Chapter 5

Photosynthesis

e-Learning

Objectives

In *Biology 1*, we looked at the human diet – what we need to eat and why. Humans, like all animals and fungi, are **heterotrophs**. This means that we need to eat food containing organic molecules, especially carbohydrates, fats and proteins. These organic molecules are our only source of energy.

Plants, however, do not need to take in any organic molecules at all. They obtain their energy from sunlight. They can use this energy to build their own organic molecules for themselves, using simple inorganic substances. They first produce carbohydrates from carbon dioxide and water, by **photosynthesis**. They can then use these carbohydrates, plus inorganic ions such as nitrate, phosphate and magnesium, to manufacture all the organic molecules that they need. Organisms that feed in this way – self-sufficient, not needing any organic molecules that another organism has made – are **autotrophs**.

So heterotrophs depend on autotrophs for the supply of organic molecules on which they feed. Some heterotrophs feed directly on plants, while others feed further along a food chain. But eventually all of an animal's or fungus's food can be traced back to plants, and the energy of sunlight.

In this chapter, we will look in detail at how plants transfer energy from sunlight to chemical energy in organic molecules. In Chapter 6, we will see how all living organisms can then release the trapped energy from these molecules and convert it into a form that their cells can use. This process is called **respiration**, and it involves oxidation of the energy-containing organic substances, forming another energy-containing substance called **ATP**. Every cell has to make its own ATP. You can find out more about ATP in Chapter 6.

An overview of photosynthesis

Photosynthesis happens in several different kinds of organisms, not only plants. There are many kinds of bacteria that can photosynthesise. Photosynthesis also takes place in **phytoplankton**, tiny organisms that float in the upper layers of the sea and lakes. Here, though, we will concentrate on photosynthesis in green plants, because this is the ultimate source of almost all of our food.

You should already be familiar with the overall equation for photosynthesis:

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

However, in reality photosynthesis is a complex **metabolic pathway** – a series of reactions linked to each other in numerous steps, many of which are catalysed by enzymes. These reactions take place in two stages. The first is the **light-dependent stage**, and this is followed by the **light-independent stage**. Both of these stages take place inside chloroplasts (Figure 5.1).

Extension

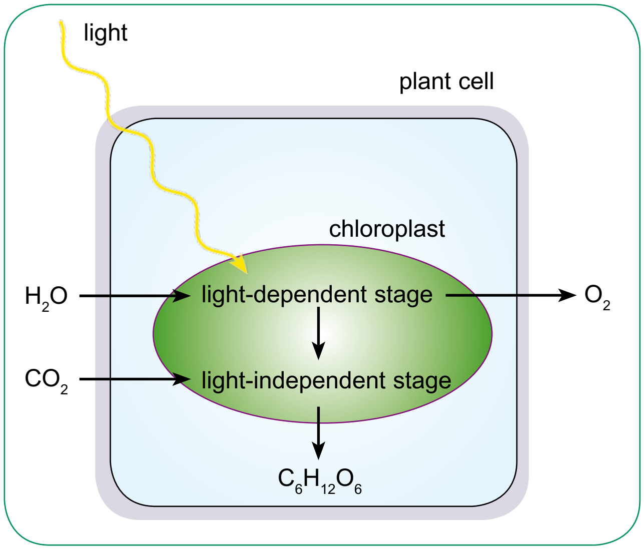

Figure 5.1 The stages of photosynthesis.

The structure of a chloroplast

Figure 5.2 shows the structure of a typical chloroplast. Chloroplasts are found in only some types of plant cells, especially in palisade mesophyll tissue and spongy mesophyll tissue in leaves. Each cell may have ten or more chloroplasts inside it.

A chloroplast is surrounded by two membranes, forming an **envelope**. There are more membranes inside the chloroplast, which are arranged so that they enclose fluid-filled sacs between them. The membranes are called **lamellae** and the fluid-filled sacs are **thylakoids**. In some parts of the chloroplasts, the thylakoids are stacked up like a pile of pancakes, and these stacks are called **grana**. The 'background material' inside the chloroplast is called the **stroma**.

Embedded tightly in the membranes inside the chloroplast are several different kinds of **photosynthetic pigments**. These are coloured substances that absorb energy from certain wavelengths (colours) of light. The most abundant pigment is **chlorophyll**, which comes in two forms, **chlorophyll *a*** and **chlorophyll *b*** (Figure 5.3).

