Unit 3 · Photosynthesis

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Plant Physiology (Units 2–6 together): 11 of 75 marks; 3 MCQs (knowledge, application, higher ability) and 1 long question (8 marks: knowledge 1, understanding 3, application 2, higher ability 2)
- **The paper:** Botany 37 + Zoology 38; each part: MCQs × 1 (5 Botany, 6 Zoology) · 4 short × 4 · 2 long × 8; one OR in each short and long group; 3 hours; 1 mark per expected point
- **MCQ (1 mark)**
  - anabolic; anoxygenic: which organisms; O_2 from water
  - pigments in the thylakoid membranes; Hill reaction
  - chlorophyll absorbs blue and red; reaction center; P680
  - order of carriers PSII → PSI; cyclic: last acceptor P700
  - first stable product of C_3; RuBisCO; PGA reduction; 18 ATP for 6 CO_2
  - compensation point; maize C_4; Kranz anatomy; cells in the C_4 cycle
- **Short and long (in parts)**
  - photosynthesis in plants; balanced equation, significance
  - pigments; chlorophyll and its types
  - a photosystem from a figure; light absorption in a photosystem
  - flowchart of non-cyclic photophosphorylation; cyclic vs non-cyclic
  - light reaction vs dark reaction; the Calvin cycle with a diagram
  - Hatch–Slack pathway; C_3 vs C_4; why C_4 is more efficient
  - light and temperature; all factors

Key terms

Photosynthesis: green plants, algae and some bacteria turn **light energy** into **chemical energy**, building CO_2 and water into sugar and (plants, algae) giving out O_2.

Anabolic, endergonic, reductive: builds large molecules, stores energy, CO_2 reduced; also **carbon assimilation**.

Pigment: absorbs some wavelengths of light, not others.

Accessory pigments: all but chlorophyll a; absorb other wavelengths, pass energy to chlorophyll a.

Absorption spectrum: light a pigment absorbs at each wavelength; **action spectrum**: rate of photosynthesis at each wavelength.

Photosystem: antenna (light-harvesting complex) + **reaction center** (special pair of chlorophyll a + primary acceptor).

Photolysis of water: splitting of water by light: $2H_2O \rightarrow 4H^+ + 4e^- + O_2$.

Photophosphorylation: ATP made with the energy of light.

Chemiosmosis: ATP made by protons flowing back through **ATP synthase** (Peter Mitchell, Nobel 1978).

Assimilatory power: ATP and NADPH.

Kranz anatomy: bundle sheath ring round each bundle, mesophyll ring round it (C_4 leaves).

Photorespiration (C_2 cycle): light-dependent O_2 uptake and CO_2 release when RuBisCO fixes O_2.

Light compensation point: CO_2 fixed = CO_2 given out in respiration; **saturation point**: more light gives no more uptake.

Limiting factor (**Blackman**, 1905): the factor in shortest supply limits the rate.

Warburg effect: high O_2 lowers photosynthesis (C_3 plants).

Photosynthesis

- **raw materials**: CO_2 (stomata), water (roots, xylem); **energy**: light, absorbed by chlorophyll
- **products**: sugar → starch; **O_2** from **photolysis of water**
- **where**: mesophyll cells, **chloroplasts** ("kitchens of the cell")
- $6\,CO_2 + 12\,H_2O \longrightarrow C_6H_{12}O_6 + 6\,O_2 + 6\,H_2O$ (light, chlorophyll)

	Anoxygenic	Oxygenic
organisms	green, purple sulphur bacteria	cyanobacteria, algae, plants
H donor	H_2S	H_2O
by-product	sulphur	oxygen
pigment	bacteriochlorophyll	chlorophyll a

- $CO_2 + 2\,H_2S \longrightarrow (CH_2O) + H_2O + 2\,S$ (light)

Significance

- all food, directly or through food chains
- takes CO_2 out of the air
- keeps O_2 and CO_2 in balance
- fibers, timber, rubber, drugs, oils, paper
- fossil fuels: ancient sunlight

Pigments

Chlorophylls: absorb **blue-violet and red**, little **green** → leaves look green

