-consequence MCQ.

MCQ Practice

A cell is treated with a drug that blocks ATP synthase. Which prediction is correct?

A. The ETC stops immediately because ATP synthase is needed to power it

B. The proton gradient across the inner membrane breaks down

C. The proton gradient increases because H^+ is still pumped but cannot return ← CORRECT

D. $NADH$ production increases because more substrate is oxidised

Why: If ATP synthase is blocked, H^+ can no longer flow back into the matrix. However, the ETC continues pumping H^+ into the IMS (as long as O_2 and $NADH$ are available). The gradient therefore INCREASES but no ATP is made. Eventually the gradient becomes so steep that ETC pumping slows (back-pressure), reducing $NADH$ oxidation too.

Section 4: ATP Yield — The Full Accounting

Understanding the ATP **yield at each stage** and **why the ETC produces so much more** ATP than glycolysis is crucial for both MCQ and extended-response questions.

Complete ATP Yield Table — Per Glucose

Stage	Location	Inputs	Outputs	ATP per glucose
Glycolysis	Cytoplasm	Glucose	2 Pyruvate, 2 $NADH$	2 net
Link Reaction	Mito. matrix	2 Pyruvate	2 Acetyl-CoA, 2 CO_2, 2 $NADH$	0
Krebs Cycle	Mito. matrix	2 Acetyl-CoA	4 CO_2, 6 $NADH$, 2 $FADH_2$	2
ETC + ATP synthase	Inner mito. membrane	10 $NADH$, 2 $FADH_2$	H_2O	~34
TOTAL	**Both**	**Glucose + O_2**	CO_2 + H_2O	**~38**

Why Does the ETC Produce ~34 ATP While Glycolysis Makes Only 2?

Glycolysis and Krebs use **substrate-level phosphorylation** — ATP is made DIRECTLY when a phosphate group is transferred to ADP. This only happens at a few specific steps → low yield.

The ETC uses **oxidative phosphorylation** — a completely different mechanism:

- 10 NADH + 2 $\mathrm{FADH_2}$ carry electrons to the ETC
- As electrons pass through protein complexes, their energy pumps $\mathrm{H^+}$
- A large proton gradient drives ATP synthase to make ATP
- ~2.5 ATP per NADH and ~1.5 ATP per $\mathrm{FADH_2}$ (approximately 3 and 2 for IB)
- 10 NADH x 3 = 30 ATP
- 2 $\mathrm{FADH_2}$ x 2 = 4 ATP
- **Total from ETC: ~34** ATP

IB TIP

Note: Actual yield is slightly lower than 38 due to: some $\mathrm{H^+}$ leaking across the inner membrane, ATP synthase not being 100% efficient, and the energy cost of transporting pyruvate and ADP into the matrix. IB accepts 36-38 ATP as the aerobic yield per glucose.

MCQ Practice

Which statement explains why $\mathrm{FADH_2}$ **yields fewer** ATP **molecules than** NADH **during oxidative phosphorylation?**

A. $\mathrm{FADH_2}$ carries fewer electrons than NADH

B. $\mathrm{FADH_2}$ cannot enter the mitochondrial matrix

C. $\mathrm{FADH_2}$ **donates electrons at a later point in the ETC, bypassing Complex I, so fewer** $\mathrm{H^+}$ **are pumped** ← CORRECT

D. $\mathrm{FADH_2}$ is oxidised in the cytoplasm, not the mitochondria

Why: $\mathrm{FADH_2}$ delivers electrons directly to ubiquinone (between Complexes I and III), bypassing Complex I entirely. Since Complex I pumps $\mathrm{H^+}$ as electrons pass through it, skipping it means fewer $\mathrm{H^+}$ are pumped into the IMS, creating a smaller contribution to the proton gradient, and therefore fewer ATP molecules are synthesised per $\mathrm{FADH_2}$.

Section 5: MCQ Strategy and Common Traps

IB Biology Paper 1 MCQs test whether you know **exact locations, exact sequences, exact products**, and can **follow chains of consequence**. The most effective strategy: read the question, **predict your answer before looking at options**, then check. This prevents attractive wrong answers from misleading you.

