Index

The big picture

? Guiding question(s)

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

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Why do we eat food? There are a few reasons, but one of the primary ones is that food provides us with the energy required for our bodies to function and keep us alive. Without energy we cannot survive.

Figure 1 illustrates some of the variety of foods available to us.

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Figure 1. Our food provides us with the energy we need to survive.

Credit: MEDITERRANEAN, Getty Images

So if our food provides us with energy, where does our food get its energy from? Remember energy cannot be created or destroyed, it can only be transferred and transformed.

This subtopic explores the process of photosynthesis, the source of almost all of the energy needed by most living things on Earth.

Prior learning

Before you study this subtopic make sure that you understand the following:

- That ATP is the molecule that distributes energy within cells (see section C1.2.1—3 (/study/app/bio/sid-422-cid-755105/book/atp-id-45979/)).
- Adaptations of the chloroplast for photosynthesis (see section B2.2.4—6 (/study/app/bio/sid-422-cid-755105/book/structure-and-function-of-double-membranes-hl-id-44251/)).
- Effects of temperature, pH and substrate concentration on the rate of enzyme activity section (see section C1.1.8—10 (/study/app/bio/sid-422-cid-

Student view

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755105/book/thermodynamics-of-enzymes-id-44899/)).

Practical skills

Once you have completed this subtopic, you can gain chromatography skills by going to Practical 4: Investigating pigments present in plant leaves through chromatography (/study/app/bio/sid-422-cid-755105/book/investigating-pigments-id-46695/).

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Photosynthesis

Learning outcomes

By the end of this section you should be able to:

- Explain how the energy transformation of light energy to chemical energy is needed for most life processes in ecosystems.
- Describe photosynthesis as the conversion of carbon dioxide to glucose.
- Describe the production of oxygen as a by-product of photosynthesis.

Anytime you walk outside in the sunshine, you are able to feel the energy of the sun. Regardless of where you are in the world, there can be no doubt that the sun has an impact on the Earth. But just how important is it?

Student
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Overview
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755105/o

Transformation of light energy to chemical energy

Our sun is one of countless stars in our galaxy. When it comes to stars in general, it is not particularly special, but for everything on Earth it means life. Energy from the sun warms the Earth, making global temperatures suitable for life to exist, in large part because water exists mostly as liquid. But it is the light from the sun that is the true giver of life. Organisms have developed the ability to absorb this light energy from the sun and convert it into chemical energy in the form of glucose and other carbon compounds, thus providing the energy for almost all ecosystems on the planet.

The unique ability of organisms to harness light energy and use it to build glucose has allowed the great diversity of life that exists and has existed over Earth's history to evolve and flourish. Whether you are studying the food webs of the Serengeti ecosystem of East Africa, the Amazon River basin ecosystem of South America or the hidden ecosystem under the Arctic ice, the sun is the source of all of the energy. Producers, such as plants, algae and cyanobacteria, absorb light and produce glucose and other carbon compounds. Primary consumers eat the producers, absorbing the energy they have stored. Secondary consumers then eat those creatures and so on. Every organism, regardless of the trophic level it belongs to, relies upon the energy from the sun that was converted using photosynthesis.

Creativity, activity, service

Strands: Creativity, Activity, Service
Learning outcome: Demonstrate how to initiate and plan a CAS experience

Community gardening project

This project could involve designing and setting up a small-scale garden where you have the opportunity to grow plants and learn about the process of photosynthesis firsthand.

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Creativity: You can demonstrate creativity by designing and planning the layout of the garden, selecting appropriate plant species and implementing innovative techniques to optimise photosynthesis, such as creating vertical

Student view

gardens or using hydroponic systems.

Activity: You can actively engage in planting, caring for and maintaining the garden. This includes activities like watering, fertilising, monitoring plant growth and observing the effects of different environmental factors on photosynthesis, such as light intensity or temperature.

Service: The community gardening project can have a service component by involving local community members. You can organise workshops or educational sessions to teach community members about the importance of photosynthesis, sustainable gardening practices and the benefits of growing their own food. They can also collaborate with local organisations or schools to share their knowledge and support broader community engagement in gardening activities.

Conversion of carbon dioxide to glucose

Photosynthesis is one of the most important biological processes on Earth. When cyanobacteria evolved the ability to use the energy from the sun to convert carbon dioxide to glucose and other carbon compounds, life on Earth was forever changed.

In order to convert carbon dioxide (CO_2) into glucose ($C_6H_{12}O_6$), a source of hydrogen is needed. Water (H_2O) is one of the most accessible sources of hydrogen on Earth so it makes sense that these organisms would have made use of it. To access the hydrogen, it first needs to be removed from the water. Photolysis is the stage of photosynthesis in which water is split by light (photo – light and lysis – splitting). The energy in photons is used to split water molecules, generating hydrogen ions, electrons and oxygen.

Figure 1 shows a simple summary of the process of photolysis.

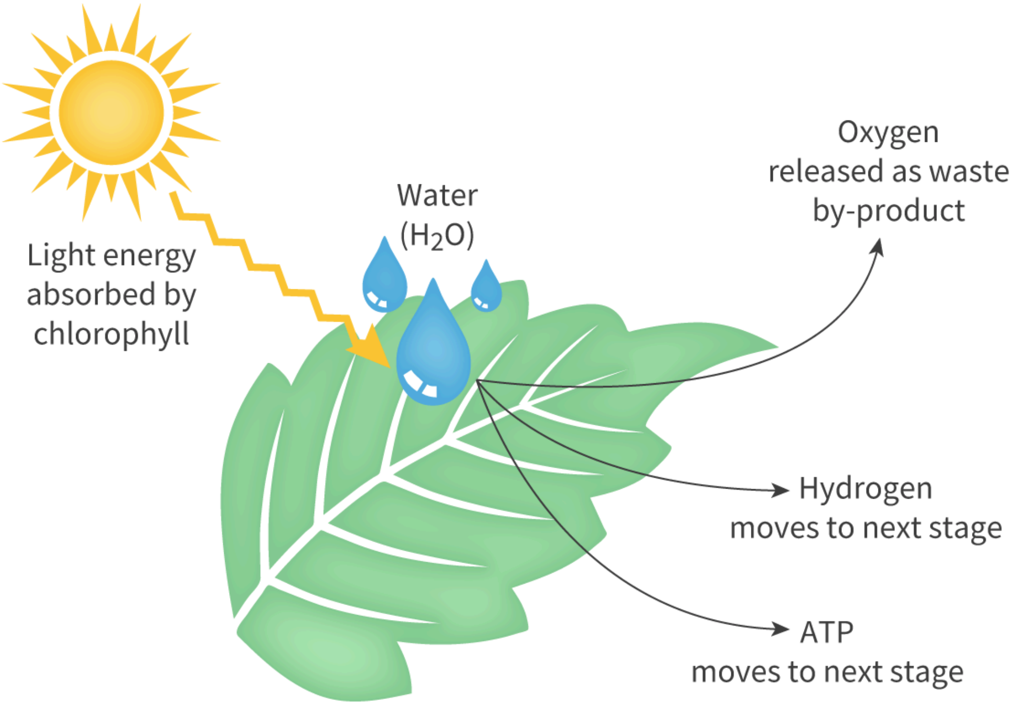

Figure 1. A simplified diagram of photolysis.

More information for figure 1

The diagram illustrates a simplified process of photolysis. It features a leaf with graphical elements representing various parts of the process. At the top left, a sun with rays symbolizes light energy being absorbed by chlorophyll within the leaf. Blue water droplets labeled 'Water (H2O)' are visually interacting with the leaf. Arrows indicate the movement and transformation of elements: one arrow shows oxygen being released as a waste by-product, labeled 'Oxygen released as waste by-product'. Two additional arrows show products moving to the next stage, labeled 'Hydrogen moves to next stage' and 'ATP moves to next stage'. The diagram summarizes the key elements involved in photolysis, highlighting the roles of light energy, water, and the release of oxygen, hydrogen, and ATP in the process.

[Generated by AI]

The equation for photolysis is:

$$2H_2O + \text{photons} \rightarrow 4H^+ + O_2 + 4e^-$$

There are two main sets of reactions in photosynthesis. These are referred to as the light-dependent reactions and the light-independent reactions. Photolysis is a part of the light-dependent reactions whose role is to generate energy in the form of ATP

Overview (/study/ap 422- cid- 755105/o

using the electrons from the splitting of water. This requires light and occurs in the thylakoids of chloroplasts. The oxygen produced is released as a waste product, as shown in **Figure 2**.

The ATP is then used, along with the hydrogen (H^+ and e^-) removed from the water, in the light-independent reactions, during which carbon fixation occurs. Carbon fixation is the conversion of inorganic carbon to organic carbon. In other words, the carbon dioxide from the air is combined with hydrogen using the energy from ATP to form glucose and other carbon compounds. These reactions do not require light and take place in the stroma of chloroplasts.

Overall, the word equation for photosynthesis is:

$$\text{carbon dioxide} + \text{water} \xrightarrow{\text{light}} \text{glucose} + \text{oxygen}$$

Oxygen as a by-product of photosynthesis

The release of oxygen as a waste product by photosynthetic organisms has, over billions of years, changed the composition of Earth's atmosphere. Without such organisms, we would not have oxygen to breathe and most of life as we know it would never have evolved. As we have seen, the oxygen is generated as a by-product of the splitting of water, photolysis. Use **Interactive 1** to explore how oxygen built up in the Earth's atmosphere over time, where time is geological time measured in units of billions of years, or giga-annums (Ga). 1 Ga = 1 billion years = 10^9 years.

Student view

Overview
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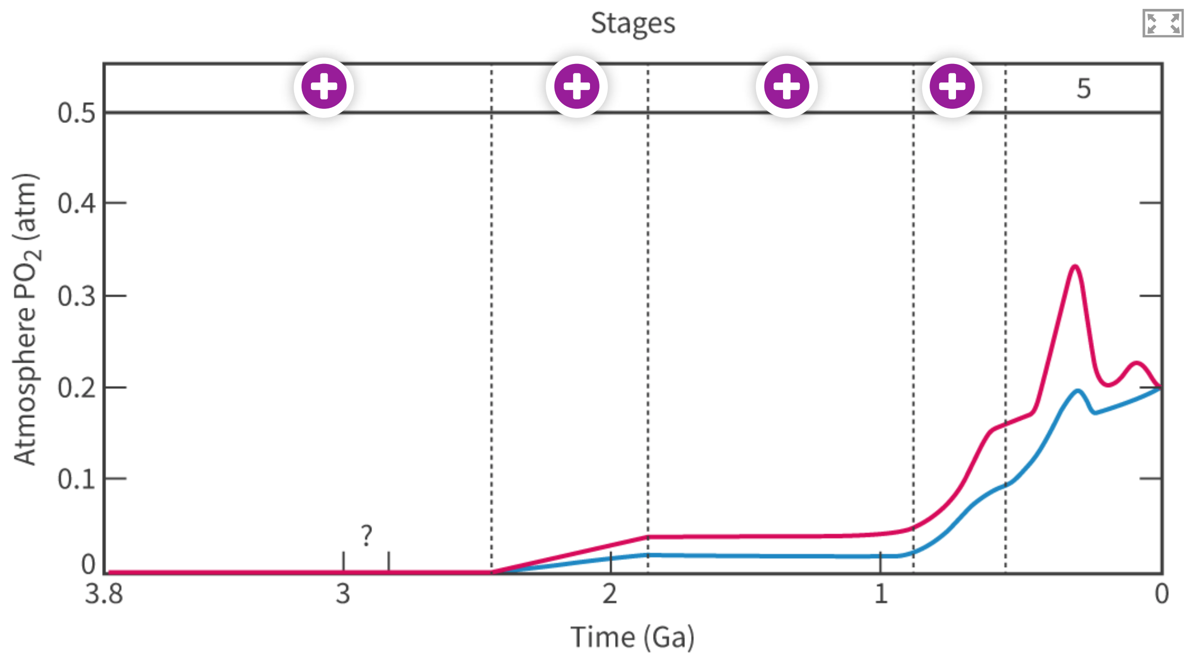

Interactive 1. Oxygen Build-up in the Earth's Atmosphere Over Time.

More information for interactive 1

An interactive graph representing how oxygen levels ($PO2$) in Earth's atmosphere changed over geological time (measured billions of years ago, Ga).

