C1.3 Photosynthesis

IB / A Level Exam Preparation Notes

Guiding questions

1. How is energy from sunlight absorbed and used in photosynthesis?
2. How do abiotic factors interact with photosynthesis?

These notes condense the topic into exam-ready explanations, comparison tables, labelled process summaries, practical skills, higher-level extensions, and mark-scheme-style answers.

Core emphasis	HL emphasis	Skills emphasis
Photosynthesis equation; oxygen as a by-product; pigments; absorption/action spectra; limiting factors; carbon dioxide enrichment experiments.	Photosystems; light-dependent reactions; photolysis; photophosphorylation; NADP reduction; Calvin cycle; Rubisco; interdependence of stages.	Chromatography and Rf calculations; measuring oxygen production or carbon dioxide uptake; graph interpretation; variables, controls and hypotheses.

High-yield summary

Photosynthesis transforms light energy into chemical energy in organic carbon compounds. In plants, algae and cyanobacteria, water is split; oxygen is released as a waste product; hydrogen/electrons are used to reduce carbon dioxide to carbohydrates.

Core equation: $6CO_2 + 6H_2O$ --light--> $C_6H_{12}O_6 + 6O_2$.

For HL, ATP and reduced NADP from the thylakoid light-dependent reactions power carbon fixation and reduction in the Calvin cycle in the stroma.

Fast syllabus checklist

Reference	What you must be able to do
C1.3.1	Explain that photosynthesis transforms light energy into chemical energy in carbon compounds, supplying most ecosystem energy.
C1.3.2-3	Write the word and balanced equations; state that oxygen comes from water splitting and is a by-product.
C1.3.4	Separate/identify photosynthetic pigments using chromatography and calculate Rf values.
C1.3.5-6	Interpret absorption and action spectra; explain excitation of electrons and wavelength specificity.
C1.3.7	Investigate photosynthesis rate by changing CO_2 concentration, light intensity or temperature; identify variables and controls.
C1.3.8	Explain greenhouse and FACE carbon dioxide enrichment experiments and why field/lab controls differ.
HL C1.3.9-14	Describe photosystems, photolysis, non-cyclic and cyclic photophosphorylation, chemiosmosis, NADP reduction and thylakoid roles.
HL C1.3.15-18	Describe the Calvin cycle: Rubisco, RuBP, GP, TP, ATP/NADPH use, RuBP regeneration and synthesis of other compounds.
HL C1.3.19	Explain the interdependence of light-dependent and light-independent reactions.

Exam command words to practise

Command	What examiners expect
State / identify	A short factual answer; no long explanation required.
Outline	Give key points in sequence or with brief detail.
Explain	Give reasons, mechanisms or cause-and-effect links.
Compare and contrast	Give similarities and differences; use linked pairs where possible.
Calculate	Show formula, substitution and answer with units if relevant.
Evaluate	Use data to support both strengths and limitations before reaching a judgement.

1. Photosynthesis: the big idea

Photosynthesis is the metabolic process in which light energy is absorbed and converted into chemical energy stored in carbon compounds. In ecosystems, this is the starting point for most food chains because photoautotrophs make organic molecules that can be used by themselves and by heterotrophs.

Overall word equation

carbon dioxide + water --light--> glucose + oxygen

Balanced equation

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

Substance	Role in photosynthesis	Exam note
Carbon dioxide	Reduced to form glucose and other organic carbon compounds.	CO_2 supplies the carbon atoms in carbohydrates.
Water	Split during photolysis to provide electrons and hydrogen ions.	Oxygen released by photosynthesis comes from water, not carbon dioxide.
Light	Provides energy to excite electrons in photosynthetic pigments.	Light is required directly in light-dependent reactions.
Glucose / sugar phosphate	Stores chemical energy in covalent bonds.	Glucose is a useful simplified product; plants often make TP, sucrose, starch or cellulose.
Oxygen	Released as a waste product of water splitting.	O_2 transformed Earth's atmosphere and enabled aerobic respiration.

