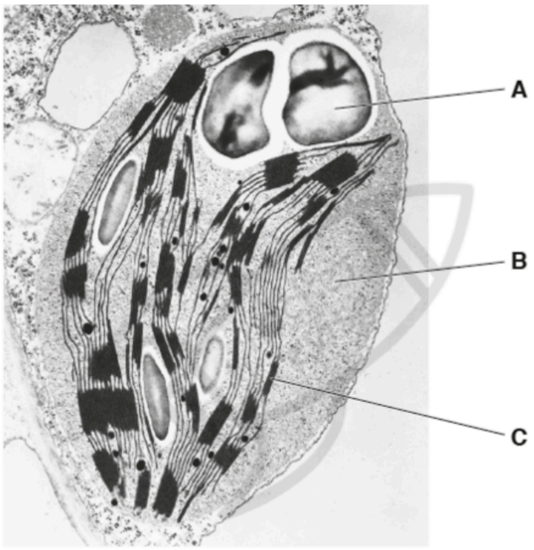
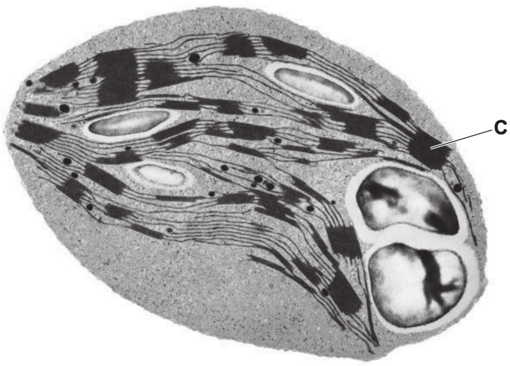
# 13.1 Photosynthesis as an Energy Transfer Process

## Chloroplasts

**Transmission electron micrographs of a chloroplast:**

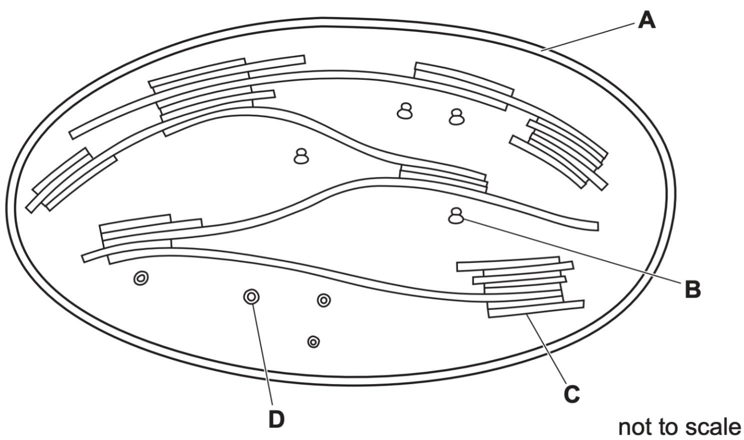



| | |
|---|---|
| **A** | Starch grain |
| **B** | Stroma |
| **C** | Thylakoid / thylakoid membrane |




| | |
|---|---|
| **C** | granum / grana (stack of thylakoids) |

**Diagram of a chloroplast:**



| | |
|---|---|
| **A** | Chloroplast envelope (double membrane) |
| **B** | Ribosomes |
| **C** | Granum (stack of thylakoids) |
| **D** | Circular chloroplast DNA |

**Describe the relationship between the function of a chloroplast and its structure.**

| | **Structure** | **Function** |
|---|---|---|
| 1 | thylakoid(s)/ granum/ grana | light dependent reaction / photophosphorylation |
| 2 | thylakoid membrane(s) | have (named) pigments / photosystems / LHC / electron carriers / ETC / ATP synthase |
| 3 | thylakoid membranes/ grana have large surface area/ are many in number | to absorb (more) light |
| 4 | stroma | for light independent reaction / Calvin cycle |
| 5 | stroma | has (named) enzymes / RuBP / reduced NADP |
| 6 | stroma colourless OR stroma contains water | so light reaches thylakoids OR as a medium for reactions / for photolysis |
| 7 | DNA / ribosomes | make (named) chloroplast proteins / proteins for photosynthesis |
| 8 | starch grains / lipid droplets | store (named) product of photosynthesis / (chemical) energy |
| 9 | envelope | compartmentalisation |

**Explain how the structure of a granum is linked to its function.**

- Granum is a stack of many thylakoids, for increased/ large surface area.
- Increased/ large surface area maximises absorption of light (energy).
- Thylakoid membranes/ grana contain photosynthetic/ named/ primary/ accessory pigments to absorb light (energy).
- Thylakoid membranes/ grana contain electron carriers/ ETC to transfer/ release energy from excited electrons.
- Thylakoid membranes/ grana contain photosystems/ antenna complex and reaction centre; they are are light harvesting structures.
- Thylakoid space or lumen forms proton gradient / have high concentration of protons.

- Thylakoid membrane is relatively impermeable, to maintain the proton gradient for chemiosmosis.
- It contains ATP synthase to make ATP.
- It contains oxygen-evolving complex/ OEC for the photolysis of water.

| **Process / substance involved in photosynthesis** | **Location in chloroplast** |
|---|---|
| ATP synthase | Thylakoid membrane |
| Rubisco | Stroma |
| Phopsholipid bilayer | Chloroplast envelope, Thylakoid membrane |
| Starch grain | Stroma |
| Calvin cycle | Stroma |
| Photosystem II | Thylakoid (membranes) / lamellae / grana |
| Non-cyclic photophosphorylation | thylakoid (membranes) / lamellae / granum / grana |
| Carbon dioxide used (substrate) | Stroma |
| Reduced NADP used (substrate) | Stroma |
| Oxygen produced (product) | Thylakoid membrane |
| ATP produced (product) | Thylakoid membrane |
| Hexose produced (product) | Stroma |
| Light absorption | Thylakoid (membranes) / grana / lamellae |
| Light dependent stage | Thylakoid membrane |
| Light independent stage | Stroma |
| Storage site of the carbohydrate product of photosynthesis | Starch grain |
| Photosynthetic pigments | Thylakoid membrane / granum / grana / lamellae |
| Contains genes that code for some of the enzymes used in photosynthesis | Circular chloroplast DNA (in stroma) |

| | |
|---|---|
| Site of synthesis of some of the enzymes used in photosynthesis. | Ribosomes (in stroma) |

# Stages of Photosynthesis

*Energy transferred as ATP and reduced NADP from the light-dependent stage is used during the light independent stage (Calvin cycle) of photosynthesis to produce complex organic molecules.*

**Outline the way in which hydrogen is made available to reduce the hydrogen acceptor in the light dependent stage of photosynthesis.**

- water is split by photolysis
- in photosystem II
- this reaction is catalysed using an enzyme
- hydrogen ions and electrons from photolysis combine to form hydrogen

**Name the products of the light dependent stage of photosynthesis.**

- reduced NADP
- ATP
- oxygen

**Name the products of the light dependent stage that are needed for the light independent stage.**

- reduced NADP (NADPH)
- ATP

**State the role of reduced NADP in the light independent stage.**

- Reduces GP (glycerate–3–phosphate)
- To TP (triose phosphate)
- By donating hydrogen (H) / electrons to GP

# Thylakoids & the Stroma

*Within a chloroplast, the thylakoids (thylakoid membranes and thylakoid spaces), which occur in stacks called grana, are the site of the light-dependent stage and the stroma is the site of the light-independent stage.*

# Chloroplast Pigments

**Describe the role of photosynthetic pigments.**

- absorb / harvest / capture / trap light / photons.
- to excite electrons.

- for cyclic / non-cyclic photophosphorylation / electron transport chain.
- accessory pigment passes energy to primary pigment / reaction centre.
- pigments form a light harvesting cluster / photosystem / PSI / PSII.

**Describe the role of the chlorophyll b, carotene and xanthophyll in photosynthesis.**

- They are accessory pigments.
- Accessory pigments are part of light-harvesting cluster in photosystems.
- They absorb light/ photons.
- They absorb different wavelengths of light to chlorophyll a/ primary pigment/ reaction centre, that chlorophyll a cannot efficiently absorb.
- This increases range of light energy that can be used for photosynthesis.
- They pass energy/ photons to chlorophyll a/ primary pigment/ reaction centre.

**Copper(II) ions (Cu2+) inhibit the function of a proportion of the chlorophyll a present in single-celled, photosynthetic protoctists.**

| lake | concentration of functional chlorophyll a / $\mu g\ dm^{-3}$ | |
|---|---|---|
| | month **A** | month **B** |
| unpolluted | 3.45 | 0.24 |
| polluted with copper ions | 1.79 | 0.24 |

**a. Describe and suggest explanations for the results shown.**

Description

- In month A functional chlorophyll concentration is higher in unpolluted lake than polluted lake.
- In month B functional chlorophyll concentration is same in both lakes.
- In both lakes, functional chlorophyll concentration is higher in month A than in month B.

Explanation

- In polluted lake copper ions inhibit / damage / disrupt chlorophyll.
- In month B protoctists are dormant / spores / resist entry of ions.
- May be summer / hotter / higher light intensity / longer days in month A so more chlorophyll.
- Flooding might have decreased Cu2+ concentration in month B.
- Evaporation may have increased Cu2+ concentration in month A.

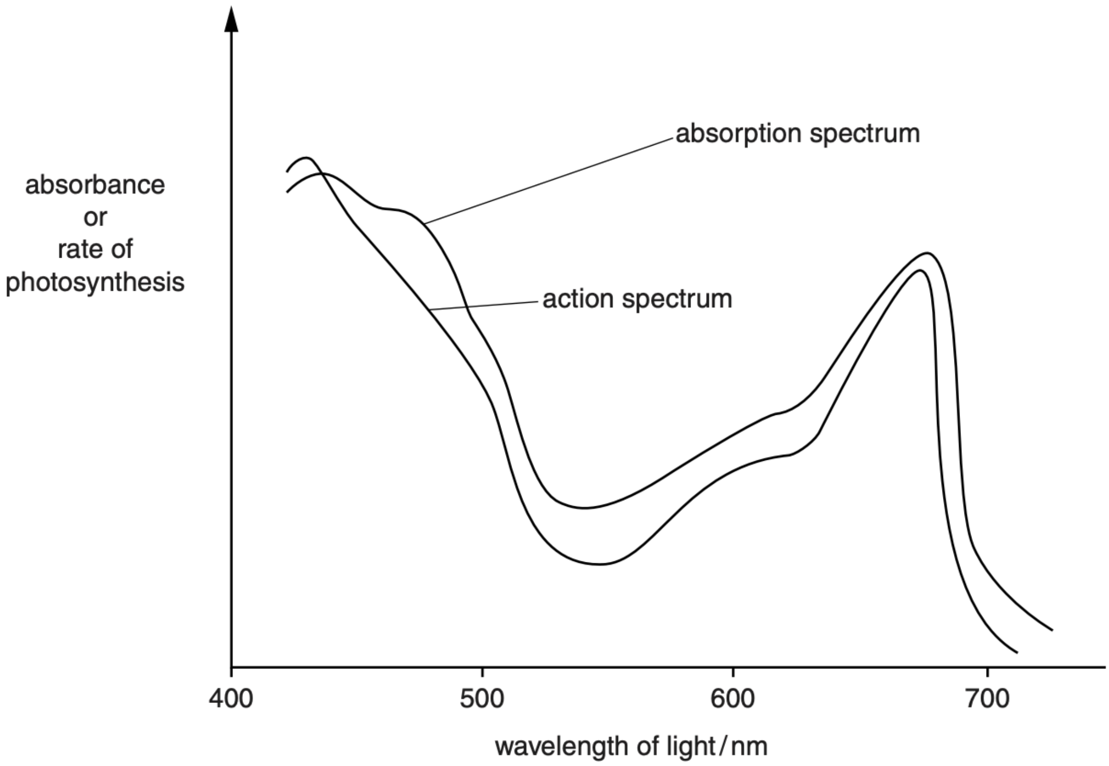
**b. Suggest how copper ions change the structure of chlorophyll a.**

- substitute for magnesium ion / Mg2+

# Absorption Spectra & Action Spectra

**Distinguish between an absorption spectrum and an action spectrum.**
- <u>Absorption spectrum:</u> shows the absorbance / absorption of different wavelengths of light by chloroplast pigments.
- <u>Action spectrum:</u> shows the rate of photosynthesis at different wavelengths of light

**(b)** Fig. 2.2 shows an absorption spectrum for chloroplast pigments and a photosynthetic action spectrum for the same plant.