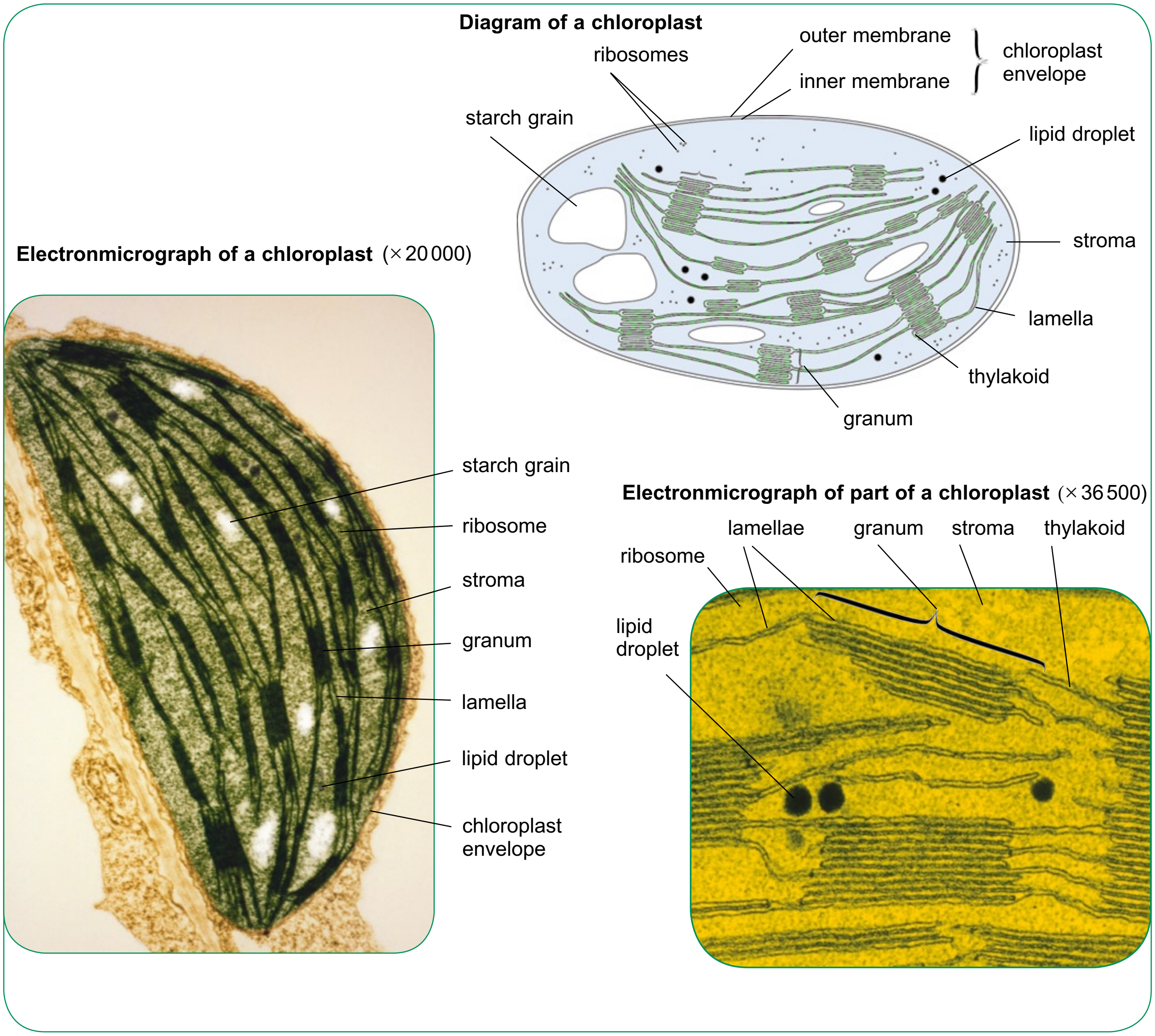
Diagram of a chloroplast

Electronmicrograph of a chloroplast (×20 000)

Electronmicrograph of part of a chloroplast (×36 500)

Figure 5.2 The structure of a chloroplast.

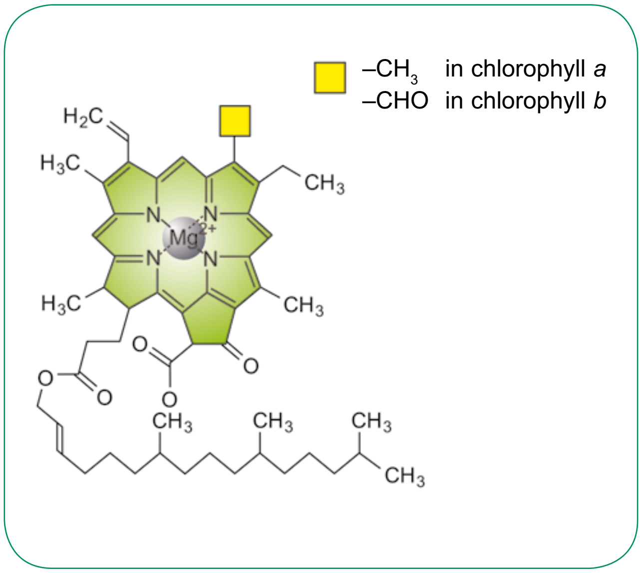

Figure 5.3 A chlorophyll molecule.

Chloroplasts often contain **starch grains**, because starch is the form in which plants store the carbohydrate that they make by photosynthesis. They also contain **ribosomes** and their own small circular strand of **DNA**. (You may remember that chloroplasts have evolved from bacteria that first invaded eukaryotic cells over a thousand million years ago.)

Biofuels

The ability of plants to transfer light energy into chemical energy means that they can be used to provide fuels for us to use – for example, for generating electricity or in vehicle engines. As stocks of fossil fuels run down, and as carbon dioxide levels in the atmosphere continue to increase, there has been a sharp increase in the use of crop plants to produce fuels rather than food. For example, rape seed is being increasingly used to produce biodiesel, rather than food for animals or humans.

At first sight, this would appear to very good for the environment. Using plants to provide fuels is theoretically 'carbon-neutral'. The carbon dioxide that is given out when the fuels are burnt is matched by the carbon dioxide that the plants take in as they photosynthesise and grow. However, if we take into account the energy that is used in harvesting the plants, converting the biomass to a useful form of fuel and transporting that fuel to points of sale, then there is still a net emission of carbon dioxide to the atmosphere.

But the greatest problem is the effect that the increasing quantity of crops grown to produce biofuels is having on the availability and price of food. For example, as huge areas of land in the USA are taken over to grow corn (maize) to produce fuel, there is less maize on sale for cattle feed or to make foods for humans. Prices have increased, in some cases so much so that poorer people, especially in neighbouring countries like Mexico, are finding it much more difficult to buy enough food for their needs.

We also need to consider effects on ecosystems. Producing large quantities of biofuels will take up large areas of land. There is a danger that some countries will cut down forests to provide extra land for this purpose, damaging habitats and endangering species that live there.