- porphyrin head with **Mg** at its center; phytol tail in the membrane
- **chlorophyll a**: primary; in all oxygenic organisms; $C_{55}H_{72}O_5N_4Mg$, ~893; blue-green
- **b**: yellow-green, plants, green algae; **c**: brown algae, diatoms; **d**: cyanobacteria

Carotenoids: absorb violet, blue (400–500 nm); protect chlorophyll from strong light

- **carotenes**: orange, $C_{40}H_{56}$ (β-carotene → vitamin A)
- **xanthophylls**: yellow, contain O: lutein $C_{40}H_{56}O_2$

Phycobilins: **water-soluble**; red algae, cyanobacteria

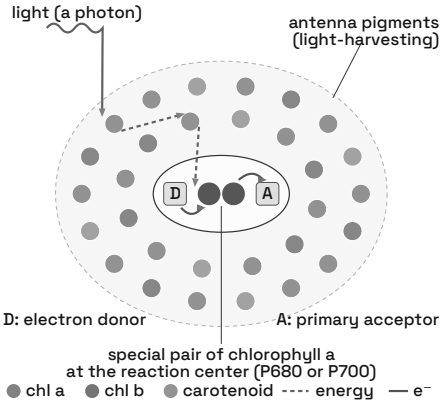
- **phycoerythrin**: red, absorbs green, blue-green → red algae live deep
- **phycocyanin**: blue, absorbs orange-red

Chloroplast: semi-autonomous (own DNA, 70S ribosomes)

- **grana**: stacks of **thylakoids** (2–100, often 10–20); membranes hold pigments, photosystems → **light reaction**
- granal thylakoids and **stroma lamellae**; **lumen** inside each thylakoid (H^+ pumped in)
- **stroma**: RuBisCO, DNA, ribosomes → **dark reaction**

Photosystems

- antenna: 200–400 pigment molecules; photon → **excited** → energy passed by **resonance** (not the electron) → reaction center
- reaction center's special pair loses an electron to the **primary acceptor**; gets one back from a donor
- **PSII = P680**, mostly in grana; **PSI = P700**, stroma lamellae



A photosystem: antenna and reaction center.

Light reaction (thylakoids)

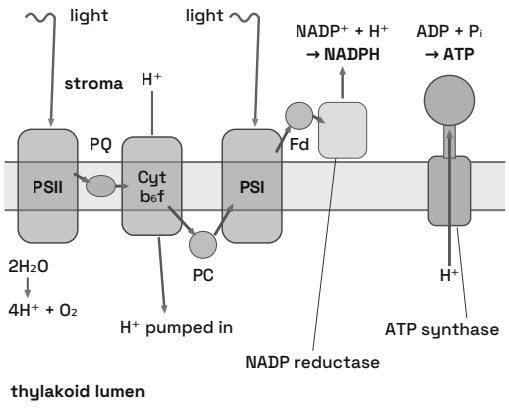
- also photochemical reaction, **Hill's reaction**; makes ATP, NADPH, O_2
- **photo-excitation**: special pair excited → gives up an electron → $P680^+$ / $P700^+$
- **photolysis**: $P680^+$ pulls electrons from water; **oxygen-evolving complex** (Mn, Ca^{2+}, Cl^-) on the lumen side; $2\,H_2O \longrightarrow 4\,H^+ + 4\,e^- + O_2$
- **photophosphorylation**: electron transport pumps H^+ into the lumen (pH ~5 vs 8) → H^+ back through **ATP synthase**: ADP + P_i → ATP
- **NADP reduction**: $NADP^+ + 2e^- + 2H^+ \rightarrow NADPH + H^+$ (often written $NADPH_2$)

Non-cyclic (Z-scheme)

- H_2O → P680 (PSII) → pheophytin → PQ → cyt b_6f (H^+ pumped, ATP) → PC → P700 (PSI) → primary acceptor → Fe–S → Fd → NADP reductase → NADPH
- P680 refilled from water → **O_2**
- products: **ATP, NADPH, O_2**

Cyclic

- PSI only: P700 → primary acceptor → Fe–S → Fd → PQ → cyt b_6f (ATP) → PC → P700
- products: **ATP only**; no NADPH, no photolysis, no O_2
- extra ATP (Calvin cycle needs 3 ATP : 2 NADPH); C_4 bundle sheath; when $NADP^+$ runs out



The light reaction in the thylakoid membrane.

