BIOLOGY

Photosynthesis

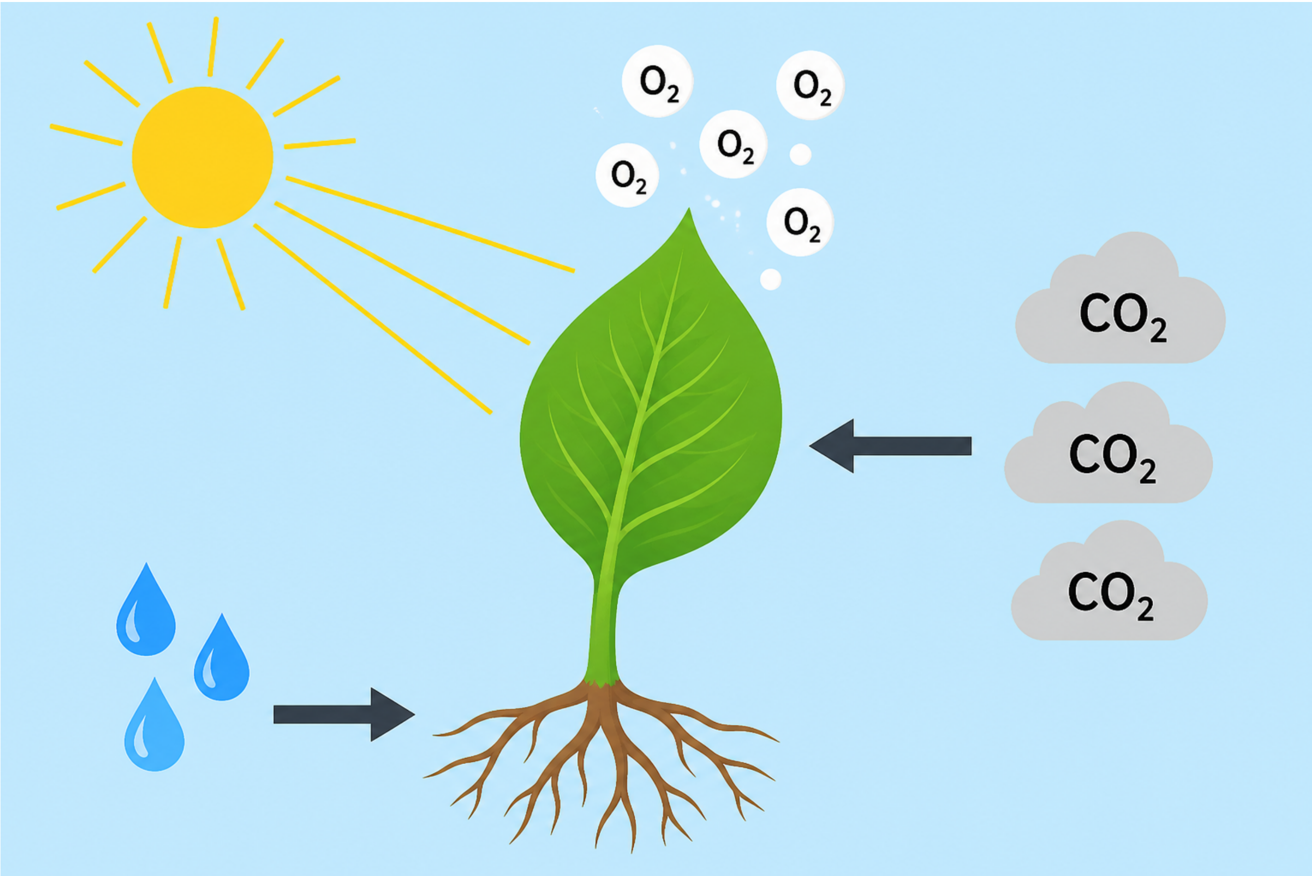
The net equation, the light reactions, the Calvin cycle, pigments, rate factors, C3 vs C4 vs CAM, and a 10-question practice set with full solutions.