Redox framing

Water is oxidized because it loses electrons/hydrogen. Carbon dioxide is reduced because it gains hydrogen/electrons to become carbohydrate.

Photosynthesis therefore involves an energy-requiring redox transformation: low-energy CO_2 and H_2O are converted into higher-energy organic compounds.

Key terminology

Term	Definition
Autotroph	An organism that produces its own organic molecules from inorganic substances.
Photoautotroph	An autotroph that uses light as its energy source.
Heterotroph	An organism that obtains organic molecules from other organisms.
Pigment	A molecule that absorbs specific wavelengths of light.
Photon	A discrete packet of light energy.
Carbon fixation	The conversion of inorganic carbon dioxide into organic carbon compounds.

2. Photosynthetic pigments and chromatography

Leaves look green because chloroplasts contain pigments, especially chlorophylls, that absorb red and blue light more strongly than green light. The reflected/transmitted green wavelengths reach our eyes.

Main pigment groups

Pigment	Typical colour	Main importance
Chlorophyll a	Blue-green	Primary pigment at reaction centres; essential for electron emission.
Chlorophyll b	Yellow-green	Accessory pigment; broadens the wavelengths absorbed.
Carotene	Orange	Accessory pigment; often travels far in chromatography because it is highly soluble in non-polar solvents.
Xanthophyll	Yellow	Accessory pigment; helps absorb additional wavelengths and can protect photosystems.

Chromatography separates pigments because each pigment has a different solubility in the mobile phase and a different attraction to the stationary phase.

Rf calculation

Rf = distance moved by pigment / distance moved by solvent front

Typical pigment	Approximate Rf value	Interpretation
Carotene	0.95	Most soluble / least attracted to paper in the example solvent.
Xanthophyll	0.71	Intermediate movement.
Chlorophyll a	0.65	Moves less far than carotene.
Chlorophyll b	0.45	Moves least far in this example.

Worked Rf example

A pigment spot moves 8.4 cm and the solvent front moves 12.0 cm.

Rf = 8.4 / 12.0 = 0.70. This value is closest to xanthophyll in the table above.

A higher Rf value usually means the pigment was more soluble in the solvent and/or had lower affinity for the paper.

Common exam mistakes

- Do not say pigments separate because they have different colours. Colour lets you identify bands after separation; it is not the cause of separation.
- Do not forget that Rf values have no units because they are ratios.
- Do not assume a pigment's Rf value is fixed in all experiments. Different solvents or stationary phases can change Rf values.

3. Absorption spectra and action spectra

Visible light ranges approximately from violet-blue wavelengths around 400 nm to red wavelengths around 700 nm. Pigments absorb only some wavelengths because electron excitation requires photons with suitable energy.

Concept	What it shows	How to interpret
Absorption spectrum	Percentage or amount of light absorbed by a pigment or group of pigments at different wavelengths.	High absorption means that wavelength is strongly absorbed by the pigment.
Action spectrum	Rate of photosynthesis at different wavelengths.	High rate means that wavelength is effective for photosynthesis.
Relationship	The action spectrum usually resembles the combined absorption spectra of photosynthetic pigments.	Red and blue light usually produce high photosynthesis rates; green light is less effective.

Photon absorbed by pigment	Electron excited to higher energy level	Energy transferred through pigment array	Chemical energy formed ATP / NADPH / carbohydrate

Key interpretation points

- Blue light has a shorter wavelength and higher photon energy than red light.
- Chlorophylls absorb strongly in violet-blue and red regions.
- Green wavelengths are absorbed less and are more likely to be reflected; this is why many leaves appear green.
- Carotenoids broaden the range of wavelengths that can support photosynthesis.
- If a pigment absorbs little light at a wavelength, that pigment contributes little to the photosynthesis rate at that wavelength.

Exam tip: graph comparisons

When asked to compare absorption and action spectra, mention both a similarity and a difference. Example: both vary with wavelength and pigment composition, but absorption spectra measure light absorbed while action spectra measure the photosynthetic rate.