Photosynthetic pigments

A pigment is a substance whose molecules absorb some wavelengths (colours) of light, but not others. The wavelengths it does not absorb are either reflected or transmitted through the substance. These unabsorbed wavelengths reach our eyes, so we see the pigment in these colours.

The majority of the pigments in a chloroplast are chlorophyll *a* and chlorophyll *b*. Both types of chlorophyll absorb similar wavelengths of light, but chlorophyll *a* absorbs slightly longer wavelengths than chlorophyll *b*. This can be shown in a graph called an **absorption spectrum** (Figure 5.4).

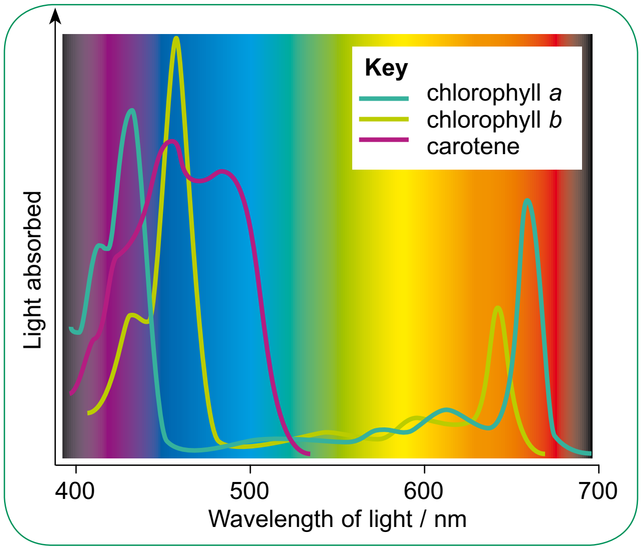

Figure 5.4 Absorption spectra for chlorophyll and carotene.

Other pigments found in chloroplasts include **carotenoids**, such as carotene. These absorb a wide range of short wavelength light, including more blue-green light than the chlorophylls. They are **accessory pigments**. They help by absorbing wavelengths of light that would otherwise not be used by the plant. They pass on some of this energy to chlorophyll. They probably also help to protect chlorophyll from damage by very intense light.

SAQ

1 **a** Use Figure 5.4 to explain why chlorophyll looks green.

b What colour are carotenoids?

Answer

The two stages of photosynthesis

The light-dependent stage of photosynthesis happens on the thylakoid membranes. Light energy is absorbed by chlorophyll. Some of this energy is then used to make ATP (Figure 5.5). Water molecules are split to produce hydrogen ions, electrons and oxygen. The hydrogen ions and electrons are picked up by a coenzyme called **NADP**, forming **reduced NADP**. The oxygen is a waste product and is excreted from the chloroplast.

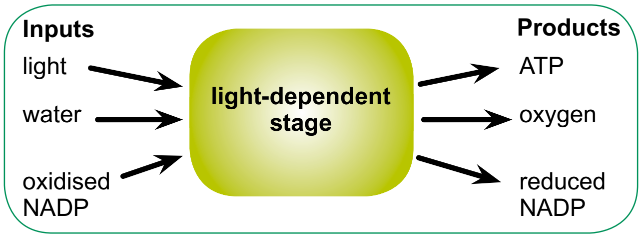

Figure 5.5 Simplified overview of the light-dependent stage of photosynthesis.

The ATP and reduced NADP produced in the light-dependent stage are now used in the light-independent stage, which takes place in the stroma of the chloroplast. This contains a compound called **RuBP**, which combines with carbon dioxide to form a compound that reacts to form a three-carbon sugar called **triose phosphate**. The reactions follow a cycle, at the end of which RuBP is regenerated. These reactions are known as the **Calvin cycle** (Figure 5.6).

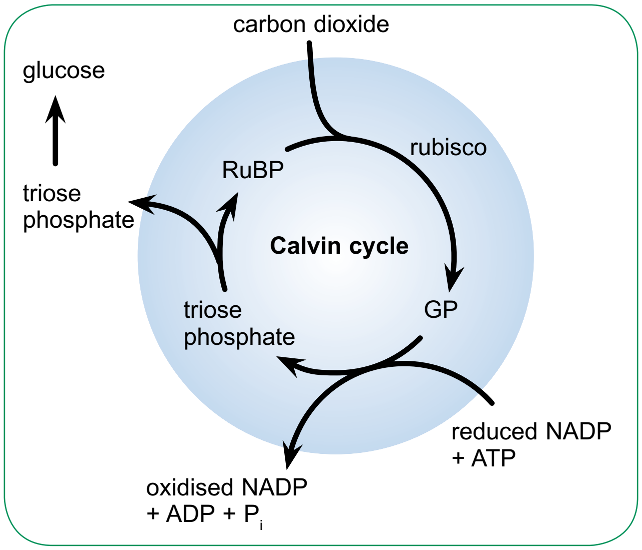

Figure 5.6 Simplified overview of the light-independent stage of photosynthesis.

Now that you have an overall picture of what happens in photosynthesis, we need to look at each stage in more detail.

The light-dependent stage

As we have seen, this stage of photosynthesis takes place on the thylakoids inside the chloroplast. It involves the absorption of light energy by chlorophyll, and the use of that energy and the products from splitting water to make ATP and reduced NADP.

Photosystems

The chlorophyll molecules are arranged in clusters called **photosystems** in the thylakoid membranes (Figure 5.7). Each photosystem spans the membrane, and contains protein molecules and pigment molecules. Energy is captured from photons of light that hit the photosystem, and is funnelled down to a pair of molecules at the **reaction centre** of the photosystem complex.

There are two different sorts of photosystem, **PSI** and **PSII**, both with a pair of molecules of chlorophyll *a* at the reaction centre.

