Rewarding Learning

eGUIDE//Biology

Biochemistry, Genetics and Evolutionary Trends

Unit A2 2 5.2 Photosynthesis

This e-book is designed to complement other support materials and enhance the understanding of this unit for students at GCE level. The topics covered are in accordance with those topics present in the current specification.

Contents

Photosynthesis

5.2

Learning Outcomes from A2 2 5.2

Students should be able to:

- Demonstrate knowledge and understanding of the sites in the chloroplast where the reactions of photosynthesis occur
- Demonstrate knowledge and understanding of the light-dependent stage of photosynthesis
- Demonstrate knowledge and understanding of the light-independent stage of photosynthesis
- Demonstrate knowledge and understanding that light is absorbed by chlorophyll and associated pigments
- Demonstrate knowledge and understanding of the external factors that limit the rate of photosynthesis
- *Carry out practical work including; paper chromatography of plant pigments and calculation of Rf values, and demonstrating the role of hydrogen acceptors using redox indicators (for example DCPIP).*

What is Photosynthesis?

Photosynthesis is the process whereby organisms such as plants, some protists and some bacteria use the energy from sunlight to convert (fix) atmospheric carbon dioxide into carbohydrates, that is, light energy is converted into chemical energy.

The organisms which can convert light energy into chemical energy in this way are called autotrophs as they are capable of making their own food from inorganic compounds such as CO_2. In the food chains they are referred to as producers.

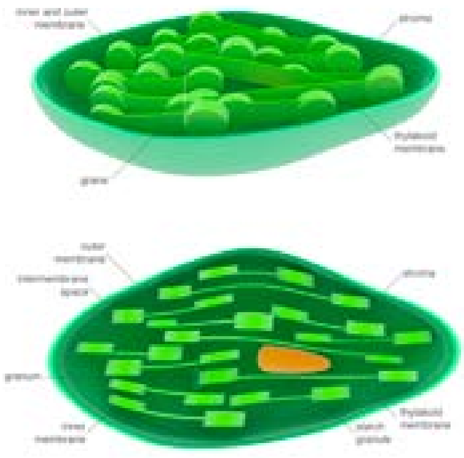
Photo = light; synthesis = to make.
It is convenient to think of photosynthesis in this way as it takes place in two stages;

- The light-dependent reactions
- The light-independent reactions

Site of Photosynthesis

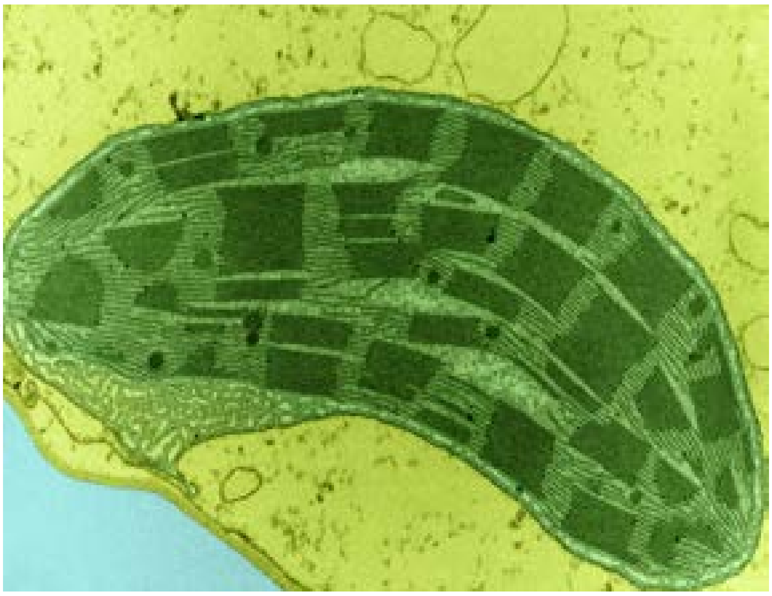
Photosynthesis takes place in the chloroplasts of plant cells.

The internal structure of a chloroplast is illustrated in the next image. The perspective view (top) shows the outer (light green) and inner (dark green) membranes enclosing a fluid called stroma and membrane structures called thylakoids (green) that form both grana (stacks) and lamellae (flat planes). It is the thykaloids that are the site of photosynthesis, the capturing of energy from sunlight using the green pigment chlorophyll. The sectioned view (bottom) shows a granule of starch (orange), a metabolic product of photosynthesis.