The horizontal axis represents Time (Ga), where 1 Ga = 1 billion years ago. Time progresses from ancient to more recent. The vertical axis represents Atmospheric Oxygen ($PO2$), measuring oxygen partial pressure in the atmosphere (atm). The values range from 0.1 to 0.5 atm. The red and blue lines represent the range of estimates of historical oxygen levels.

The graph is divided into five stages, with hotspots represented by plus signs, based on time period. Hotspot 1 on stage 1. Hotspot 2 on stage 2. Hotspot 3 on stage 3. Hotspot 4 on stages 4 and 5. Clicking on the hotspots reveals the oxygen buildup in the Earth's atmosphere in that period.

The following items are revealed at respective hotspots:

Hotspot 1: Stage 1 (3.85–2.45 Ga): Practically no $O2$ in the atmosphere.

Hotspot 2: Stage 2 (2.45–1.85 Ga): $O2$ produced but absorbed in oceans and seabed rock.

Hotspot 3: Stage 3 (1.85–0.85 Ga): $O2$ starts to come out of the oceans as a gas but is absorbed by land surfaces and the formation of the ozone layer.

Hotspot 4: Stages 4 and 5 (0.85 Ga—present): $O2$ sinks are filled; the gas begins to accumulate in the atmosphere.

The graph shows that before 2.4 Ga Earth had almost no oxygen. The first rise is seen around 2.4 Ga which remains stable up to about 1 Ga. Fluctuations and a rise are seen in stages 4 and 5. It shows how photosynthesis transformed Earth's atmosphere from oxygen-poor to oxygen-rich.

Student view

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Figure 2 is a pie chart detailing the main contributors to oxygen in our atmosphere.

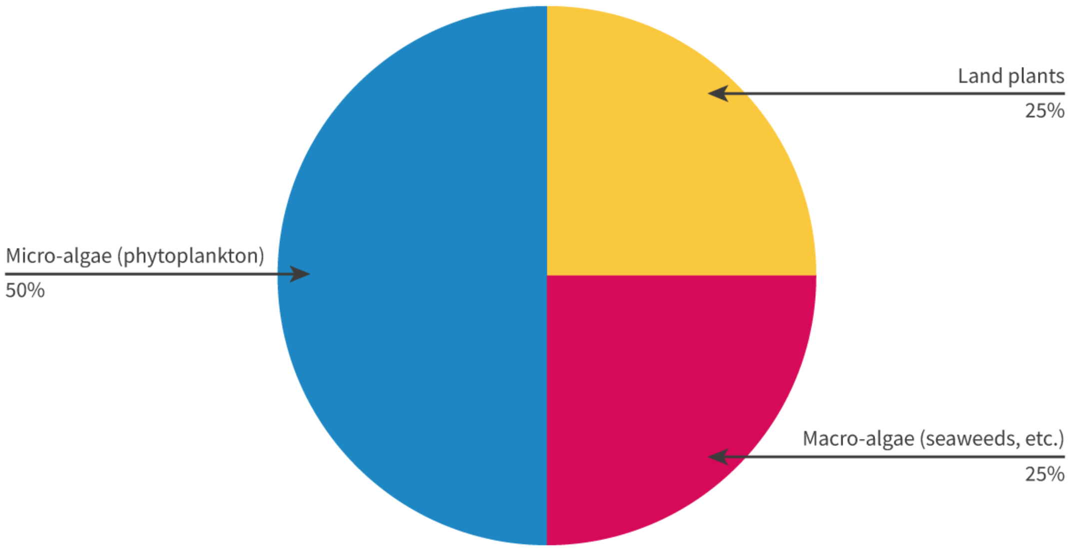

Figure 2. Approximate global contributions to atmospheric oxygen.

More information for figure 2

The image is a pie chart depicting the approximate global contributions to atmospheric oxygen. It is divided into three segments:

1. **Micro-algae (phytoplankton)** - This section occupies 50% of the pie chart, representing the largest contributor to atmospheric oxygen.
2. **Land plants** - This segment is 25% of the pie, indicating that land plants contribute a quarter of the total atmospheric oxygen.
3. **Macro-algae (seaweeds, etc.)** - Also making up 25% of the pie, this segment shows the contribution from macro-algae to atmospheric oxygen.

Each section is labeled with both the contributor type and its percentage contribution. Arrows point from the labels to their respective segments on the pie chart.

[Generated by AI]

Try the group activity below to discuss the importance of photosynthesis for life on Earth.

Student
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Overview
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Activity

- **IB learner profile attribute:**
  - Communicator
  - Thinker
- **Approaches to learning:**
  - Thinking skills — Being curious about the natural world
  - Communication skills — Practising active listening skills
- **Time required to complete activity:** 15—20 minutes
- **Activity type:** Group activity

Classroom discussion: Have a class discussion about the importance of photosynthesis in the ecosystem. Allow a short time (5 minutes) before the discussion for the following:

- Brainstorm different ways in which photosynthesis affects your daily life, such as through the food you eat or the air you breathe.
- Discuss the consequences of reduced photosynthesis rates and the impact that human activities, such as deforestation, mangrove clearing and urbanisation, can have on the process as well as how that can impact humans.

5 section questions

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Chromatography, and action and absorption spectra

C1.3.4: Separation and identification of photosynthetic pigments by chromatography

C1.3.5: Absorption of specific wavelengths of light by photosynthetic pigments

C1.3.6: Similarities and differences of absorption and action spectra

Student view

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Learning outcomes

By the end of this section you should be able to:

- Describe the process of chromatography for separating pigments and the use of R_f values to identify pigments.
- Describe and explain the absorption of different wavelengths of light by photosynthetic pigments.
- Compare absorption and action spectra.

Almost all plants are green and this is primarily due to the pigment chlorophyll, however in temperate parts of the world that experience winter, the leaves change colour in the autumn. Where do the other colours come from?

Figure 1 illustrates the dramatic colour change that happens to trees in temperate climates between summer and autumn.

Credit: Baac3nes, Getty Images

Credit: Nick Brundle Photography, Getty Images

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Figure 1. The differences in colours between leaves in spring/summer and in autumn in temperate parts of the northern hemisphere.

Chromatography

Photosynthesis takes place in chloroplasts. Chloroplasts are the tiny organelles in plant and algal cells where photons (the fundamental particles of light) are captured. The chloroplast looks green because chlorophyll *a* and chlorophyll *b*, the main pigments that capture the photons, reflect green light and absorb most of the other wavelengths in the visible light spectrum. There are other accessory pigments involved in photosynthesis, including xanthophyll and carotenoids. These pigments reflect yellow and orange light, respectively.

Paper chromatography is a technique used to separate mixtures of substances based on the movement of the different substances on a piece of paper by capillary action. The technique makes use of a mobile phase and a stationary phase for the separation process. In the case of paper chromatography, the paper is the stationary phase while the solvent used to develop the chromatogram is the mobile phase. The pigments are commonly separated using an alcohol/solvent mixture.

Despite the fact that a leaf might look green, it can contain several different coloured pigments, such as chlorophylls, beta-carotene and xanthophyll, that can be separated using paper chromatography. The pigments are first extracted from the leaves by using a suitable solvent that dissolves most plant pigments. A sample of the extract is then placed on chromatography paper and transferred to a container with the chromatography solvent (see **Figure 2**). The pigments move at different rates on the stationary phase, so they separate out to form a chromatogram.

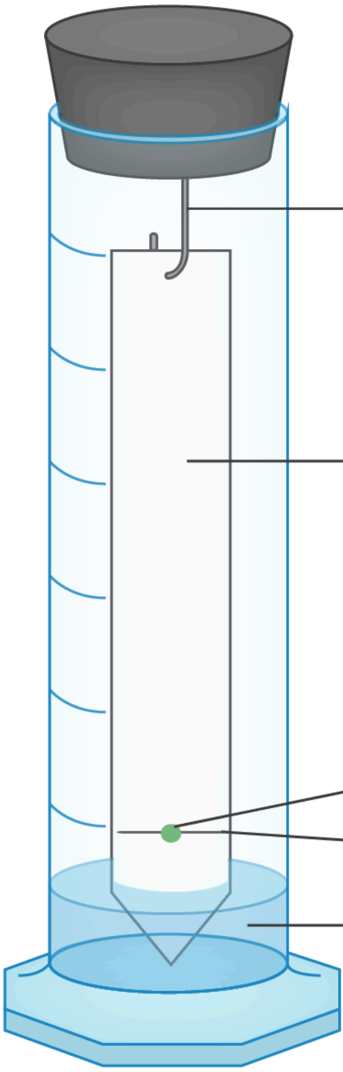

Figure 2. Paper chromatography setup. Note that the pencil line on which the extract is placed must be above the solvent level.

More information for figure 2

The image is a diagram of a paper chromatography setup. At the top, there is a pin securing a strip of filter paper inside a cylindrical container. The filter paper hangs vertically and reaches into the solvent at the bottom of the container. A sample of an extract is placed on a pencil line drawn on the filter paper. This line is positioned above the solvent level in the container. Labels point to key components of the setup: the pin at the top, the filter paper, the sample of extract on the filter paper, the pencil line marking the position of the extract, and the solvent at the bottom of the container. This setup demonstrates how different pigments can be separated using paper chromatography.

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Overview
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The ratio of the distance moved by a pigment to the distance moved by the solvent is a constant and is known as the retention factor, R_f:

$$R_f = \frac{\text{distance travelled by sample}}{\text{distance travelled by solvent}}$$

Worked example 1

Calculate the R_f of a pigment that travelled 45 mm with a solvent front that moved 85 mm.

$$R_f = \frac{45 \text{ mm}}{85 \text{ mm}}$$

$$R_f = 0.53$$

By comparing the calculated R_f value to known R_f values of plant pigments, the pigments present in the plant extract can be deduced.

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Practical skills

Tool 1: Experimental techniques — Applying techniques

You should be able to calculate R_f values from the results of chromatographic separation of photosynthetic pigments and identify them by colour and by calculated values. Thin-layer chromatography or paper chromatography can be used.

Figure 3 shows an example of a chromatogram that may be obtained by paper chromatography of leaf pigments.

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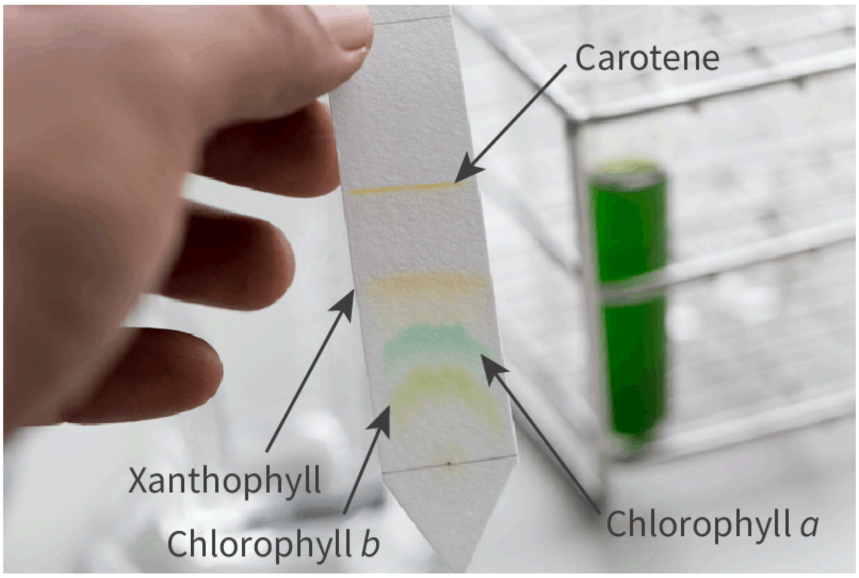


Figure 3. Examples of different photosynthetic pigments separated using paper chromatography.

Credit: Sinhyu, Getty Images.

More information for figure 3

The image shows a hand holding a strip of paper that has been used for paper chromatography, a method used to separate different pigments. The paper shows distinct bands corresponding to different photosynthetic pigments: carotene, xanthophyll, chlorophyll b, and chlorophyll a. Each pigment band is labeled with an arrow pointing to it. The background includes a blurred view of a rack and containers filled with green solution, possibly the extracted pigment solution used in the chromatography process.