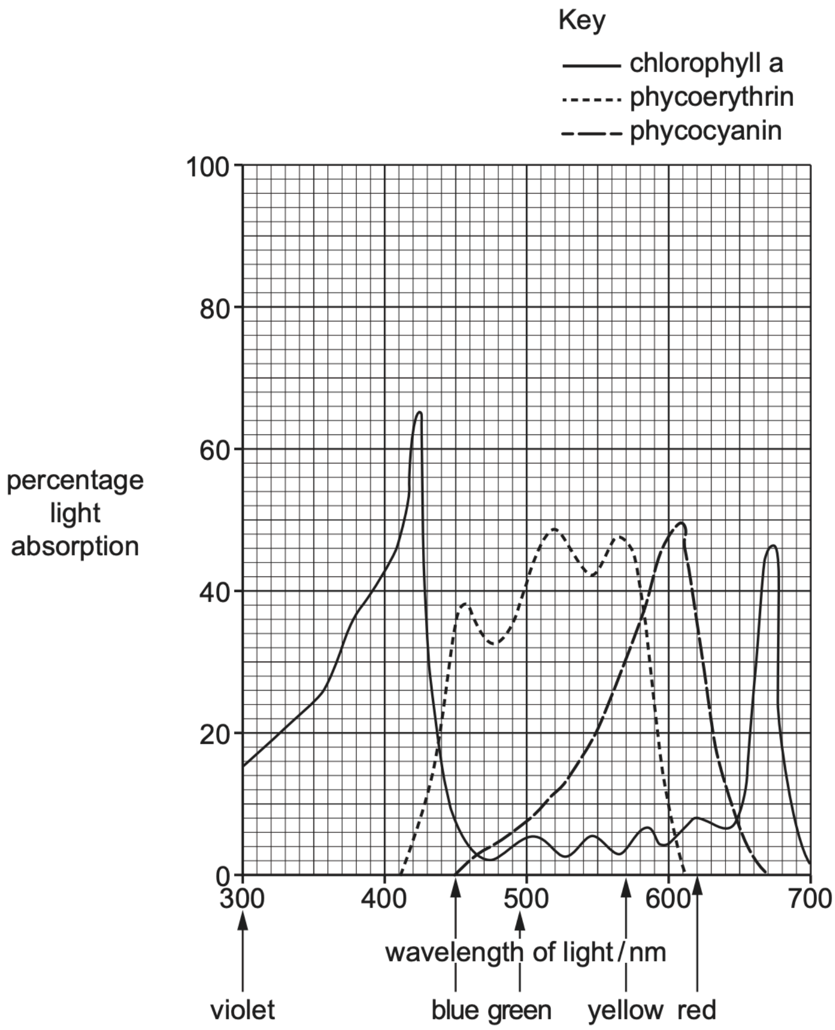



**Explain why the two curves have similar shapes.**
- light / energy absorbed by the pigments is used in photosynthesis.
- greater rate of photosynthesis at wavelengths that are absorbed most.

**<u>Data analysis questions:</u>**

Red algae = multicellular aquatic protoctists that live in deep water.
Two accessory pigments of red algae chloroplasts:
- phycoerythrin (appears red), often present in large concentrations
- phycocyanin (appears blue).

First few metres of water nearest the surface absorb red wavelengths of light. If the water also contains particles of organic material, it absorbs blue wavelengths.
Absorption spectra of some pigments in red algae chloroplasts:




**Describe the differences in the absorption spectra of the 3 photosynthetic pigments shown in the graph, and explain how these differences help red algae to survive in deep water.**

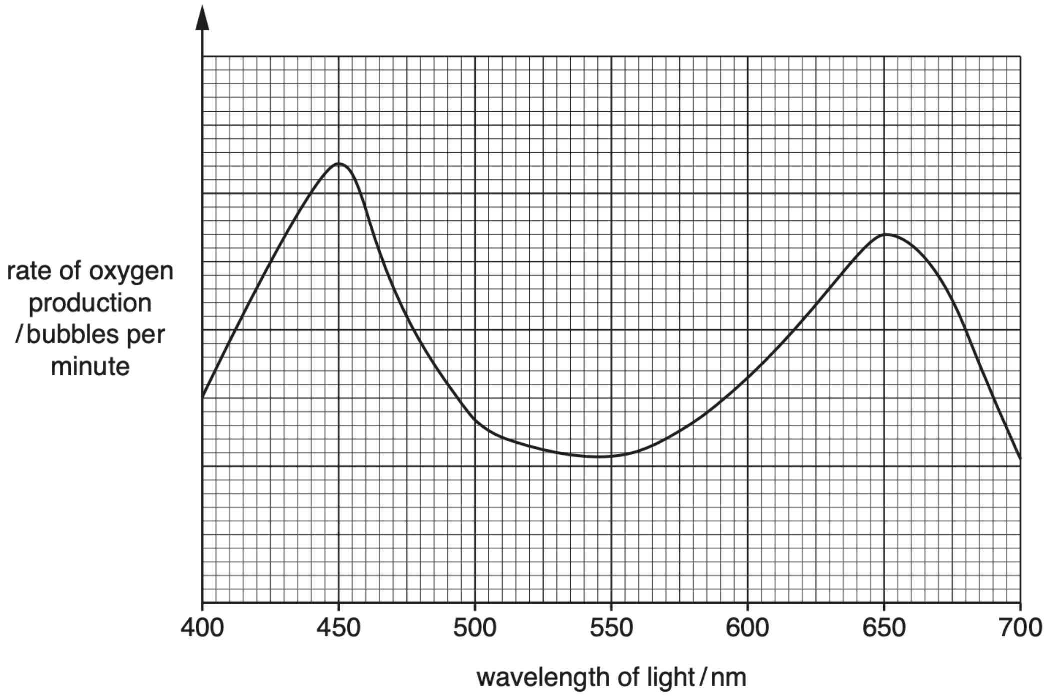
Description:

- identify wavelengths for chlorophyll (a) absorption.
- identify wavelengths for phycoerythrin absorption.
- identify wavelengths for phycocyanin absorption.
- chlorophyll (a) has peaks / absorbs mainly in blue and red.
- phycoerythrin absorbs in blue and green and yellow.
- phycocyanin absorbs in (green) yellow and red.

Explanation:

- red algae / deep water get(s) green (and yellow) light.
- chlorophyll (a) absorbs no / little green (and yellow) light.
- phycoerythrin / phycocyanin / accessory pigments absorbs wavelengths not absorbed by chlorophyll (a).
- combined pigments absorb greater range of / any / all wavelengths.
- increases / more / higher rate of light dependent stage / photosynthesis.
- so more / lots of (named) organic compounds / growth.

Equal-sized Elodea canadensis (aquatic plants) are exposed to different wavelengths of light for the same period of time. As each plant photosynthesised, number of bubbles of oxygen leaving the plant was counted. For each wavelength, rate of oxygen production was calculated. Results:




**Describe and explain the results shown.**

Description:

- highest/ peaks at 450nm (blue) and 650nm (red) OR lowest around 545nm (535–555 nm – green).

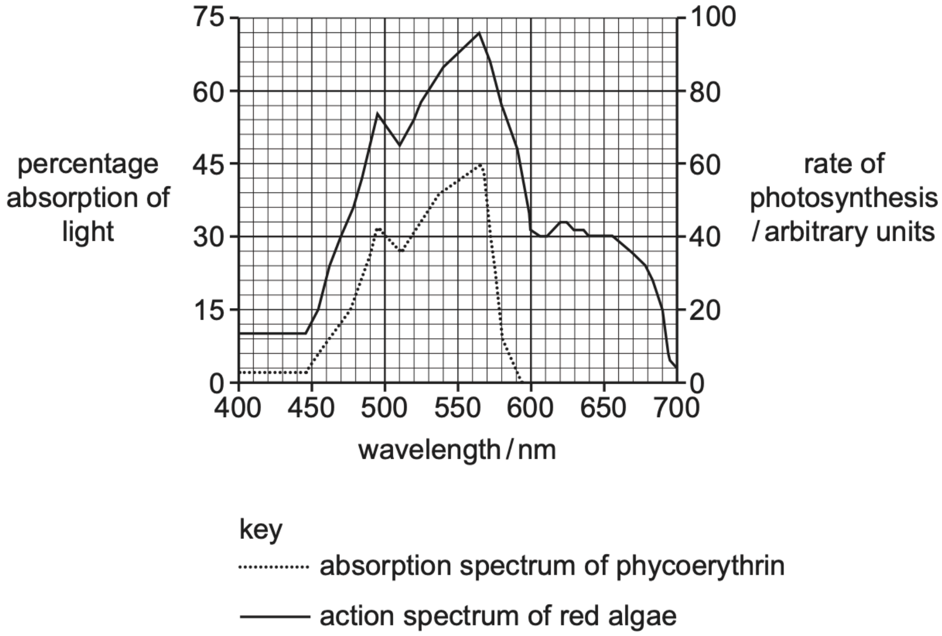
Explanations for blue/ red:

- Elodea/ plant/ chloroplasts/ accessory pigments absorb/ use red and blue wavelengths of light most effectively.
- These absorbed wavelengths are used in the light-dependent stage of photosynthesis (non-cyclic photophosphorylation).
- As a result, more ATP and reduced NADP formed → more photolysis of water → more oxygen produced.
- In green region, light is reflected/ transmitted rather than absorbed, so photosynthesis is less efficient.

Red algae are multicellular photosynthetic protoctists that contain phycoerythrin (a photosynthetic pigment).

Fig. 4.1 shows:

- the absorption spectrum of phycoerythrin
- the action spectrum of red algae.




a. **Explain how the data in Fig. 4.1 show that phycoerythrin is not the only photosynthetic pigment in red algae.**
   - phycoerythrin does not absorb light above 590–600nm.
   - but photosynthesis still takes place above 590–600nm.

b. **Phycoerythrin is not the primary pigment (reaction centre pigment) for photosynthesis in red algae. Suggest the role of phycoerythrin in photosynthesis in red algae.**
   - accessory pigment
   - absorbs light energy up to 595 nm
   - and passes it to primary pigment / reaction centre / chlorophyll a.

Relative abundance of five different chloroplast pigments in the algae of corals:

| chloroplast pigment | percentage of total |
|---|---|
| chlorophyll a | 39 |
| peridinin | 39 |
| chlorophyll c2 | 13 |
| dinoxanthin | 7 |
| β-carotene | 2 |

Light wavelengths at which each algal chloroplast pigment shows its two largest peaks of light absorption:

| chloroplast pigment | peak 1 wavelength /nm | peak 2 wavelength /nm |
|---|---|---|
| chlorophyll a | 430 | 662 |
| peridinin | 456 | 485 |
| chlorophyll c2 | 450 | 396 |
| dinoxanthin | 442 | 471 |
| β-carotene | 454 | 480 |

a. **Corals kept in tanks are often illuminated by lamps radiating mostly violet and blue light with wavelengths in the range of 400–490 nm. With reference to both tables, suggest why lamps radiating mostly violet and blue light are expected to increase coral growth.**
   - pigments absorb violet-blue / 400–49 nm lamp colours well/ best/ most/ at 8 out of 10 peaks.
   - Rate of photosynthesis of algae increases with more light absorbed.
   - Coral growth increases with more algal photosynthesis.
   - Chlorophyll a & peridinin are the most abundant pigments/ most important.
   - Violet-blue / 400–490 nm predominate at the depths where corals live.

| colour of filter | wavelength of light/nm | time taken to decolourise DCPIP/s | rate of light dependent stage of photosynthesis/$s^{-1}$ |
|---|---|---|---|
| purple | 425 | 37 | 27.0 |
| blue | 450 | 84 | 11.9 |
| green | 525 | 480 | 2.1 |
| orange | 625 | 45 | ......................... |
| red | 675 | 50 | 20.0 |

b. **With reference to the table, describe and explain the effect of light wavelength on the rate of the light dependent stage of photosynthesis.**

<u>Description</u>

- Rate of photosynthesis/ light dependent reaction is highest/ fastest/ most in purple/ at 425nm.
- It is lowest/ slowest/ least in green/ at 525nm.