Q. The image below is a TEM of a corn (*Zea* sp.) leaf mesophyll, showing a chloroplast (colour enhanced TEM). Label the following on the photograph:

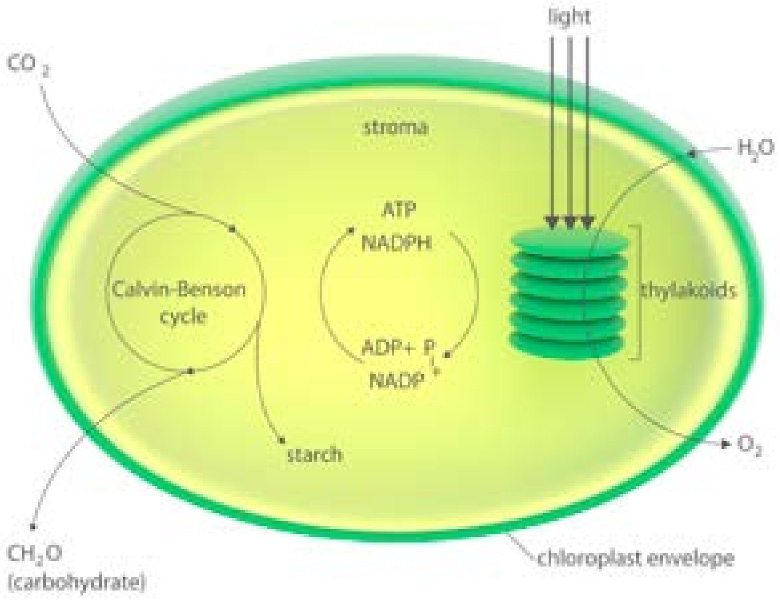
- Outer membrane
- Inner membrane
- Stroma
- Thylakoid membrane
- Granum
- Intergranal lamellae
- Intermembrane space



Overview of the process of Photosynthesis

The light-dependent reactions occur in the thylakoids. Light energy is used to split water by photolysis. Oxygen is produced in this reaction. ATP and reduced NADP (NADPH) are also produced to drive the light-independent reactions.

The light-independent reactions occur in the stroma. The energy from ATP and the reducing power of NADPH are used in the fixation of atmospheric C from carbon dioxide to produce carbohydrates.



Photosynthesis can be broken down into separate processes (the light-dependent reactions and the light-independent reactions) taking place in the chloroplast.
'What is photosynthesis?' by Jeremy LeCornu
https://www.youtube.com/watch?v=B8pQJzvS0D8

Breakdown of clip	Definition of Autotrophs & Heterotrophs	
	Photosynthetic Autotrophs	1min 26s
	Plant cell and Chloroplast structure	2min 10s
	Photosynthesis	3min 48s

Light-dependent Reactions

The light-dependent reactions in photosynthesis occur in the thylakoid membranes of the chloroplast.

The Z-scheme describes how light energy is converted into chemical energy in this stage through the passage of electrons through two photosystems. They contain a number of light trapping pigments and have molecules of chlorophyll at their reaction centre. The other pigments present are known as accessory pigments and help chlorophyll to trap light of differing wavelengths.

Photosystem I is found mainly on the intergranal lamellae and contains chlorophyll P_{700} at its reaction centre (absorbs light of wavelength 700nm).

Photosystem II is found mainly on the granal lamellae, and contains chlorophyll P_{680} at its reaction centre (absorbs light of wavelength 680nm).

Note: The photosystems are designated I and II on the basis of when they were discovered, not on the order of the reactions as they occur simultaneously.

The Z Scheme

The Z scheme can be broken down into steps to make it easier to understand.

1. **Photoactivation of PSII**
   A photon of light striking PSII is absorbed by the pigments and passes to the chlorophyll at the reaction centre. As a result a pair of energised electrons are emitted from the chlorophyll and pass to an electron acceptor at a higher energy state. The electrons then pass down through a series of electron carriers at decreasing energy levels and, as they do so, release free energy that is used to make ATP from ADP and Pi. The electrons eventually reach PSI where they replace electrons emitted from PSI.