[Generated by AI]

Thin-layer chromatography uses the same principle as paper chromatography, except that in this case, the stationary phase is usually silica gel, aluminium oxide or cellulose instead of paper. Thin-layer chromatography tends to give a better result than paper chromatography as well-defined and well-separated spots are obtained.

Absorption of light by photosynthetic pigments

The electromagnetic (EM) spectrum is the range of frequencies and wavelengths of electromagnetic radiation emitted from the sun. Visible light represents a very narrow range of this spectrum between approximately 400 and 750 nm, as shown in **Figure**

Overview (/study/ap 422- cid- 755105/o

4. It is the electromagnetic radiation in this range as visible light that can be absorbed in photosynthesis and used to form carbon compounds.

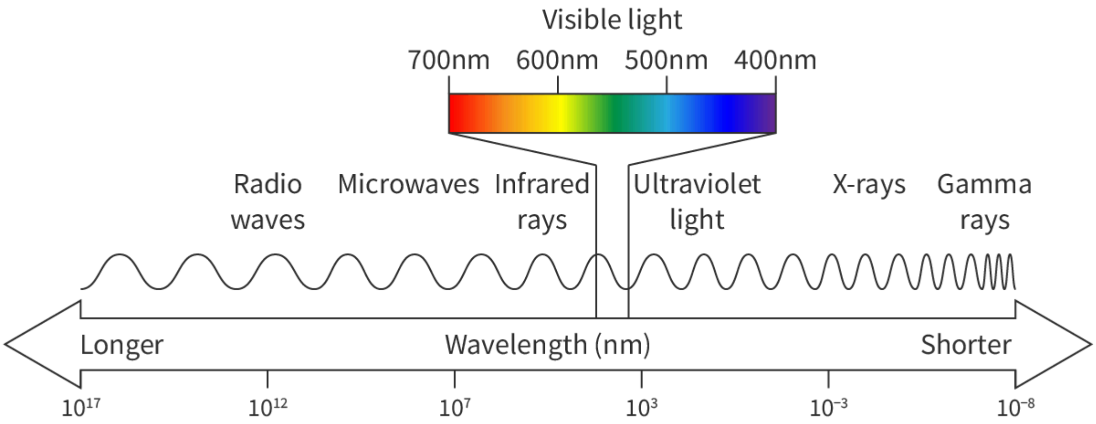


Figure 4. The electromagnetic spectrum, with visible light highlighted.

More information for figure 4

The diagram represents the electromagnetic spectrum, showing a range of electromagnetic waves from radio waves to gamma rays. The spectrum is depicted as a horizontal line with an arrow pointing to the right, indicating increasing frequency and decreasing wavelength. The wavelength scale is marked in nanometers (nm) with significant notations at powers of ten. It starts from longer wavelengths at 10^17 with radio waves, then transitions to microwaves, infrared rays, visible light, ultraviolet light, X-rays, and finally gamma rays at the shortest end of the spectrum around 10^-8.

A notable section of the diagram highlights visible light, ranging from approximately 400 nm to 700 nm, depicted as a colorful band transitioning from violet to red. This section is emphasized with vertical lines marking important wavelength values such as 400 nm, 500 nm, 600 nm, and 700 nm. The diagram indicates how visible light sits between infrared rays and ultraviolet light.

[Generated by AI]

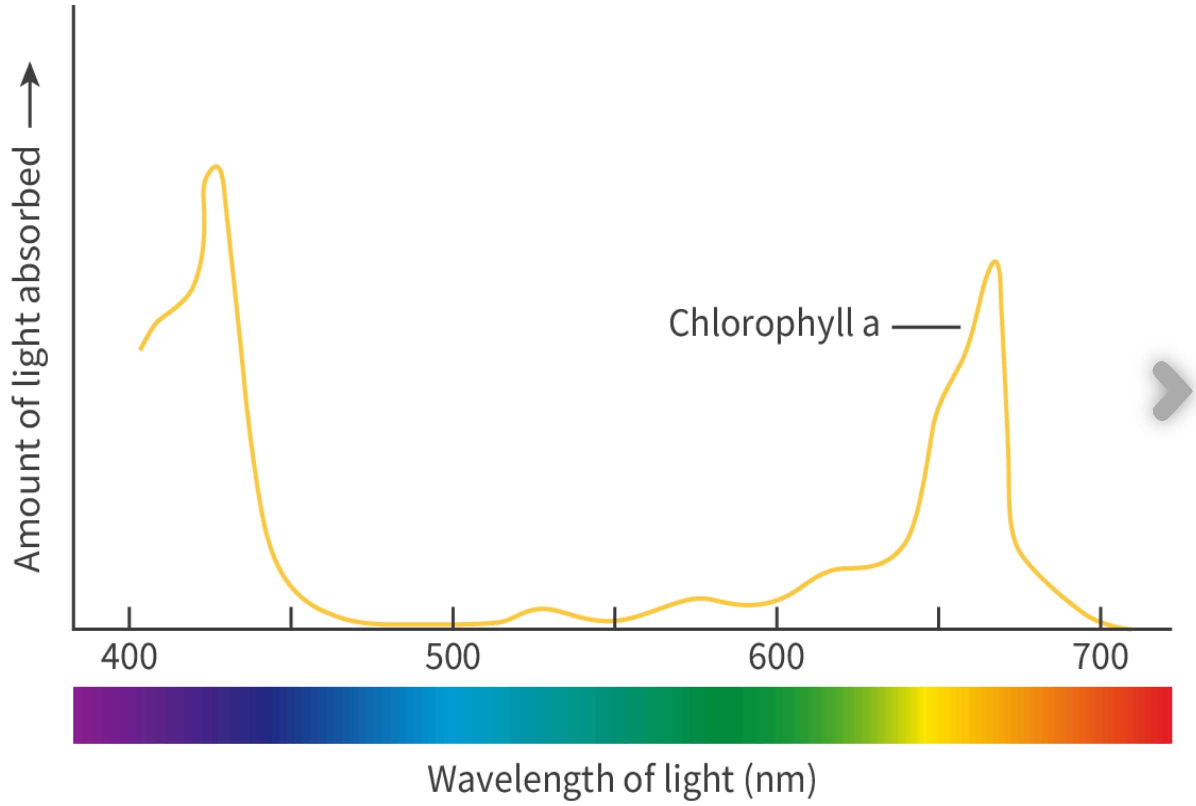
The different photosynthetic pigments, such as chlorophyll *a* and *b* as well as xanthophyll and the carotenoids, all absorb and reflect different wavelengths of light. The wavelengths reflected give the pigments their colour. It is the energy from the radiation at the absorbed wavelengths that drives photosynthesis. The photons of

Student view

Overview (/study/ap 422-cid-755105/o

light and the energy they carry excite electrons in the chlorophyll which are then used to power the light-dependent stage. Those electrons are replaced with the electrons released from the photolysis of water.

The wavelengths of light absorbed by each pigment can be represented in a graph known as an absorption spectrum. The absorption spectra for chlorophyll *a* and *b* and carotenoid are shown in **Interactive 1**.



Interactive 1. Absorption Spectra of Major Photosynthetic Pigments.

More information for interactive 1

An interactive slideshow with four slides exhibits the absorption spectra of chlorophyll a, chlorophyll b, and carotenoid. Each slide features a graph plotting the wavelength of light in nanometers (nm) on the x-axis and the amount of light absorbed on the y-axis. The x-axis ranges from 400 to 700 nanometers and includes a strip representing the visible light spectrum.

Users can switch between the slides using arrows on the right and left. Or, they can also use the circle dots at the bottom to navigate between the slides.

Student view

Overview
(/study/ap
422-
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Read below to understand the information provided in each slide.

Slide 1: The graph represents the wavelength of light absorbed by Chlorophyll a

A yellow curve starts at 400 nanometers, peaks, then decreases until 450 nanometers, stabilizes up to 510 nanometers, and increases gradually with three small peaks at 525, 575, and 626 nanometers. It then increases steeply and reaches a peak near 660 nanometers, and finally decreases and ends near 710 nanometers. The peak at 660 nanometers is marked as chlorophyll a, which lies in the red region of the visible spectrum.
[Note: The wavelength values indicated are approximate.]

Slide 2: The graph represents the wavelength of light absorbed by Chlorophyll b

A blue curve starts at 400 nanometers, rises to a peak at 455 nanometers, and then decreases until 470 nanometers. It plateaus with minor fluctuations until 610 nanometers, rises again to form a second peak at 640 nanometers, and finally decreases and ends at 675 nanometers. The peak at 640 nanometers is labeled chlorophyll b, which lies in the red-orange region of the visible spectrum.
[Note: The wavelength values indicated are approximate.]

Side 3: The graph represents the wavelength of light absorbed by Carotenoid

A pink curve starts at 380 nanometers, increases gradually, falls to form a dip at 450 nanometers, then increases to form a peak at 480 nanometers, and gradually decreases to end at 525 nanometers. The peak of 480 nanometers is referred to as carotenoid, which falls in the blue region of the spectrum.
[Note: The wavelength values indicated are approximate.]

Slide 4

A comparison of all three curves from the previous slides, with peaks of chlorophyll a, chlorophyll b, and carotenoid marked.

This slideshow helps users understand that the carotenoid peak exhibits the highest amount of light absorbed, followed by the chlorophyll a peak and then the chlorophyll b peak.

Student
view

Overview
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Comparing absorption and action spectra

We can also plot the overall rate of photosynthesis against the wavelength of light. This is called an action spectrum. A graph like that given in **Figure 5** shows the photosynthetic activity at each wavelength and can be generated using a variety of measurements from oxygen production to carbon dioxide absorption.

An action spectrum is a good indicator of which wavelengths are most efficient for photosynthesis. Some wavelengths cause a higher photosynthetic rate than others. The action spectrum in **Figure 5** shows the different rates of photosynthesis that occur at different wavelengths of visible light. Note that the highest rates of photosynthesis occur at the blue and red wavelengths, while the lowest rates occur at the green. This matches the absorption spectra of the photosynthetic pigments quite closely as it is their ability to absorb light energy that allows photosynthesis to occur.

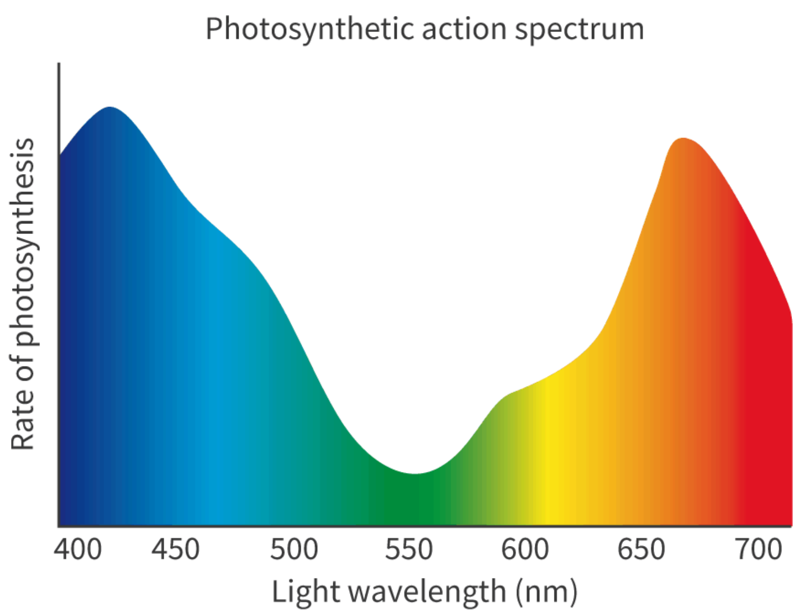

Figure 5. The action spectrum of photosynthesis showing how the rate of photosynthesis is dependent on the wavelength of visible light.

More information for figure 5

The graph shows the action spectrum of photosynthesis, illustrating the relationship between the rate of photosynthesis and light wavelength. The X-axis represents light wavelength in nanometers (nm), ranging from 400 to 700 nm. The Y-axis represents the rate of photosynthesis, although specific units are not provided.

Student
view

The graph features a curve that peaks in two regions: once around the 450 nm mark, which falls in the blue light spectrum, and again near 680 nm, corresponding to the red light spectrum. The lowest photosynthetic rate occurs around 550 nm, where green light is dominant. This indicates that photosynthesis is most efficient under blue and red light while being least efficient under green light, reflecting the absorption characteristics of photosynthetic pigments.

