Cambridge

A2 Level

Biology

Code (9700)

Chapter 12 and Chapter 13

Energy and respiration, photosynthesis

The need for energy in living organisms

All living organisms require a continuous supply of energy to stay alive, either from the absorption of light energy or from chemical potential energy (energy stored in nutrient molecules). The process of photosynthesis transfers light energy to chemical potential energy, and so almost all life on Earth depends on photosynthesis, either directly or indirectly.

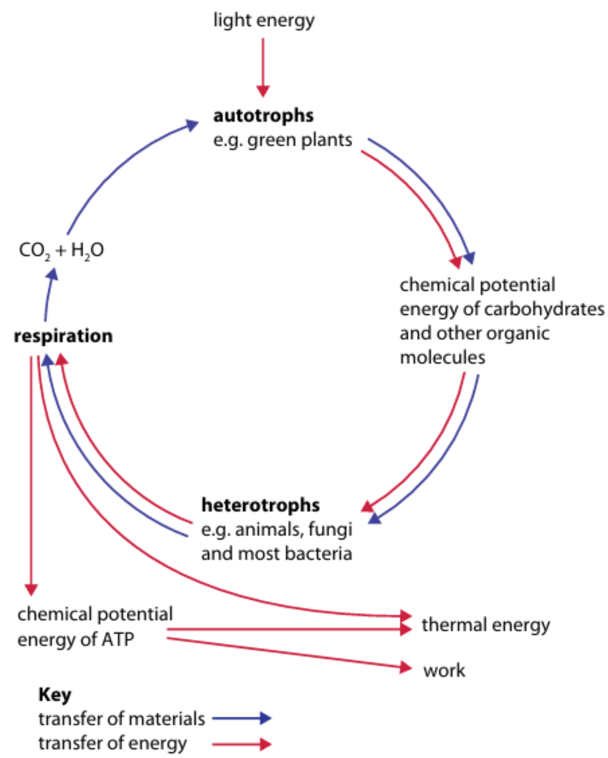


Figure 12.2 Transfer of materials and energy in an ecosystem.

Work

Work in a living organism includes:

■ ■ the synthesis of complex substances from simpler ones (anabolic reactions), such as the synthesis of polysaccharides from monosaccharides, lipids from glycerol and fatty acids, polypeptides from amino acids, and nucleic acids from nucleotides

■ ■ the active transport of substances against a diffusion gradient, such as the activity of the sodium–potassium pump (Figure 4.18, page 87)

■ ■ mechanical work such as muscle contraction (page 344) and other cellular movements;

■ ■ in a few organisms, bioluminescence and electrical discharge.

For a living organism to do work, energy-requiring reactions must be linked to those that yield energy. In the complete oxidation of glucose ($C_6H_{12}O_6$) in aerobic conditions, a large quantity of energy is made available:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2870\,kJ$$

Glucose is actually quite stable, because of the activation energy that has to be added before any reaction takes place (Figure 12.3). In living organisms, the **activation energy** is overcome by lowering it using enzymes (page 56), and also by raising the energy level of the glucose by phosphorylation (page 272).

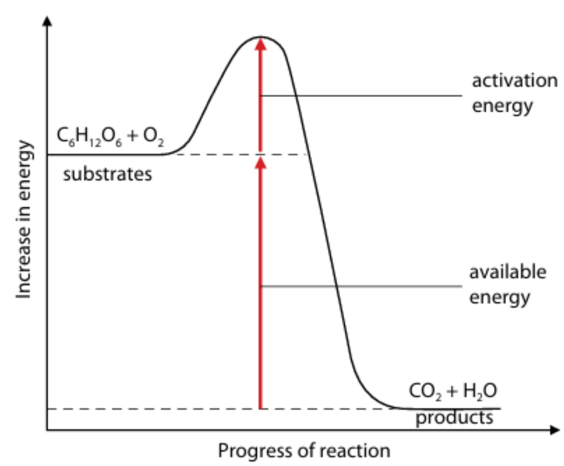


Figure 12.3 Oxidation of glucose.

However, a much more flexible system actually occurs in which energy-yielding reactions in all organisms are used to make an intermediary molecule, **ATP.**

ATP

ATP as energy 'currency'

Look back at the structure of ATP, shown in Figure 6.4, page 113. When a phosphate group is removed from ATP, adenosine diphosphate (ADP) is formed and 30.5 kJmol−1 of energy is released

This description is misleading and should be avoided, since the energy does not come simply from breaking those bonds, but rather from changes in chemical potential energy of all parts of the system

These reactions are all reversible. It is the interconversion of ATP and ADP that is all-important in providing energy for the cell:

$$ATP + H_2O \rightleftharpoons ADP + H_3PO_4 \pm 30.5\,kJ$$

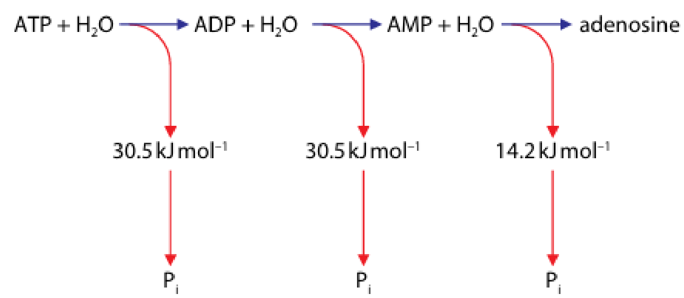


Figure 12.4 Hydrolysis of ATP (P_i is inorganic phosphate, H_3PO_4).