	Non-cyclic	Cyclic
photosystems	PSII and PSI	PSI only
electron path	linear: $H_2O \rightarrow NADP^+$	P700 → P700
first donor	water	P700
last acceptor	$NADP^+$	P700
photolysis, O_2	yes	no
products	ATP, NADPH	ATP only
wavelengths	below 680 nm (PSI to 700)	700 nm and beyond
predominates	grana	stroma lamellae

Dark reaction (stroma)

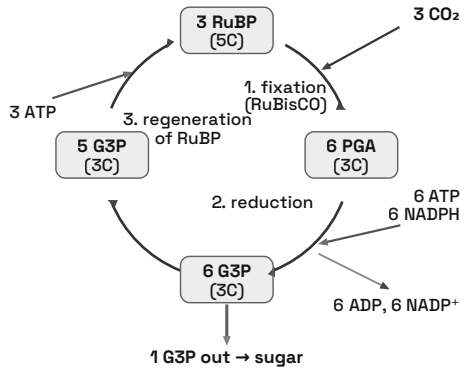
- light-independent; **Blackman's reaction**; uses ATP and NADPH; runs by **day** (enzymes light-activated), stops in the dark
- pathways: **Calvin (C_3)**, **Hatch–Slack (C_4)**, **CAM**; C_4 and CAM feed the Calvin cycle

Calvin–Benson cycle (Calvin, Benson, Bassham, 1946–53; *Chlorella*, $^{14}CO_2$; Calvin Nobel 1961)

1. **carboxylation**: RuBP (5C) + CO_2 → (RuBisCO) → **2 PGA** (3C); 3 CO_2 → 6 PGA
2. **reduction** (glycolytic reversal): 6 PGA + 6 ATP + 6 NADPH → 6 **G3P**; 1 G3P leaves (product); 2 G3P → 1 glucose
3. **regeneration**: 5 G3P + 3 ATP → 3 RuBP

- per CO_2: 3 ATP, 2 NADPH; per glucose (6 turns): **18 ATP, 12 NADPH**

  $6\,RuBP + 6\,CO_2 + 18\,ATP + 12\,NADPH \longrightarrow C_6H_{12}O_6 + 6\,RuBP + 18\,ADP + 18\,P_i + 12\,NADP^+$
- C_3 plants (~9 in 10): rice, wheat, potato, beans, mustard, most trees
- photons: 12 NADPH = 24 e^- × 2 photons = **48 photons** per glucose; 12 H_2O split, 6 O_2



The Calvin cycle.

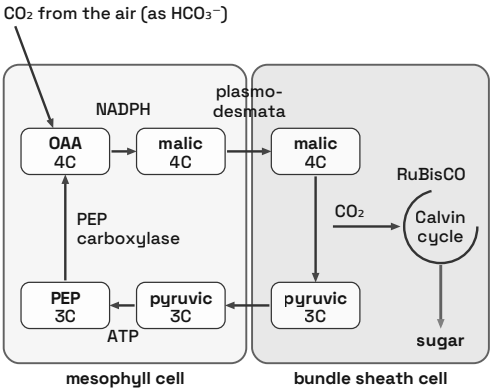
C_4 and CAM plants

Hatch–Slack (C_4) (Hatch and Slack, 1966): first stable product **OAA** (4C)

- maize, sugarcane, sorghum, kodo, amaranth, dubo
- **Kranz anatomy**, **dimorphic chloroplasts**: mesophyll (grana, **PEP carboxylase**, no RuBisCO); bundle sheath (no grana in maize, **RuBisCO**)
- CO_2 fixed **twice**

1. **mesophyll**: $CO_2 \rightarrow HCO_3^-$ (carbonic anhydrase); PEP (3C) + HCO_3^- → (PEP carboxylase) → OAA (4C)
2. OAA + NADPH → **malic acid** (malate dehydrogenase) → bundle sheath by plasmodesmata
3. **bundle sheath**: malic acid → (NADP-malic enzyme) → CO_2 + pyruvic acid + NADPH; CO_2 → Calvin cycle (5–10 × air's CO_2)
4. pyruvic acid → mesophyll → PEP (pyruvate phosphate dikinase; ATP → AMP = 2 ATP)

- $6CO_2 + 6H_2O + 6PEP +$ **30 ATP** $+ 12\,NADPH \rightarrow C_6H_{12}O_6 + \ldots$



The C_4 pathway.