4. Measuring the rate of photosynthesis

Photosynthesis rate can be measured directly by oxygen production or carbon dioxide consumption. Because plants also respire, a correction for respiration may be needed, especially in low light or darkness.

Method	What is measured	Strength	Limitation
Bubble count from aquatic plant	Number of oxygen bubbles per unit time.	Simple and quick.	Bubble size may vary, so it is less precise.
Gas volume in a photosynthometer	Volume of oxygen produced over time.	More quantitative than counting bubbles.	Requires careful sealing and temperature control.
pH / hydrogen carbonate indicator	Carbon dioxide uptake changes acidity and indicator colour.	Useful visual method.	Colour matching is semi-quantitative unless a colorimeter is used.
O_2 or CO_2 electronic sensors	Gas concentration change over time.	Precise and can log data continuously.	Equipment must be calibrated; chambers must be controlled.
Biomass change	Mass increase over longer periods.	Relevant to plant growth.	Indirect; mass also depends on respiration, water content and mineral supply.

Rate calculations

Rate = change in oxygen produced or carbon dioxide used / time

Example	Calculation	Answer
Oxygen volume rises from 0.2 cm^3 to 1.4 cm^3 in 6 min.	(1.4 - 0.2) / 6	0.20 cm^3 min^{-1}
CO_2 concentration falls from 500 ppm to 380 ppm in 20 min.	(500 - 380) / 20	6 ppm min^{-1} consumed

Designing a limiting-factor experiment

Independent variable: the factor changed, e.g. light intensity, CO_2 concentration or temperature.

Dependent variable: photosynthesis rate, measured by oxygen production or carbon dioxide uptake.

Controlled variables: plant species/size, duration, wavelength of light, pH, water volume, distance from lamp unless it is the independent variable, and initial CO_2 concentration unless it is the independent variable.

Reliability: repeat trials and calculate a mean; exclude anomalies only with justification.

5. Limiting factors and abiotic conditions

Blackman's law of limiting factors states that when a process depends on several factors, the rate is limited by the factor in shortest supply or at the least favourable value.

Abiotic factor	Expected graph pattern	Reason
Light intensity	Rate increases at first, then plateaus.	More photons excite more electrons until another factor, such as CO_2 or enzyme capacity, becomes limiting.
Temperature	Rate increases to an optimum, then falls sharply.	Higher temperature increases molecular collisions, but excessive heat denatures enzymes and disrupts membranes.
Carbon dioxide concentration	Rate increases at first, then plateaus.	More CO_2 increases carbon fixation until light intensity, temperature or enzyme capacity becomes limiting.
Water availability	Low water lowers photosynthesis.	Water is a reactant and stomatal closure reduces CO_2 entry during water stress.
Chlorophyll / chloroplast content	Low pigment content lowers rate.	Fewer pigments absorb less light energy.

Greenhouse and FACE experiments

Experiment type	What it does	Why it matters
Enclosed greenhouse CO_2 enrichment	CO_2, temperature, water and other variables can be manipulated in a controlled environment.	High control improves internal validity but conditions may not represent natural ecosystems.
FACE (free-air carbon dioxide enrichment)	CO_2 is increased around plants growing in natural or agricultural field conditions.	More realistic ecological validity, but fewer variables can be fully controlled.
Future photosynthesis predictions	Researchers compare growth, photosynthesis rate, crop quality, pollen production and ecosystem responses under elevated CO_2.	Higher CO_2 can increase photosynthesis in some plants, but heat, water stress, minerals, pests and reduced crop protein can limit benefits.

Controlled variables in CO_2 enrichment

Examples include plant species, age, light intensity, water supply, mineral nutrients, soil type, temperature, humidity and exposure time. In field experiments, not all can be controlled perfectly, so careful replication and monitoring are essential.

6. HL: light-dependent reactions and photosystems

The light-dependent reactions occur in thylakoid membranes. Photosystems are structured arrays of chlorophyll and accessory pigment molecules with a special chlorophyll a pair at the reaction centre.