Extension

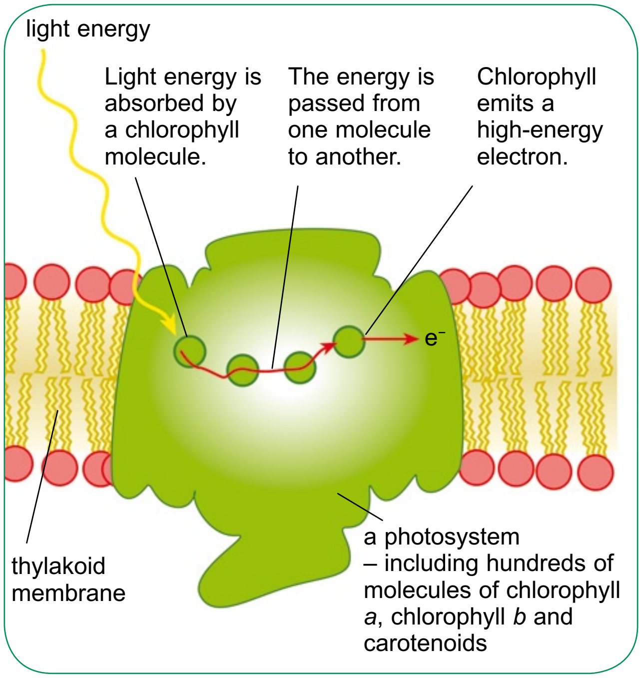

Figure 5.7 A photosystem in a thylakoid membrane.

Photophosphorylation

Photophosphorylation means 'phosphorylation using light'. It refers to the production of ATP, by combining a phosphate group with ADP, using energy that originally came from light:

ADP + phosphate ⟶ ATP

Photophosphorylation happens when an electron is passed along a series of **electron carriers**, forming an **electron transport chain** in the thylakoid membranes. The electron starts off with a lot of energy, and it gradually loses some of it as it moves from one carrier to the next. The energy is used to cause a phosphate group to react with ADP.

Extension

Cyclic photophosphorylation

This process involves only PSI, not PSII. It results in the formation of ATP, but not reduced NADP (Figure 5.8).

Light is absorbed by PSI and the energy passed on to electrons in the chlorophyll *a* molecules at the reaction centre. In each chlorophyll *a* molecule, one of the electrons becomes so energetic that it leaves the chlorophyll molecules completely. The electron is then passed along the chain of electron carriers. The energy from the electron is used to make ATP. The electron, now having lost its extra energy, eventually returns to chlorophyll *a* in PSI.

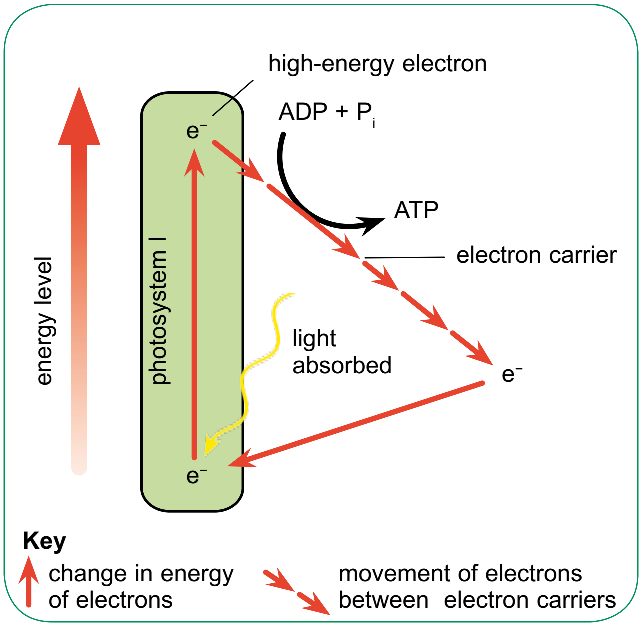

Figure 5.8 Cyclic photophosphorylation.

Non-cyclic photophosphorylation

This process involves both kinds of photosystem. It results not only in the production of ATP, but also of reduced NADP.

Light hitting either PSI or PSII causes electrons to be emitted. The electrons from PSII pass down the electron carrier chain, generating ATP by photophosphorylation. However, instead of going back to PSII, the electrons instead replace the electrons lost from PSI.

The electrons emitted from PSI are not used to make ATP. Instead, they help to reduce NADP.

For this to happen, hydrogen ions are required. These come from another event that happens when light hits PSII. PSII contains an enzyme that splits water when it is activated by light. The reaction is called **photolysis**:

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

The hydrogen ions are taken up by NADP, forming reduced NADP. The electrons replace the ones that were emitted from PSII when light hit it. The oxygen diffuses out of the chloroplast and eventually out of the leaf, as an excretory product.

The Z-scheme

The **Z-scheme** is simply a way of summarising what happens to electrons during the light-dependent reactions. It is a kind of graph, with the *y*-axis indicating the 'energy level' of the electron (Figure 5.9).

Start at the bottom left, where light hits photosystem II. The red vertical line going up shows the increase in the energy level of electrons as they are emitted from this photosystem. You can also see where these electrons came from – the splitting of water molecules. (In fact, it probably isn't the same electrons – but the electrons from the water replace the ones that are emitted from the photosystem.)

If you keep following the vertical line showing the increasing energy in the electrons, you arrive at a point where it starts a steep dive downwards. This shows the electrons losing their energy as they pass along the electron carrier chain. Eventually they arrive at photosystem I.

You can then track the movement of the electrons to a higher energy level when PSI is hit by light, before they fall back downwards as they lose energy and become part of a reduced NADP molecule.