2. **Photoactivation of PSI**
   A photon of light energy striking PSI causes a pair of electrons to be emitted from the chlorophyll molecule at its reaction centre, to a higher energy level and picked up by another electron acceptor. These electrons also pass down through a series of electron acceptors at decreasing energy levels, but this time the final electron acceptor is NADP (Nicotinamide adenine dinucleotide phosphate), which is reduced to produce NADPH (reduced NADP). The electron 'holes' left by the excitation of these electrons are filled by electrons from PSII as above. The electron 'holes' left in PSII as a result of the excitation of electrons are filled by electrons released through the splitting of water. This process, called photolysis (photo =light; lysis = to split), uses light energy for the decomposition of water releasing oxygen, hydrogen ions and electrons as below;

$$H_2O \xrightarrow{\text{Light}} \tfrac{1}{2}\,O_2 + 2H^+ + 2e^-$$

   The $2H^+$ ions are used alongside the electrons from PSI to reduce NADP to NAPDH.

Q: Add the above equation to the diagram of the Z Scheme on page 6 and show (using arrows) what happens to the oxygen, electrons and hydrogen ions produced by the photolysis of water.
Use the website below to check the answer.
http://www.biotopics.co.uk/a2/light-dependent_reactions.html

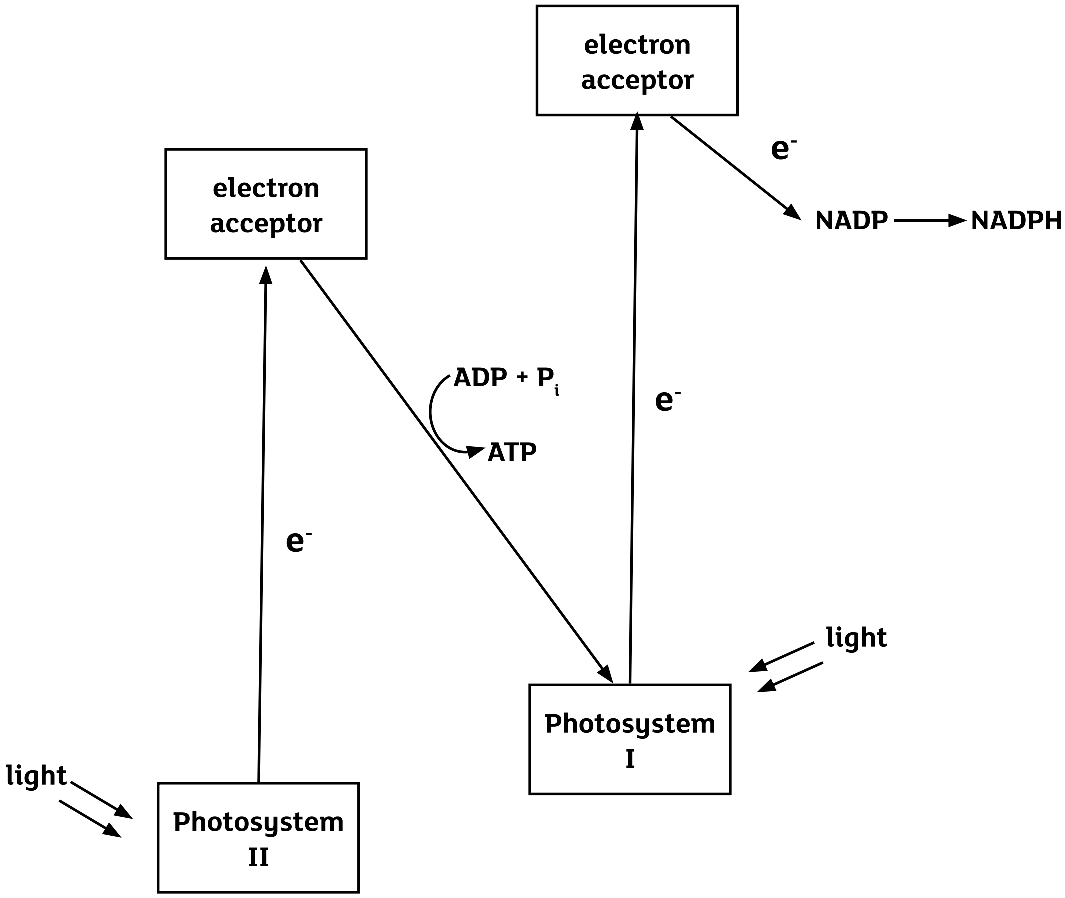


Diagram of the Z scheme.