Feature	Photosystem II	Photosystem I
Reaction centre	P680	P700
Most efficient absorption	680 nm	700 nm
Main role	Excites electrons that enter the first electron transport chain; lost electrons are replaced by photolysis of water.	Re-excites electrons and helps reduce NADP to NADPH.
Associated product	Contributes to proton gradient and oxygen release.	Reduced NADP (NADPH).

Photosystem structure

Accessory pigments absorb photons of varied wavelengths	Energy transfer from pigment to pigment	Reaction centre special chlorophyll a receives energy	Primary electron acceptor captures emitted excited electron

Why a structured array is useful

- A single pigment molecule cannot run photosynthesis alone.
- Different accessory pigments absorb different wavelengths, broadening the action spectrum.
- Many pigments funnel energy to a reaction centre efficiently.
- Chlorophyll a is the primary pigment because its excited electrons can be emitted to the electron acceptor.

Photolysis

In photosystem II, light energy drives the splitting of water: H_2O --> $2H^+ + 2e^- + 1/2O_2$.

Electrons replace those lost from P680, protons contribute to the proton gradient, and oxygen is released as waste.

7. HL: photophosphorylation and chemiosmosis

Photophosphorylation is the production of ATP using light energy. In chloroplasts, an electron transport chain in the thylakoid membrane pumps protons into the thylakoid space. Protons then diffuse back to the stroma through ATP synthase, driving ATP production.

Step	Non-cyclic photophosphorylation
1	Photons excite electrons in photosystem II.
2	Photolysis of water replaces electrons lost from photosystem II and releases O_2.
3	Excited electrons pass along an electron transport chain; released energy pumps H^+ into the thylakoid space.
4	A proton gradient forms across the thylakoid membrane.
5	H^+ diffuses through ATP synthase into the stroma, phosphorylating ADP to ATP.
6	Electrons reach photosystem I, are re-excited, and eventually reduce NADP to NADPH.

Feature	Cyclic photophosphorylation	Non-cyclic photophosphorylation
Photosystem used	Photosystem I only.	Photosystems II and I.
Electron path	Electrons cycle back to the cytochrome complex.	Electrons flow from water to NADP.
Products	ATP only.	ATP, NADPH and oxygen.
Photolysis	No water splitting.	Water is split at photosystem II.
When useful	When extra ATP is needed and NADPH is already abundant.	Main route during oxygenic photosynthesis.

Comparison with respiration chemiosmosis

Feature	Mitochondria	Chloroplasts
Membrane	Inner mitochondrial membrane / cristae.	Thylakoid membrane.
Protons pumped into	Intermembrane space.	Thylakoid space / lumen.
Protons flow back into	Matrix.	Stroma.
Electron source	Reduced NAD and FAD from respiration.	Excited electrons from photosystems.
ATP synthase role	Phosphorylates ADP to ATP.	Photophosphorylates ADP to ATP.

8. HL: the Calvin cycle

The light-independent reactions, also called the Calvin cycle, occur in the stroma. They are not directly powered by light, but they depend on ATP and reduced NADP from the light-dependent reactions.

Carbon fixation RuBP + CO_2 --Rubisco--> unstable 6C compound	GP formation unstable 6C splits into two GP molecules	Reduction GP + ATP + NADPH --> TP	Regeneration most TP + ATP --> RuBP

Molecule / enzyme	Full name / nature	Role
RuBP	Ribulose bisphosphate, 5C.	CO_2 acceptor; regenerated so the cycle can continue.
Rubisco	Ribulose bisphosphate carboxylase.	Catalyses carbon fixation; abundant but relatively slow and less effective at low CO_2.
GP	Glycerate 3-phosphate, 3C.	First stable product after carbon fixation.
TP	Triose phosphate, 3C.	Product of GP reduction; used for sugar synthesis or RuBP regeneration.
ATP	Energy carrier.	Provides energy for GP conversion to TP and RuBP regeneration.
NADPH	Reduced NADP.	Provides reducing power to convert GP to TP.