<u>Explanation</u>

- Chlorophyll absorbs purple and orange best but does not absorb green (reflects green).
- Accessory pigments help absorb additional wavelengths.
- Light excites electrons / triggers electron transport chain.
- This triggers non-cyclic photophosphorylation.
- This matches action spectrum, which shows that photosynthesis is most efficient at wavelengths where absorption of light by pigments is highest.

# Chromatography of Chloroplast Pigments

**Outline the method used to separate and identify the pigments present in an extract from chloroplasts.**

- Chromatography is used.
- Place spot of extract /pigments on pencil line/ base line/ line of origin on chromatography paper/ TLC plate.
- Dry and repeat / reapply spot to concentrate the extract.
- End/ base of chromatogram is suspended/ dipped in solvent, ensuring spot is above solvent level, so solvent travels up paper.
- Cover chamber to stop evaporation of solvent.
- Remove chromatogram before solvent front reaches top.
- Measure distance travelled by solvent front and pigment/ spot.
- Calculate Rf value = distance travelled by spot/pigment ÷ distance travelled by solvent front.
- Compare Rf value with known Rf value to identify pigment(s).

**Explain how the results of chromatography would be used to confirm that a certain pigment is present in one plant and not in another.**

- calculate Rf values.
- compare Rf values of pigments both plants.
- find pigment present on chromatogram from one plant but absent from other plant OR Rf value of pigment in plant will not be the same as Rf values of pigments in the other plant.
- Identify pigment using reference values to confirm the presence of that pigment.

# Photophosphorylation

*Cyclic photophosphorylation and non-cyclic photophosphorylation occur during the light-dependent stage of photosynthesis.*

*In cyclic photophosphorylation:*

- *only photosystem I (PSI) is involved*
- *photoactivation of chlorophyll occurs*
- *ATP is synthesised*

*In non-cyclic photophosphorylation:*

- *photosystem I (PSI) and photosystem II (PSII) are both involved*
- *photoactivation of chlorophyll occurs*
- *the oxygen-evolving complex catalyses the photolysis of water*
- *ATP and reduced NADP are synthesised*

*During photophosphorylation:*

- *energetic electrons release energy as they pass through the electron transport chain.*
- *the released energy is used to transfer protons across the thylakoid membrane.*
- *protons return to the stroma from the thylakoid space by facilitated diffusion through ATP synthase, providing energy for ATP synthesis.*

**Outline the process of cyclic photophosphorylation.**

- Occurs in photosystem I (PSI, P700) only.
- Light energy is absorbed by chlorophyll a/ primary pigment in reaction centre.
- Electrons become excited and move to higher energy level.
- The excited electrons are emitted from chlorophyll a/ primary pigment/ reaction centre.
- To electron carrier/ acceptor.
- Electrons pass along series of electron carriers/ electron transport chain/ ETC.
- As electrons pass along carriers, energy is released which is used to pump H+/ protons into thylakoid space / lumen.
- This generates proton gradient across thylakoid membrane.
- H+/ protons diffuse back to stroma through ATP synthase.
- ATP is made/ synthesised (chemiosmosis occurs).
- Electron returns to photosystem 1/ P700/ chlorophyll a/ primary pigment/ reaction centre, to complete the cycle.

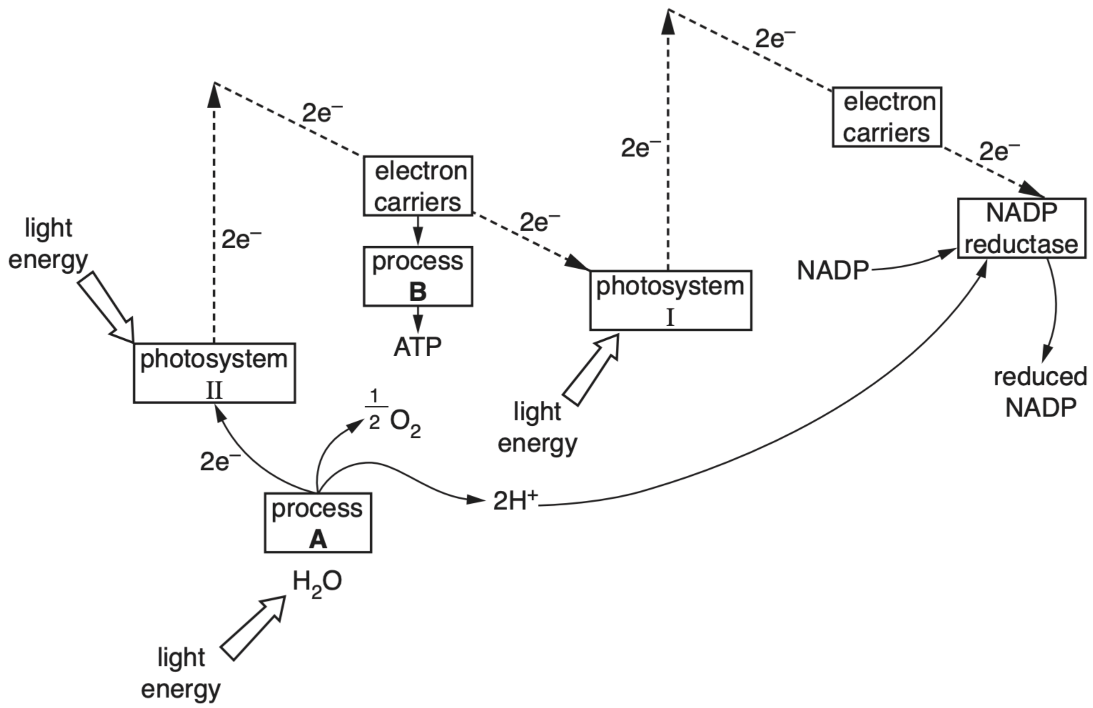
**Similarities between cyclic photophosphorylation and non-cyclic photophosphorylation:**

- photoactivation of chlorophyll occurs in both.
- ETC involved in both.
- ATP produced in both.

**Differences between cyclic photophosphorylation and non-cyclic photophosphorylation:**

| **Cyclic** | **Non-cyclic** |
|---|---|
| Involves only PSI | Involves both PSI and PSII |
| Produces only ATP | Produces ATP and reduced NADP |
| Does not involve photolysis of water // No oxygen-evolving complex involved | Involves photolysis of water // Oxygen-evolving complex involved |
| Electrons emitted from PSI returned to PSI // PS1 is source of electrons | Electrons emitted from PSII are replaced by water // water is source of electrons |

**Non-cyclic photophosphorylation in chloroplast:**




| | |
|---|---|
| **Process A** | photolysis of water |
| **Process B** | chemiosmosis / cyclic photophosphorylation |

**State what happens to the oxygen produced by process A.**

- diffuses out / lost / expelled / released from leaf / stomata / plant.
- used in aerobic respiration / oxidative phosphorylation.

**Name the primary pigment in photosystem I and photosystem II.**

- chlorophyll a

**Describe the role of photosystem II in the absorption of light.**

- PSII contains light harvesting complex (LHC).
- LHC has accessory pigments (e.g. carotenoids, chlorophyll b) that absorb photons of different wavelengths of light.
- Absorbed light / photons are passed to reaction centre that contains chlorophyll a (P680 - primary pigment).
- This excites electrons in P680, which are passed to ETC, and initiates non-cyclic photophosphorylation.
- Presence of multiple pigments causes more/ different wavelengths/ energy frequencies to be absorbed.

**Explain why herbicides that prevent cyclic photophosphorylation and non-cyclic photophosphorylation stop carbohydrate being produced in the chloroplast.**

- no ATP and reduced NADP made.
- no GP / TP made OR no Calvin cycle / light-independent reaction.
- no regeneration of RuBP.

# The Calvin Cycle

*3 main stages of the Calvin cycle:*

1. *rubisco catalyses the fixation of carbon dioxide by combination with a molecule of ribulose bisphosphate (RuBP), a 5C compound, to yield two molecules of glycerate 3-phosphate (GP), a 3C compound.*
2. *GP is reduced to triose phosphate (TP) in reactions involving reduced NADP and ATP.*
3. *RuBP is regenerated from TP in reactions that use ATP*

*Calvin cycle intermediates are used to produce other molecules:*

- *GP to produce some amino acids*
- *TP to produce carbohydrates, lipids and amino acids*

**Outline the reactions occurring in the stroma that lead to the production of a polysaccharide.**

- Carbon dioxide binds to RuBP (ribulose biphosphate) – a 5C compound.

- This is catalysed by rubisco (ribulose bisphosphate carboxylase).
- Unstable 6C compound is formed.
- This immediately splits into two molecules of GP (glycerate-3-phosphate) – a 3C compound.
- GP is reduced to TP (triose phosphate).
- In reactions involving reduced NADP and ATP from the light-dependent stage.
- Some TP is used to regenerate RuBP (to restore the cycle), in reactions that use ATP.
- The remaining TP is used to produce hexose sugars/ glucose.
- Glucose units undergo condensation/ polymerisation/ form glycosidic bonds to produce polysaccharides.

**Name 2 compounds that are used in the conversion of glycerate-3-phosphate (GP) to triose phosphate (TP) in the Calvin cycle.**
- ATP (provides energy)
- reduced NADP / NADPH (provides reducing power / hydrogen)

**Outline the use of intermediate products of the Calvin cycle.**
- GP produces some amino acids.
- TP regenerates/ produces RuBP so the Calvin cycle can continue.
- TP is used in synthesis of:
    - Carbohydrates: glucose / sucrose / starch / cellulose
    - Nucleic acids: ribose / deoxyribose
    - Lipids: glycerol / fatty acids / acetyl (coA)
    - Amino acids
- TP produces respiration substrates: TP/ glucose derived from it can enter glycolysis and be converted to pyruvate/ acetyl coA – for respiration.

<u>Carbohydrates</u>
- Glucose for respiration.
- Sucrose for translocation.
- Starch for storage.
- Cellulose to make cells walls.

<u>Lipids</u>
- Fatty acids and glycerol/ lipid to make membranes.
- Fatty acids and glycerol/ lipid/ fats for storage.
- Fatty acids to make acetyl CoA (for Krebs cycle).

<u>Amino acids</u>
- Amino acids to make proteins/ enzymes.
- Proteins for growth / repair.

**Name one compound that needs nitrogen from nitrates and name the Calvin cycle intermediate from which it is synthesised.**

- <u>Compound that needs nitrogen:</u> amino acids/ proteins/ nucleotides.
- <u>Calvin cycle intermediate:</u> glycerate-3-phosphate OR triose phosphate.

**Explain how the Calvin cycle is affected when rubisco denatures.**

- less / no CO2 fixation / carboxylation of RuBP.
- less / no GP made into / converted to TP.
- less / no regeneration of RuBP.
- less / no glucose / hexose made.

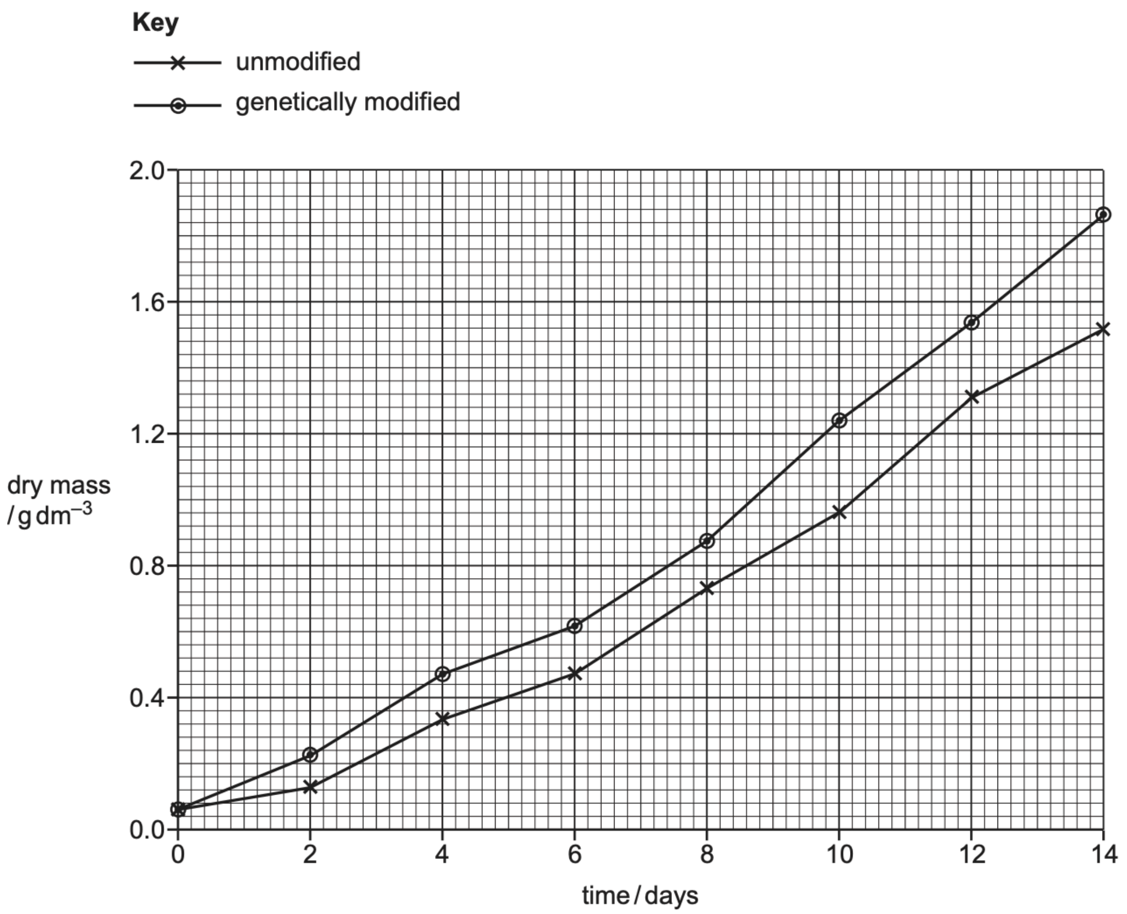
**<u>Data analysis question:</u>**

Algae are aquatic photosynthetic protoctists. Some researchers genetically modified the unicellular alga, *Chlorella vulgaris*, to try to increase the rate of the light independent stage of photosynthesis.