The light-independent stage

Now the ATP and reduced NADP that have been formed in the light-independent stage are used to help to produce carbohydrates from carbon dioxide. These events take place in the stroma of the chloroplast. As we have seen, the cyclic series of reactions is known as the Calvin cycle (Figure 5.10).

SAQ

2 Copy and complete the table to compare cyclic and non-cyclic photophosphorylation. (If a box in a particular row is not applicable, write n/a.)

	Cyclic photophosphorylation	**Non-cyclic photophosphorylation**
Is PSI involved?		
Is PSII involved?		
Where does PSI obtain replacement electrons from?		
Where does PSII obtain replacement electrons from?		
Is ATP made?		
Is reduced NADP made?		

Answer

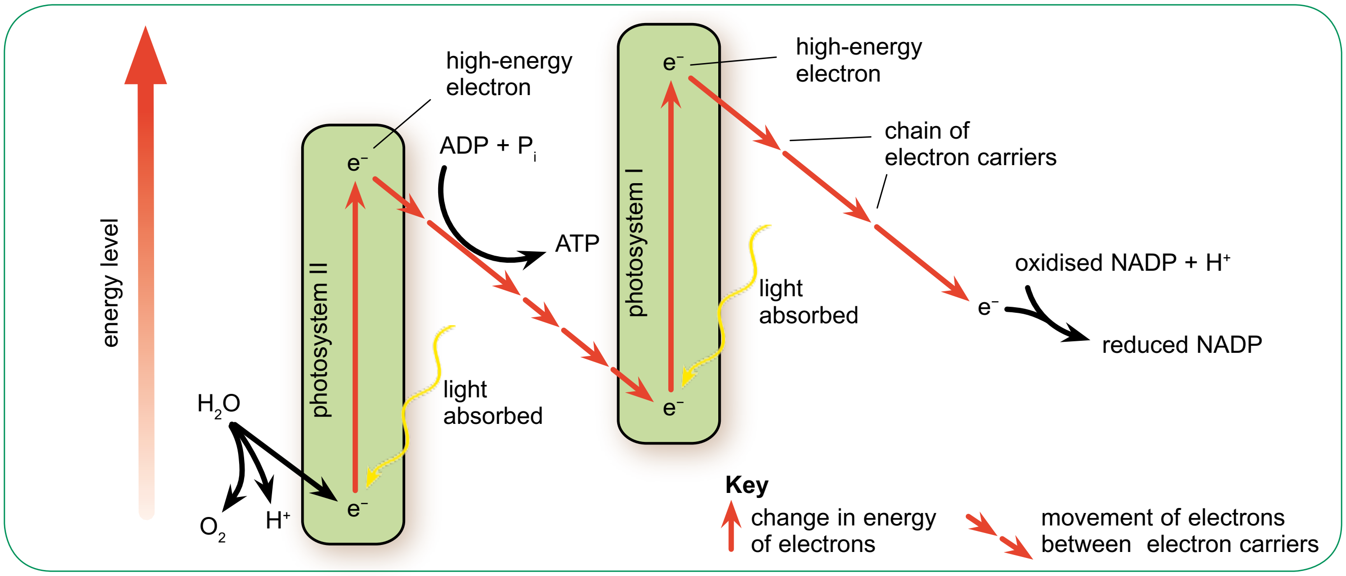

Figure 5.9 The Z-scheme, summarising non-cyclic photophosphorylation.

The chloroplast stroma contains an enzyme called **rubisco** (its full name is ribulose bisphosphate carboxylase). This is thought to be the most abundant enzyme in the world. Its function is to catalyse the reaction in which carbon dioxide combines with a substance called **RuBP** (ribulose bisphosphate).

RuBP molecules each contain five atoms of carbon. The reaction with carbon dioxide therefore produces a six-carbon molecule, but this immediately splits to form two three-carbon molecules. This three-carbon substance is **glycerate 3-phosphate**, usually known as **GP**.

Now the two products of the light-dependent stages come into play. The reduced NADP and the ATP are used to provide energy and phosphate groups, which change the GP into a three-carbon sugar called **triose phosphate** (**TP**). This is the first carbohydrate that is made in photosynthesis.

There are many possible fates of the triose phosphate. Five-sixths of it are used to regenerate RuBP. The remainder can be converted into other

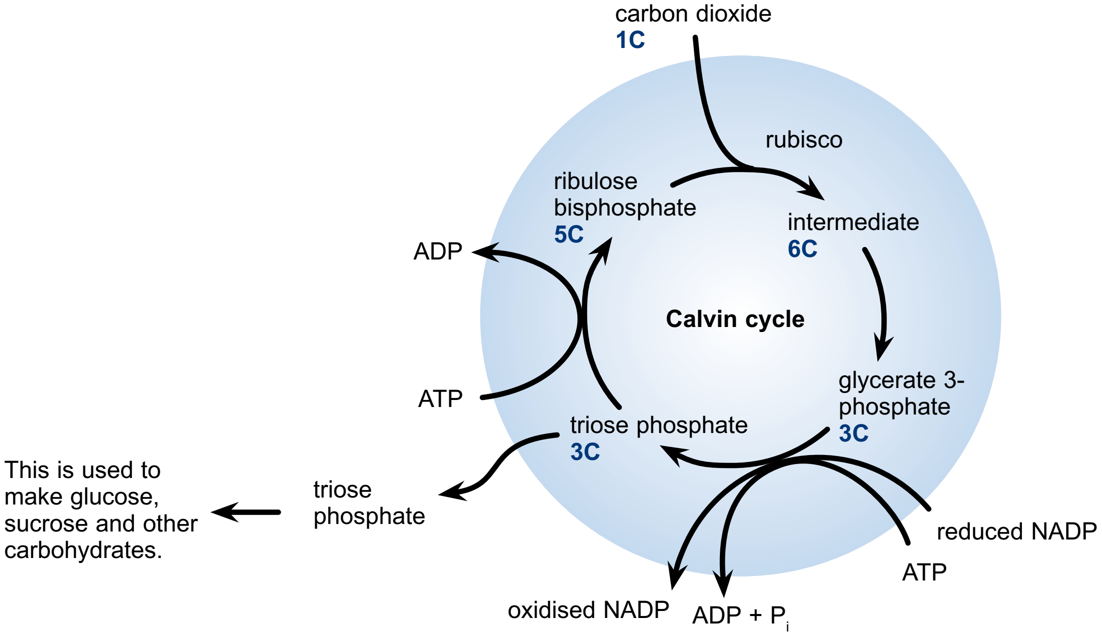

Figure 5.10 The Calvin cycle.

