MDCAT Biology Unit 2: Bioenergetics, study guide with practice MCQs

What MDCAT asks

Bioenergetics covers the two energy pathways every cell depends on: photosynthesis, which traps light energy in glucose, and cellular respiration, which releases that energy as ATP. On the PMDC weighting the unit's two subtopics together carry about 2 to 3 of the 81 Biology questions. Questions ask *where* a stage happens, *what goes in and comes out*, and the counts of ATP, NADH, NADPH and CO_2.

B2.1 Photosynthesis

Photosynthesis converts light energy into the chemical energy of glucose:

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

Twelve water molecules on the left and six on the right make one point clear: all the oxygen released comes from the splitting of water, not from carbon dioxide. There are two stages, both inside the chloroplast: the light-dependent reactions, on the thylakoid membranes (stacked into grana), make ATP, NADPH and O_2; the light-independent reactions (Calvin cycle), in the stroma, use that ATP and NADPH to reduce CO_2 to sugar.

B2.1.1 Photosynthetic pigments, absorption and action spectra, and the role of chlorophyll

Light is absorbed by pigments held in the thylakoid membranes:

- **Chlorophyll a**: blue-green, present in all plants, algae and cyanobacteria. It is the only pigment that takes part directly in the light reactions, because it forms the **reaction centre** of each photosystem.
- **Chlorophyll b**: yellow-green, an accessory pigment that absorbs slightly different wavelengths from chlorophyll a and so widens the range of light the leaf can use.
- **Carotenoids**: carotenes (orange) and xanthophylls (yellow). Accessory pigments that absorb blue-violet light, pass the energy to chlorophyll a, and protect chlorophyll from excess light.

A chlorophyll molecule has a flat **porphyrin head** with a magnesium ion (Mg^{2+}) at its centre, and a hydrocarbon **phytol tail** that anchors it in the membrane.

The **absorption spectrum** of a pigment shows how much light it absorbs at each wavelength: chlorophyll a absorbs most strongly in the violet-blue region (around 430 nm) and the orange-red region (around 660 nm), and little green, which is reflected, so leaves look green. The **action spectrum** shows the *rate of photosynthesis* at each wavelength. Its peaks fall in the same blue and red regions, the evidence that light absorbed by chlorophyll drives photosynthesis; it is slightly broader because accessory pigments fill the gaps.

B2.1.2 Light-dependent reactions: photosystems, photolysis, cyclic and non-cyclic photophosphorylation

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Pigments are grouped into **photosystems**: an **antenna complex** of a few hundred chlorophyll and carotenoid molecules around a **reaction centre** of chlorophyll a. Antenna pigments pass absorbed energy inward; the reaction centre then loses an excited electron to a primary acceptor. **Photosystem II** has reaction centre **P680** and acts first in the chain, although it was discovered second; **photosystem I** has **P700**.

Photolysis is the light-driven splitting of water at PS II:

$2H_2O \rightarrow 4H^+ + 4e^- + O_2$

The electrons replace those lost by P680; the oxygen is a by-product.

Non-cyclic photophosphorylation uses both photosystems. Electrons flow: water → PS II (P680) → plastoquinone → cytochrome b_6f complex → plastocyanin → PS I (P700) → ferredoxin → NADP reductase → $NADP^+$. As they pass the cytochrome complex, protons are pumped into the thylakoid space and flow back through **ATP synthase**, which makes ATP (**chemiosmosis**). Finally $NADP^+$ is reduced to NADPH. Products: **ATP, NADPH and O_2**.

Cyclic photophosphorylation uses PS I only. The excited electron from P700 returns to P700 through ferredoxin and the cytochrome complex. The only product is **ATP**: no photolysis, no oxygen, no NADPH. It supplies the extra ATP the Calvin cycle needs (3 ATP per 2 NADPH).