*C. vulgaris* was modified to increase the expression of the gene coding for aldolase. Aldolase is an enzyme that causes an increase in the concentration of rubisco.

Two cultures of *C. vulgaris*, one that was not genetically modified (unmodified) and one genetically modified, were grown under controlled conditions for 14 days. Samples were taken from the cultures at regular intervals during the 14 days to obtain measurements of dry mass.

The results are shown in Fig. 2.1.



a. **With reference to the graph, describe the differences between the results for the two cultures.**
    - genetically modified has a higher dry mass throughout the experiment.
    - genetically modified has a slightly higher rate of / steeper increase in dry mass.
    - the largest difference in dry mass is after day 8.
    - paired data quote with units.

b. **Explain how the Calvin cycle was affected by the genetic modification of C. vulgaris.**
    - more rubisco so greater rate of / more carbon dioxide fixation.
    - so greater rate of / more GP produced.
    - so greater rate of / more TP produced from GP.
    - so greater rate of / more regeneration of RuBP.
    - so greater rate of / more Calvin cycle.
    - carbon fixation is a rate-limiting step / concentration of rubisco is a limiting factor

c. **Planting large numbers of trees is one way to reduce global atmospheric CO2 concentration. Large scale culture of genetically modified C. vulgaris could also reduce global atmospheric CO2 concentration. Suggest advantages of using genetically modified C. vulgaris instead of trees to reduce global atmospheric CO2 concentration.**
    - faster growth rate / reproduction.
    - quicker to set up.
    - cheaper to set up.
    - as aquatic not using useful land.
    - can culture / grow algae in the lab.

NOTE:
- enzyme with a high optimum temperature: PEP carboxylase
- enzyme in bundle sheath cells: Rubisco
- compound that releases carbon dioxide into bundle sheath cells = malate
- cells that stop oxygen reaching bundle sheath cells = mesophyll cells

# 13.1 Investigation of Limiting Factors

**Explain what is meant by a limiting factor in relation to photosynthesis.**
- The factor that is in shortest supply or at its lowest value.
- The single factor that directly affects rate of photosynthesis at a given time, among several other factors.

**State examples of limiting factors of photosynthesis.**

- Light intensity
- Carbon dioxide concentration
- Temperature

**Explain why light intensity can be a limiting factor in photosynthesis.**

- light energy / photons
- are needed for light-dependent stage / photophosphorylation / photolysis / photoexcitation / photoactivation.
- to make reduced NADP / ATP.
- to open stomata for $CO_2$ to enter.

**Explain how very dry conditions cause $CO_2$ concentration to become the main limiting factor of photosynthesis in plants.**

- In dry conditions, stress response occurs.
- Plants produce stress hormone abscisic acid (ABA).
- ABA triggers signalling cascade with $Ca^{2+}$ as second messenger, causing guard cells to lose turgor.
- Stomata close.
- Thus there is decrease in/ no $CO_2$ diffusing/ moving to air spaces/ palisade cells/ mesophyll cells/ chloroplasts/ stroma.

**In an investigation of the effect of carbon dioxide concentration on the rate of photosynthesis, the air in the soil and the air around the leaves of the plants were separated using a chamber with a gas-tight seal. Suggest why.**

- to keep out unwanted $CO_2$ in air around leaves.
- ref. to respiration of soil organisms, eg. bacteria / fungi / seeds.
- ref. to respiration of plant roots.

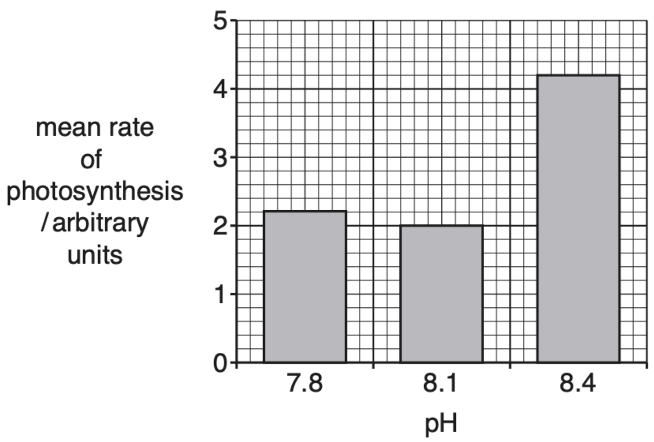
**Give examples of human activities that contribute greatly to the increase in global atmospheric $CO_2$ concentration.**

- industrialisation/ transportation/ power stations/ burning of fuels.

| day length /hours | rate of photosynthesis /arbitrary units | |
|---|---|---|
| | low carbon dioxide concentration | high carbon dioxide concentration |
| 12 | 2.0 | 2.5 |
| 14 | 3.0 | 5.0 |
| 16 | 4.0 | 7.0 |
| 18 | 5.5 | 11.0 |
| 20 | 7.5 | 18.0 |

a. **With reference to the table, explain the difference in the rate of photosynthesis at high carbon dioxide concentration compared to low carbon dioxide concentration.**
   - More carbon dioxide react with RuBP / more CO2 fixation / more carbon dioxide available to bind to rubisco.
   - More Calvin cycle / light independent reaction.

b. **With reference to the table, describe and explain the effect of increasing day length (light exposure period) on the rate of photosynthesis in high carbon dioxide concentration.**
   - as day length increases rate of photosynthesis increases / positive correlation
   - data quote: two day lengths in hours and two carbon dioxide concentrations / difference between two carbon dioxide concentrations.
   - more light is absorbed by photosystems / pigments / named pigment.
   - more photophosphorylation / light dependent reaction / photolysis.
   - more oxygen / reduced NADP / ATP / glucose / starch produced.




a. **With reference to the figure, explain the effect on the rate of photosynthesis when the pH increases from 8.1 to 8.4.**
   - pH 8.4 is optimum pH of rubisco / enzymes.

- fewer H+ / protons result in higher rate of photosynthesis / activity of enzymes

**b. The lower pH values represent ocean acidification. Suggest why the results for the lower pH values do not fully support the idea that seaweeds can help to reduce ocean acidification.**

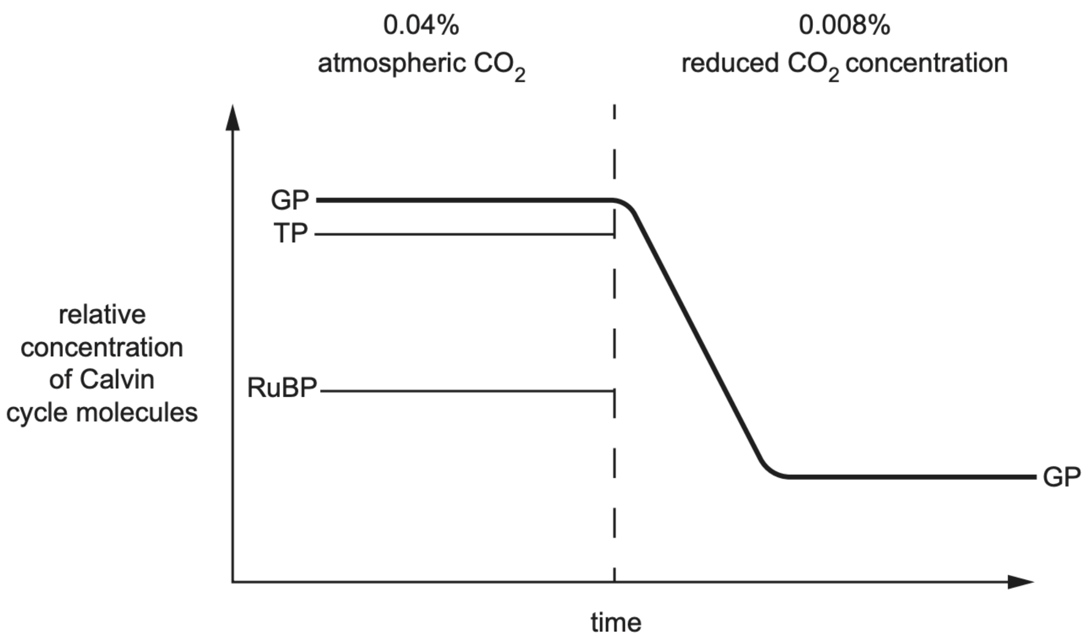
- less carbon dioxide absorbed / fixed so ocean acidification not reduced.

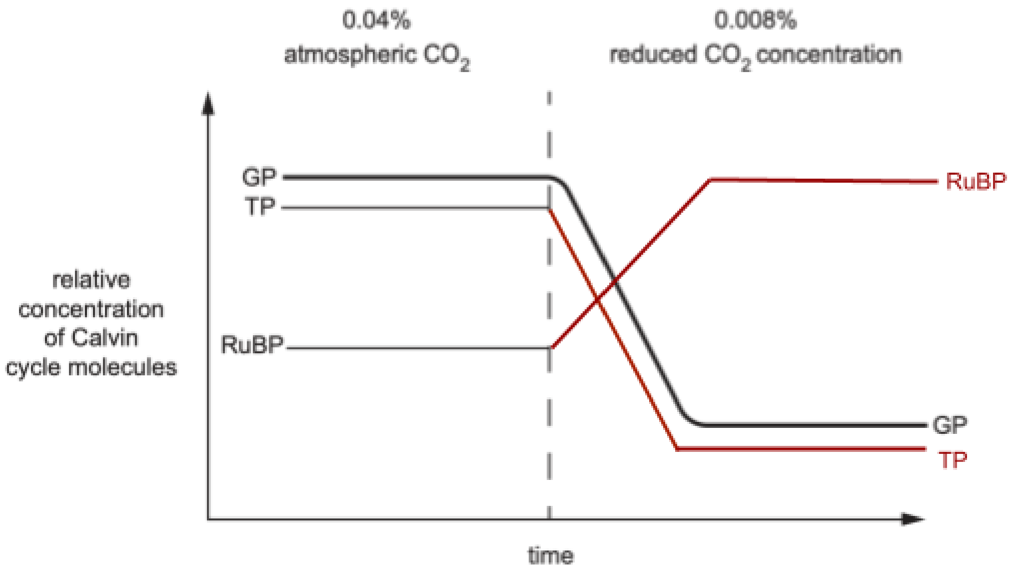
**(ii)** The concentration of carbon dioxide ($CO_2$) can also be a limiting factor. It has an effect on the Calvin cycle in the light-independent stage of photosynthesis.

Ribulose bisphosphate (RuBP), triose phosphate (TP) and glycerate 3-phosphate (GP) are three important molecules in the Calvin cycle.

Fig. 2.1 shows how the concentration of GP changes when the concentration of $CO_2$ is reduced from 0.04% (atmospheric) to 0.008%.