carbohydrates. For example, two triose phosphates can combine to produce a hexose phosphate molecule. From these, glucose, fructose, sucrose, starch and cellulose can be formed.

The triose phosphate can also be used to make lipids and amino acids. For amino acid production, nitrogen needs to be added, which plants obtain from the soil in the form of nitrate ions or ammonium ions.

SAQ

3 Suggest what happens to the ADP, inorganic phosphate and NADP that is formed during the Calvin cycle.

Answer

Factors affecting the rate of photosynthesis

Photosynthesis requires several inputs. It needs raw materials in the form of carbon dioxide and water, and energy in the form of sunlight. The light-independent stage also requires a reasonably high temperature, because the rates of reactions are affected by the kinetic energy of the molecules involved.

If any of these requirements is in short supply, it can limit the rate at which the reactions of photosynthesis are able to take place.

SAQ

4 The rate of the light-dependent reactions is not directly affected by temperature. Can you suggest why this is?

Answer

Light intensity

Light provides the energy that drives the light-dependent reactions, so it is obvious that when there is no light, there is no photosynthesis. If we provide a plant with more light, then it will photosynthesise faster.

However, this can only happen up to a point. We would eventually reach a light intensity where, if we give the plant more light, its rate of photosynthesis does not change. Some other factor, such as the availability of carbon dioxide or the quantity of chlorophyll in its leaves, is preventing the rate of photosynthesis from continuing to increase.

This relationship is shown in Figure 5.11. Over the first part of the curve, we can see that rate of photosynthesis does indeed increase as light intensity increases. For these light intensities, light is a **limiting factor**. The light intensity is limiting the rate of photosynthesis. If we give the plant more light, then it will photosynthesise faster.

But, from point X onwards, increasing the light intensity has no effect on the rate of photosynthesis. Along this part of the curve, light is no longer a limiting factor. Something else is. It is most likely to be the carbon dioxide concentration.

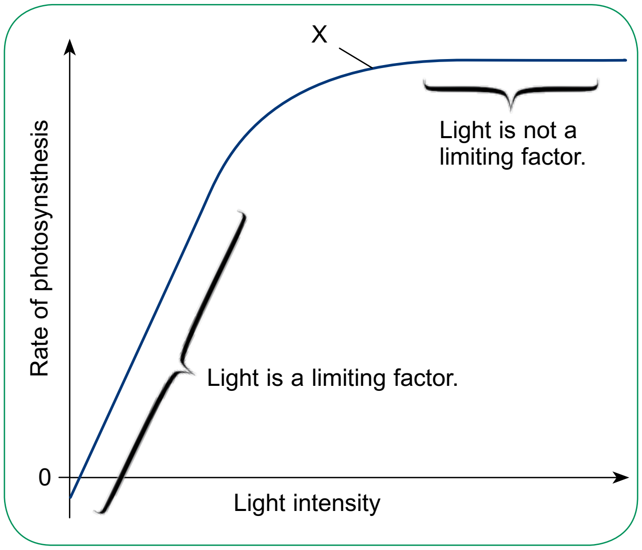

Figure 5.11 The effect of light intensity on the rate of photosynthesis.

Carbon dioxide concentration

The concentration of carbon dioxide in the air is very low, only about 0.04%. Yet this substance is needed for the formation of every organic molecule inside every living thing on Earth.

Plants absorb carbon dioxide into their leaves by diffusion through the stomata. During daylight, carbon dioxide is used in the Calvin cycle in the chloroplasts, so the concentration of carbon dioxide inside the leaf is even lower than in the air outside, providing the diffusion gradient that keeps it moving into the leaf.

Carbon dioxide concentration is often a limiting factor for photosynthesis. If we give plants extra carbon dioxide, they can photosynthesise faster.

Figure 5.12 shows the relationship between carbon dioxide concentration and rate of photosynthesis. Figure 5.13 shows the effect of carbon dioxide at different light intensities.

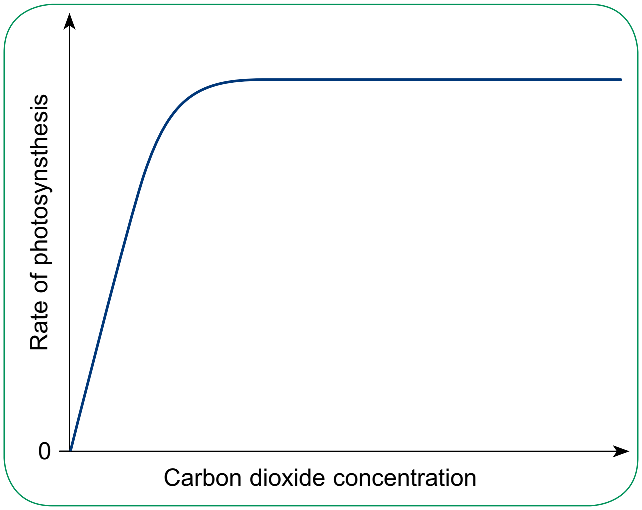

Figure 5.12 The effect of carbon dioxide on rate of photosynthesis.