Feature	Non-cyclic	Cyclic
Photosystems	PS II and PS I	PS I only
Source of electrons	Water (photolysis)	P700; electrons return to it
Final electron acceptor	NADP+	P700 (a loop)
O_2 released	Yes	No
Products	ATP, NADPH, O_2	ATP only

B2.1.3 Light-independent reactions (Calvin cycle) and the factors limiting photosynthesis

The Calvin cycle runs in the stroma. It uses no light directly but depends completely on ATP and NADPH from the light reactions. Three phases, counted per **three** CO_2 fixed:

1. **Carbon fixation.** CO_2 joins the five-carbon acceptor **ribulose 1,5-bisphosphate (RuBP)**, catalysed by **RuBisCO**. The unstable six-carbon product splits at once into two three-carbon **phosphoglyceric acid (PGA)**. Three CO_2 give six PGA.
2. **Reduction.** Each PGA is phosphorylated by ATP and reduced by NADPH to **glyceraldehyde 3-phosphate (G3P)**, also called PGAL: 6 ATP and 6 NADPH for six G3P.
3. **Regeneration of RuBP.** Five of the six G3P (15 carbons) are rearranged, using 3 more ATP, into three RuBP. **One G3P leaves the cycle** as net product.

So three CO_2 cost 9 ATP and 6 NADPH and yield one G3P; two G3P combine outside the cycle to make one glucose. Hence **six CO_2, 18 ATP and 12 NADPH per glucose**, or **3 ATP and 2 NADPH per CO_2**. The cycle lives on ATP and NADPH, so it stops within minutes of darkness.

Limiting factors. Blackman's law of limiting factors: the rate is set by the factor in shortest supply, and raising any other has no effect until that one is raised.

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- **Light intensity**: raises the rate until the graph flattens and another factor takes over. The **compensation point** is where photosynthesis equals respiration, with no net gas exchange.
- **CO_2 concentration**: air holds only about 0.03 to 0.04% CO_2, usually the limiting factor on a bright warm day; greenhouses raise it to about 0.1%.
- **Temperature**: the Calvin cycle is enzyme-controlled, so the rate rises to an optimum and then falls as enzymes denature.
- **Water**: shortage closes the stomata and cuts off CO_2.

MDCAT trap: where the oxygen comes from, and what "light-independent" means.

First, students write that the oxygen a plant releases comes from CO_2. It does not: carbon dioxide is reduced whole, and every O_2 comes from photolysis of water at PS II. Label the water with ^{18}O and the label appears in the O_2; label the CO_2 and it ends up in glucose. Second, students treat the Calvin cycle as a night-time process because it is "light-independent". It uses no photon directly, but it burns ATP and NADPH that only the light reactions supply, so it stops soon after the light goes off. Rules: oxygen from water; photolysis at PS II; cyclic gives ATP only; non-cyclic gives ATP, NADPH and O_2; each CO_2 costs 3 ATP and 2 NADPH.

Worked example: reading a limiting-factor experiment.

A pondweed at 25 °C in CO_2-enriched water releases 8 bubbles of oxygen per minute at light intensity 1 unit, 16 at 2 units, 30 at 4 units and 30 at 8 units. What limits the rate at each step?

Step 1: From 1 to 2 units the rate doubles exactly, so light intensity is limiting.

Step 2: From 2 to 4 units the rate rises less than proportionally, so light is ceasing to be limiting.

Step 3: From 4 to 8 units there is no change. CO_2 is in excess, so the limiting factor is most likely temperature.

Answer: light at low intensity, temperature at high intensity; warming to 30 °C should raise the rate at 8 units.

B2.2 Cellular respiration

Cellular respiration is the controlled oxidation of food, usually glucose, to release energy captured in ATP:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy (ATP and heat)

Hydrogen stripped from the substrate by dehydrogenases is loaded onto **NAD^+** and **FAD**, forming **NADH** and **$FADH_2$**, which deliver the electrons to oxygen through the electron transport chain, where most ATP is made.