SUBJECT	LEVEL	INCLUDES
Biology	High school and early college	Practice set, answer key, revision sheet

Read this note online, with updates: gauravtiwari.org/study-notes/photosynthesis

INSIDE

Photosynthesis is the process by which plants, algae, and cyanobacteria convert sunlight, water, and carbon dioxide into glucose and oxygen. It is the entry point for solar energy into the biosphere. Without photosynthesis there is no food chain, no atmospheric oxygen, no fossil fuels.



What a leaf takes in and gives out: sunlight and water in, carbon dioxide drawn from the air, oxygen released.

The Net Equation of Photosynthesis

The simplest summary of photosynthesis fits in one line:

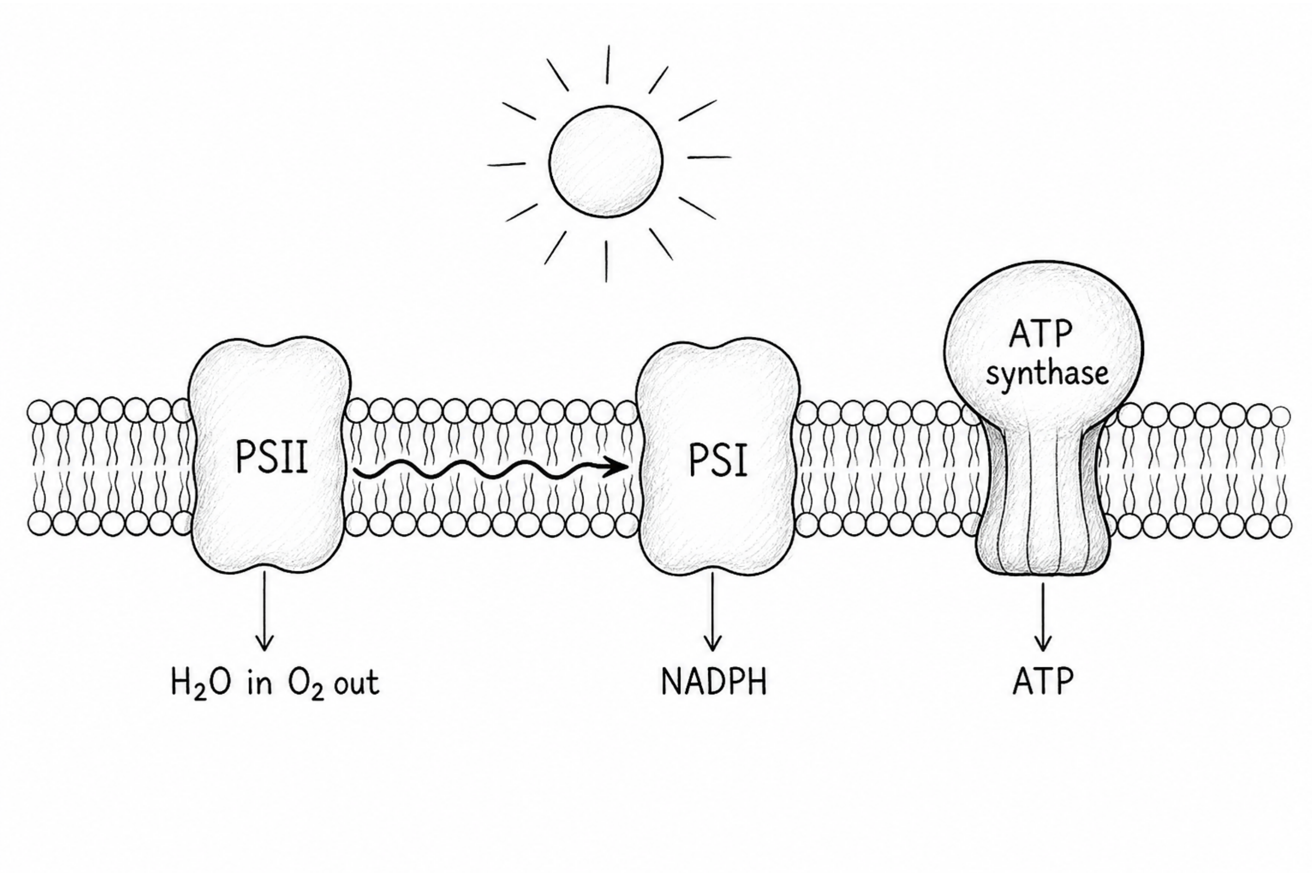
$$6\,CO_2 + 6\,H_2O + \text{light energy} \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