Important stoichiometry

For one 6-carbon sugar phosphate: 6 CO_2 are fixed, 12 GP are produced, 12 TP are formed, 2 TP leave the cycle and 10 TP regenerate 6 RuBP.

This requires 18 ATP and 12 NADPH. A useful shortcut: five-sixths of TP must be used to regenerate RuBP if glucose/sugar phosphate is the product.

Why Rubisco matters

- It catalyses the conversion of inorganic carbon dioxide into organic carbon compounds.
- It is very abundant because it works relatively slowly.
- It is less effective when carbon dioxide concentration is low, so plants need high concentrations of Rubisco in the stroma.

9. Products beyond glucose and interdependence

Glucose is often used in simplified equations, but the immediate carbohydrate product of the Calvin cycle is triose phosphate. TP and other Calvin cycle intermediates can be used to build many compounds.

Product type	How it relates to Calvin cycle intermediates
Glucose / sugar phosphate	Made from TP and used in respiration or biosynthesis.
Sucrose	Formed when glucose combines with fructose; commonly transported in plants.
Starch	Storage polysaccharide made from glucose units.
Cellulose	Structural polysaccharide made from glucose units in cell walls.
Lipids	Fatty acids and glycerol can be produced from metabolic pathways linked to GP or TP.
Amino acids / proteins	Carbon skeletons from Calvin cycle intermediates combine with nitrogen from mineral nutrients.

Interdependence of photosynthesis stages

If this is missing...	Immediate effect	Why
Light	Light-dependent reactions stop; Calvin cycle soon stops.	No ATP or NADPH is produced to power GP reduction and RuBP regeneration.
Water	Photolysis stops; PSII cannot replace lost electrons; oxygen production stops.	Water supplies electrons and protons.
CO_2	Calvin cycle stops; light-dependent reactions become limited.	NADP and ADP are not regenerated efficiently, disrupting electron flow and ATP/NADPH cycling.
NADP	Electron flow from photosystem I slows/stops.	NADP is the terminal electron acceptor of the light-dependent reactions.
ADP + Pi	ATP production slows/stops.	ATP synthase needs ADP and inorganic phosphate.

Thylakoid light reactions use light + water	Produce ATP + NADPH + O_2	Stroma Calvin cycle uses CO_2 + ATP + NADPH	Returns ADP + Pi + NADP

10. Practical and data-handling skills

Photosynthesis questions often test experimental design, graph interpretation and calculations. Use the patterns below to structure answers.

Variables and hypotheses

Investigation	Possible hypothesis	Independent variable	Dependent variable	Key controls
Effect of light intensity	Increasing light intensity increases photosynthesis rate until another factor becomes limiting.	Distance from lamp or measured lux.	O_2 produced per minute.	CO_2, temperature, plant species/size, wavelength, time.
Effect of CO_2 concentration	Increasing CO_2 concentration increases photosynthesis rate until light or temperature becomes limiting.	Sodium hydrogen carbonate concentration or CO_2 ppm.	O_2 produced or CO_2 used per minute.	Light intensity, temperature, plant species/size, pH, time.
Effect of temperature	Photosynthesis rate increases to an optimum then decreases as enzymes denature.	Water bath temperature.	O_2 produced per minute.	Light intensity, CO_2, plant species/size, acclimation time.

Graph interpretation sentence stems

- As [independent variable] increases from ___ to ___, [dependent variable] increases/decreases from ___ to ___.
- The relationship is positive/negative/no correlation in this range.
- The rate plateaus because another factor becomes limiting.
- The rate decreases at high temperature because enzymes/proteins denature and active sites lose their shape.
- At the compensation point, oxygen produced by photosynthesis equals oxygen used in respiration.

NOS: validity and reliability

Validity: the method measures what it is intended to measure. Improve by controlling confounding variables and using direct measures such as gas sensors.

Reliability: repeated measurements are consistent. Improve by repeats, means, calibrated apparatus and standardized procedures.