Stage	Site	Per glucose: CO_2	NADH	$FADH_2$
Glycolysis	Cytoplasm	0	2	0
Link reaction (twice)	Mitochondrial matrix	2	2	0
Krebs cycle (two turns)	Mitochondrial matrix	4	6	2

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Electron transport chain	Inner mitochondrial membrane (cristae)	0	uses 10	uses 2
Total		**6**	**10**	**2**

Stage	ATP made directly
Glycolysis	2 net (4 made, 2 used)
Link reaction (twice)	0
Krebs cycle (two turns)	2
Electron transport chain	32 to 34 (oxidative)
Total	**36 or 38** (see B2.2.2)

B2.2.1 Glycolysis, link reaction and Krebs cycle, and where each occurs

Glycolysis takes place in the cytoplasm, needs no oxygen, and is the one stage shared by aerobic and anaerobic respiration. One six-carbon glucose becomes two three-carbon **pyruvic acid** (pyruvate) molecules in ten enzyme steps:

- **Energy investment phase.** Glucose is phosphorylated twice, to glucose 6-phosphate and then fructose 1,6-bisphosphate. **2 ATP are spent.** The sugar then splits into two triose phosphates (G3P).
- **Energy pay-off phase.** Each G3P is oxidised by NAD^+ (2 NADH per glucose) and converted to pyruvic acid, making 2 ATP per triose by **substrate-level phosphorylation**, the direct transfer of a phosphate from a substrate to ADP. **4 ATP are made.**

Net per glucose: **2 pyruvic acid, 2 NADH, 2 ATP**, and no CO_2. Everything after this is counted twice per glucose, because there are two pyruvic acids.

With oxygen present, pyruvic acid enters the mitochondrion. The **link reaction** (oxidative decarboxylation) takes place in the **matrix**, catalysed by pyruvate dehydrogenase:

pyruvic acid (3C) + CoA + NAD^+ → acetyl CoA (2C) + CO_2 + NADH

Per glucose: 2 acetyl CoA, 2 CO_2, 2 NADH, no ATP.

The **Krebs cycle** (citric acid cycle) also runs in the **matrix**. Acetyl CoA (2C) hands its acetyl group to **oxaloacetic acid (4C)** to form **citric acid (6C)**, which is then oxidised and decarboxylated: citric acid → isocitric acid → α-ketoglutaric acid (5C; first CO_2, first NADH) → succinyl CoA (4C; second CO_2, second NADH) → succinic acid (1 ATP by substrate-level phosphorylation, made as GTP in animals) → fumaric acid (FAD → $FADH_2$) → malic acid → oxaloacetic acid (third NADH).

Per turn: **2 CO_2, 3 NADH, 1 $FADH_2$, 1 ATP**. Per glucose, two turns: 4 CO_2, 6 NADH, 2 $FADH_2$, 2 ATP. All six carbons of glucose have now left as CO_2, yet only 4 ATP have been made directly; the pay-off is the 10 NADH and 2 $FADH_2$ carrying hydrogen to the ETC.

B2.2.2 The electron transport chain, oxidative phosphorylation and the ATP yield

The **electron transport chain** is a series of carriers in the **inner mitochondrial membrane**: NADH dehydrogenase (complex I) → ubiquinone (coenzyme Q) → cytochrome b-c_1 (complex III) → cytochrome c → cytochrome oxidase (complex IV). NADH donates its electrons to complex I; $FADH_2$

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donates to ubiquinone through complex II, **bypassing complex I**. Electrons lose energy at each step. **Oxygen is the final electron acceptor**:

$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

This is the only step that uses oxygen; without it the carriers stay reduced, NADH cannot be reoxidised, and the Krebs cycle and link reaction halt for lack of NAD^+.