Six molecules of carbon dioxide and six of water, driven by light, produce one molecule of glucose and six of oxygen. Written that way it looks like a single chemical reaction. In reality it is the integrated output of dozens of enzymatic steps in two distinct stages. The two stages can be separated cleanly, even spatially: the light reactions happen in the thylakoid membrane, the Calvin cycle happens in the surrounding stroma.

The oxygen released comes from the water, not from the CO_2. Labeling experiments with the heavy isotope ^{18}O found the label in the released gas, and exam papers test this almost every year because the equation alone suggests the wrong answer.

Stage 1: The Light Reactions

The light reactions take place in the thylakoid membrane of the chloroplast. Their job is to capture photon energy, split water, release oxygen, and produce two energy-carrying molecules (ATP and NADPH) that the Calvin cycle will use in stage 2.



The light reactions in the thylakoid membrane: water in and oxygen out at PSII, ATP from the proton gradient, NADPH at PSI.

Photosystem II (PSII)

PSII is named in reverse order of discovery, not function. It is actually the first step. A photon excites a chlorophyll-a molecule at the reaction center called P680. The excited electron is captured by an electron transport chain. To replace the lost electron, PSII splits water: $2\,H_2O \longrightarrow 4\,H^+ + O_2 + 4\,e^-$. This is where atmospheric oxygen comes from. Every breath you take traces back to PSII somewhere on Earth, mostly in the oceans.