Animation of Z Scheme of photosynthesis. Freeze the final frame and allow the students to draw their own diagrams of the Z Scheme.
https://www.youtube.com/watch?v=t4RlsDDsNi8

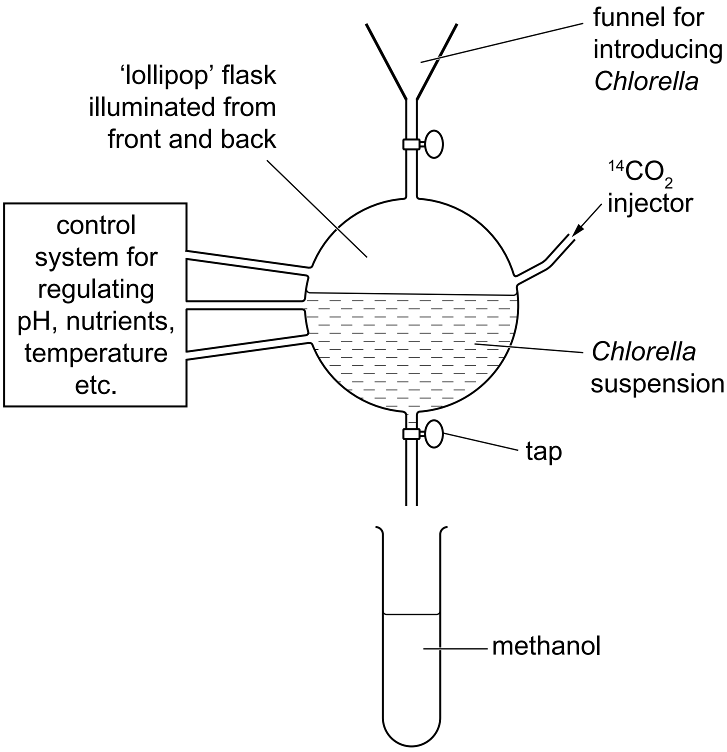
Summary of the products of the light-dependent reactions of photosynthesis

Product	Where/how it is produced?	What happens to it?
Oxygen	Produced by the splitting of water (photolysis) in the granum.	It is either released through stomata or used in respiration.
ATP	Produced from ADP and P*i* as electrons pass along the electron transport chain from PSII to PSI.	ATP provides the energy to drive the next stage – the light-independent reactions or Calvin Cycle.
NADPH	Produced when NADP acts as the final electron acceptor for the electrons from PSI.	NADPH (reduced NADP) provides the reducing power to drive the next stage – the light-independent reactions or Calvin Cycle.

The Light Independent Reactions – the Calvin Cycle

The light-independent reactions of photosynthesis occur in the stroma of the chloroplast. They do not need light energy to occur but are dependent on receiving the products, ATP and NADPH from the light-dependent reactions. The process is known as the Calvin Cycle after the American scientist, Melvin Calvin, who discovered it during World War II.

The diagram below shows the apparatus Calvin used. The apparatus is sometimes referred to as the "Lollipop apparatus" due to the shape of the flattened-sided glass flask.



He used:

- the single celled green algae – *Chlorella* (to carry out photosynthesis)
- a light source
- radioactive carbon^{14} (injected as hydrogen-carbonate ions)
- boiling methanol to kill the algae and stop the reactions at various short time intervals.

After each time interval, he homogenised the algae/methanol sample and analysed the contents using 2-way chromatography. The radioactive compounds which had ^{14}C incorporated into them were easily identified by exposure to a photographic plate. By gradually increasing the time intervals Calvin showed that increasing numbers of intermediates were formed in each successive sample up to a limit, when the numbers levelled off. He used these results to identify the order in which the intermediates were formed and therefore revealed the pathway of carbon dioxide as it is "fixed" into organic compounds through the cycle.

View a short animation of Calvin's experiment here;
http://www.snabonline.com/Content/TopicResources/Topic5/Activities/Interactives/5_6/5--6.swf