[Generated by AI]

Practical skills

Tool 3: Mathematics — Graphing

Students should be able to determine rates of photosynthesis from data for oxygen production and carbon dioxide consumption for varying wavelengths. They should also be able to plot this data to make an action spectrum.

Worked example 2

In an experiment to measure the rate of photosynthesis, 25 ml of oxygen is produced over 2 hours. Calculate the rate of oxygen production.

$$\frac{25\text{ ml}}{2\text{ h}} = 12.5\text{ ml/h}$$

Try drawing an action spectrum using the data in the activity below.

Activity

- **IB learner profile attribute:** Inquirer

Overview
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- **Approaches to learning:** Thinking skills — Being curious about the natural world;reflecting on the credibility of results
- **Time required to complete activity:** 25—30 minutes
- **Activity type:** Individual activity

An investigation was carried out to determine the action spectrum of an aquatic plant called *Elodea*. As this plant photosynthesises, it releases oxygen gas which can be collected and measured. Use the data from **Table 1** to construct an action spectrum. You will need to calculate means and rates for each wavelength, scale and label your axes appropriately, plot your points accurately and draw a suitable line.

Table 1. Data from photosynthesis investigation using *Elodea*.

Wavelength (nm)	Volume of oxygen produced in 6 hours (n					
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mea
400	17.2	16.5	17.9	16.8	17.6	
450	15.1	16.8	15.9	17.5	16.2	
500	7.8	8.2	7.9	8.1	8.3	
550	3.6	3.4	3.2	3.7	3.5	
600	5.9	6.2	6.4	6.1	6.3	
650	14.8	15.2	15.5	14.9	15.3	
700	13.7	13.9	14.2	13.8	14.0	

5 section questions

Student view

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Limiting factors

Learning outcomes

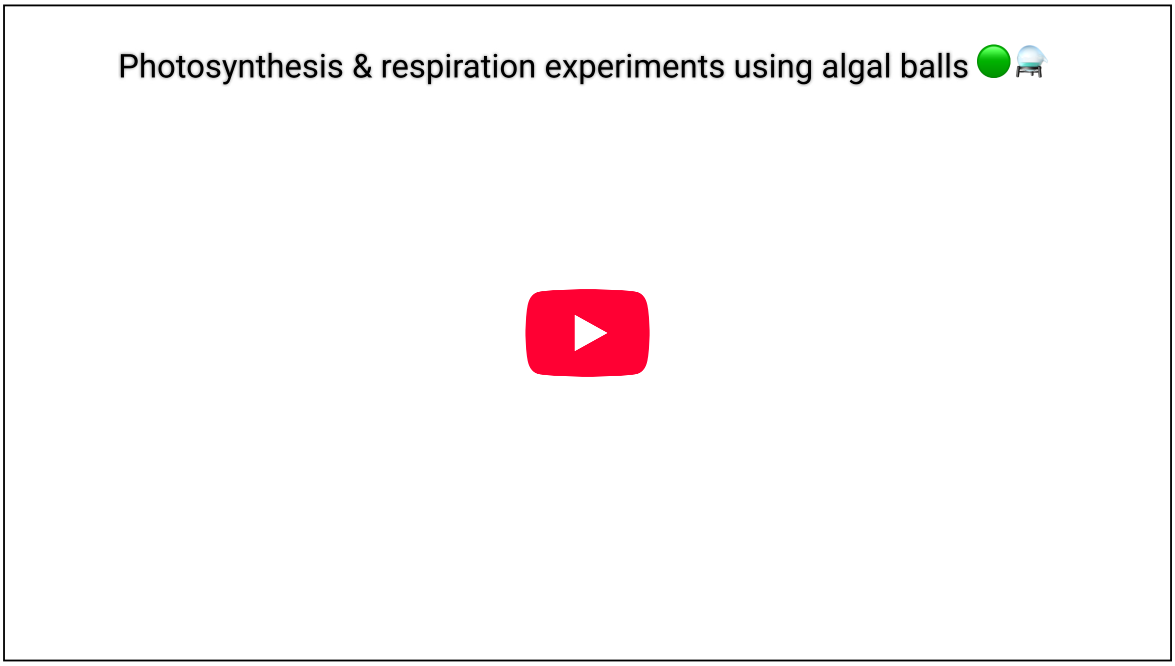
By the end of this section you should be able to:

- Determine through investigation the effects of limiting factors on the rate of photosynthesis.
- Describe carbon dioxide enrichment experiments as a means of predicting future rates of photosynthesis and plant growth.

Would you expect photosynthesis to happen at a constant rate? If not, what sorts of non-living (abiotic) factors might you expect to have a significant effect on photosynthesis? How could you investigate this?

Investigating factors that affect the rate of photosynthesis

The rate of photosynthesis is limited by a number of environmental factors including carbon dioxide concentration, light intensity and temperature. These can be investigated using experimental techniques. An ideal plant to use in these experiments would be a water plant such as *Elodea*. Using a water plant enables conditions to be controlled easily and means that the oxygen produced can be counted as bubbles or collected in a measuring cylinder or gas syringe. This allows for an accurate measurement of volume to be made and a rate of photosynthesis to be calculated. Another option would be cultivating some algae and using them to produce algal balls. **Video 1** shows you how these can be made and how they can potentially be used in photosynthesis experiments.



Video 1. How algal balls can be made and used to investigate photosynthesis.

An easy way to control and change temperatures in photosynthesis investigations is through the use of a water bath. Light intensity can be controlled and changed by moving a primary light source closer to or further away from the plant. Carbon dioxide concentration can be adjusted using sodium hydrogen carbonate which can be added to and dissolved in the water containing the plant under investigation.

Another way to measure the rate of photosynthesis is to use hydrogen carbonate indicator solution. This indicator will change colour as the concentration of carbon dioxide changes. **Figure 1** shows how the indicator changes colour. If the plant is not photosynthesising and is only respiring, the carbon dioxide concentration will increase and the indicator will turn more orange or yellow. If the plant is photosynthesising, carbon dioxide is being absorbed and the indicator will become more purple.

Overview
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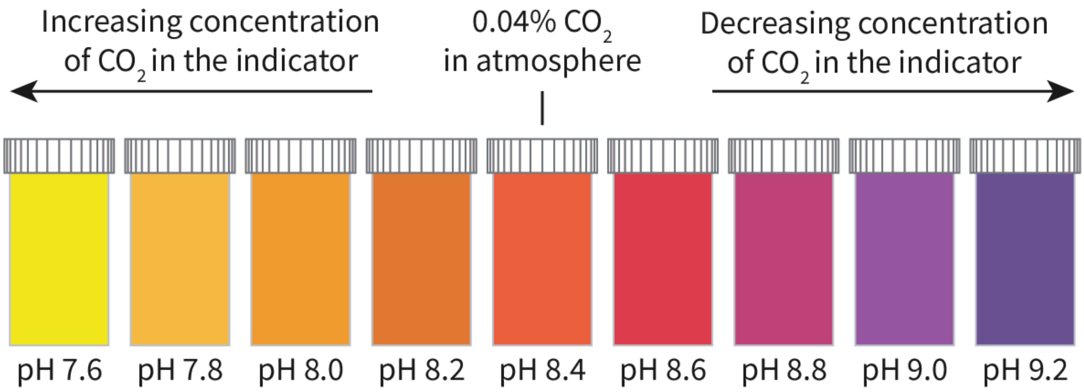

Figure 1. Hydrogen carbonate indicator and how its colour changes as carbon dioxide concentration changes.

More information for figure 1

The image shows a series of test tubes filled with hydrogen carbonate indicator, illustrating the color changes as the pH level changes due to varying carbon dioxide concentrations. From left to right, the colors shift from yellow at pH 7.6 to dark purple at pH 9.2. The colors represent increasing and decreasing concentrations of CO2. A yellow color at pH 7.6 indicates high CO2 concentration, transitioning through orange and red hues at pH 8.0 to 8.6, and shifting to pink, purple, and dark purple from pH 8.8 to 9.2, indicating decreasing CO2 concentration. The image includes labels for each pH value, and arrows at the top indicate the direction of CO2 concentration changes.

[Generated by AI]

Practical skills

Inquiry 1: Exploring and designing — Exploring

You should be able to suggest hypotheses for the effects of these limiting factors and explore protocols based upon your understanding of photosynthesis, and test these by experimentation.

Student view

Overview (/study/app 422- cid- 755105/o

Nature of Science

Aspect: Hypotheses

Hypotheses are provisional explanations that require repeated testing. During scientific research, hypotheses can either be based on theories and then tested in an experiment or be based on evidence from an experiment already carried out. In this case, you can decide whether to suggest hypotheses for the effects of limiting factors on photosynthesis before or after performing your experiments. You should be able to identify the dependent and independent variables in any experiment.

Carbon dioxide enrichment experiments

Mainly due to human activity, the concentration of carbon dioxide in our atmosphere is increasing. Understanding how plants will respond to these higher levels of CO_2 is important. It will allow us to better predict future food production. This can be investigated using carbon dioxide enrichment experiments.

There are two main methods for this. The first is using enclosed greenhouses where the concentration of CO_2 can be carefully monitored and controlled. Elevated levels of CO_2 can be created by burning fuels or other sources. If other conditions are controlled, and there is a control greenhouse without enriched CO_2 but with all other conditions kept the same, the effect of CO_2 enrichment can be measured in a variety of ways. Total biomass produced could be measured or the yield of the fruits or vegetables grown. The limitations of these studies are that, as they are done in controlled conditions, there are natural factors and variables that are not able to be taken into account.

The second method, carried out in a natural ecosystem, is known as free-air carbon dioxide enrichment experiments or FACE. In these experiments, CO_2 is released around a circular area between 1 m and 30 m in diameter. Pipes surround the area and release CO_2 continuously. Sensors within the area monitor CO_2 levels to

Student view

Overview (/study/ap 422- cid- 755105/o

ensure elevated concentrations are maintained. This allows for a more natural way of measuring the impact of higher levels of CO_2 in the atmosphere. However, this method is usually very expensive to carry out.

Nature of Science

Aspect: Experiments

Finding methods for careful control of variables is part of experimental design. This may be easier in the laboratory but some experiments can only be done in the field. Field experiments include those performed in natural ecosystems. You should be able to identify a control variable in an experiment.

Try the activity below in which you will design an investigation into the effect of carbon dioxide concentration on the rate of photosynthesis.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:**
  - Thinking skills — Designing procedures and models
  - Self-management skills — Breaking down major tasks into a sequence of stages
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Design an investigation to determine the effect of different concentrations of CO_2 on the rate of photosynthesis. You should include the following in your design:

- the independent variable and its values
- the dependent variable and how it will be measured

Student view

Overview
(/study/app/bio/sid-422-cid-755105/o

- the significant control variables, why they should be controlled and how they will be controlled
- any confounding variables that cannot be controlled but should be monitored
- a list of materials/apparatus
- any safety precautions
- a step-by-step, repeatable method
- a suitable results table for collecting the data.

5 section questions

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Photosystems (HL)

C1.3.9: Photosystems as arrays of pigment molecules (HL)

C1.3.10: Advantages of the structured array of pigment molecules in a photosystem (HL)

C1.3.11: Generation of oxygen by the photolysis of water in photosystem II (HL)

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/photosystems-hl-id-46520/print/) Assign

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe photosystems as arrays of pigments within membranes of photosynthetic organisms that generate and emit excited electrons.
- Explain the advantage that an array of pigments in a photosystem has over individual pigment molecules.
- Describe the photolysis of water in terms of a means of replacing lost electrons in photosystem II and the production of oxygen as a waste product.

Student view

Overview
(/study/ap
422-
cid-
755105/o

The ability to absorb sunlight and use it is an incredibly special ability. What structures do plants and other photosynthetic organisms have that make this possible? We now have technology (solar panels) that can do a similar thing, absorbing the sun's energy and converting it into another form of energy. Solar panels are actually better at it than plants, as they can absorb a wider range of the EM spectrum from infrared to UV.

Photosystems

As we have seen, photosynthesis is the process by which organisms, such as plants, algae and cyanobacteria, use light energy to carry out chemical reactions and produce sugars or other carbon compounds. This process begins within photosystems, which are molecular arrays of chlorophyll and accessory pigments within protein complexes, located in membranes. In plants they are found on the membranes within chloroplasts.