Complete Fig. 2.1 by sketching the lines for RuBP and TP when the concentration of $CO_2$ is reduced from 0.04% to 0.008%.

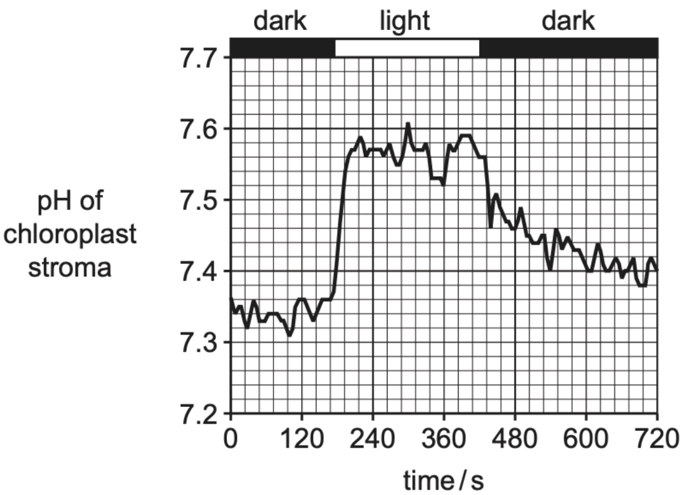





An experiment was carried out to investigate the effect of changing light conditions on the pH of the chloroplast stroma. Scientists followed pH changes in chloroplast stroma using fluorescent chemicals that can be used as pH indicators.

- Chloroplasts were isolated from cells.
- A suspension of chloroplasts was prepared and kept in the dark for 180 seconds.
- The chloroplasts were exposed to a period of light of fixed intensity for 240 seconds, then returned to dark conditions.
- The pH of chloroplast stroma was continuously measured and recorded.

Fig. 3.2 shows the results of this experiment.




**a. Describe the results shown.**

- the pH is higher in the light than in the dark OR the pH increases from dark to light OR the pH decreases from light to dark.
- the pH increases sharply when changed to light.
- the pH levels off in light.

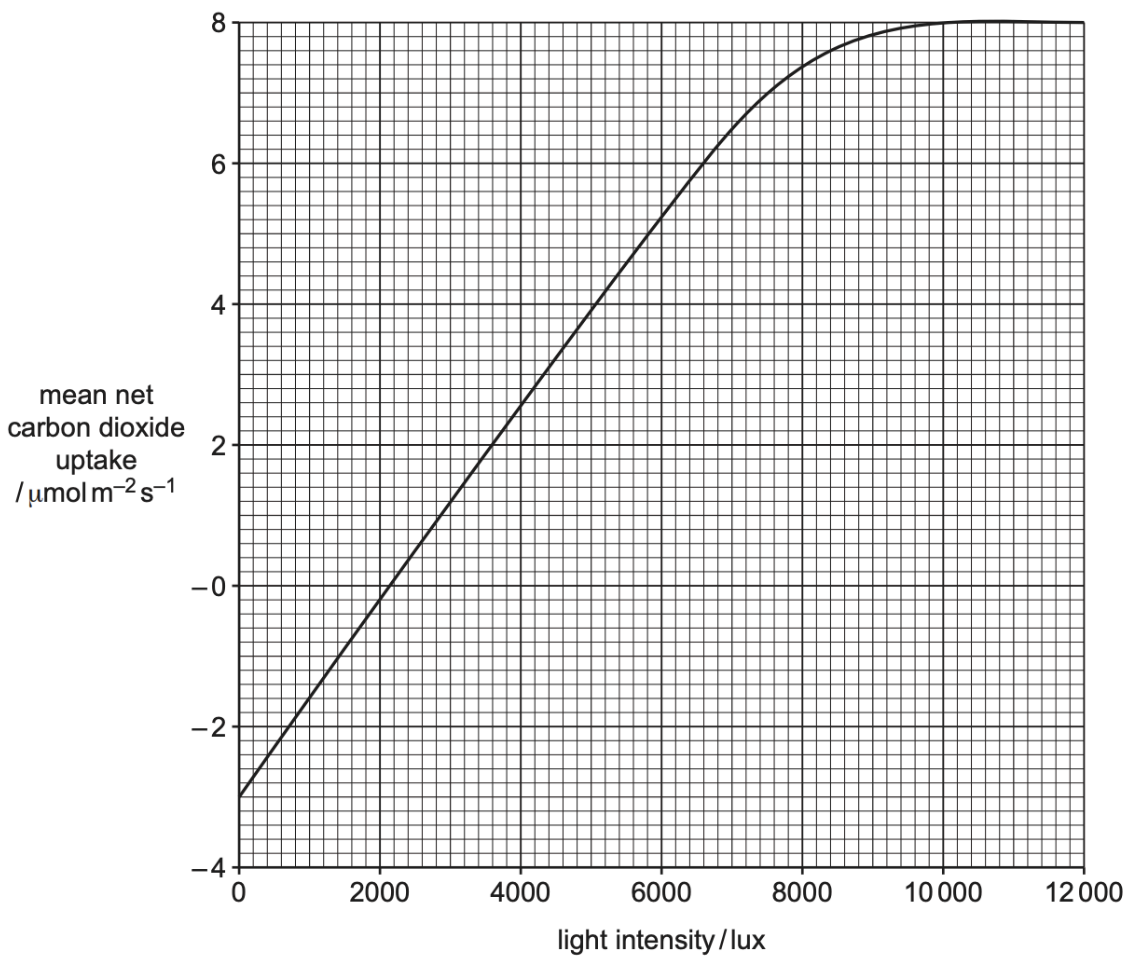
- the pH decreases gradually / less steeply when returned to the dark OR decrease in pH does not return to original (dark) pH.
- ref. to fluctuations anywhere / described.
- comparative figures to support.

**b. Discuss how the results shown support that chemiosmosis occurs during photophosphorylation.**

- the stroma has higher pH when H+ ions move out of stroma / into thylakoid space / lumen.
- leads to increased H+ concentration in the thylakoid space / lumen.
- H+ diffuse back into stroma through ATP synthase.

An investigation was carried out to measure the net carbon dioxide uptake by a banana plant at different light intensities.

Fig. 6.2 shows the results of the investigation.




**a. With reference to the graph, describe and explain the results at a light intensity of 1000 lux.**

- CO2 uptake below zero / CO2 released / CO2 uptake is negative.
- little photosynthesis occurring.
- due to low light intensity.

- rate of respiration higher than rate of photosynthesis.

**b. With reference to the graph, describe and explain what can be concluded from the graph at light intensities of between 2000 lux and 7000 lux.**

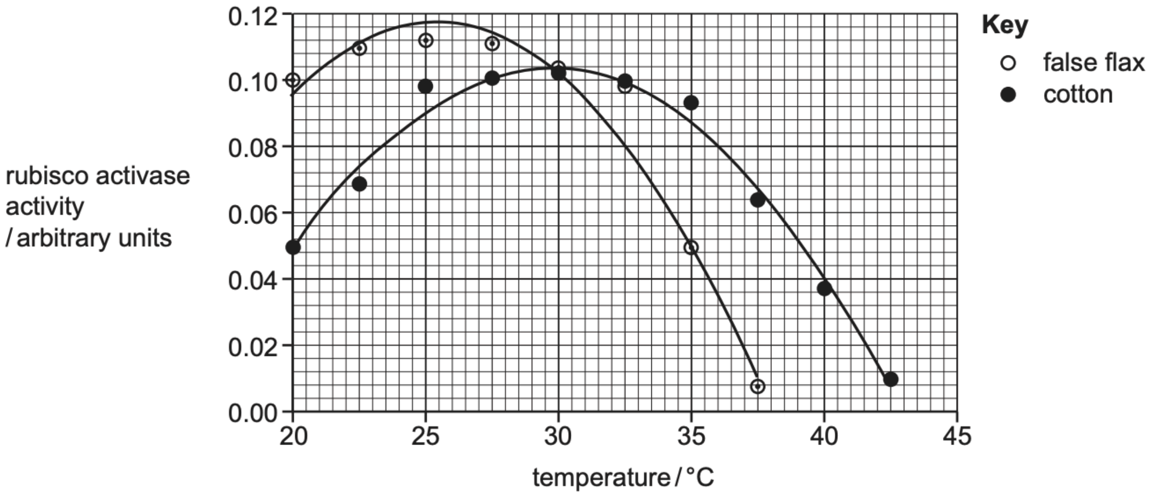
- as light intensity increases, rate of CO2 uptake increases.
- data quote to support.
- because rate of photosynthesis / light-dependent reactions / light-independent reactions increases.
- light intensity is limiting factor.

2 **(a)** Cotton, *Gossypium hirsutum*, and false flax, *Camelina sativa*, are crop plants that are grown in different parts of the world.

Rubisco activase is an enzyme in the stroma of chloroplasts that is needed to maintain the activity of a second enzyme, rubisco.

Scientists measured the activity of rubisco activase in cotton and in false flax at a range of temperatures.

Fig. 2.1 shows the results.




**a. With reference to the graph, compare the results obtained for cotton and false flax.**

<u>Differences</u>

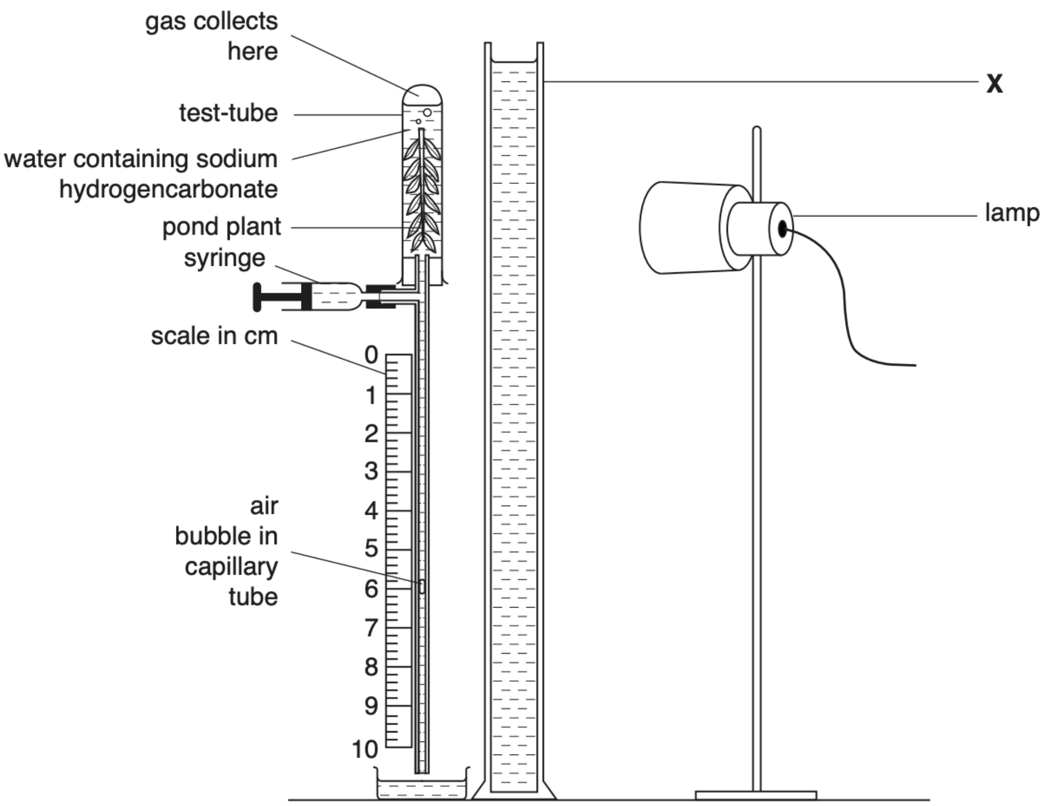
- cotton enzyme / rubisco activase has a higher, optimum temperature / temperature at which activity is highest.
- maximum / highest / peak activity higher in flax enzyme / rubisco activase than in cotton.
- cotton enzyme / rubisco activase can work at higher temperature than flax.
- at stated temp <30 °C, flax enzyme has higher activity than cotton.
- at stated temp >30 °C, cotton enzyme has higher activity than flax.

Similarities
- activity of both increases then decreases as temperature increases.
- enzyme / rubisco activase activity same at 30 °C.

**b. Suggest reasons for the differences shown.**
- cotton is adapted to/ lives in areas with higher temperatures.
- different genes / alleles in cotton vs. flax.
- different primary structure of rubisco activase in cotton vs. flax.
- different tertiary structure of rubisco activase in cotton vs. flax.