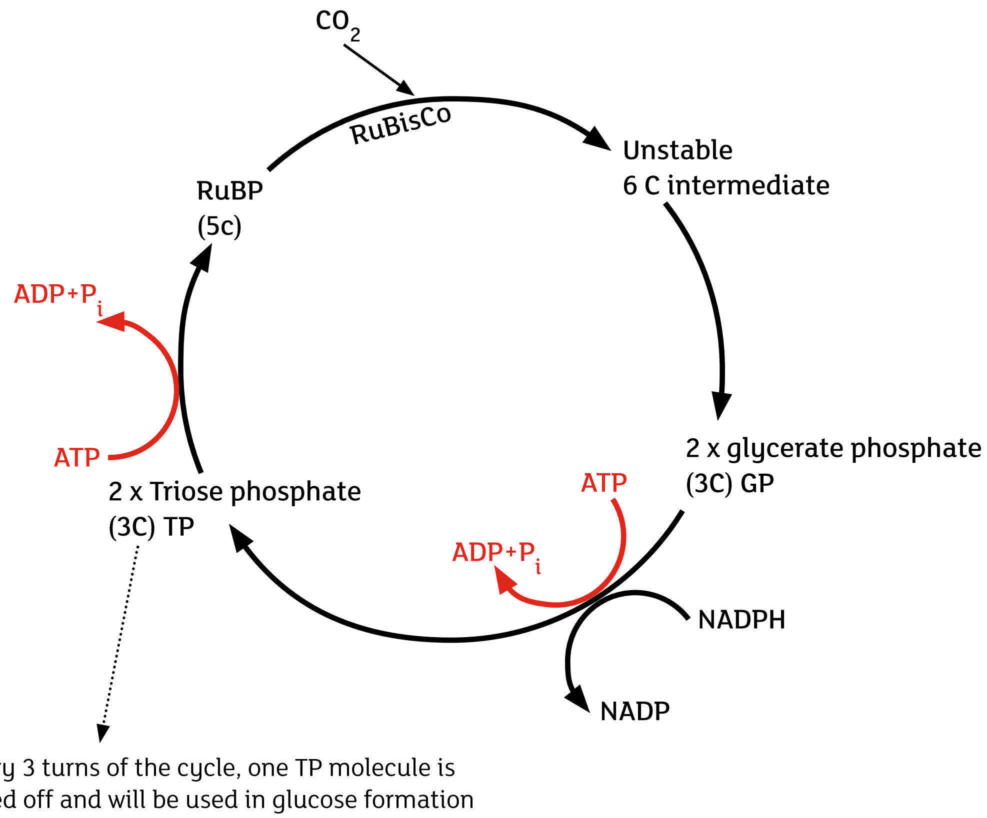
Q. Suggest why Calvin used a specially flattened 'lollipop' flask in this investigation.
Q. The time that the *Chlorella* was exposed to radioactive carbon was increased by only a few seconds for consecutive samples. Suggest why.

The Calvin Cycle

It is a cyclical pathway by which CO_2 is 'fixed' into organic molecules; the basis for food molecules such as glucose (a hexose sugar). Important molecules involved in this pathway are:

1. Ribulose Bisphosphate (RuBP) – a five-carbon sugar molecule which starts and ends the cycle.
2. RuBisCo – a very important enzyme which catalyses the addition of CO_2 to RUBP in the initial step. Without this enzyme (the most abundant in nature) the ability of autotrophic and heterotrophic organisms to obtain food would cease.
3. ATP – from the light-dependent reactions provides the energy required.
4. NADPH – from the light- dependent reactions provides the reducing power required.

The steps in the cycle are summarised in the diagram below.



Steps in the cycle.

1. CO_2 from the air binds to a 5C molecule of RuBP, (catalyzed by RuBisCO) to form an unstable 6C intermediate.
2. The unstable intermediate breaks down immediately to form two 3C molecules of glycerate phosphate (GP).
3. Each GP molecule is reduced by NADPH (from light dependent reactions) to form a molecule of triose phosphate (TP). The energy needed to do this comes from the breakdown of ATP (from the light dependent reactions).
4. For each turn of the cycle, one TP molecule is '*syphoned off*' to be used in the creation of glucose and other food molecules.
5. The remaining TP molecules are rearranged to regenerate RuBP and the cycle begins again.

The Calvin Cycle can be thought of as having 3 phases:

1. Fixation
2. Reduction
3. Regeneration.

Q. Show where these 3 phases are occurring on the diagram of the Calvin Cycle on page 9.
Note: For each turn of the cycle only one C molecule enters through CO_2, therefore;
It takes 3 turns of the cycle to produce one molecule of 3C triose phosphate (TP)
It takes 6 turns of the cycle to produce one molecule of 6C glucose.
In terms of C atoms for 6 turns of the cycle:

6RuBP	= 6 × 5	= 30 C atoms
$6CO_2$	= 6 × 1	= 6 C atoms

These will generate 12 × TP molecules (3C) = 36 C atoms
Total: 36 C atoms
Of these:
2 × TP will be syphoned off to form1 × (6C) glucose = 6 C atoms
10 × TP will be rearranged to form 6 × (5C) RuBP molecules = 30 C atoms

Q. Redraw the diagram of the Calvin Cycle above, as it would look for 6 turns of the cycle (using the correct number of each molecule involved), to produce 1 molecule of glucose.