Electron Transport Chain and ATP Synthase

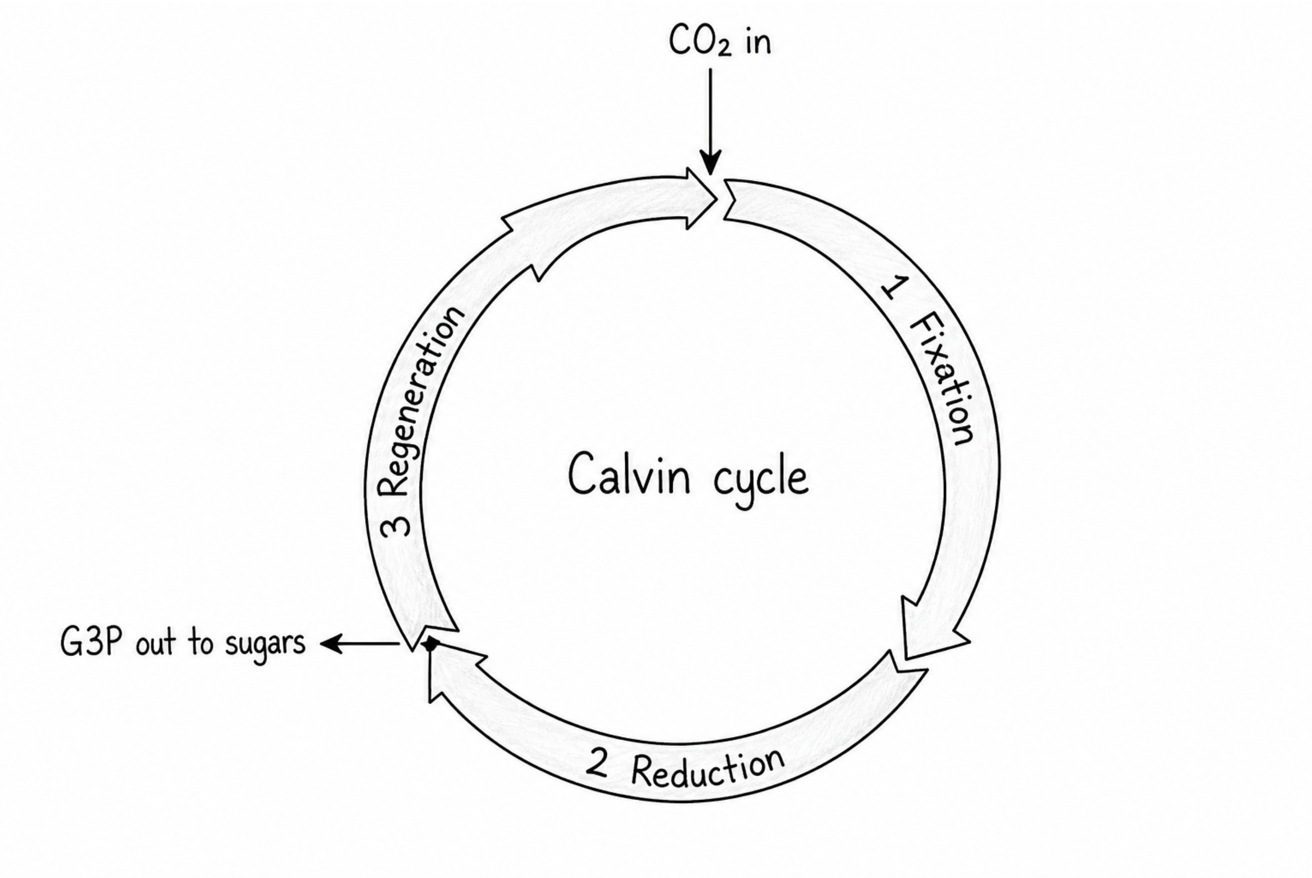
The excited electron moves down an electron transport chain, releasing energy that pumps protons into the thylakoid lumen. The resulting proton gradient drives ATP synthase, which produces ATP. The mechanism is identical in principle to oxidative phosphorylation in the mitochondria, life uses the same trick everywhere.

Photosystem I (PSI)

A second photon excites a chlorophyll molecule at PSI (reaction center P700). The high-energy electron from PSI reduces NADP+ to NADPH. The light reactions therefore yield three products: O_2 (released as a byproduct), ATP, and NADPH. NADPH and ATP both move into the stroma for use in stage 2.

Stage 2: The Calvin Cycle

The Calvin cycle (also called the light-independent reactions or the C3 pathway) takes place in the stroma. It does not directly require light, but it depends on the ATP and NADPH produced by the light reactions. The cycle fixes CO_2 into sugar in three phases.