The Most Common MCQ Traps — Memorise These

EXAM ALERT

Common Wrong Answer / Misconception	Correct Understanding
O_2 comes from CO_2 in photosynthesis	O_2 comes from PHOTOLYSIS of water ($H_2O \rightarrow O_2$). CO_2 is fixed into glucose — never releases O_2.
Krebs cycle is on the inner membrane	Krebs cycle is in the MATRIX. The ETC and ATP synthase are on the INNER MEMBRANE.
Glycolysis is in the mitochondria	Glycolysis is in the CYTOPLASM. It occurs in BOTH aerobic and anaerobic conditions.
PS II comes after PS I in electron flow	PS II comes FIRST (P680, splits water). PS I comes second (P700, reduces $NADP^+$). Numbers are confusing.
Fermentation produces ATP	Fermentation's purpose is to regenerate NAD^+. It produces NO additional ATP beyond glycolysis.
$FADH_2$ and NADH yield equal ATP	NADH yields ~3 ATP; $FADH_2$ yields ~2 ATP. $FADH_2$ skips Complex I so fewer H^+ are pumped.
Calvin cycle needs light	Calvin cycle uses ATP and NADPH from light reactions but does NOT directly require light itself. It stops when LIGHT STOPS only because ATP/NADPH run out.
Link reaction produces ATP	Link reaction produces ONLY CO_2, NADH, and Acetyl-CoA. NO ATP is produced at this stage.
CO_2 is released in glycolysis	No CO_2 in glycolysis. CO_2 is released in the LINK REACTION (1 per pyruvate) and KREBS CYCLE (2 per turn).
Non-cyclic and cyclic produce the same products	Non-cyclic → ATP + NADPH + O_2. Cyclic → ATP ONLY. This is a very frequent MCQ distinction.

Five MCQ Strategy Rules for IB Biology

1. **Predict before reading options:** Cover the answers. Decide what you think the answer is. Then check. This avoids being misled by plausible-sounding distractors.
2. **Location questions — go to your mental map:** Ask: is this a membrane process (ETC, light reactions) or a fluid/matrix process (Krebs, Calvin, glycolysis)? This eliminates 2-3 wrong options instantly.
3. **"Cannot proceed because…" questions — trace the chain:** Work step by step: what stops first? What runs out next? For example: no O_2 → ETC stops → NADH not oxidised → NAD^+ runs out → Krebs stops.
4. **Product counting questions — add up from your diagrams:** Know exact yields: Glycolysis = 2 ATP; Link = 0 ATP, 2 NADH; Krebs = 2 ATP, 6 NADH, 2 $FADH_2$, 4 CO_2; ETC = ~34 ATP.
5. **"Increases/decreases" questions — think about the feedback:** e.g. "light stops → what happens to GP?" → ATP and NADPH drop → GP CANNOT be reduced → GP ACCUMULATES. Always follow the logic, not the memory.

MCQ Practice

During aerobic respiration, where are the protons (H^+) that flow through ATP synthase coming from?

A. From the hydrolysis of ATP in the matrix

B. From water produced at Complex IV

C. From the oxidation of $NADH$ and $FADH_2$, pumped into the intermembrane space by the ETC ← CORRECT

D. From the breakdown of glucose during glycolysis

Why: When $NADH$ and $FADH_2$ deliver electrons to the ETC, the energy released pumps H^+ from the matrix into the intermembrane space (via Complexes I, III, and IV). These accumulated H^+ then flow back through ATP synthase into the matrix, driving ATP synthesis. Water is produced AT Complex IV (where O_2 accepts electrons), not as a source of H^+ for ATP synthase.

MCQ Practice

A plant is moved from red light to green light only. What happens to the rate of photosynthesis?

A. It increases because plants can use all visible light equally

B. It stays the same because the Calvin cycle does not require light

C. It decreases significantly because chlorophyll absorbs very little green light ← CORRECT

D. It stops completely because green light has too little energy to excite electrons

Why: Chlorophyll a and b absorb mainly blue and red light — they REFLECT green light (which is why leaves look green). Very little green light is absorbed, so photosynthesis rate drops sharply. It does not stop completely because carotenoids absorb some green-adjacent wavelengths. The action spectrum confirms photosynthesis is lowest in the green region.

MCQ Practice

Which statement about the relationship between photosynthesis and aerobic respiration is correct?

A. Both processes occur only in plant cells

B. The ATP produced in photosynthesis is directly used in respiration

C. Oxygen produced in photosynthesis is the same oxygen consumed in aerobic respiration ← CORRECT

D. Both processes produce carbon dioxide as a final waste product

Why: O_2 produced by photolysis in the light reactions is the same O_2 that acts as the terminal electron acceptor in the mitochondrial ETC. This links the two processes: the oxygen cycle. ATP from photosynthesis is NOT directly transferred to respiration — it is used to make glucose in the Calvin cycle, and glucose is then respired. Respiration occurs in ALL living cells, not just plants. Respiration releases CO_2; photosynthesis CONSUMES CO_2.