The glucose that is produced can be used in respiration, or used as a building block for other molecules such as starch or cellulose.

'The Light Independent Reaction of Photosynthesis' by Mr Pollock
https://www.youtube.com/watch?v=s_1MbHFBetA
This short animation demonstrates the Calvin Cycle and how the numbers add up so that glucose is produced and RuBP is regenerated.
https://www.youtube.com/watch?v=0UzMaoaXKaM
This animation shows the stages in photosynthesis
https://www.youtube.com/watch?v=joZ1EsA5_NY
Breakdown of clip Introduction

Stages and location of each	1min 40s
PSlI	3min 12s
PSI	4min 13s
Calvin Cycle	5min

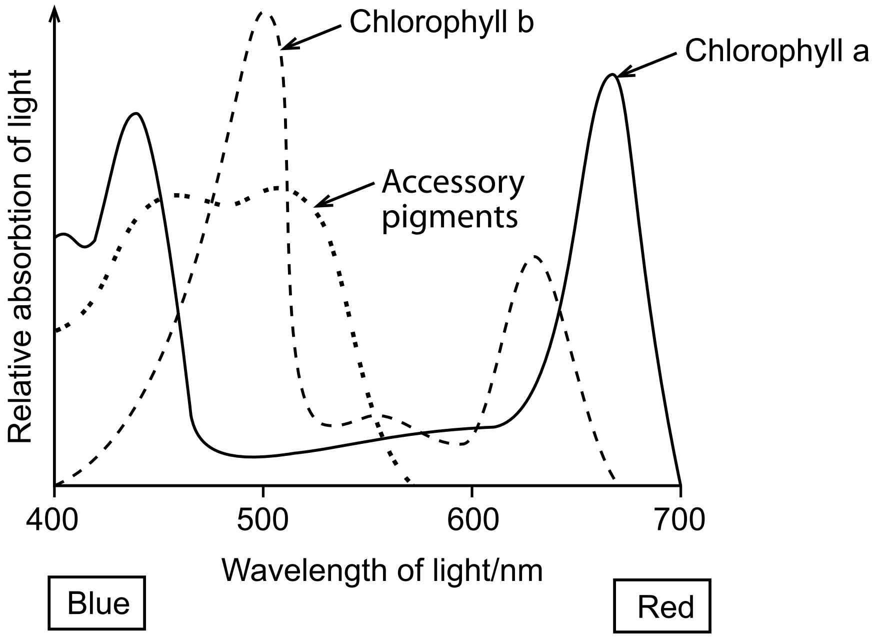
An overall summary can be found in the video 'Photosynthesis: Crash Course Biology #8'
https://www.youtube.com/watch?v=sQK3Yr4Sc_k

The Pigments – Absorption Spectrum and Action Spectrum

Absorption Spectrum

The role of chlorophyll and accessory pigments in absorbing the light energy required for photosynthesis and its subsequent conversion into chemical energy through the Z scheme has been covered. The absorption spectra for the pigments, which show the wavelengths of light absorbed will now be examined.

The diagram below shows the absorption spectrum for the photosynthetic pigments in a typical terrestrial plant.



From the diagram it is clear to see that the wavelengths of light absorbed (shown by the peaks) are mainly in the blue/violet and red regions of the visible spectrum, that the light wavelengths that can be seen. There is little or no absorption of light in the green regions of the spectrum, so green light is reflected or transmitted. This is why leaves appear green.

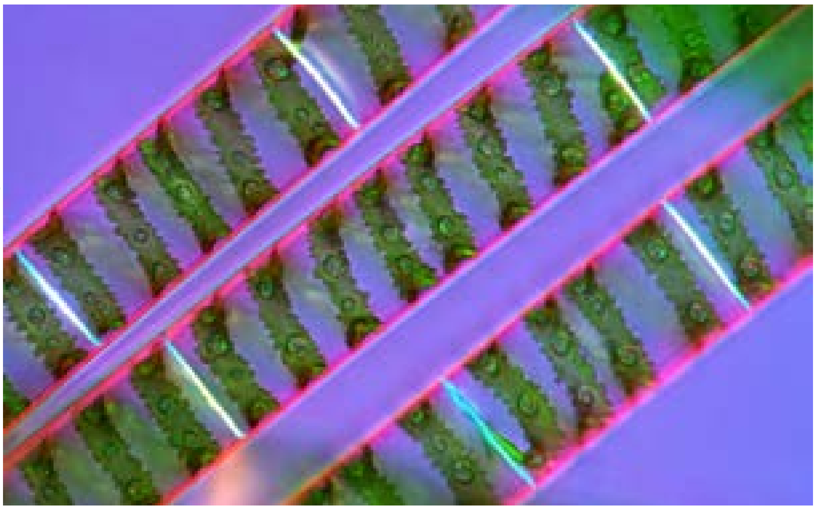
Watch the video 'Outline the differences in absorption of red, blue and green light by Chlorophyll'.
https://www.youtube.com/watch?v=WYKBEYRkhLg