Photosystems play a crucial role in capturing light energy and converting it into chemical energy. One specific chlorophyll *a* molecule within the photosystem serves as the reaction centre.

The arrangement of pigments within the photosystems allows them to absorb light energy across a range of wavelengths. These pigments, including both chlorophyll *a* and *b* and accessory pigments, work together to maximise light absorption and energy transfer to the reaction centre.

When photons of light strike the pigment molecules within the photosystem, they excite the electrons within these molecules. The excited electrons are then transferred through the pigment array until they reach the reaction centre chlorophyll molecule. At the reaction centre, a photochemical reaction occurs, resulting in the emission of an excited electron. This process is known as photoactivation.

There are two types of photosystems embedded in the thylakoid membrane: photosystem I and photosystem II. One important difference between the two is that photosystem I is most sensitive to light wavelengths of 700 nm, while photosystem II is most sensitive to light wavelengths of 680 nm. Photosystem II, as shown in **Figure 1**, is the one that is first activated by light.

Student
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Overview
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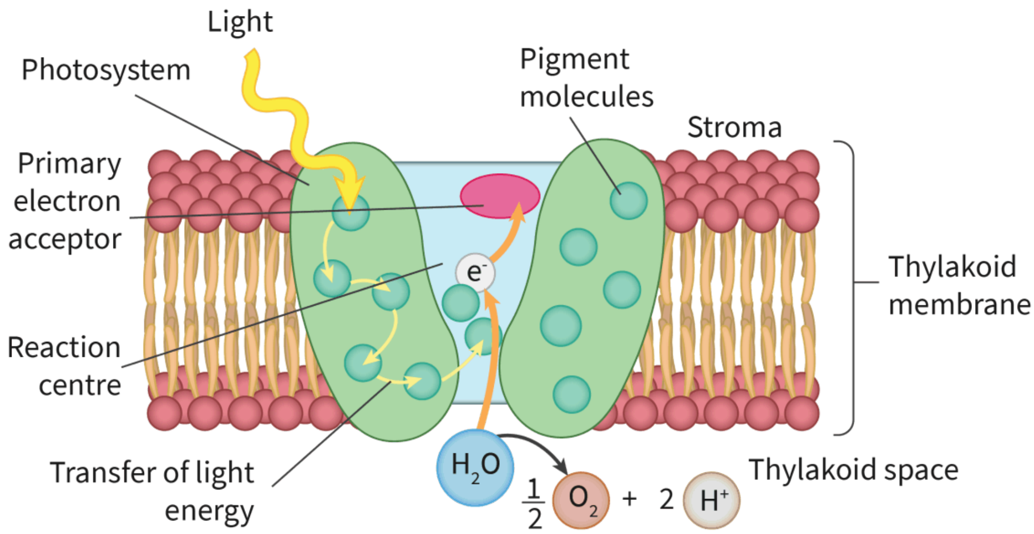

Figure 1. Photosystem II.

More information for figure 1

The diagram depicts photosystem II within the thylakoid membrane. The thylakoid membrane is illustrated with a layer of phospholipids, represented by a double layer of pink spheres connected by beige lines, symbolizing the lipid bilayer. The system starts with a beam of light striking the photosystem, which is labeled at the top left.

The main components within the system include the primary electron acceptor, a label pointing to a part on the left side of the membrane. Light energy, depicted as yellow arrows, is shown being transferred through the pigment molecules, represented as green ovals within the structure. These pigment molecules facilitate the transportation of electrons, indicated by smaller black arrows leading towards the reaction center at the bottom. The reaction center facilitates the splitting of water (H2O). This reaction is also shown by arrows splitting water into half an O2 molecule and two hydrogen ions (H+), with an electron (e-) also being indicated in this process.

Associated reactive elements include red oxygen molecules (O2) and blue water molecules (H2O) depicted at the bottom. The diagram labels key areas such as the 'Stroma', at the top right, and 'Thylakoid space', at the bottom right. These labels describe the internal spaces within the chloroplasts where photosynthesis reactions occur.

[Generated by AI]

It is important to note that photosystems are always located in membranes, whether in cyanobacteria or the chloroplasts of photosynthetic eukaryotes. Their presence in membranes allows for the efficient capture and utilisation of light energy for photosynthesis.

Student
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Study skills

Photosystem II and photosystem I are most sensitive to wavelengths of 680 and 700 nm, respectively. This does not mean they only absorb those wavelengths; their arrays of pigments allow them to absorb a wide range of wavelengths. It is just that those specific wavelengths are most effective at activating the chlorophylls and exciting the electrons in each reaction centre.

Advantages of many pigment molecules in a photosystem

Photosystems are essential to photosynthesis. Only through the use of arrays of many pigment molecules can enough light energy be absorbed to photoactivate the central chlorophyll molecule. This causes the excitation and release of the electrons that will provide the energy for the rest of the light-dependent phase of photosynthesis. The collection of hundreds of pigment molecules allows for a wider range of wavelengths to be absorbed. The cumulative energy absorbed by each of the pigments is efficiently funnelled to the reaction centre of the photosystem where the central chlorophyll *a* molecule is found.

If pigments were not arranged in this way and the light energy from the photons was only absorbed by individual pigments, there would not be enough energy to cause the emission of electrons. In addition, there would be little to no conversion of that light energy into chemical energy as the process would be too inefficient.

Generation of oxygen in photosystem II

The release of electrons from the chlorophyll molecule at the reaction centre of photosystem II creates a very unstable molecule in its oxidised state. The reaction centre, because of its oxidised state, now becomes a powerful oxidising agent. It is the reason that water molecules can be split or lysed (photolysis) to give up their electrons to the reaction centre. Photolysis of water generates electrons for use in the light-dependent reaction, because it constantly replaces electrons lost by photosystem II.

Overview
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The photolysis of water is also the process that generates oxygen as a waste product. The photolysis reaction is as follows:

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$$

Try the following activity to reflect on your learning in this section.

Activity

- **IB learner profile attribute:** Reflective
- **Approaches to learning:**
  - Thinking skills — Providing a reasoned argument to support conclusions; Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 45 minutes
- **Activity type:** Individual activity

Reflect on the advantages of the structured array of pigment molecules in a photosystem. Consider the following questions and write down your responses:

1. Why is it important to have a large number of pigment molecules in a photosystem?

2. How does the arrangement of pigments allow for a wider range of wavelengths to be absorbed?

3. Why is it necessary to funnel the absorbed energy to the reaction centre?

Now, focus on the process of the photolysis of water in photosystem II. Think about the significance of this process and its role in generating oxygen. Answer the following questions:

4. Why does the reaction centre of photosystem II become a powerful oxidising agent?

5. What is the purpose of water being split or lysed during photolysis?

6. How does the photolysis of water contribute to the generation of oxygen?

Student
view

Overview
(/study/ap
422-
cid-
755105/o

(Optional) **Further research:** If you would like to delve deeper into the topic, use the internet or other resources to explore additional information about photosystems, the photolysis of water and the production of oxygen during photosynthesis. Note down any interesting findings or additional insights.

Summarise your understanding: Write a brief summary that explains the role of photosystems in capturing and converting light energy, the advantages of their structured array of pigment molecules and the generation of oxygen through the photolysis of water. Use your own words and make sure to include the key concepts discussed in this section.

(Optional) **Share and discuss:** If you are studying in a group or classroom setting, share your summary with your peers. Discuss your findings, compare your responses and clarify any questions or uncertainties you may have.

5 section questions

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Thylakoids (HL)

C1.3.12: ATP production by chemiosmosis in thylakoids (HL) C1.3.13: Reduction of NADP by photosystem I (HL)

C1.3.14: Thylakoids as systems for performing the light-dependent reactions (HL)

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/thylakoids-hl-id-46521/print/) Assign

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe the production of ATP by chemiosmosis through both cyclic and non-cyclic photophosphorylation.
- Describe the reduction of NADP by photosystem I.

Student
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Overview
(/study/ap
422-
cid-
755105/o

- Explain the importance of the thylakoids as the site of photolysis, chemiosmosis and reduction of NADP.

Chloroplasts are the organelles in plants in which photosynthesis takes place. What sorts of structures are found in chloroplasts that make photosynthesis possible? Think about how mitochondria are adapted to carry out cell respiration. Might there be similarities?

Chemiosmosis

The light-dependent stage of photosynthesis begins with the absorption of light energy in the photosystems. As we have seen, this releases electrons that are then used in the rest of the light-dependent stage.

One of the main purposes of the light-dependent stage of photosynthesis is to produce ATP by chemiosmosis. In plants, this occurs in the thylakoids of the chloroplasts. This is known as photophosphorylation.

The excited electrons released from the reaction centre are channelled to a series of proteins in the membrane, an electron transport chain (ETC). As excited electrons are transferred along electron carriers, they drop in energy level. This releases energy, which is then used to carry out chemiosmosis. Hydrogen ions (protons) are pumped from the stroma into the thylakoid lumen. As the thylakoid membrane is impermeable to protons, the hydrogen ions quickly accumulate and establish an electrochemical gradient . The proton gradient resulting from this higher concentration of protons provides the potential energy for an ATP synthase complex to drive the production of ATP, just like in cellular respiration. As hydrogen ions diffuse through the ATP synthase complex, sufficient energy is released to phosphorylate ADP to ATP. Since this process is ultimately driven by energy derived from photons (particles of light), it is referred to as photophosphorylation.

Photophosphorylation can be either cyclic or non-cyclic. In cyclic photophosphorylation, light energy causes the excitation of electrons from photosystem I. These electrons then move along the electron transport chain, pumping H^+, establishing a proton gradient and generating ATP with

Student
view

Overview
(/study/ap
422-
cid-
755105/o

ATP synthase. The electrons will return to PSI after moving along the ETC, replacing those that were lost. It is cyclic as the electrons are lost *from* and return *to* the same photosystem.

Figure 1 illustrates a summary of cyclic photophosphorylation.

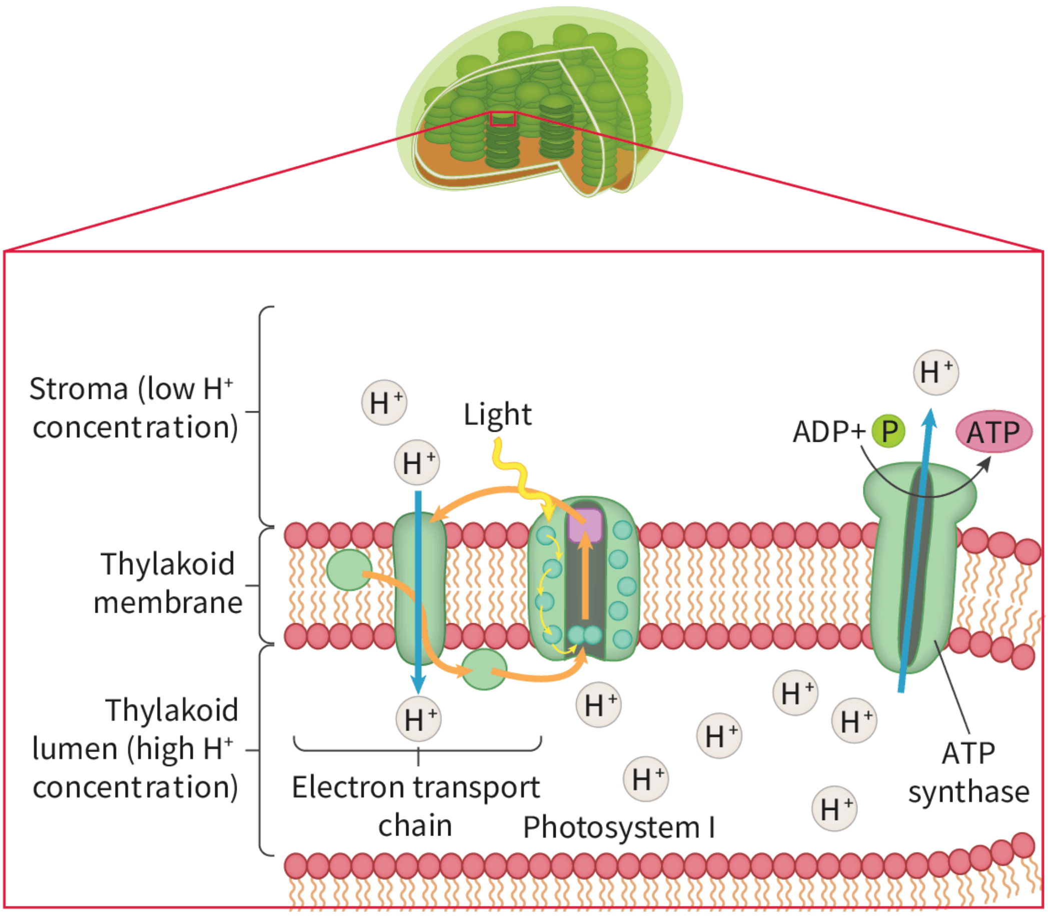

Figure 1. Cyclic photophosphorylation.