Section 6: HL Content — Complete Checklist HL

This checklist covers every AHL (Additional Higher Level) point for photosynthesis and respiration in the 2025 IB Biology syllabus. If you are HL, every item on this list is assessable.

HL Photosynthesis — What You Must Know

AHL Topic	Key Points to Know
Chloroplast adaptations (B2.2.5)	Large thylakoid membrane surface area; small lumen volume builds H^+ gradient fast; stroma compartmentalises Calvin cycle enzymes
Photosystem structure (C1.3.5)	Antenna complex = array of accessory pigments; reaction centres P680 (PS II) and P700 (PS I); $P680^+$ is strongest biological oxidising agent
Non-cyclic vs cyclic photophosphorylation (C1.3.6)	Non-cyclic: PS I + PS II, products ATP + NADPH + O_2. Cyclic: PS I only, product ATP only. Electron flow directions.
NADP reduction (C1.3.7)	Ferredoxin → NADP reductase → $NADP^+ + 2e^- + H^+(\text{stroma}) \rightarrow NADPH$
Chemiosmosis in thylakoid (C1.3.12)	H^+ pumped into lumen by PQ + cyt b6f; small lumen volume → steep gradient; H^+ returns via ATP synthase → ATP
Calvin cycle mechanism (C1.3.8)	3 stages: carbon fixation (RuBisCO, CO_2 + RuBP → GP), reduction (ATP + NADPH, GP → G3P), regeneration (ATP, G3P → RuBP). Per glucose: 18 ATP + 12 NADPH
Interdependence of stages (C1.3.9)	Light stops → ATP/NADPH fall → GP accumulates → G3P falls → RuBP falls. CO_2 falls → RuBP accumulates, GP falls.
Calvin's experiment	$^{14}CO_2$ + paper chromatography → GP was first stable product; proved C3 pathway

HL Respiration — What You Must Know

AHL Topic	Key Points to Know
NAD as hydrogen carrier (C1.2.7)	NAD^+ accepts H during oxidation of substrate → NADH; NADH delivers electrons to ETC; NAD^+ regenerated by ETC (aerobic) or fermentation (anaerobic)
Glycolysis stages (C1.2.8)	4 stages: phosphorylation (-2 ATP), lysis, oxidation (2 NADH), ATP formation (+4 ATP). Net: 2 ATP + 2 NADH. Cytoplasm. Both aerobic and anaerobic.
Lactate fermentation (C1.2.9)	Pyruvate → lactate + NAD^+. Purpose: regenerate NAD^+. Reversible. No extra ATP.
Yeast fermentation (C1.2.10)	Pyruvate → acetaldehyde + CO_2, then acetaldehyde + NADH → ethanol + NAD^+. Irreversible. Used in baking/brewing.
Link reaction (C1.2.11)	Pyruvate → Acetyl-CoA. Decarboxylation + oxidation. Per pyruvate: 1 CO_2 + 1 NADH. Matrix.
Krebs cycle (C1.2.12)	Per turn: 2 CO_2, 3 NADH, 1 $FADH_2$, 1 ATP. Key intermediates: citrate (6C), oxaloacetate (4C). Matrix.
ETC and proton gradient (C1.2.13/14)	NADH → Complex I, $FADH_2$ → ubiquinone (skips I). H^+ pumped at I, III, IV into IMS. Gradient = proton motive force.
Chemiosmosis (C1.2.15)	H^+ flows through ATP synthase → ADP + P_i → ATP. ~3 H^+ per ATP. NADH → ~3 ATP, $FADH_2$ → ~2 ATP.
Role of O_2 (C1.2.16)	O_2 = terminal electron acceptor at Complex IV. $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$. Without O_2: ETC stops, NAD^+ runs out, Krebs stops.
Lipids vs carbohydrates (C1.2.17)	Lipids: higher energy per gram, more C-H bonds, less O already bound. Fatty acids → Acetyl-CoA via beta-oxidation. Glycolysis and anaerobic respiration use carbohydrates ONLY.