Q. What is the importance of having accessory pigments as well as different forms of chlorophyll?

Action spectrum

An action spectrum shows which wavelengths work best for photosynthesis, that is, are most effective. As shown from absorption spectra, pigment molecules in photosynthetic organisms absorb specific wavelengths of light. The absorption spectrum can be aligned with the action spectrum and show the wavelengths of light that are maximally absorbed by photosynthetic pigments are also the most effective for the photosynthetic processes.

In 1883 Thomas Engelmann devised an experiment to learn which wavelengths of light were the most effective in carrying out photosynthesis in the green alga *Spirogyra*, which has one long spiral chloroplast. Englemann split light into its different wavelengths along the length of the *Spirogyra* using a prism, and used oxygen-dependent bacteria to demonstrate where most photosynthesis was taking place; the bacteria are attracted to oxygen-rich areas. He found that they accumulated near the parts of the alga illuminated with red and blue light. He concluded that those are the wavelengths that work best for photosynthesis as the alga released more oxygen as a photosynthetic by-product. These wavelengths correspond with the regions of maximum light absorption in the absorption spectrum.



Spirogyra light micrograph

Watch an effective animation of Englemann's experiment.
https://www.youtube.com/watch?v=Rt37Hyn4Qv4

The correlation between the action and absorption spectra for chlorophyll and accessory pigments is explained by Alex Lee in the video link.
https://www.youtube.com/watch?v=a7VrP8jc0Ng

Limiting factors in Photosynthesis

A limiting factor in any reaction is one that limits the rate at which the reaction takes place. In photosynthesis the most common limiting factors are:

- Light intensity
- Temperature
- Carbon dioxide concentration

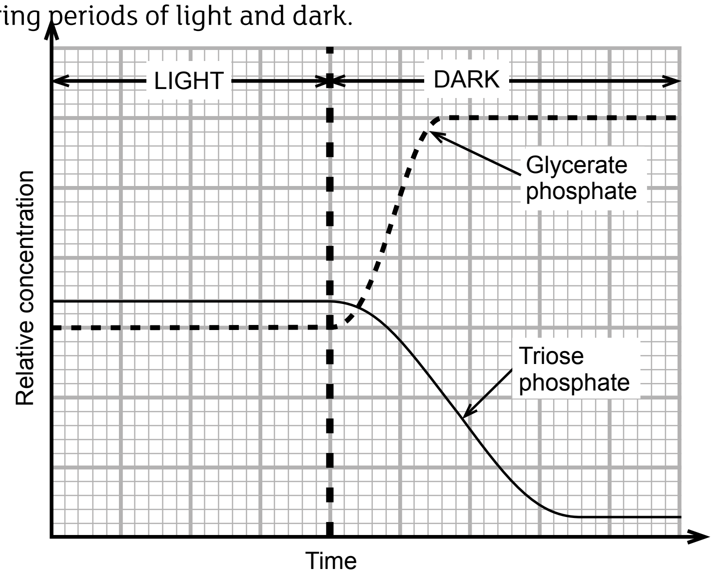
Q. Watch the following video 'Limiting factors on the rate of photosynthesis' by Stephanie Castle.
https://www.youtube.com/watch?v=hWL3GWoHAOw

Use the video to draw and annotate graphs showing.

1. The effect of light intensity on the rate of photosynthesis.
2. The effect of temperature on the rate of photosynthesis.
3. The effect of carbon dioxide concentration on the rate of photosynthesis.

Give the reasons for each factor being a limiting factor and the stage(s) of photosynthesis in which it has an impact and explain why.
To help watch the short video 'Interpretation of limiting factors in photosynthesis in terms of the chemical reactions involved' by Mr Pollock.
https://www.youtube.com/watch?v=go8V2GQq268

Q. The graph below shows the concentration of glycerate phosphate and triose phosphate during periods of light and dark.



Explain the change in the concentration of triose phosphate and glycerate phosphate when light is no longer available, as shown in the graph on page 13.