More information for figure 1

The diagram shows the process of cyclic photophosphorylation within a thylakoid membrane inside a chloroplast. The structure is divided into three main areas: the stroma, the thylakoid membrane, and the thylakoid lumen, with differing concentrations of hydrogen ions (H+). Light energy is depicted entering a photosystem within the thylakoid membrane. Electrons are excited and travel through an electron transport chain, which is also located in the membrane. This process helps to generate a proton gradient across the membrane, where a higher concentration of protons exists in the thylakoid lumen.

ADP (adenosine diphosphate) and inorganic phosphate (P) combine in the presence of ATP synthase to form ATP (adenosine triphosphate). This enzyme is highlighted in the membrane as the site where protons pass back into the stroma, driving the synthesis of ATP, which is

Student
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Overview
(/study/ap
422-
cid-
755105/o

the main product of the cyclic process. Overall, the diagram illustrates the movement of hydrogen ions, the role of light energy, and the synthesis of ATP without the production of NADPH, characterizing cyclic photophosphorylation.

[Generated by AI]

In non-cyclic photophosphorylation, light energy excites electrons in PSII, which are then passed along the ETC, pumping H^+ and generating ATP. The electrons then enter PSI where they are re-energised with light energy, passed to ferredoxin and then used to reduce NADP.

Figure 2 summarises the processes involved in non-cyclic photophosphorylation.

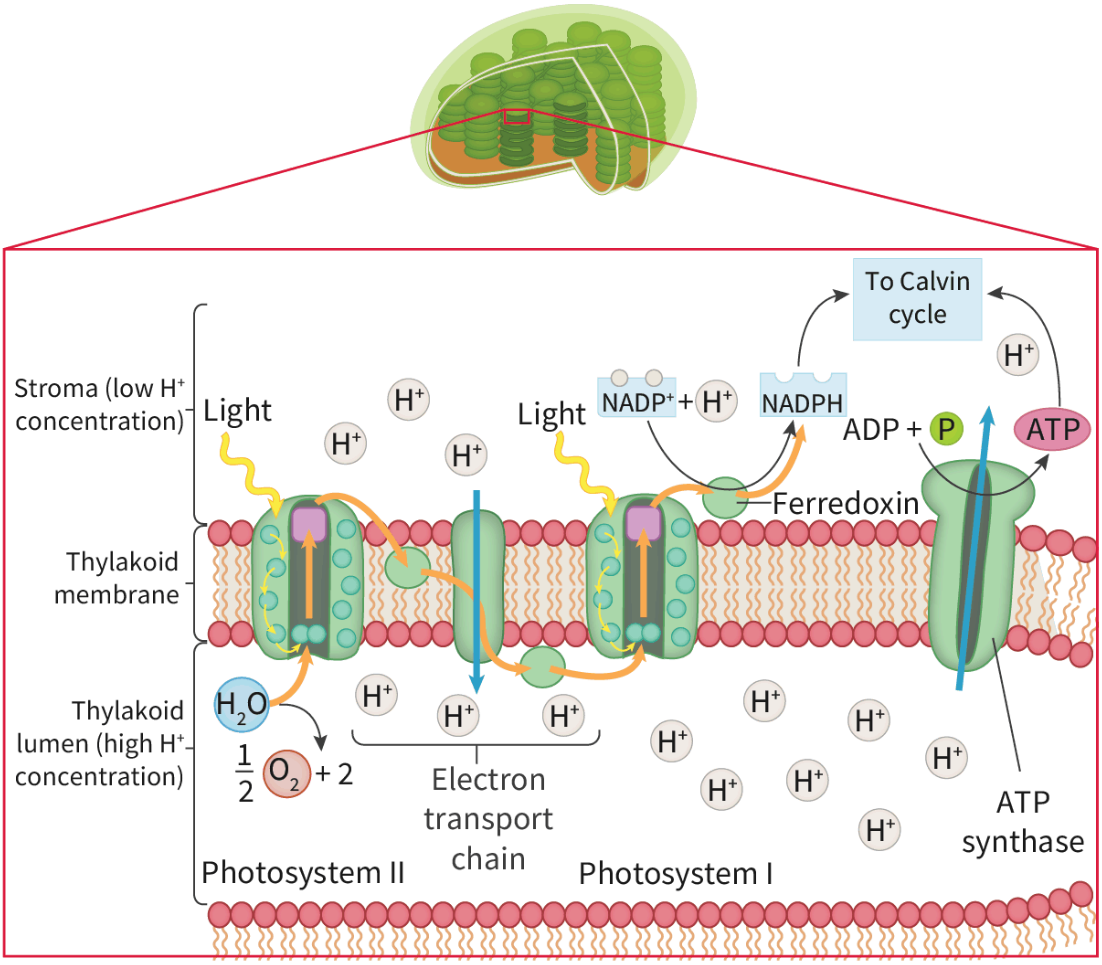

Figure 2. Non-cyclic photophosphorylation.

More information for figure 2

The image is a detailed diagram illustrating the process of non-cyclic photophosphorylation occurring in a chloroplast. At the top, a chloroplast is depicted, highlighting the thylakoid membranes where the process occurs. Within the magnified section of the thylakoid

Student
view

Overview
(/study/ap
422-
cid-
755105/o

membrane, there are key components labeled:

- **Photosystem II**: Located on the left, where light energy initiates the process by exciting electrons. Water molecules (H2O) are split, releasing oxygen (O2) and protons (H+), contributing to a high concentration of H+ in the thylakoid lumen.
- **Electron Transport Chain**: Electrons from Photosystem II move through the chain, transporting H+ ions across the membrane, enhancing the proton gradient.
- **Photosystem I**: Positioned on the right, receives electrons energized by light and works together with ferredoxin to reduce NADP+ to NADPH.
- **ATP Synthase**: Utilizes the proton gradient to convert ADP and inorganic phosphate (Pi) into ATP as H+ ions flow back into the stroma, which has a lower H+ concentration.
- The diagram also shows the cyclic flow of NADP+ and ATP into the Calvin cycle.

Arrows indicate the flow of electrons and ions, emphasizing the spatial separation and function within the membrane.

[Generated by AI]

Theory of Knowledge

To what extent do the names and labels that we use help or hinder the acquisition of knowledge?

Terms like photophosphorylation can seem overwhelming at first. Try breaking them down to make them easier to understand and remember.

It might seem odd that the first photosystem is named photosystem II. This is actually due to the fact that photosystem I was discovered first. Does this hinder or help our understanding of these processes?

Reduction of NADP by photosystem I

Nicotinamide adenine dinucleotide phosphate (NADP) is an important electron carrier. It functions in very much the same way as NAD does in cellular respiration. It is able to take on electrons and become reduced, while

Student
view

Overview
(/study/ap
422-
cid-
755105/o

oxidising something else. NADP accepts two electrons from photosystem I as well as two H^+ from the stroma to become reduced NADP.

Figure 3 illustrates the structures of both NADP and reduced NADP.

Study skills

NAD is the electron/hydrogen carrier in cell respiration. NADP is the electron/hydrogen carrier in photosynthesis. Think of the P in NADP as standing for photosynthesis to help you remember which is which.

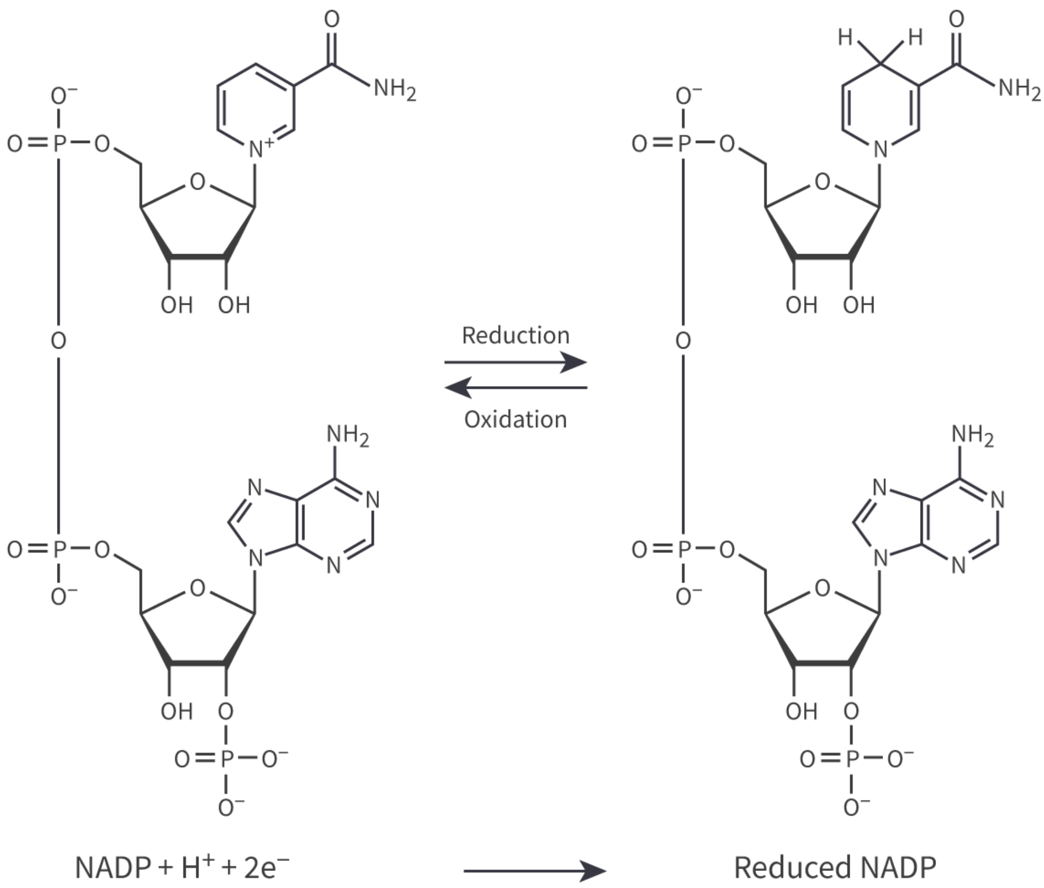

Figure 3. The structures of NADP and reduced NADP.

More information for figure 3

The diagram illustrates the chemical structures and conversion between NADP and its reduced form. On the left, the structure of NADP is depicted, consisting of two nucleotide units. This structure includes a ribose sugar linked to an adenine base, and another ribose linked to a nicotinamide group, each with phosphate groups. The "NADP + H^+ + $2e^-$" label signifies the addition of protons and electrons.

Student
view

On the right, the structure of reduced NADP is shown. This form appears similar but highlights the conversion of the nicotinamide group through reduction, resulting in a change in its ring structure. The forward and reverse arrows labeled "Reduction" and "Oxidation" indicate the reversible nature of this reaction, facilitating the transfer of electrons in biological processes.

[Generated by AI]

In non-cyclic photophosphorylation, the electrons excited and lost from photosystem I are used to reduce NADP to reduced NADP. This process is an essential step in photosynthesis because without it, the light-independent stage of photosynthesis could not occur. Both ATP and reduced NADP are required to produce carbon compounds in the light-independent stage.