Oxidative phosphorylation. Complexes I, III and IV use the energy released to pump protons from the matrix into the **intermembrane space**, building a proton gradient. Protons flow back into the matrix through **ATP synthase**, which joins ADP and inorganic phosphate into ATP (**chemiosmosis**, Peter Mitchell). The 4 ATP of glycolysis and the Krebs cycle are substrate-level phosphorylation; all the rest is oxidative.

The ATP count. FSc textbooks use: each NADH yields **3 ATP** (its electrons pass all three pumping complexes), each $FADH_2$ yields **2 ATP** (it skips complex I). From one glucose:

- 10 NADH × 3 = 30 ATP
- 2 $FADH_2$ × 2 = 4 ATP
- 4 ATP by substrate-level phosphorylation (2 glycolysis, 2 Krebs cycle)
- **Total 38 ATP**

Many textbooks give **36 ATP** for eukaryotic cells instead. The 2 NADH of glycolysis are made in the cytoplasm and cannot cross the inner membrane; a shuttle often delivers their hydrogen to FAD, so they yield 2 ATP each, losing 2 overall. Both 36 and 38 are taught and MDCAT generally avoids making you choose; if a question gives its own values per carrier, use those.

B2.2.3 Aerobic and anaerobic respiration compared, and respiration of fats and proteins

Without oxygen the mitochondrial stages stop and the cell can make ATP only by glycolysis. But glycolysis consumes NAD^+. **Fermentation** regenerates NAD^+ by dumping the hydrogen of NADH onto pyruvic acid so that glycolysis can continue; it makes no ATP itself, so the yield stays at the **2 ATP net** of glycolysis.

- **Alcoholic fermentation** (yeast, plant roots in waterlogged soil): pyruvic acid (3C) → acetaldehyde (2C) + CO_2 (pyruvate decarboxylase), then acetaldehyde + NADH → ethanol + NAD^+ (alcohol dehydrogenase). Two CO_2 per glucose.
- **Lactic acid fermentation** (muscle in hard exercise, red blood cells, *Lactobacillus*): pyruvic acid + NADH → lactic acid + NAD^+ (lactate dehydrogenase). **No CO_2** is released. The extra oxygen breathed after exercise (the **oxygen debt**) oxidises the lactic acid or returns it to the liver to be rebuilt into glucose.

Feature	Aerobic	Anaerobic (fermentation)
Oxygen	Required as final electron acceptor	Not required
Site	Cytoplasm, then mitochondrion	Cytoplasm only
Breakdown of glucose	Complete, to CO_2 and H_2O	Incomplete, to ethanol + CO_2 or lactic acid
ATP per glucose	36 or 38	2

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Acceptor of hydrogen from NADH	Oxygen, via the ETC	Acetaldehyde (yeast) or pyruvic acid (muscle)
CO_2 per glucose	6	2 in yeast, 0 in muscle

Fats. Lipase splits a triglyceride into glycerol and three fatty acids. **Glycerol** is converted to a triose phosphate (G3P) and enters glycolysis. **Fatty acids** are cut two carbons at a time in the matrix by **beta-oxidation**, each pair leaving as **acetyl CoA**, which enters the Krebs cycle directly. Being rich in hydrogen, fat yields more than twice the energy of carbohydrate per gram (about 9 kcal/g against 4).

Proteins. Amino acids are respired mainly when carbohydrate and fat run short. The amino group is removed first by **deamination** in the liver, giving ammonia (excreted as **urea**). The carbon skeleton (a keto acid) enters as pyruvic acid, acetyl CoA or a Krebs cycle intermediate. The **respiratory quotient** (RQ = CO_2 released ÷ O_2 consumed) is about 1.0 for carbohydrate, 0.7 for fat and 0.8 to 0.9 for protein.

MDCAT trap: counting once instead of twice.