**c. Use the information given to suggest and explain a way to improve the tolerance of a crop to high temperatures.**
- take gene / DNA for rubisco activase.
- from cotton and insert into flax / named crop plant / embryo.
- to maintain rubisco action at high temperatures / >37.5 °C / up to 42.5 °C.

Investigating effect of light intensity on rate of photosynthesis:




Light intensity can be changed by placing the lamp at different distances from the pond plant.

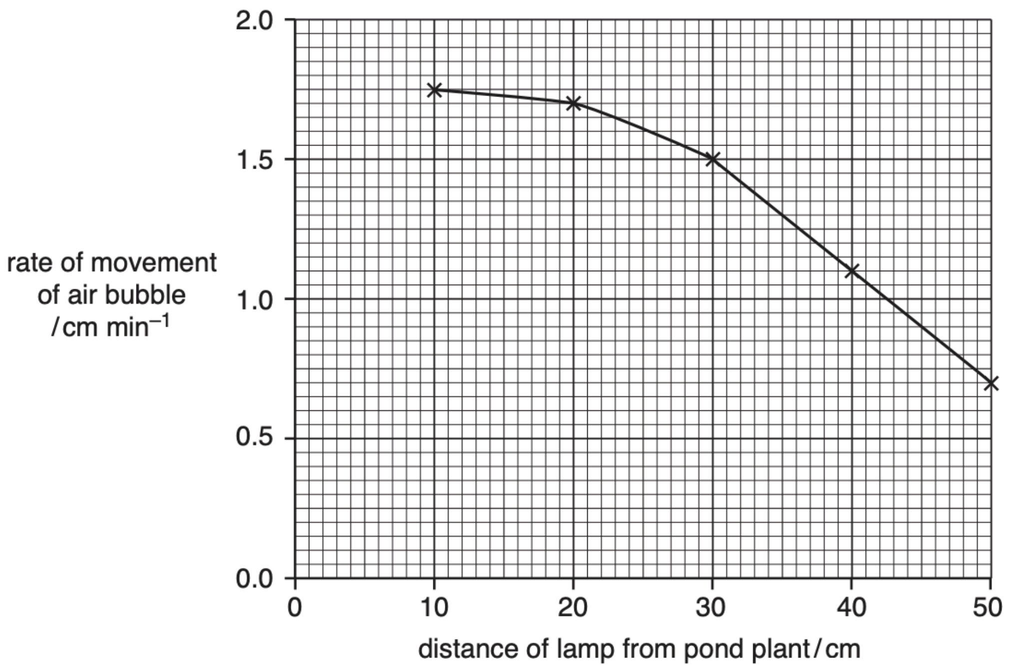
**a. Apparatus X = thin glass container filled with water. Explain its function.**
- Stops heat from lamp reaching the plant.

- So temperature does not change.
- Because temperature affects the rate of photosynthesis / enzymes involved in photosynthesis.

**b. Before completing the assembly of the apparatus, sodium hydrogencarbonate is added to the water surrounding the pond plant in the test-tube. Explain why.**
- to provide carbon dioxide

**c. Name the gas collected in the test-tube.**
- Oxygen

The investigation was carried out with the lamp at distances of 10, 20, 30, 40 and 50cm from the pond plant. For each of these distances, the air bubble in the capillary tube was initially positioned at 0cm on the scale and, after 5 minutes, the distance moved by the air bubble was measured. The rate of movement of the air bubble was then calculated. Results:



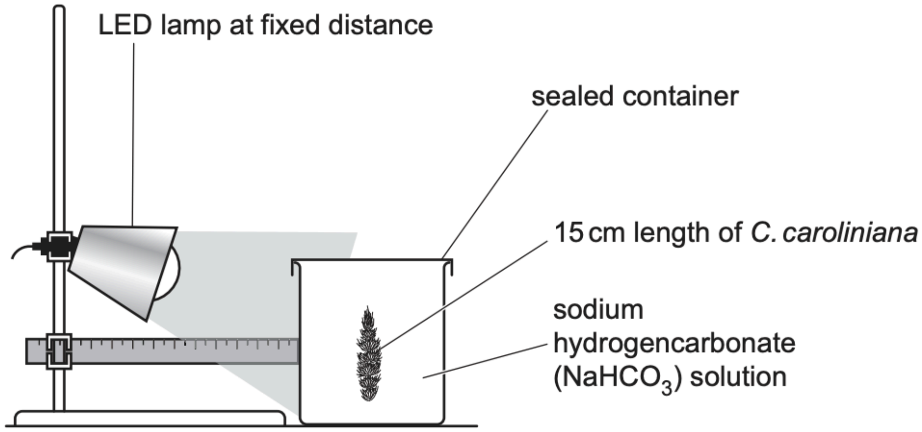

**d. Describe the relationship between the rate of photosynthesis and light intensity.**
- As light intensity increases, the rate of photosynthesis increases.
- Data quote: 2 values of rate of movement of air bubble + 2 values of distance of lamp from pond, plus units).

**e. At distances of less than 10cm, the rate of movement of the air bubble was the same as at 10cm. Explain why there was no change in the rate of movement of the air bubble at distances less than 10cm.**
- light intensity is no longer a limiting factor
- temperature / carbon dioxide concentration could be the limiting factor.

The rate of photosynthesis is affected by many environmental factors.

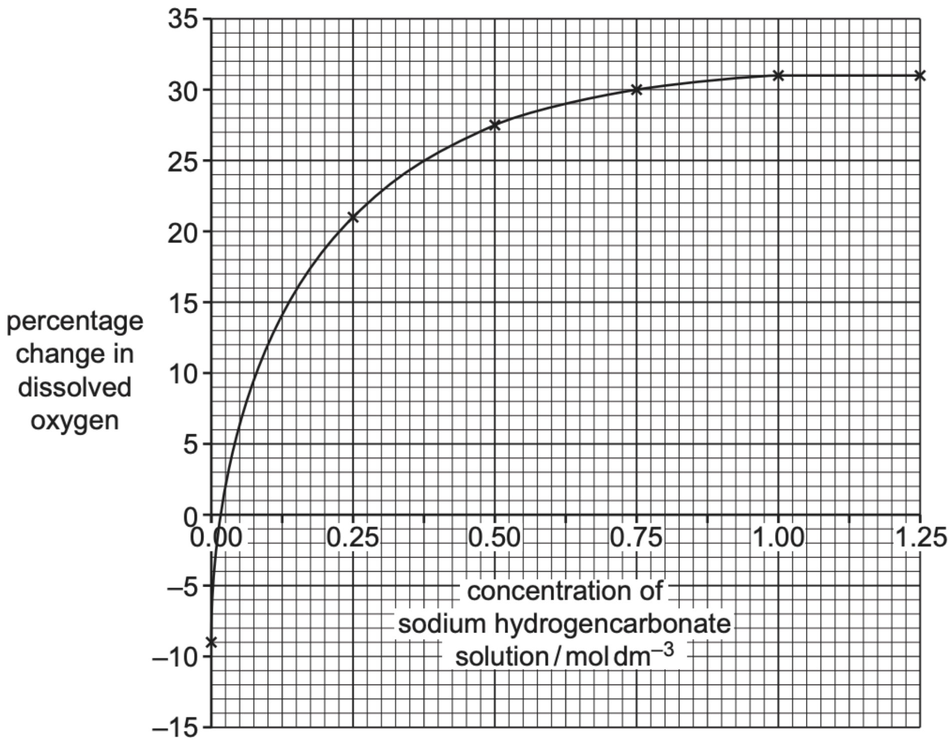
A student carried out an experiment to investigate the relationship between the concentration of carbon dioxide available to an aquatic plant, *Cabomba caroliniana*, and its rate of photosynthesis.

Fig. 1.1 shows the experimental set-up for this investigation.




- Sodium hydrogencarbonate solution was used as a source of carbon dioxide.
- The concentration of carbon dioxide was varied using six different concentrations of sodium hydrogencarbonate solution.
- All *C. caroliniana* plants were kept in the dark before the light was switched on at the start of the experiment.
- Five replicates were carried out at each concentration.
- The rate of photosynthesis was obtained by calculating the percentage change in dissolved oxygen concentration in the solution over five minutes.

Fig. 1.2 shows the results of the investigation.



a. **With reference to the graph, explain the pattern of results obtained between 0.25 mol dm–3 and 1.25 mol dm–3 of sodium hydrogencarbonate solution.**
    - from 0.25 to 1.00 mol dm–3, concentration / CO2 is limiting factor OR at >1.00 mol dm–3 concentration / CO2 is no longer limiting factor.
    - at >1.00 mol dm–3 light intensity / temperature is limiting factor.
    - CO2 needed / used for Calvin cycle / for light independent stage OR CO2, reacts with / fixed by RuBP.

b. **The percentage change in dissolved oxygen at 0.00 mol dm–3 of sodium hydrogencarbonate solution is negative. Suggest reasons for this negative value.**
    - little / no photosynthesis
    - aerobic respiration uses oxygen

c. **To minimise temperature changes, the student decided to use an LED lamp as a light source. LED lamps release very little heat energy. Explain the importance of minimising temperature changes in this experiment.**
    - to control a variable / to ensure a fair test / so CO2 is the only variable.
    - low temperature / kinetic energy decreases rate / reaction / photosynthesis / O2 production / O2 increase.
    - low temperature / kinetic energy decreases (named) enzyme-substrate, collisions / complexes.
    - lower temperature is a limiting factor / may limit rate.
    - high temperature / kinetic energy decreases rate / reaction / photosynthesis / O2 production / O2 increase.
    - high temperature / kinetic energy denatures (named) enzymes.
    - high / increased temperature causes / increases photorespiration.

Corals grow in shallow seawater, and consist of colonies of small animals called polyps. Polyps have photosynthetic protoctists called algae inside their cells. The algae that live within cells of polyps can also live independently as free-living algae. Rate of photosynthesis of algae that live within cells of coral polyps is higher than that of free-living algae.

**Suggest and explain how living inside the cells of coral polyps increases rate of photosynthesis in the algae compared to free-living algae.**

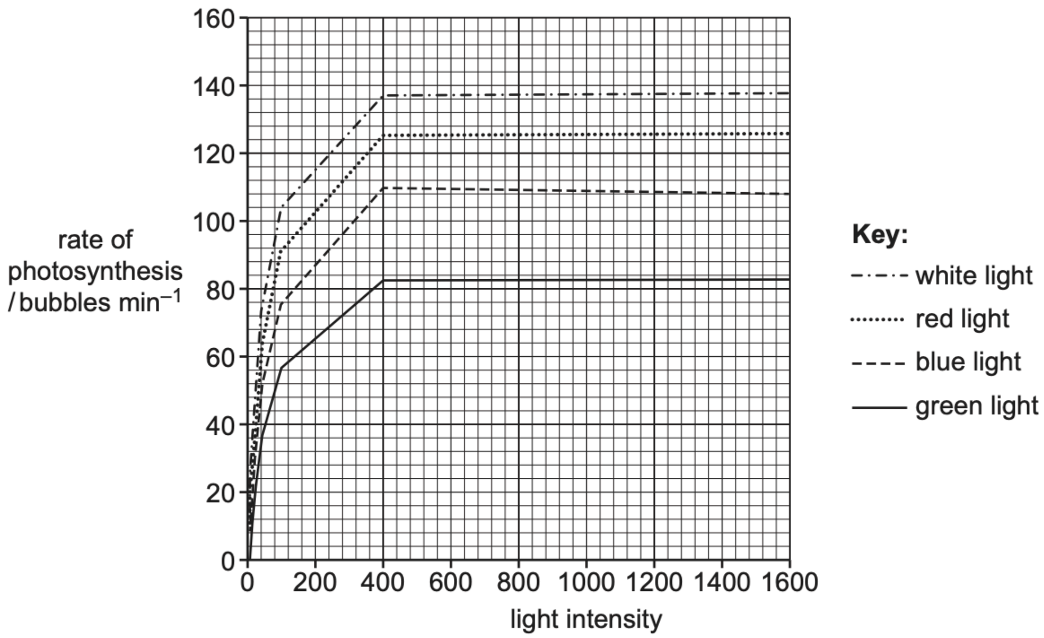
- Coral polyps carry out respiration/ metabolism, releasing carbon dioxide which diffuses directly into algal cells.
- This provides high concentration/ not limiting $CO_2$ for Calvin cycle/ light-independent reactions.
- Polyps also release metabolic heat, to maintain optimal temperature for enzyme activity in photosynthesis.