Thylakoids

Chloroplasts are the organelles within plant cells that carry out photosynthesis. It is the specialised structure of the thylakoids that allows the light-dependent stage of photosynthesis to occur effectively. Thylakoids are flattened membrane-bound sacs. Their membranes have the photosystems, electron transport chain and ATP synthase embedded in them to carry out their essential processes: photolysis, ATP production via chemiosmosis and the reduction of NADP. The small intermembrane spaces within the thylakoids are ideal for allowing the establishment of electrochemical gradients as H^+ ions are pumped into them. Without these spaces, the gradient could not be established as the production of ATP via chemiosmosis would not occur and there would not be sufficient energy for the production of carbon compounds. It is also within the intermembrane space of thylakoids that water is split by photolysis, releasing oxygen.

Within a chloroplast are stacks of thylakoids called grana, filling much of the space within the chloroplast. These stacks provide a large surface area to allow for as many photosystems, ETCs and ATP synthases as possible.

Watch **Video 1** for an overview of the light-dependent reactions of photosynthesis.

Student
view

Video 1. A summary of the light-dependent reactions of photosynthesis.

Try the activity below to compare chemiosmosis with the electron transport chain in cell respiration and in photosynthesis.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Providing a reasoned argument to support conclusions, Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Pair activity

In pairs, compare and contrast the electron transport chains and chemiosmosis in cell respiration and photosynthesis. Organise your information using either a table to list similarities and differences, or by creating a Venn diagram to compare the two processes. Use the information found in this resource as a starting point but you may wish to delve a bit deeper into the specific details of each using some online resources.

Here is a resource to get you started:

Overview
(/study/ap
422-
cid-
755105/o

https://slcc.pressbooks.pub/collegebiology1/chapter/etcs-in-respiration-and-photosynthesis/ (https://slcc.pressbooks.pub/collegebiology1/chapter/etcs-in-respiration-and-photosynthesis/)

Wikipedia page (https://en.wikipedia.org/wiki/Electron_transport_chain) on electron transport chains is another good starting point. While the information on the Wikipedia page may be unreliable, using the links and references from this page to do further research is a good way to find resources:

5 section questions

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Calvin cycle (HL)

C1.3.15: Carbon fixation by Rubisco (HL) C1.3.16: Synthesis of triose phosphate using reduced NADP and ATP (HL)

C1.3.17: Regeneration of RuBP in the Calvin cycle using ATP (HL)

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/calvin-cycle-hl-id-46522/print/) Assign

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe carbon fixation by Rubisco and the significance of Rubisco as an enzyme.
- Describe the process of generating triose phosphate using ATP and reduced NADP.
- Describe the regeneration of RuBP and the completion of the Calvin cycle using ATP.

Student
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We know plants need carbon dioxide for photosynthesis. Just how do plants make use of this gas that we get rid of as a waste product? How can they take this gas, that there is so little of in our atmosphere, and build the molecules that ultimately power almost all life on Earth?

Carbon fixation by Rubisco

Now that we have generated ATP and reduced NADP from the light-dependent reactions of photosynthesis, we can move on to the light-independent reactions. This begins with the fixation of carbon. Carbon fixation is one of the most important biochemical reactions we know. It is the start of all carbohydrate compounds found in photosynthetic organisms.

Atmospheric carbon dioxide is 'fixed' by adding it to ribulose bisphosphate (RuBP), a 5-carbon compound, forming two molecules of glycerate 3-phosphate (GP), a 3-carbon compound. The reaction is catalysed by a large enzyme, ribulose-1,5-bisphosphate carboxylase, commonly referred to as Rubisco. This is the first step in what is known as the Calvin cycle, named after Melvin Calvin, a biochemist who worked out most of the details of this cyclic pathway. He was awarded the Nobel Prize in Chemistry in 1961.

The Calvin cycle takes place in the stroma of the chloroplasts, where there is a high concentration of Rubisco. There are two reasons for this: Rubisco is a 'slow' enzyme and the Calvin cycle is rather inefficient due to its high energy requirement. Additionally, Rubisco can be competitively inhibited by oxygen, binding to it in preference to carbon dioxide, making it very inefficient at low concentrations of carbon dioxide. To speed up the process, many molecules of Rubisco enzyme are needed.

International Mindedness

By leveraging international expertise and collaboration, researchers aim to develop crops with improved Rubisco efficiency. This could have significant implications for global food production, climate change mitigation and sustainable agriculture.

Overview
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422-
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Synthesis of triose phosphate

The next step in the Calvin cycle is to convert the glycerate 3-phosphate (GP) to triose phosphate, another 3-carbon compound that can then be used to synthesise carbon compounds such as glucose. This is done using ATP and reduced NADP. Each GP molecule requires one ATP and one reduced NADP. The ATP provides the energy and reduced NADP reduces the GP to triose phosphate through the addition of hydrogen. This step uses up all of the products of the light-dependent reactions.

$$6CO_2 + 6H_2O \dashrightarrow C_6H_{12}O_6 + 6O_2$$

If we use the balanced chemical equation for photosynthesis we see that six molecules of carbon dioxide are used. That means that if we fix those six molecules of carbon dioxide, we will end up with 12 molecules of triose phosphate at the end of this stage of the Calvin cycle.

Figure 1 summarises the stages of the Calvin cycle.

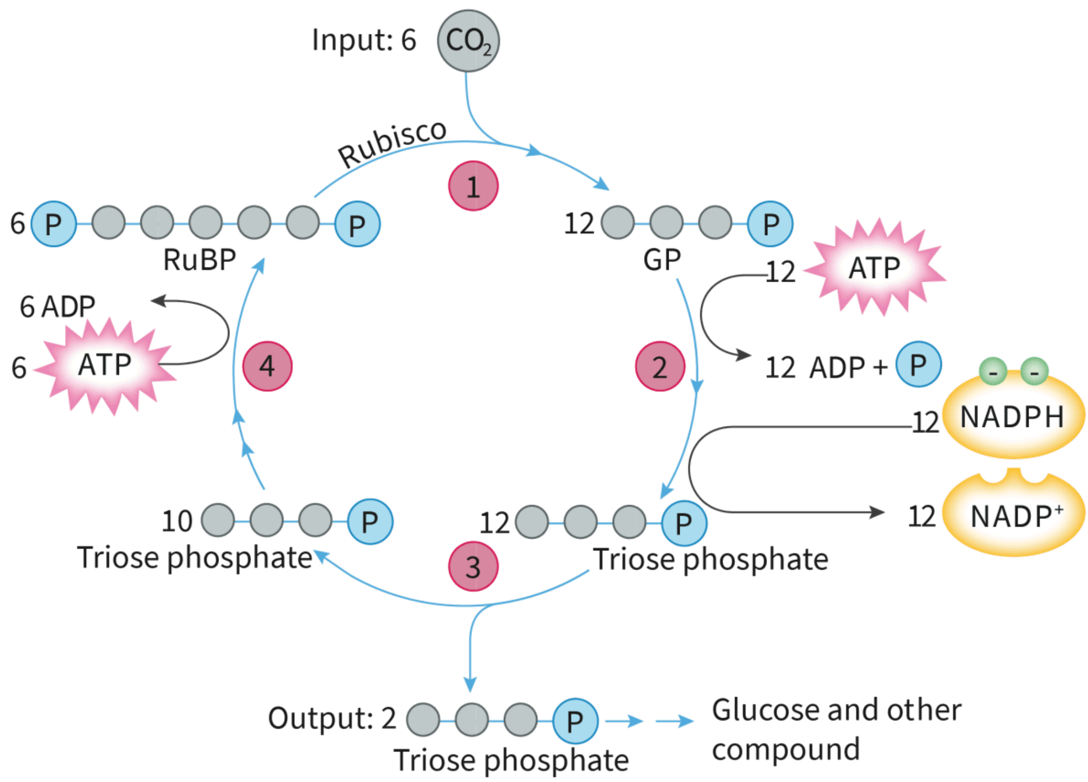

Figure 1. A summary of the Calvin cycle.

More information for figure 1

The diagram represents the Calvin cycle, consisting of multiple stages with arrows indicating the flow of elements and compounds. At the top, CO2 is shown as the input interacting with RuBP in the presence of the enzyme Rubisco. The cycle progresses to the formation of 12 GP molecules,

Student view

which are then transformed by 12 ATP molecules, producing 12 ADP and leaving phosphate groups. This is followed by the conversion of 12 NADPH into 12 NADP+, resulting in the formation of 12 triose phosphate molecules. The cycle continues with steps indicating the involvement of ATP and ADP, culminating in an output of 2 triose phosphate molecules used to produce glucose and other compounds. Various intermediates, like RuBP, GP, and triose phosphate, are labeled and shown in sequence with numbered steps to indicate the progression of the cycle. The diagram includes process labels such as ATP, ADP, NADPH, and NADP+, and the roles they play in the reactions.

[Generated by AI]

Regeneration of RuBP

It is important to realise that as this is a cycle, the initial compound (RuBP) must be regenerated in order for the cycle to continue. As it is a 5-carbon compound and triose phosphate is a 3-carbon compound, we are able to make 6 RuBP from 10 triose phosphates. If we remember that from our initial six molecules of CO_2 we formed 12 triose phosphates, that means we can use only two of those to synthesise carbon compounds as the other 10 are required for the regeneration of RuBP. It should also be noted here that the regeneration of each RuBP requires the energy of one ATP molecule.

Watch **Video 1** for an overview of the Calvin cycle.

Video 1. A summary video about the Calvin cycle.

Overview
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Complete the activity which follows by creating a mind map to summarise your learning of photosynthesis.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:**
  - Communication skills — Using digital media for communicating information
  - Thinking skills — Combining different ideas in order to create new understandings
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Individual activity

Create a mind map to outline the entire process of photosynthesis. The keywords listed below may serve as a starting point but there will be others you could/should include. Adding images and or sketches to your mind map will make it more memorable. Consider using an online tool such as coggle.it (https://coggle.it/) or miro (https://miro.com/).

Keywords

Photosynthesis
Chloroplast
Chlorophyll
Pigments
Light-dependent reactions
Light-independent reactions
Thylakoid
Stroma
ATP (Adenosine triphosphate)
Reduced NADP (nicotinamide adenine dinucleotide phosphate)
Carbon fixation
Calvin cycle
RuBP (ribulose-1,5-bisphosphate)
Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase)
Triose phosphate
Carbon dioxide (CO_2)
Oxygen (O_2)

Student
view

Overview
(/study/ap
422-
cid-
755105/o

Photolysis
Chemiosmosis
Absorption spectrum
Electron transport chain
Photosystem I
Photosystem II
Cyclic photophosphorylation
Non-cyclic photophosphorylation

5 section questions

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Products of photosynthesis (HL)

C1.3.18: Synthesis of carbon compounds using the products of the Calvin cycle and mineral nutrients (HL)

C1.3.19: Interdependence of the light-dependent and light-independent reactions (HL)

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Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe the production of a variety of carbon compounds from photosynthesis.
- Explain the link between the light-dependent and light-independent reactions and how the light-independent reactions cannot continue in the absence of light.

We have all learned before that one of the products of photosynthesis is glucose. But what about all the other forms of carbohydrates and other carbon compounds? Where do they come from?

Student view

Overview (/study/ap 422- cid- 755105/o

Uses of the products of the Calvin cycle

All carbon compounds synthesised in plants can be traced back to triose phosphate. Whether it is a carbohydrate like glucose or starch, an amino acid or a fatty acid, they are all produced using the intermediate products of the Calvin cycle. Each carbon compound is produced using its own metabolic pathway and other materials are often added, such as the mineral nutrients absorbed by plants through their roots. Amino acids, for example, contain nitrogen which is acquired from nitrates.

In addition to the synthesis of carbohydrates, amino acids and fatty acids, the products of the Calvin cycle play a crucial role in the formation of other essential carbon compounds in plants. These compounds serve various functions in plant metabolism and growth. One important group of carbon compounds synthesised using the products of the Calvin cycle is nucleotides. Nucleotides are the building blocks of DNA and RNA, which are vital for genetic information storage and protein synthesis. The formation of nucleotides involves the incorporation of ribose sugar, derived from triose phosphate, along with nitrogenous bases and phosphate groups.

Making connections

Having an understanding of the structures and properties of different biological molecules is helpful here. See subtopics A1.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43236/), B1.1 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43530/) and B1.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43531/).

Interdependence of the light-dependent and light-independent reactions

The light-dependent and light-independent reactions both require the other to be functioning in order for them to continue. The light-independent reactions require the ATP and reduced NADP from the light-dependent reactions. If the light reactions stop, the light-independent reactions will also stop once they use up their supplies of ATP and reduced NADP.