Most wrong answers here come from forgetting that one glucose gives two pyruvic acids, so every stage after glycolysis runs twice per glucose. The figures students memorise are per turn: 1 CO_2 and 1 NADH in the link reaction; 2 CO_2, 3 NADH, 1 $FADH_2$ and 1 ATP per turn of the Krebs cycle. "Per glucose" means double all of these: 2 CO_2 and 2 NADH from the link reaction; 4 CO_2, 6 NADH, 2 $FADH_2$ and 2 ATP from the cycle. A reliable check is carbon: six carbons enter as glucose, so exactly six CO_2 must come out (2 link, 4 Krebs).

Worked example: tallying one glucose before the electron transport chain.

Question: For one glucose respired aerobically, how many CO_2, NADH, $FADH_2$ and directly made ATP exist by the end of the Krebs cycle, and what total ATP follows if NADH = 3 ATP and $FADH_2$ = 2 ATP?

Step 1, glycolysis (once): 0 CO_2, 2 NADH, 0 $FADH_2$, 2 ATP net.

Step 2, link reaction (twice): 2 CO_2, 2 NADH, 0 ATP.

Step 3, Krebs cycle (two turns): 4 CO_2, 6 NADH, 2 $FADH_2$, 2 ATP.

Step 4, totals: 6 CO_2, 10 NADH, 2 $FADH_2$, 4 ATP.

Step 5, ETC: 10 × 3 = 30, plus 2 × 2 = 4, plus 4 direct = 38 ATP. If the question says the glycolytic NADH enters via FAD, subtract 2 to get 36.

Answer: 6 CO_2, 10 NADH, 2 $FADH_2$, 4 ATP directly; 38 ATP in total (36 with the shuttle correction).

Practice MCQs

1. Which pigment forms the reaction centre of both photosystem I and photosystem II?
   A. Chlorophyll b
   B. Beta-carotene
   C. Chlorophyll a
   D. Xanthophyll

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2. A green plant is given water whose oxygen atoms are the heavy isotope ^{18}O, and ordinary carbon dioxide. After an hour in the light, most of the ^{18}O will be in:
   A. The glucose produced
   B. The carbon dioxide inside the leaf
   C. The starch stored in the chloroplast
   D. The oxygen gas released
3. An inhibitor blocks photosystem II completely but leaves photosystem I working. Which product of the light-dependent reactions can the chloroplast still make?
   A. ATP
   B. NADPH
   C. Oxygen
   D. Hydrogen ions from photolysis
4. In the Calvin cycle, three molecules of CO_2 are fixed by RuBisCO. How many molecules of G3P leave the cycle as net product after RuBP has been regenerated?
   A. 1
   B. 2
   C. 3
   D. 6
5. A plant is kept at 25 °C in dim light. Doubling the CO_2 concentration does not change its rate of photosynthesis, but doubling the light intensity nearly doubles it. The limiting factor was:
   A. CO_2 concentration
   B. Light intensity
   C. Temperature
   D. Water supply
6. The conversion of pyruvic acid to acetyl CoA takes place in the:
   A. Cytoplasm
   B. Inner mitochondrial membrane
   C. Intermembrane space of the mitochondrion
   D. Mitochondrial matrix
7. In aerobic respiration of glucose, carbon dioxide is released during:
   A. Glycolysis only
   B. The link reaction and the Krebs cycle
   C. The electron transport chain
   D. Glycolysis and the electron transport chain
8. Cyanide stops cytochrome oxidase from passing electrons to oxygen. In a poisoned cell, which happens first?
   A. Glycolysis stops immediately because it needs oxygen
   B. ATP synthase pumps protons out of the matrix faster
   C. NADH accumulates, NAD^+ runs short, and the Krebs cycle slows
   D. $FADH_2$ is converted to NADH to by-pass the block
9. Yeast cells are grown in a sealed flask of glucose solution with no oxygen. Per molecule of glucose used, how many molecules of CO_2 are released and how many ATP are gained?
   A. 0 CO_2 and 2 ATP
   B. 2 CO_2 and 2 ATP
   C. 6 CO_2 and 2 ATP

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D. 2 CO_2 and 38 ATP

10. Before the carbon skeleton of an amino acid can be respired, the cell must first:
    A. Phosphorylate it using two ATP
    B. Convert it into glucose in the liver
    C. Remove its amino group by deamination
    D. Reduce it using NADH from glycolysis

1. C. Chlorophyll a forms both reaction centres (P680 and P700); chlorophyll b and the carotenoids are accessory pigments.