11. High-yield comparison tables

Photosynthesis vs respiration

Feature	Photosynthesis	Cell respiration
Overall energy change	Stores light energy as chemical energy.	Releases chemical energy from organic molecules to make ATP.
Simplified equation	CO_2 + H_2O -> glucose + O_2.	Glucose + O_2 -> CO_2 + H_2O + ATP.
Main cellular location	Chloroplasts in plants and algae; photosynthetic membranes in cyanobacteria.	Cytoplasm and mitochondria in eukaryotes.
Gas exchange tendency in light	Consumes CO_2 and releases O_2.	Consumes O_2 and releases CO_2.
Redox	CO_2 is reduced; water is oxidized.	Glucose is oxidized; oxygen is reduced.

Light-dependent vs light-independent reactions

Feature	Light-dependent reactions	Light-independent reactions / Calvin cycle
Location	Thylakoid membranes.	Stroma.
Inputs	Light, water, ADP + Pi, NADP.	CO_2, ATP, NADPH, RuBP.
Outputs	O_2, ATP, NADPH.	TP / sugar phosphate, ADP + Pi, NADP, regenerated RuBP.
Main events	Photon absorption, photolysis, electron transport, proton gradient, ATP synthesis, NADP reduction.	Carbon fixation by Rubisco, GP reduction to TP, RuBP regeneration.
Direct light requirement	Yes.	No, but indirectly depends on light reaction products.

Chloroplast locations

Structure	Function
Double membrane	Controls movement of substances into and out of the chloroplast.
Stroma	Fluid matrix containing enzymes for the Calvin cycle, including Rubisco.
Thylakoid membrane	Contains photosystems, electron transport chains and ATP synthase.
Thylakoid space / lumen	Small compartment where protons accumulate to form a steep gradient.
Granum	Stack of thylakoids; increases membrane surface area for light-dependent reactions.

12. Common mistakes and how to avoid them

Mistake	Correction
Saying oxygen comes from carbon dioxide.	Oxygen released by photosynthesis comes from water during photolysis.
Calling the Calvin cycle 'light-dependent'.	It is light-independent directly, but indirectly requires ATP and NADPH from the light-dependent reactions.
Saying green light is not used at all.	Green light is usually less effective, not completely useless.
Confusing NADP and NAD.	NADP/NADPH are used in photosynthesis; NAD/NADH are emphasized in respiration.
Forgetting the compensation point.	At some light intensities, photosynthetic O_2 production equals respiratory O_2 consumption, so net gas exchange is zero.
Using 'amount of light' vaguely.	Use light intensity, wavelength, or duration depending on the experiment.
Not specifying controls.	Name controlled variables and explain why controlling them improves validity.
Saying cyclic photophosphorylation produces NADPH.	Cyclic photophosphorylation produces ATP only.

One-minute memory map

Light-dependent: thylakoids; light + H_2O -> O_2 + ATP + NADPH.

Calvin cycle: stroma; CO_2 + ATP + NADPH -> TP/sugars + ADP + Pi + NADP.

Pigments: absorb red/blue best; reflect green; chromatography separates by solubility/affinity.

Limiting factors: light, CO_2, temperature and water can restrict photosynthesis rate.

13. Exam-style practice questions

Core questions

Q	Question
1	State the reactants and products of photosynthesis using a word equation. (2)
2	Explain why oxygen is described as a by-product of photosynthesis. (2)
3	A pigment moved 9.6 cm and the solvent front moved 12.0 cm. Calculate the Rf value. (2)
4	Compare and contrast absorption and action spectra. (4)
5	Explain why green light usually gives a lower rate of photosynthesis than red or blue light. (3)
6	Describe a method to investigate the effect of light intensity on photosynthesis in an aquatic plant. (5)
7	Explain why increasing carbon dioxide concentration may increase photosynthesis rate only up to a plateau. (3)
8	Suggest one advantage and one limitation of FACE experiments compared with greenhouse CO_2 experiments. (2)