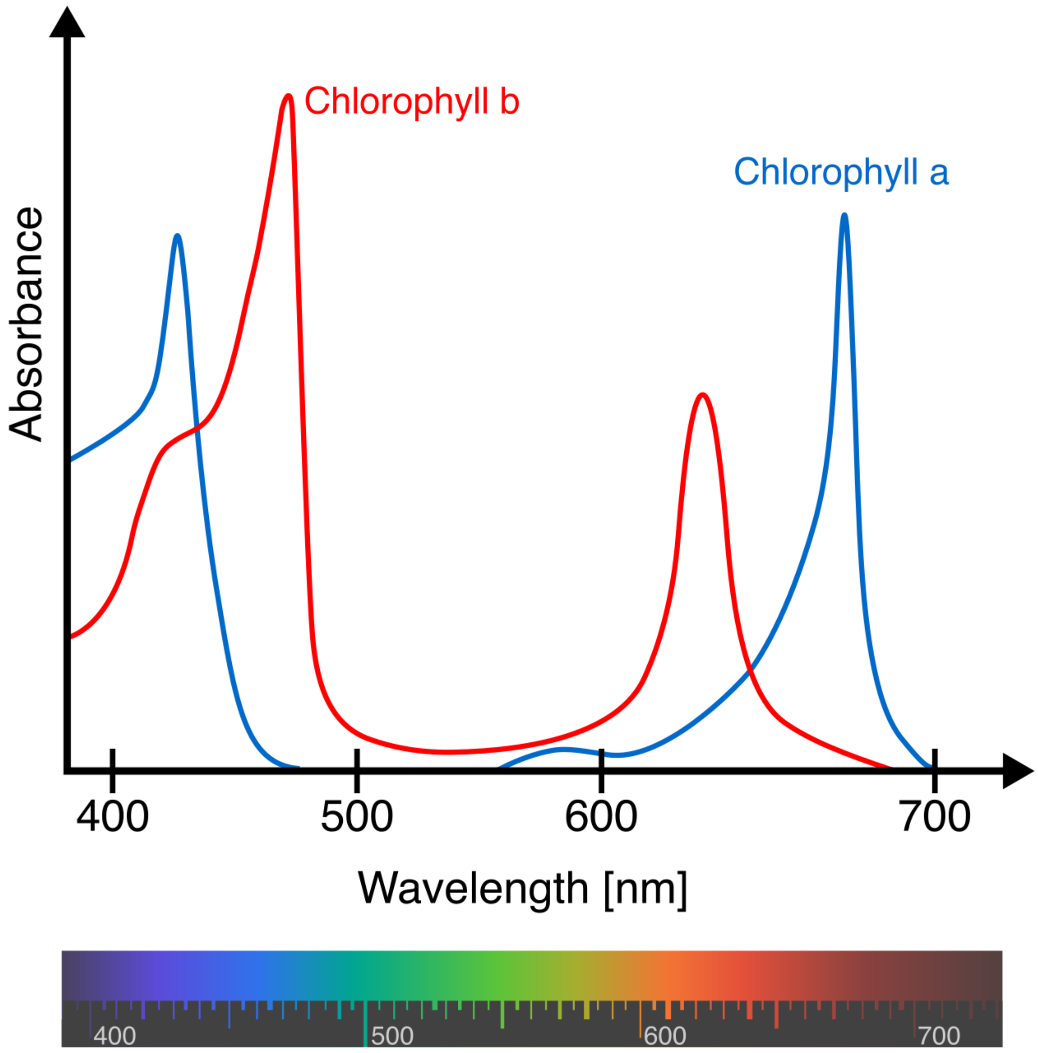
One pass of the Calvin cycle: fixation, reduction, regeneration, with G3P leaving after the reduction step.

1. **Carbon fixation.** The enzyme RuBisCO attaches a CO_2 molecule to a 5-carbon sugar (ribulose-1,5-bisphosphate, or RuBP). The unstable 6-carbon product immediately splits into two 3-carbon molecules of 3-phosphoglycerate (3-PGA). RuBisCO is the most abundant protein on Earth, but it is also notoriously inefficient and slow.
2. **Reduction.** Each 3-PGA is phosphorylated by ATP and then reduced by NADPH to glyceraldehyde-3-phosphate (G3P), a 3-carbon sugar. For every three CO_2 molecules entering the cycle, six G3P are produced. Five of those six G3P regenerate RuBP; one exits to build glucose, sucrose, or starch.
3. **Regeneration.** The remaining five G3P molecules pass through a series of rearrangements that consume more ATP and regenerate three RuBP, ready for the next CO_2.

Stoichiometry: producing one glucose molecule ($C_6H_{12}O_6$) requires six turns of the Calvin cycle, 18 ATP, and 12 NADPH. All of that comes from the light reactions running in parallel in the thylakoid.

Chlorophyll and the Other Pigments

Chlorophyll a is the primary pigment of photosynthesis in plants and cyanobacteria. It absorbs strongly in the blue (around 430 nm) and red (around 662 nm) regions of the spectrum and weakly in the green, which is why leaves look green: green light is reflected rather than absorbed.