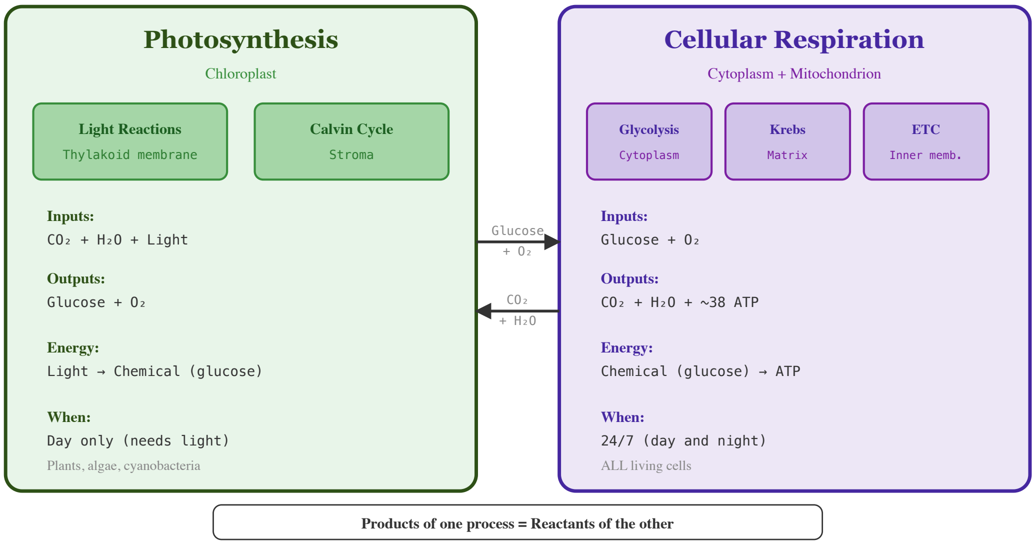
IB TIP

Tip: Print this checklist and tick each box as you can explain it from memory with no notes. Any unticked item = revision priority.

Section 7: Photosynthesis vs Cellular Respiration — Side-by-Side Comparison

These two processes are the **inverse** of each other. Understanding how they connect is one of the most tested concepts in IB Biology.

Overview Comparison



Photosynthesis and Cellular Respiration are inverse processes — they drive the carbon and oxygen cycles on Earth

Detailed Comparison Table

Feature	Photosynthesis	Cellular Respiration
Overall equation	$6CO_2 + 6H_2O \to C_6H_{12}O_6 + 6O_2$	$C_6H_{12}O_6 + 6O_2 \to 6CO_2 + 6H_2O + \sim 38$ ATP
Energy conversion	Light energy → chemical energy	Chemical energy → ATP
Organelle	Chloroplast	Mitochondrion (+ cytoplasm)
Organisms	Plants, algae, cyanobacteria	ALL living cells
When	Day only (requires light)	24/7 (day and night)
Gas exchange	Takes in CO_2, releases O_2	Takes in O_2, releases CO_2
Water	Consumed (photolysis)	Produced (at ETC)
Glucose	Produced (Calvin cycle)	Consumed (glycolysis)
Electron carriers	NADPH (carries electrons)	NADH and $FADH_2$ (carry electrons)
ATP production method	Chemiosmosis (thylakoid)	Chemiosmosis (inner membrane) + substrate-level
H^+ gradient location	Thylakoid lumen (inside)	Intermembrane space
Key enzyme	RuBisCO (carbon fixation)	ATP synthase (ATP production)
Stages	Light reactions → Calvin cycle	Glycolysis → Link → Krebs → ETC

What They Share (Similarities)

Shared Feature	In Photosynthesis	In Respiration
Chemiosmosis	H^+ gradient across thylakoid membrane drives ATP synthase	H^+ gradient across inner mitochondrial membrane drives ATP synthase
Electron transport chain	Thylakoid membrane (PS II → PS I)	Inner mitochondrial membrane (Complexes I-IV)
ATP synthase	In thylakoid membrane	In inner mitochondrial membrane
Electron carriers	NADPH	NADH, $FADH_2$
Compartmentalisation	Reactions separated between thylakoid and stroma	Reactions separated between matrix and inner membrane
CO_2 **involvement**	Fixed by RuBisCO	Released by decarboxylation

EXAM ALERT

The IB frequently asks: **"Compare and contrast photosynthesis and respiration."** Use this table structure in your answer. Always mention: (1) they are inverse reactions, (2) both use chemiosmosis and ATP synthase, (3) both have electron transport chains, (4) products of one are reactants of the other.

IB TIP

Common MCQ trap: "Respiration only occurs at night." This is FALSE — respiration occurs 24/7 in ALL living cells. During the day, plants do BOTH photosynthesis AND respiration simultaneously. The net gas exchange depends on the rate of each process.

IB Biology HL — Photosynthesis & Cellular Respiration — Complete Study Guide — 2025 Syllabus — Good luck!