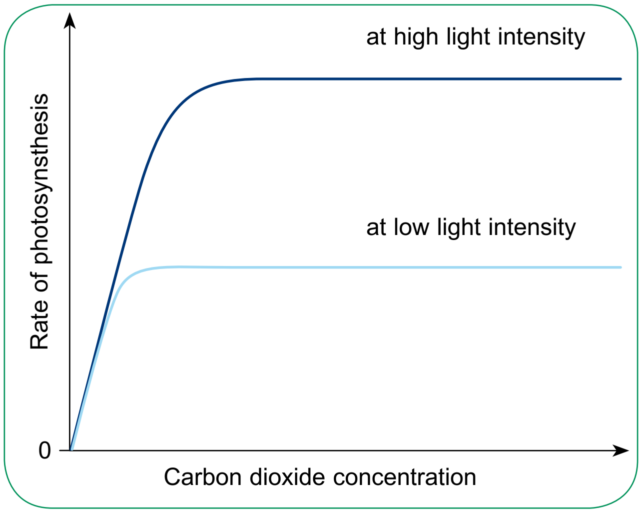

Figure 5.13 The effect of carbon dioxide concentration on the rate of photosynthesis at different light intensities.

SAQ

5 **a** Over which part of the curve in Figure 5.12 is carbon dioxide a limiting factor for photosynthesis?

b Suggest why the curve flattens out at high levels of CO_2.

Answer

Temperature

Temperature affects the kinetic energy of molecules. The higher the temperature, the faster molecules move, and the more frequently they collide with one another. They also collide with more energy. The greater frequency and energy of collisions means that the reaction rate increases.

In photosynthesis, though, this effect is only seen in the light-independent reactions. The rate of the light-dependent reactions is not directly affected by temperature, because the energy that drives them comes from light, not the kinetic energy of molecules.

In living organisms, most reactions are catalysed by enzymes, so we also need to consider the effect of temperature on them. Just like any molecules, their kinetic energy increases as temperature increases. However, as you will remember, beyond a certain temperature (different for different enzymes) they begin to lose their shape, and therefore their catalytic properties. Plant enzymes often have lower optimum temperatures than enzymes found in mammals, because they have evolved to work in the environmental temperatures in which the plant normally lives.

Things are complicated, however, by a peculiar property of the enzyme rubisco. Rubisco has an unfortunate tendency to stop doing what is supposed to do – catalyse the combination of carbon dioxide with RuBP – and start doing something else when temperature rises. It switches to catalysing a reaction in which *oxygen* is combined with RuBP. This is very wasteful, as it wastes RuBP. It is called **photorespiration**, and it can seriously reduce the rate of photosynthesis in many plant species, when temperature and light intensity are high. (Photorespiration is a misleading name, as it is not really respiration at all.)

The effect of light on the Calvin cycle

The Calvin cycle is the light-independent stage of photosynthesis. It is given that name because it does not require energy input from light. It *does* however, need energy input from the light-dependent stage, in the form of ATP and reduced NADP.

Imagine that light is shining on a chloroplast. The light-dependent stage is generating ATP and reduced NADP, and the reactions of the Calvin cycle are working continuously.

Now the light is switched off. The light-dependent stage stops, so the supply of ATP and NADP to the Calvin cycle also stops. These substances are needed to fuel the conversion of GP to TP. So now GP can no longer be converted into TP, and the GP just builds up. The rest of the cycle keeps running, until most of the TP is used up. Then it grinds to a halt.

Figure 5.14 shows what happens to the relative amounts of GP and TP when the light is switched off. As we would expect, the levels of TP plummet, while the levels of GP rise. If the light is switched on again, they go back to their 'normal' relative levels.

The effect of carbon dioxide concentration on the Calvin cycle

Carbon dioxide is a vital input to the Calvin cycle. If carbon dioxide is in short supply, then less GP is made, and therefore less TP.

The lack of carbon dioxide means that there is less for RuBP to react with, so RuBP might be expected to build up, and this does happen.

But remember that RuBP has to be replaced from TP. The lower rate of synthesis of TP means that there is less available to convert to RuBP or to other carbohydrates, amino acids or lipids. Normally, the plant will prioritise the replacement of RuBP, ensuring that its levels remain reasonably high. If the low carbon dioxide concentration continues over a long period of time, however, then there is little point in the plant maintaining high concentrations of RuBP, as it does not have much carbon dioxide to combine with. Some species of plants appear to adapt to this situation by allowing the level of RuBP to fall.