- Polyps supply mineral ions (e.g. nitrates, phosphates, magnesium) that are essential for synthesis of chlorophyll.

:) At each distance from the lamp, the experiment was repeated using a red filter in front of the lamp to give a different wavelength of light. The experiment was repeated using a blue filter and then using a green filter. Each filter transmitted the same light intensity.

The student calculated the mean rate of bubble production as a measure of the rate of photosynthesis.

Fig. 5.1 shows a graph of the results.




**a. With reference to the graph:**
**- state the range over which light intensity is the limiting factor**
**- explain why light intensity above this range is not limiting the rate of photosynthesis.**

- 0 – 400
- temperature / concentration of carbon dioxide becomes the limiting factor
- at a lower than optimum temperature, less kinetic energy so fewer collisions between rubisco and CO2 OR a lower temp will limit the rate of (named) enzyme-controlled reactions.
- with a lower than optimum CO2 concentration, less fixation of CO2
- all enzymes / processes in photosynthesis already at highest rate / optimum OR maximum amount of light is being absorbed by the pigments.

**b. At a light intensity of 1600, explain why different colour filters result in different rates of photosynthesis.**

- different wavelengths of light absorbed by different pigments.
- red light is absorbed the most.

- green light is absorbed less / reflected.
- shorter the wavelength the greater the energy / red light has more energy than blue light.
- the more light / energy absorbed the more light dependent reaction / photophosphorylation occurs.

Biochemical processes involving carbon dioxide change the external environment of the aquatic plant, *Elodea canadensis*, and the pond snail, *Lymnaea stagnalis*. Carbon dioxide dissolves in water to form carbonic acid.

A student set up 8 test-tubes. Each test-tube contained 30 $cm^3$ of distilled water containing a pH indicator, bromothymol blue.

Fig. 5.1 shows the experimental set up for these 8 test-tubes.

The test-tubes were left for 12 hours.

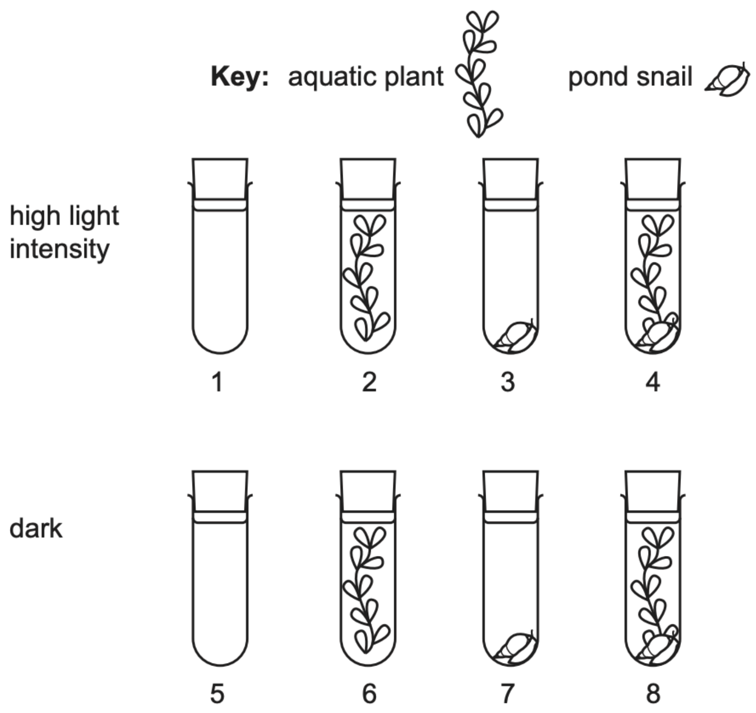



**Fig. 5.1**

Fig. 5.2 shows how the colour of bromothymol blue changes with pH.

| | | |
|---|---|---|
| blue | ↑ | increasing pH |
| green | | neutral pH |
| yellow | ↓ | decreasing pH |

**Fig. 5.2**

All tubes were green at the start of the experiment.

The results of the experiment are shown in Table 5.1.

**Table 5.1**

| test-tube | colour after 12 hours |
|---|---|
| 1 | green |
| 2 | blue |
| 3 | yellow |
| 4 | green |
| 5 | green |
| 6 | yellow-green |
| 7 | yellow |
| 8 | yellow |

a. **Explain the results of test-tubes 2, 3 and 4.**

Test-tube 2:

- plant carries out photosynthesis.
- uses up $CO_2$ in the Calvin cycle / light independent stage OR less $CO_2$ causes pH to increase.

Test-tube 3:

- snail carries out respiration.
- produces $CO_2$ in the link reaction / Krebs cycle OR more $CO_2$ causes pH to decrease.

Test-tube 4:

- both photosynthesis and respiration take place.
- $CO_2$ produced in respiration is used in photosynthesis OR oxygen produced in photosynthesis is used in respiration.

b. **Explain the colour change in test-tube 6.**

- no / less photosynthesis so no / less $CO_2$ used.
- no light dependent stage / no non-cyclic photophosphorylation / no Calvin cycle / no carbon dioxide fixation.

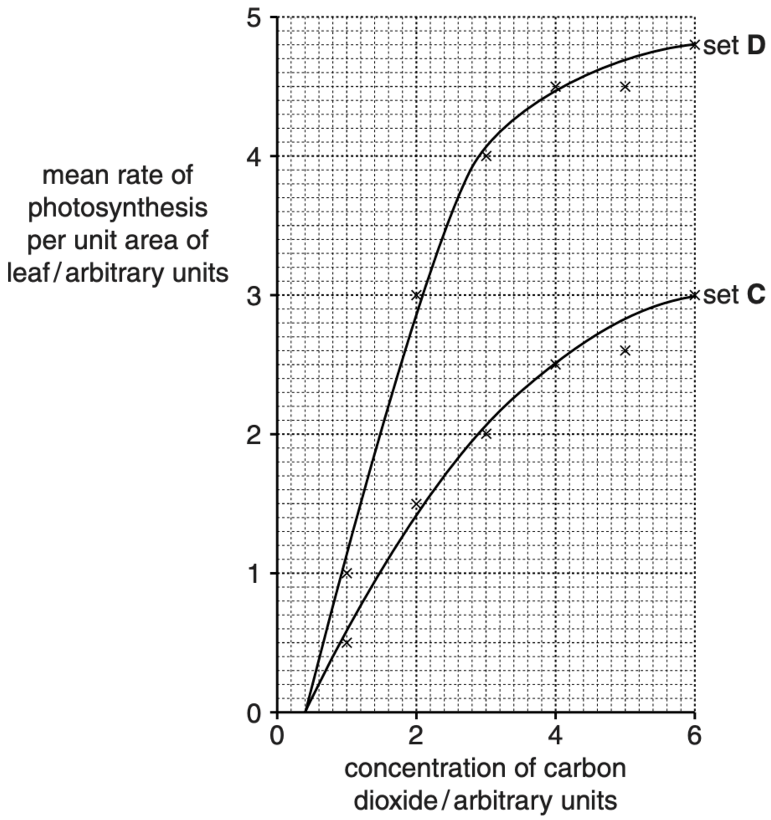
- respiration occurs producing $CO_2$.
  respiration rate slower in aquatic plants/ test-tube 6 than pond snails/ test-tube 7.
- so only slight decrease in pH.

**(d)** In a second investigation, two sets of plants, **C** and **D**, were grown from seed, as before, in different carbon dioxide concentrations:

- **C** – normal atmospheric concentration of carbon dioxide (0.033%)
- **D** – normal atmospheric concentration of carbon dioxide ×2 (0.066%).

When the plants matured, conditions in the growth chambers were changed to investigate the rate of photosynthesis of each set of plants in different concentrations of carbon dioxide.

The results are shown in Fig. 2.2.




**Suggest explanations for the higher rate of photosynthesis per unit area of leaf shown by the plants in set D compared with those in set C.**

- D adapted to high $CO_2$ / can use more $CO_2$ per unit leaf area.
- D have more chloroplasts / chlorophyll.
- D have more rubisco / RuBP.
- D have more stomata.
- D have thinner leaves.
- For more/faster diffusion of $CO_2$.

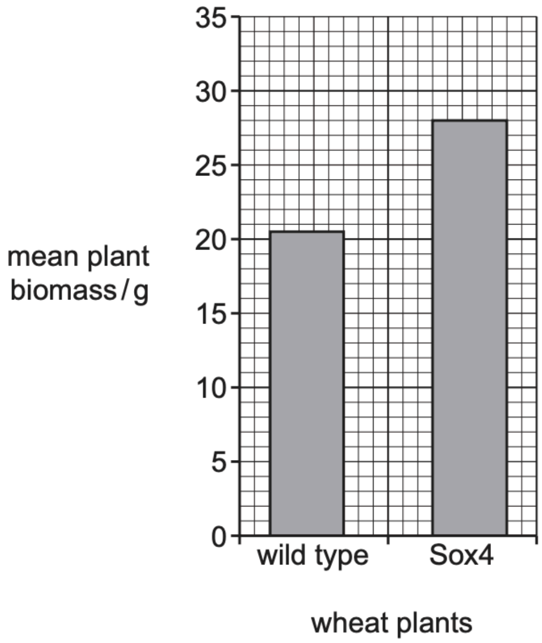
A factor that can limit the rate of photosynthesis is the rate of regeneration of RuBP.

Sedoheptulose-1,7-bisphosphatase (SBPase) is an enzyme in the Calvin cycle that controls the rate of regeneration of RuBP. SBPase is coded for by the gene *SBPase*.

In an experiment, wheat plants were genetically modified to make more SBPase by introducing the *SBPase* gene from another grass species, *Brachypodium distachyon*. The resulting GM wheat plants were named Sox4.

- Wild type plants (not GM) and Sox4 plants were grown in a greenhouse.
- Light intensity, $CO_2$ concentration and temperature were kept constant.
- Mature plants were removed and dried to measure the biomass.

Fig. 2.2 shows the mean plant biomass for the wild type plants and GM Sox4 plants.




**a. Suggest and explain why Sox4 plants have a different mean plant biomass than wild type plants.**

- Sox4 plants have an extra copy of SBPase gene.
- new SBPase / SBPase gene more efficient.
- overall increased expression / transcription of SBPase gene, so more SBPase.
- increased rate of / more regeneration / production of RuBP.
- so increased / more carbon fixation / Calvin cycles / light independent reaction / TP / GP.
- more glucose / sucrose for respiration / ATP production OR more starch / lipid for storage OR more cellulose for cell walls.
- more amino acids / proteins for growth.
- more cell division / cell elongation / mitosis.

**b. Suggest how nitrate deficiency in soil could limit the quantity of SBPase made by Sox4 plants.**

nitrogen needed to produce:

- nucleotides for transcription of SBPase gene / expression of SBPase gene / mRNA production.
- amino acids for protein synthesis / SBPase production / enzyme production.