- **why efficient**: PEP carboxylase never takes O_2, works at 0–10 ppm CO_2; CO_2 concentrated round RuBisCO → **almost no photorespiration**; more sugar per liter of water
- Terai: maize (C_4) in summer, wheat (C_3) in winter

	C_3	C_4
first product	PGA (3C)	OAA (4C)
CO_2 acceptor	RuBP	PEP, then RuBP
enzyme	RuBisCO	PEP carboxylase, RuBisCO
Kranz anatomy	absent	present
chloroplasts	one kind	two kinds
CO_2 fixed	once	twice
ATP per glucose	18	30
photorespiration	high	almost nil
CO_2 compensation point	40–100 ppm	0–10 ppm
best temperature	15–30 °C	30–40 °C

CAM (cacti, *Aloe*, *Agave*, pineapple, *Kalanchoe*): fixations separated in **time**

- **night**: stomata **open**; PEP carboxylase → OAA → **malic acid** stored in vacuoles (sour by morning)
- **day**: stomata **closed**; malic acid → CO_2 → Calvin cycle
- little water lost; slow growth

Photorespiration (C_2 cycle)

- RuBisCO fixes **O_2**: RuBP → 1 PGA + 1 **phosphoglycolic acid** (2C); worse in heat and with stomata closed (~1 in 4 at 25 °C)
- **chloroplast**: phosphoglycolic → glycolic acid
- **peroxisome**: glycolic → glyoxylic acid (H_2O_2, catalase) → **glycine**
- **mitochondrion**: 2 glycine → **serine** + **CO_2** + NH_3
- **peroxisome**: serine → hydroxypyruvic → glyceric acid
- **chloroplast**: glyceric acid + ATP → PGA → Calvin cycle
- wasteful: no sugar, no ATP; uses ATP, NADPH; 1 C in 4 lost; C_4 plants hardly photorespire

Factors affecting photosynthesis

External

- **light intensity**: rate ∝ light at first; compensation point; saturation point; very strong → **solarization**
- **light quality**: **red** highest, **blue** second (Engelmann); **green** least, not inhibitory
- **duration**: total depends on it, rate doesn't; flashes give more than continuous light
- **CO_2**: ~0.04% (424 ppm); commonest limiting factor; ↑ to ~0.1% raises C_3 rate; ~1% closes stomata
- **water**: indirect: stomata close, protoplasm dehydrated
- **temperature**: best **15–35 °C**; rate doubles per 10 °C up to the optimum; then enzymes denatured
- **oxygen**: high O_2 lowers rate (**Warburg effect**, 1920)
- **minerals**: Mg (chlorophyll), Fe, Mn, Ca, Cl (water splitting), Cu (plastocyanin), N; lack → **chlorosis**

Internal

- **chlorophyll** (Emerson, 1929: rate ∝ chlorophyll content); albinos die
- **leaf anatomy**: cuticle, stomata, air spaces, palisade, Kranz
- **leaf age**: mature leaf fastest
- **end products** pile up → slower
- **protoplasmic factors**: hydrated protoplasm, active enzymes

COMMON MISTAKES

✗ Oxygen given out comes from CO_2
✓ from **water** (photolysis).

✗ Cyclic photophosphorylation makes NADPH and O_2
✓ **ATP only**; PSI only.

✗ Cyclic only in bacteria, two sites of ATP
✓ plants use it; protons pumped at the cytochrome complex.

✗ Dark reaction happens at night
✓ runs **by day**, needs fresh ATP, NADPH.

✗ First stable product of C_4 is malic acid
✓ **OAA**.

✗ C_4 plants use fewer ATP
✓ **30** per glucose against 18; they win by no photorespiration.

✗ CAM plants open stomata by day
✓ **at night**.

✗ Green light is inhibitory
✓ least effective, still used deeper in the leaf.

✗ RuBisCO takes O_2 only below 100 ppm CO_2
✓ at any level; more in heat.