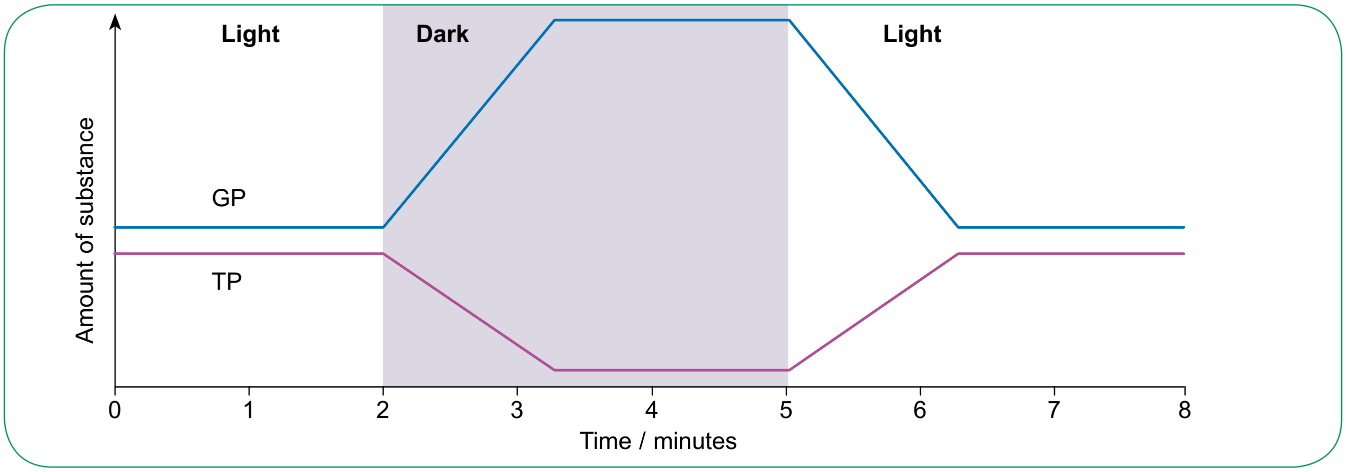

Figure 5.14 The effect of light and dark on the relative levels of TP and GP in a chloroplast.

SAQ

6 a Explain why the Calvin cycle stops running when there is no light and the TP is used up.

b Make a copy of Figure 5.14. Add another line to show what you would expect to happen to the levels of RuBP during this eight-minute period.

Answer

7 What effect would you expect a rise or a fall in temperature to have on the relative levels of GP, TP and RuBP? (Assume that the temperature does not go high enough to denature enzymes.) Explain your reasoning.

Answer

Summary

Glossary

- Autotrophs make their own organic nutrients using inorganic materials. Heterotrophs require organic nutrients that have been made by other organisms. Plants are autotrophs. Animals and fungi are heterotrophs.
- In photosynthesis, energy from light is transformed into chemical energy in organic molecules. This energy can then be released from the organic molecules by respiration.
- Photosynthesis is a two-stage process. In the light-dependent reaction, light is absorbed by chlorophyll and used to split water and produce ATP and reduced NADP. In the light-independent stage, this ATP and reduced NADP are used to produce carbohydrates from carbon dioxide.
- Photosynthesis takes place in chloroplasts. A chloroplast has an envelope surrounding it. Membranes in the stroma form thylakoids, which are stacked to form grana. The light-dependent reaction takes place on the thylakoids, and the light-independent reaction in the stroma.
- Photosynthetic pigments such as chlorophyll absorb energy from light. The energy causes electrons to be emitted from the pigments. Chlorophyll molecules are found in photosystems, of which there are two kinds – PSI and PSII.
- In cyclic photophosphorylation, electrons emitted from PSI are passed along a chain of electron carriers, releasing their energy which is used to make ATP. The electrons return to PSI.
- In non-cyclic photophosphorylation, electrons are emitted from both PSI and PSII. The electrons from PSII pass down the electron transport chain and ATP is formed. These electrons are then taken up by PSI. The electrons from PSI, together with hydrogen ions from the splitting of water, are used to reduce NADP. The electrons lost from PSII are replaced by electrons produced from the splitting of water.
- In the Calvin cycle, the enzyme rubisco catalyses the reaction of RuBP with carbon dioxide. This results in the formation of two molecules of GP. Energy from ATP and NADP is used to convert GP to TP. Most of the TP is used to regenerate RuBP, while the rest is converted to other carbohydrates, lipids or amino acids.
- Low levels of light, low levels of carbon dioxide and low temperatures can all reduce the rate of photosynthesis. A factor that is holding back the rate is called a limiting factor. Increasing the level of the limiting factor increases the rate of photosynthesis.
- Although the light-independent reaction does not require light, it does require ATP and NADP that have been made in the light-dependent reaction. When there is no light, the lack of ATP and NADP causes GP to accumulate and levels of TP and RuBP to fall. Low carbon dioxide levels lead to a fall in GP and TP levels, and an initial accumulation of RuBP. Changes in temperature do not affect the relative levels of these compounds.

Stretch and challenge question

Hint

1 Describe how the structures of:
  a a leaf
  b a palisade cell
  c a chloroplast
are adapted for photosynthesis.

Questions

1 In an experiment to investigate the effect of light intensity on the rate of photosynthesis, the following procedure was carried out by some students.

- Discs were cut from the photosynthetic tissue of the brown alga *Fucus serratus*, a common rocky shore seaweed, using a cork borer.
- Ten discs were placed in each of four beakers filled with 50 cm^3 of sea water. The discs are denser than sea water and therefore sink to the bottom of the beaker.
- Each beaker was illuminated with a bench lamp placed at different distances (d) from the beaker.
- The time in minutes, at which the third disc from each batch reached the surface (t) was recorded.
- The rate of photosynthesis was determined by calculating $\frac{1000}{t}$.

A student's set of results is shown in the table.

Distance of beaker from lamp (d) / cm	Light intensity $\frac{1}{d^2}$	Time for third disc to reach the surface (t) / min	Rate of photosynthesis $\frac{1000}{t}$
5	0.04	23	43.5
10	0.01	36	27.8
15	0.004	52	19.2
20		88	

a Calculate the values for light intensity and rate of photosynthesis when the distance between beaker and lamp was 20 cm. [2]

b Explain why the discs float after being illuminated for a length of time. [3]

c Using the data in the table, describe the relationship between light intensity and the rate of phototsynthesis. [2]

d State the environmental factor limiting the rate of photosynthesis in this experiment. [1]

e State the evidence from the table you used to support your answer to **d**. [1]

f Suggest why the student is not likely to find an increase in the rate of photosynthesis when two lamps are placed 5 cm from the beaker. [2]

OCR Biology A (2804) June 2004 (part) [Total 11]

Answer