Student view

Overview
(/study/ap
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The reverse is also true, as the light-dependent reactions require NADP and ADP to be available to continue generating reduced NADP and ATP. If there was a lack of CO_2 and the light-independent reactions stopped, the cell would run out of NADP and ADP or the supply would be so low that the reaction would slow down significantly. Photosystem II would be most affected by this as it begins non-cyclic phosphorylation that requires the availability of NADP at the end. Electrons would no longer be able to flow and PSII could no longer function. **Figure 1** illustrates the interdependence of these two systems.

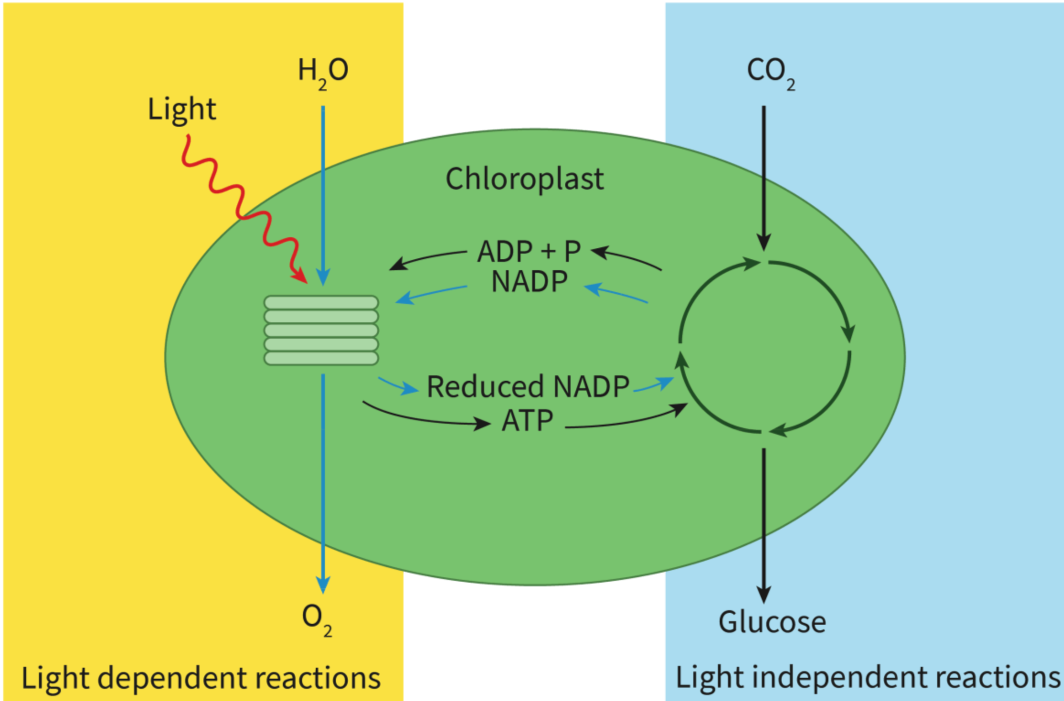

Figure 1. The interdependence of the light-dependent and light-independent reactions of photosynthesis.

More information for figure 1

The diagram illustrates the interdependence of light-dependent and light-independent reactions during photosynthesis within a chloroplast. On the left, labeled "Light dependent reactions," light energy and water (H2O) enter. This process occurs on the thylakoid membrane stacks illustrated as green parallel lines. Oxygen (O2) is released as a byproduct. The diagram shows that light-dependent reactions produce adenosine triphosphate (ATP) and reduced nicotinamide adenine dinucleotide phosphate (NADP).

On the right, labeled "Light independent reactions," carbon dioxide (CO2) enters the cycle, contributing to the production of glucose. This cycle is depicted as a circular arrow. Intermediary energy carriers, such as ATP and reduced NADP, shuttle between the light-dependent and light-

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independent processes, depicted with arrows hugging the exterior of the chloroplast. Labels include "Chloroplast," "ADP + P," "NADP," "Reduced NADP," and "ATP," illustrating the flow of molecules between the two phases of photosynthesis inside the chloroplast.

[Generated by AI]

Try the activity below to help summarise your learning on photosynthesis.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:**
  - Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
  - Social skills — Working collaboratively to achieve a common goal
- **Time required to complete activity:** 30—45 minutes
- **Activity type:** Pair activity

Working in pairs, come up with 10 questions about photosynthesis as well as a mark scheme for them. Write a mix of multiple choice and short answer questions. One question should be worth at least 4 marks. Write the mark scheme for your questions, being as specific as you can about what you expect in the answer.

Exchange your questions with another pair, answer their questions and then check each other's answers.

Discuss the questions with the other group and provide feedback on the quality of the questions and the mark scheme.

5 section questions

Summary and key terms

- Photosynthesis is the ability of photosynthetic organisms to transform light energy from the sun into chemical energy that can be used in cells. This energy is then used throughout most ecosystems on Earth.
- Photosynthesis includes both light-dependent and light-independent reactions. The splitting of water during the light-dependent reactions provides the hydrogen that will eventually be used to convert carbon dioxide into glucose in the light-independent reactions. This splitting of water also releases oxygen which, over Earth's history, has significantly altered the composition of our atmosphere.
- Chromatography can be used to identify the photosynthetic pigments of a plant. Different pigments will absorb different wavelengths of light and this can be visualised using an absorption spectrum. The overall rate of photosynthesis for different wavelengths of light can also be visualised using an action spectrum.
- There are three key limiting factors of photosynthesis: carbon dioxide concentration, light intensity and temperature. There are a variety of experimental methods that will allow you to determine the effects of each of these.
- Carbon dioxide enrichment experiments, including free-air carbon dioxide enrichment experiments (FACE), are methods used by scientists to predict the effects of increased levels of carbon dioxide in our atmosphere on plant growth.

Higher level (HL)

- Photosystems are arrays of hundreds of pigment molecules combined with proteins. These serve to absorb light energy and transfer that energy to a reaction centre containing a key molecule of chlorophyll *a*. The energy excites electrons in the chlorophyll and causes them to be emitted. In photosystem II, these electrons are replaced through photolysis as water is split.
- The electrons emitted from the photosystems are passed along an electron transport chain (ETC) where its energy is used to pump H^+ (protons) into the thylakoid intermembrane space, establishing an electrochemical gradient. These H^+ will then flow back across the membrane through ATP synthase,

generating ATP by chemiosmosis. In non-cyclic photophosphorylation, the electrons emitted from photosystem I are used, along with H^+, to reduce NADP.

- The ATP and reduced NADP are now used in the light-independent reactions, or Calvin cycle, which occurs in the stroma of the chloroplast. First carbon is fixed by the enzyme Rubisco as it combines carbon dioxide with RuBP. This forms two molecules of glycerate 3-phosphate or GP. Then ATP and reduced NADP are used to convert each GP into triose phosphate.
- As it is a cycle, RuBP must be regenerated and the majority of triose phosphate is used for this. Ten out of 12 triose phosphate molecules produced will be used to regenerate RuBP leaving only two to form a single molecule of glucose.
- Triose phosphate can also be used to build the other carbon compounds needed by cells to function, including other carbohydrates, lipids, amino acids and nucleic acids.
- The light-dependent and light-independent reactions are interdependent. They will not occur effectively or at all when the other stops.

Overview
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422-
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Key terms

Student
view

Overview
(/study/ap
422-
cid-
755105/o

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. is the process of splitting water. This releases as a waste product.
2. The technique used to separate different pigments is called . Different pigments will absorb different wavelengths of light which can be visualised with an . Total rate of photosynthesis at each wavelength of light can be seen using an .
3. The three limiting factors of photosynthesis are light intensity, and concentration.
4. [HL]Arrays of in association with proteins are known as . These work by light energy and using it to excite in a central molecule.
5. [HL]The are membrane structures in where you will find photosystems, the and ATP synthase.
6. [HL] involves both photosystem II and I and results in the production of both ATP and , while involves only photosystem I and generates only .
7. [HL]The uses the ATP and reduced NADP from the . First is fixed by combining with a 5-carbon compound called to form two molecules of glycerate 3-phosphate. The ATP and reduced NADP are then used to convert it to .

chlorophyll | carbon | carbon dioxide | cyclic photophosphorylation | action spectrum | absorption spectrum | chromatography | light-dependent reactions | triose phosphate | carbon dioxide | Photolysis | electron transport chain | photosystems | ATP | RuBP | reduced NADP | temperature | electrons | chloroplasts | Calvin cycle | pigments

Student view

Overview
(/study/ap
422-
cid-
755105/o

chloroplasts Calvin cycle pigments

Non-cyclic photophosphorylation thylakoids oxygen

absorbing

Interactive 1. Processes and Components of Photosynthesis.

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Checklist

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What you should know

After studying this subtopic you should be able to:

- Explain how the energy transformation of light energy to chemical energy is needed for most life processes in ecosystems.
- Describe photosynthesis as the conversion of carbon dioxide to glucose.
- Describe the production of oxygen as a by-product of photosynthesis.
- Describe the process of chromatography for separating pigments and the use of R_f values to identify pigments.
- Describe and explain the absorption of different wavelengths of light by photosynthetic pigments.
- Compare absorption and action spectra.
- Determine through investigation the effects of limiting factors on the rate of photosynthesis.
- Describe carbon dioxide enrichment experiments as a means of predicting future rates of photosynthesis and plant growth.

Higher level (HL)

- Describe photosystems as arrays of pigments within membranes of photosynthetic organisms that generate and emit excited electrons.

Student view

Overview
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- Explain the advantage that an array of pigments in a photosystem has over individual pigment molecules.
- Describe the photolysis of water in terms of a means of replacing lost electrons in photosystem II and the production of oxygen as a waste product.
- Describe the production of ATP by chemiosmosis through both cyclic and non-cyclic photophosphorylation.
- Describe the reduction of NADP by photosystem I.
- Explain the importance of the thylakoids as the site of photolysis, chemiosmosis and reduction of NADP.
- Describe carbon fixation by Rubisco and the significance of Rubisco as an enzyme.
- Describe the process of generating triose phosphate using ATP and reduced NADP.
- Describe the regeneration of RuBP and the completion of the Calvin Cycle using ATP.
- Describe the production of a variety of carbon compounds from photosynthesis.
- Explain the link between the light-dependent and light-independent reactions and how the light-independent reactions cannot continue in the absence of light.

Practical skills

Once you have completed this subtopic, go to Practical 4: Investigating pigments present in plant leaves through chromatography (/study/app/bio/sid-422-cid-755105/book/investigating-pigments-id-46695/) to calculate R_f values and identify pigments.

C1. Interaction and interdependence: Molecules / C1.3 Photosynthesis

Investigation

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- **IB learner profile attribute:**
  - Knowledgeable
  - Communicator
- **Approaches to learning:**
  - Communication skills – Clearly communicating complex ideas in response to open-ended questions; Using digital media for communicating information
- **Inquiry 1:** Exploring – Consult a variety of sources; Select sufficient and relevant sources of information
- **Time required to complete activity:** 45–60 minutes
- **Activity type:** Individual activity

Your task

Photosynthesis and cell respiration are often described as being opposite processes. Their balanced chemical and word equations are indeed opposite to each other. Your task is to look a bit deeper and explore how true this is. Consider the questions below as a guide.

- How are photosynthesis and cell respiration similar?
- How are photosynthesis and cell respiration different?
- How are the structures of mitochondria and chloroplasts similar?
- How are the structures of mitochondria and chloroplasts different?
- How do the different stages of both photosynthesis and cell respiration compare and contrast?
- Do abiotic factors influence both processes in the same way?

Produce a short (5–8 minute) presentation or infographic outlining what conclusions you come to and share them with your class.

If doing a presentation:

- keep the text on each slide to a minimum
- avoid reading from the slides
- use images effectively
- be prepared to answer questions
- reference sources appropriately.

If creating an infographic:

- use data and short bullet points to share information
- use images and graphs where possible
- keep text to a minimum
- reference sources appropriately.

Reflection

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Overview (/study/app/bio/sid-422-cid-755105/o

Now that you've completed this subtopic, let's come back to the guiding question introduced in The big picture (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43539/).

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

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

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Submit

Rate subtopic C1.3 Photosynthesis

Help us improve the content and user experience.

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