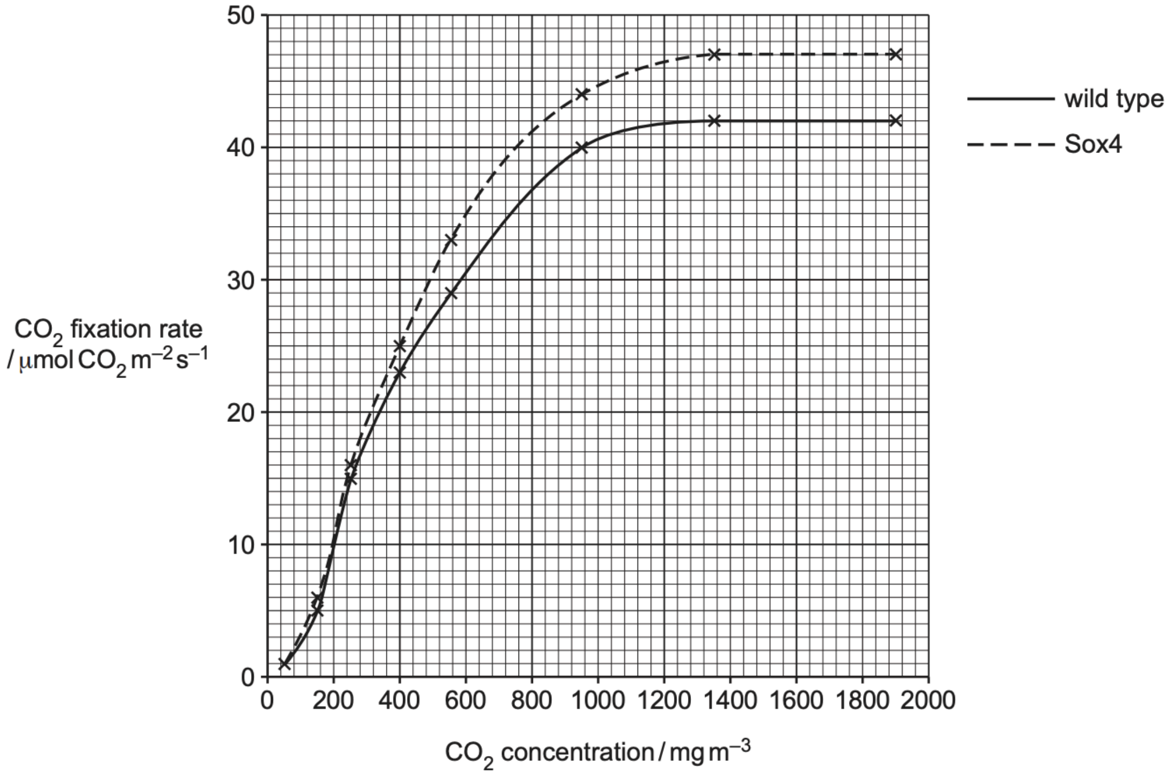
**(b)** The rate of regeneration of RuBP in the Calvin cycle is known to limit the rate of photosynthesis.

Sedoheptulose-1,7-bisphosphatase (SBPase) is an enzyme in the Calvin cycle that controls the rate of regeneration of RuBP. SBPase is coded for by the gene *SBPase*.

In an experiment, wheat plants were genetically modified to make more SBPase by introducing the *SBPase* gene from another grass species, *Brachypodium distachyon*. The resulting GM wheat plants were named Sox4.

- Wild type plants (not GM) and Sox4 plants were grown.
- A leaf from the wild type plant was placed in a sealed glass vessel.
- The carbon dioxide ($CO_2$) concentration in the vessel was increased so that the intercellular air spaces also had an increase in $CO_2$ concentration.
- The other environmental conditions were kept constant.
- The rate of fixation of $CO_2$ was measured for the leaf.
- The experiment was repeated with a leaf from a Sox4 plant.

Fig. 2.1 shows the rate of fixation of $CO_2$ by the leaves of wild type plants and Sox4 plants when the intercellular air space $CO_2$ concentration was increased.




**a. With reference to the graph, describe and explain the results shown by the wild type plants.**

- as the CO2 concentration increases the rate of fixation of CO2 increases.
- as CO2 concentration is the limiting factor.

- as the $CO_2$ concentration increases the rate of fixation of $CO_2$ remains the same / plateaus.
- as $CO_2$ concentration is no longer the limiting factor OR temperature / light intensity / RuBP regeneration is the limiting factor.
- paired data quote with units to support.

**b. With reference to the graph, describe and suggest explanations for the differences in the rate of fixation of $CO_2$ between wild type plants and Sox4 plants.**

- the rate of fixation of $CO_2$ is higher in Sox4 compared to wild type OR Sox4 reaches a higher maximum rate of $CO_2$ fixation.
- wild type 42 vs Sox4 47 μmol $CO_2$ $m^{-2}s^{-1}$.
- Sox4 has more SBPase OR there is a faster rate of regeneration of RuBP OR new SBPase more effective.
- more RuBP to react with $CO_2$ / rubisco.

**Name the natural hydrogen acceptor found in chloroplasts that is replaced by DCPIP in the Hill reaction.**

- NADP

**Rate of photosynthesis is limited by light intensity, temperature and carbon dioxide concentration. State which of these factors would have no effect on the reducing ability of a chloroplast suspension. Give a reason for your answer.**

- carbon dioxide concentration.
- not involved in light dependent reaction / photophosphorylation / photolysis OR only involved in light independent reaction / Calvin Cycle.

**State and explain the expected relationship between light intensity and time taken to decolourise DCPIP.**

<u>Expectation</u>

- as light intensity increases time taken for decolourisation decreases OR as light intensity increases rate of decolourisation increases OR as light intensity increases decolourisation is faster.

<u>Explanation</u>

- more photons / light energy absorbed
- more / faster photolysis
- more electrons excited / released OR faster rate of electron release
- more protons released OR faster rate of proton release
- more / faster reduction of DCPIP

**Predict and explain the effect on the concentration of RuBP in the chloroplasts if DCPIP becomes reduced instead of NADP.**

- RuBP decreases / becomes less.
- Because it reacts / is used up / is converted OR because it is not replaced / regenerated.

A suspension of isolated chloroplasts for measuring the rate of the Hill reaction can be prepared by carrying out the following steps:

- prepare buffer solution with the same water potential as the stroma of chloroplasts
- liquidise (homogenise) spinach leaves in ice cold buffer solution
- filter the liquid and obtain the filtrate
- centrifuge the filtrate to obtain a pellet of chloroplasts
- add the chloroplast pellet to fresh buffer solution in a beaker and mix to obtain a suspension.

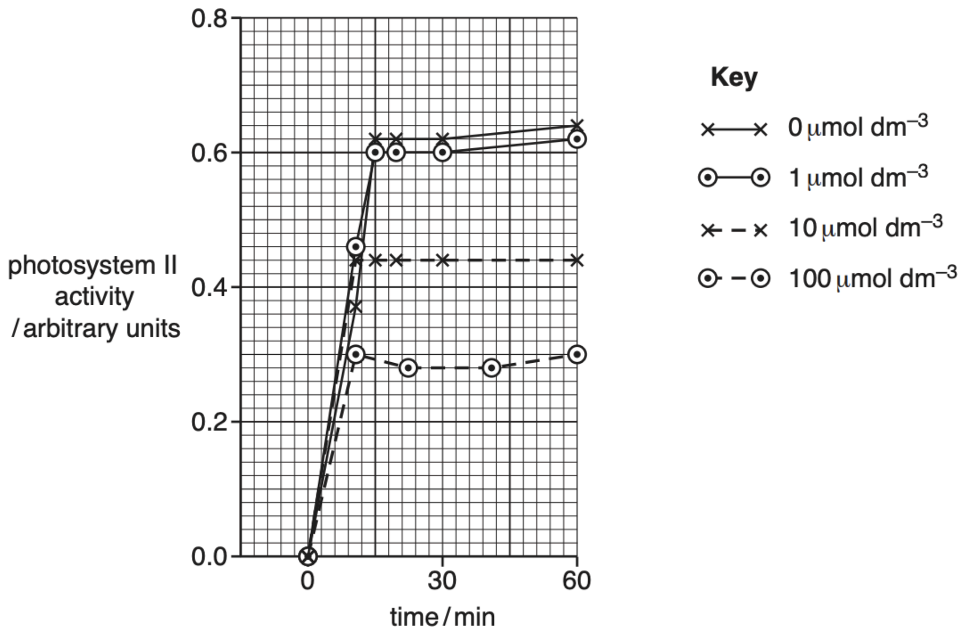
a. **Explain the reason for keeping the temperature very low**
   - to reduce / stop activity of enzymes
   - eg. to proteases / lipases
   - to prevent damage to chloroplasts

b. **Using a buffer solution**
   - to control pH / keep pH constant
   - so enzyme works at optimum / to prevent denaturation of enzyme

c. **Using a solution of the same water potential as the stroma of chloroplasts.**
   - to avoid osmosis / movement of water down a water potential gradient
   - to prevent damage to chloroplasts

Effect of cadmium ion concentration on photosystem II:

- Four different concentrations of cadmium ions: 0, 1, 10, 100 μmol $dm^{-3}$
- The plant was allowed to acclimatise in the dark before the experiment started.
- At time 0 min the light was switched on and the cadmium ions were added.
- At each concentration, the activity of photosystem II was measured over a period of 60 minutes.
- Each experiment was carried out under the same controlled conditions.




**Describe the effects of cadmium ion concentration on the activity of photosystem II**

- as concentration of cadmium ions, increases PSII activity decreases.
- supporting figures comparative quote with units.
- concentration rises by order of magnitude / factor of 10 each time.

| test-tube | contents | conditions | colour change |
|---|---|---|---|
| 1 | buffer solution + DCPIP | light | no |
| 2 | chloroplast suspension + DCPIP | light | yes |
| 3 | chloroplast suspension + DCPIP | dark | no |

**a. Explain the results for test-tube 2.**

- light dependent reaction / photophosphorylation / photolysis occurred.
- hydrogen produced / released.
- DCPIP reduced.

**b. Explain why test-tube 1 was included in the investigation.**

- to show that any change in colour is due to chloroplasts / not due to buffer.
- to make the experiment valid / to act as reference point.

**c. Suggest and explain what would happen to the chloroplasts if they were suspended in distilled water.**

- swell / burst / lyse / lysis.

- higher water potential outside chloroplast.
- water enter, by osmosis / down water potential gradient.

DCPIP can be used to investigate the effect of light wavelength on the rate of the light dependent stage of photosynthesis. One method is described here:

- Dip a small glass capillary tube into a beaker containing a suspension of isolated chloroplasts. Some of the chloroplast suspension will be drawn into tube **A**, forming a colour standard.
- Mix the rest of the chloroplast suspension with blue DCPIP solution. Dip a second capillary tube into this to draw up a sample, to form tube **B**.
- Store the chloroplast-DCPIP mixture for future use by wrapping the beaker in foil and covering it with a removable foil lid, as shown in Fig. 2.1.

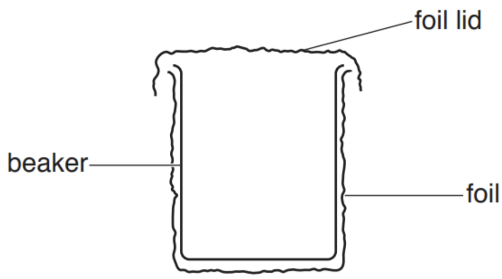



**Fig. 2.1**

- Place tube **A** and tube **B** on a white tile under a bench lamp placed 15 cm away and immediately cover them with a purple filter, as shown in Fig. 2.2.

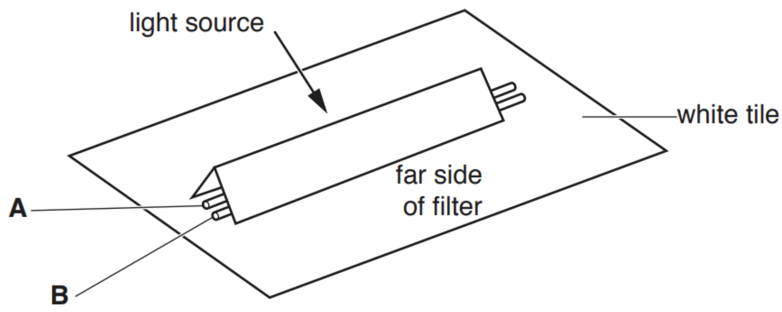



**Fig. 2.2**

- Measure the time for tube **B** to change colour to match that of tube **A**. This is the time taken for DCPIP to decolourise.
- Repeat four more times using the same tube **A** and a fresh tube **B**, placing the tubes under a different coloured filter each time.

a. **Explain the reason for: the colour standard tube A**
    - for comparison / to compare
    - to see end-point / when all DCPIP has been reduced in B

b. **Explain the reason for: covering the beaker containing the chloroplast-DCPIP mixture with foil.**

- to stop / limit light entering the beaker / mixture or to stop light reaching chlorophyll.
- to stop / limit light dependent reaction occurring.
- to stop / limit DCPIP decolourising / being reduced.
- so all tests start with the same colour of DCPIP–chloroplast mixture.

NOTE: process that slows down the rate of photosynthesis = photorespiration.
**The anatomy of C4 plants is adapted to allow the rate of photosynthesis to remain high at high temperatures. C3 plants do not have these adaptations and an additional reaction occurs at high temperatures that reduces the rate of photosynthesis. Explain why the reaction that takes place at high temperatures in C3 plants reduces the rate of photosynthesis.**
- Photorespiration occurs, which reduces rate of photosynthesis.
- Oxygen combines / reacts with rubisco / RuBP.
- Less/ no carbon dioxide combines / reacts with rubisco / RuBP OR less or no carbon fixation.