Absorption spectra of the chlorophylls: strong in the blue and red, weak in the green, which is why leaves look green.

Chlorophyll a is not the only pigment present. Chlorophyll b broadens the absorption range and passes its captured energy to chlorophyll a. Carotenoids (the orange and yellow pigments that show up when chlorophyll degrades in autumn) absorb in the blue-green and also protect the plant from oxidative damage. Different algae use additional accessory pigments such as phycobilins to capture wavelengths that chlorophyll a misses.

Factors That Affect the Rate of Photosynthesis

- **Light intensity.** Up to a saturation point, photosynthesis rate increases roughly linearly with light intensity. Above saturation, other factors become limiting.
- **CO_2 concentration.** Doubling atmospheric CO_2 in greenhouse experiments roughly doubles the photosynthesis rate in C3 plants until other factors saturate.
- **Temperature.** Photosynthesis enzymes (especially RuBisCO) have an optimum around 25-35°C in temperate plants. Above that, the enzyme denatures and the rate falls sharply.
- **Water availability.** Drought-stressed plants close their stomata to conserve water, which simultaneously shuts off CO_2 intake.
- **Chlorophyll content.** Nitrogen-deficient or iron-deficient plants produce less chlorophyll and photosynthesize more slowly. Crop yields scale heavily with leaf nitrogen status.

C3, C4, and CAM Plants

Different plants have evolved different strategies for handling the inefficiency of RuBisCO, which can wastefully bind oxygen instead of CO_2 in a process called photorespiration.

PATHWAY	EXAMPLES	HOW IT WORKS	WHERE IT WINS
C3	Rice, wheat, soybeans	Standard Calvin cycle in mesophyll cells	Cool, moist climates
C4	Maize, sugarcane, sorghum	Spatial separation: CO_2 pre-fixed in mesophyll, then concentrated in bundle-sheath cells around RuBisCO	Hot climates, high light
CAM	Cacti, pineapples, succulents	Temporal separation: stomata open only at night to fix CO_2; Calvin cycle runs during the day with stomata closed	Arid environments

Photosynthesis vs Cellular Respiration

Photosynthesis and cellular respiration are mirror processes. Photosynthesis builds glucose from CO_2 and water using light energy; cellular respiration breaks glucose back down into CO_2 and water, releasing the stored energy as ATP. Plants do both, animals only do the latter.

$$\text{Photosynthesis:} \quad 6\,CO_2 + 6\,H_2O + \text{light} \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

$$\text{Respiration:} \quad C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{ATP}$$

A plant in bright light photosynthesizes faster than it respires, and the surplus becomes growth. The light level where the 2 rates exactly balance is the compensation point: net gas exchange is zero, and below it the plant cannot grow.

Related study notes: Protein, Carbohydrate, Enzyme, Nucleic Acid.

Practice Questions

Work each question before reading its solution. The set runs from direct recall and substitution to the applied questions that exams actually use to separate grades.

Q1. Write the balanced net equation of photosynthesis and state where each stage of the process occurs.

SOLUTION

$6\,CO_2 + 6\,H_2O + \text{light} \longrightarrow C_6H_{12}O_6 + 6\,O_2$. The light reactions run in the thylakoid membrane; the Calvin cycle runs in the stroma of the chloroplast.

Q2. The oxygen released by a plant comes from which reactant? How was this established?

SOLUTION

From water, not CO_2. PSII splits water: $2\,H_2O \longrightarrow 4\,H^+ + O_2 + 4\,e^-$. Experiments feeding plants water labeled with the heavy isotope ^{18}O found the label in the released oxygen gas, settling the question directly.

Q3. Name the 3 products of the light reactions and state what each is used for.

SOLUTION

O_2, released as a byproduct of water splitting; ATP and NADPH, both consumed by the Calvin cycle in the stroma, ATP as the energy source and NADPH as the reducing power.