2. D. The oxygen released comes entirely from photolysis of water, so labelled water gives labelled O_2; the oxygen in glucose comes from CO_2.

3. A. With PS I alone, cyclic photophosphorylation still runs and makes ATP. NADPH, oxygen and the H^+ of photolysis all need PS II.

4. A. Three CO_2 give six PGA and then six G3P; five G3P (15 carbons) regenerate three RuBP, so one G3P is the net gain.

5. B. Raising a factor that is not limiting has no effect; only light changed the rate, so light was limiting.

6. D. The link reaction and the Krebs cycle both take place in the matrix.

7. B. Two CO_2 are released in the link reaction and four in the two turns of the Krebs cycle; glycolysis and the electron transport chain release none.

8. C. Without a final electron acceptor the chain stays reduced, so NADH cannot be reoxidised and the Krebs cycle runs short of NAD^+.

9. B. Yeast ferments: glycolysis gives 2 ATP net, and decarboxylation of the two pyruvic acids releases 2 CO_2 before acetaldehyde is reduced to ethanol.

10. C. Deamination removes the amino group (which becomes urea); the keto acid left enters as pyruvic acid, acetyl CoA or a Krebs cycle intermediate.

Before the test: 12 facts to recite

1. Light reactions: thylakoid membranes, products ATP, NADPH, O_2. Calvin cycle: stroma, product G3P (then glucose).
2. All oxygen released by photosynthesis comes from water, split by photolysis at PS II: $2H_2O \rightarrow 4H^+ + 4e^- + O_2$.
3. Chlorophyll a is the reaction-centre pigment: P680 in PS II, P700 in PS I. Chlorophyll b and carotenoids are accessory pigments.
4. Chlorophyll absorbs violet-blue and orange-red, reflects green. Absorption spectrum = light absorbed; action spectrum = rate of photosynthesis.
5. Non-cyclic photophosphorylation: PS II and PS I, electrons from water to $NADP^+$, makes ATP + NADPH + O_2. Cyclic: PS I only, ATP only.
6. Calvin cycle: CO_2 + RuBP (5C) → 2 PGA (3C) by RuBisCO; PGA → G3P using ATP and NADPH; RuBP regenerated using ATP. Each CO_2 costs 3 ATP and 2 NADPH; one glucose

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costs 18 ATP and 12 NADPH.

7. Limiting factors: light intensity, CO_2 concentration, temperature (and water indirectly). The rate is set by the factor in shortest supply.
8. Glycolysis: cytoplasm, no oxygen, glucose → 2 pyruvic acid, 2 ATP net (4 made, 2 used), 2 NADH, no CO_2.
9. Link reaction: matrix, each pyruvic acid → acetyl CoA + CO_2 + NADH. Krebs cycle: matrix, each turn 2 CO_2, 3 NADH, 1 $FADH_2$, 1 ATP; two turns per glucose.
10. ETC: inner mitochondrial membrane; NADH gives 3 ATP, $FADH_2$ gives 2; H^+ pumped into the intermembrane space returns through ATP synthase; oxygen is the final electron acceptor.
11. Per glucose: 6 CO_2, 10 NADH, 2 $FADH_2$, 4 ATP directly; total 38 ATP (or 36 with the shuttle cost); anaerobic respiration gives only 2.
12. Fermentation regenerates NAD^+: yeast makes ethanol + CO_2, muscle makes lactic acid with no CO_2. Fats enter as glycerol (to G3P) and acetyl CoA (beta-oxidation); amino acids are deaminated first.

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