Access to an information sheet on the 'Rate of photosynthesis: environmental factors' by the RSC through this link. Teachers can register free for access to this website.
https://www.stem.org.uk/elibrary/resource/34935/rate-of-photosynthesis-environmental-factors

Photosynthesis and Respiration – Compensation point

We know that respiration occurs all of the time in plant cells. It uses oxygen and produces carbon dioxide. We also know that photosynthesis occurs when a plant is exposed to light energy. Photosynthesis uses carbon dioxide and produces oxygen. As light intensity increases or decreases, there is a point where the amount of carbon dioxide produced by respiration is equal to the amount of carbon dioxide used in photosynthesis. At this point we can say that there is no net gain or loss of carbon dioxide by the plant. This point is called the compensation point.

The compensation point is where the rate of carbon dioxide release = the rate of carbon dioxide uptake.

Measuring the rate of Photosynthesis

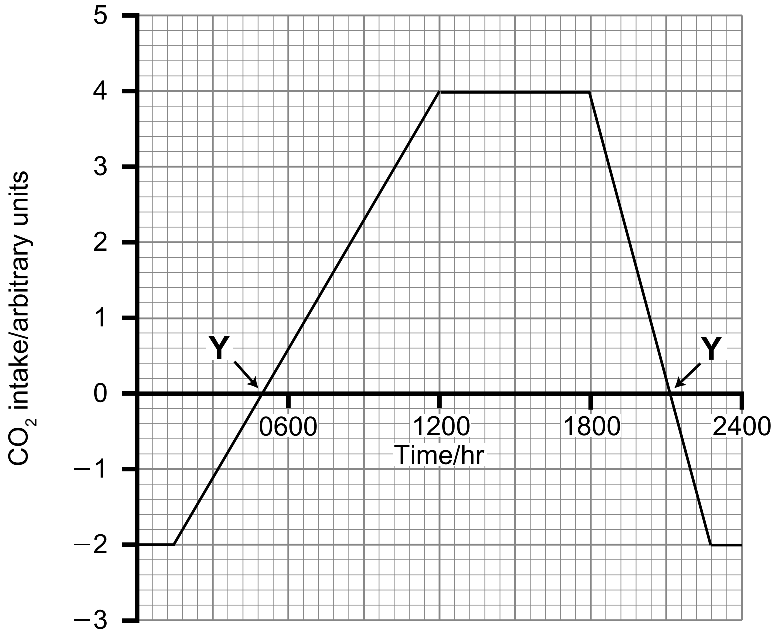
Use the following link to find information on measuring the rate of photosynthesis including:

1. measuring the uptake of CO_2
2. measuring the production of O_2
3. measuring the production of carbohydrates
4. measuring the increase in dry mass

http://www.saps.org.uk/secondary/teaching-resources/157-measuring-the-rate-of-photosynthesis#sthash.8X2ubDEy.dpuf

As the equation for respiration is almost the reverse of the one for photosynthesis, consider whether the methods actually measure photosynthesis alone (the gross rate of photosynthesis) or whether they are measuring the balance between photosynthesis and respiration (the net rate of photosynthesis).

Q. The graph below shows the rates of carbon dioxide intake by a commercial crop plant in a glasshouse over a 24-hour period.



1) State the term which is used to describe the situation indicated by positions labelled Y.
2) The graph provides information on changes in the rate of net photosynthesis in the plant as opposed to gross photosynthesis. State the evidence for this.
3) The glasshouse does not have artificial lighting. Explain why it would be economically undesirable to artificially increase the temperature throughout the 24-hour period but potentially beneficial to increase the temperature between 12 noon and 6 pm.

Useful resources

Teachers can register free for access to TES
https://www.tes.com/teaching-resource/photosynthesis-cloze-6193842
https://www.tes.com/teaching-resource/photosynthesis-revision-sheets-6301011
https://www.tes.com/teaching-resource/photosynthesis-review-6259541
https://www.tes.com/teaching-resource/photosynthesis-card-sort-6259606

CCEA past examination questions on 'PHOTOSYNTHESIS'
(all from Assessment Unit 2 2)

May/June 2015	Question 3
May/June 2014	Question 3
May/June 2013	Question 1
May/June 2012	Question 4
May/June 2011	Question 2
May/June 2010	Question 5