Q4. How many turns of the Calvin cycle, ATP, and NADPH does 1 glucose molecule cost?

SOLUTION

6 turns, 18 ATP, and 12 NADPH. Each turn fixes 1 CO_2, and glucose carries 6 carbons, so 6 turns; the ATP and NADPH bill scales with those turns at 3 ATP and 2 NADPH each.

Q5. Why do leaves look green?

SOLUTION

Chlorophyll a absorbs strongly in the blue (about 430 nm) and red (about 662 nm) but weakly in the green. Green light is reflected or transmitted rather than absorbed, so that is the color that reaches your eye. The leaf looks like the light it rejects, not the light it uses.

Q6. A student measures photosynthesis rate against light intensity and finds the curve rises, then flattens. What limits the rate in each region?

SOLUTION

On the rising section, light intensity is the limiting factor: more photons, more photochemistry. On the plateau, light is saturated and something else limits the rate, typically CO_2 concentration or temperature. The plotted variable can only be limiting where changing it changes the rate.

Q7. What is photorespiration, and why is it wasteful?

SOLUTION

RuBisCO sometimes binds O_2 instead of CO_2, sending carbon down a salvage pathway that consumes ATP and releases previously fixed CO_2 without making sugar. It undoes photosynthesis at the plant's expense, and it worsens in hot, dry conditions when closed stomata let O_2 build up inside the leaf.

Q8. Maize outperforms wheat in hot, bright climates. Explain why using their pathways.

SOLUTION

Maize is C4: it pre-fixes CO_2 in mesophyll cells and concentrates it around RuBisCO in bundle-sheath cells, suppressing photorespiration. Wheat is C3 and loses an increasing share of its fixed carbon to photorespiration as temperature rises. The C4 CO_2 pump costs extra ATP, which bright sunlight repays.

Q9. A cactus keeps its stomata shut all day. How does it still run the Calvin cycle in daylight?

SOLUTION

CAM plants open stomata at night, fix CO_2 into organic acids, and store them in vacuoles. By day, with stomata closed against water loss, the acids release CO_2 internally to feed the Calvin cycle. The separation is temporal, night versus day, rather than spatial as in C4.

Q10. Define the compensation point of a plant.

SOLUTION

The light intensity at which photosynthesis exactly balances respiration, so net gas exchange is zero: CO_2 fixed equals CO_2 released. Below it the plant runs a net loss and cannot grow; above it, net photosynthesis accumulates biomass.

Answer Key

QUICK ANSWERS

Q1 equation; thylakoid and stroma **Q2** from water; ^{18}O labeling **Q3** O_2, ATP, NADPH **Q4** 6 turns, 18 ATP, 12 NADPH **Q5** green light is reflected

Q6 light, then CO_2 or temperature **Q7** RuBisCO binds O_2, wasting carbon and ATP **Q8** C4 suppresses photorespiration **Q9** night CO_2 storage as acids **Q10** photosynthesis = respiration

Revision Sheet

The net equation

$6\,CO_2 + 6\,H_2O + \text{light} \longrightarrow C_6H_{12}O_6 + 6\,O_2$. Oxygen comes from the water.

Pigments

Chlorophyll a: main pigment, absorbs blue and red. Chlorophyll b and carotenoids: widen the antenna, protect the leaf.

Light reactions (thylakoid)

PSII (P680) splits water → electron transport chain pumps H^+ → ATP synthase makes ATP → PSI (P700) makes NADPH.

Limiting factors

Light, CO_2, temperature, water, chlorophyll. The rate follows the scarcest input; plateaus mean the limit moved elsewhere.

Calvin cycle (stroma)

Fixation (RuBisCO + RuBP) → reduction (ATP, NADPH → G3P) → regeneration. Per glucose: 6 turns, 18 ATP, 12 NADPH.

C3 / C4 / CAM

C3: standard cycle. C4: spatial CO_2 concentration, wins in heat and light. CAM: night fixation, wins in deserts.

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