HL questions

Q	Question
9	Describe the role of photosystem II in the light-dependent reactions. (4)
10	Explain how a proton gradient leads to ATP production in thylakoids. (4)
11	Distinguish cyclic and non-cyclic photophosphorylation. (4)
12	Outline carbon fixation in the Calvin cycle. Include the names RuBP, Rubisco and GP. (4)
13	Explain why a lack of CO_2 can disrupt the light-dependent reactions. (3)
14	For the production of one 6-carbon sugar phosphate, state how many CO_2, ATP and NADPH molecules are required. (3)

Multiple-choice practice

Q	Question	Options
15	Where do the light-dependent reactions occur?	A stroma B thylakoid membranes C cytoplasm D mitochondrial matrix
16	Which process releases oxygen in photosynthesis?	A carbon fixation B RuBP regeneration C photolysis D glycolysis
17	Which product of the light-dependent reactions is used to reduce GP to TP?	A oxygen B NADPH C Rubisco D CO_2
18	What is the advantage of a small thylakoid lumen?	A rapid development of a high proton concentration B storage of glucose C faster CO_2 fixation D lower pigment concentration
19	Which statement about Rubisco is correct?	A It splits water B It reduces NADP C It catalyses carbon fixation D It is found in the thylakoid lumen
20	What does cyclic photophosphorylation produce?	A ATP only B ATP and oxygen C NADPH only D glucose only

14. Mark-scheme-style answers

Q	Indicative answer
1	carbon dioxide + water --light--> glucose + oxygen; accept balanced symbols if correct.
2	Oxygen is not needed for carbohydrate formation; it is released when water is split during photolysis; protons/electrons from water are used but O_2 is waste.
3	Rf = 9.6 / 12.0 = 0.80; no units.
4	Both vary with wavelength and depend on pigments present; absorption spectrum shows light absorbed by pigments; action spectrum shows photosynthesis rate; both usually peak in blue/red and are low in green.
5	Chlorophyll absorbs green poorly; more green light is reflected/transmitted; fewer electrons are excited; lower ATP/NADPH production reduces photosynthesis rate.
6	Use aquatic plant in sodium hydrogen carbonate solution; vary light intensity by changing lamp distance or lux; keep temperature/CO_2/plant length/time/wavelength constant; measure O_2 bubbles or gas volume per minute; repeat and calculate mean.
7	CO_2 is a substrate for carbon fixation; increasing CO_2 increases rate when CO_2 is limiting; plateau occurs when another factor such as light intensity, temperature or Rubisco activity becomes limiting.
8	FACE advantage: more realistic field conditions; FACE limitation: harder to control variables. Greenhouse advantage/limitation may be expressed as reverse.
9	PSII absorbs photons at P680; excited electrons pass to a primary acceptor and electron transport chain; photolysis replaces lost electrons; water splitting releases O_2 and H^+; electron transport helps generate proton gradient for ATP synthesis.
10	Electron transport releases energy; energy pumps H^+ into thylakoid lumen; high H^+ concentration forms electrochemical gradient; H^+ diffuses through ATP synthase to stroma; ATP synthase phosphorylates ADP + Pi to ATP.
11	Cyclic uses PSI only and electrons return to the ETC; produces ATP only; non-cyclic uses PSII and PSI, electrons flow from water to NADP; produces ATP, NADPH and O_2.
12	CO_2 combines with RuBP; catalysed by Rubisco; unstable 6C compound forms; it splits into two GP molecules; GP is later reduced using ATP and NADPH.
13	Without CO_2 the Calvin cycle cannot fix carbon; ATP and NADPH are not used efficiently; ADP, Pi and NADP are not regenerated; electron flow/light reactions slow or stop.
14	6 CO_2; 18 ATP; 12 NADPH.
15-20	15 B; 16 C; 17 B; 18 A; 19 C; 20 A.

Final self-test prompts

Explain in one paragraph how light energy becomes chemical energy.

Explain why a plant can respire at night but cannot photosynthesize in the dark.

Draw the Calvin cycle with RuBP, GP and TP, then add where ATP and NADPH are used.

Design one experiment for each limiting factor: light intensity, CO_2 concentration and temperature.