Synthesis of ATP

ATP synthesis in cells occurs through two methods: respiration, where chemical potential energy is released during glycolysis and the Krebs cycle, and electrical potential energy, generated through electron transfer in mitochondria and chloroplasts. This energy is stored as a difference in proton concentration across phospholipid membranes, allowing protons to flow through a protein called ATP synthase, which produces one ATP molecule, provided ADP and Pi are present.

Note that a hydrogen atom consists of one proton and one electron. The loss of an electron forms a hydrogen ion, which is a single proton.

$$H \rightleftharpoons H^+ + e^-$$

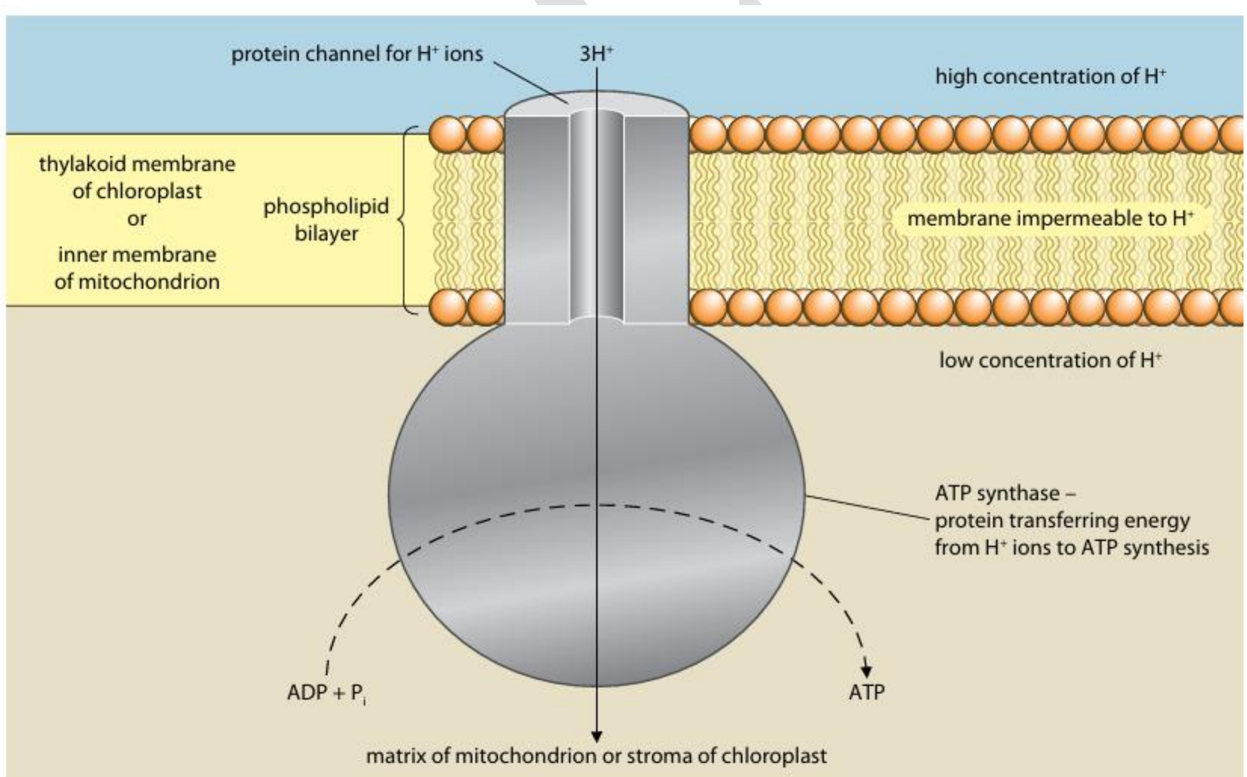


Figure 12.5 ATP synthesis (chemiosmosis).

ATP synthase has three binding sites (Figure 12.6) and a part of the molecule (γ) that rotates as hydrogen ions (H+) pass. This produces structural changes in the binding sites and allows them to pass sequentially through three phases:

- ■ ■ binding ADP and Pi
- ■ ■ forming tightly bound ATP
- ■ ■ releasing ATP.

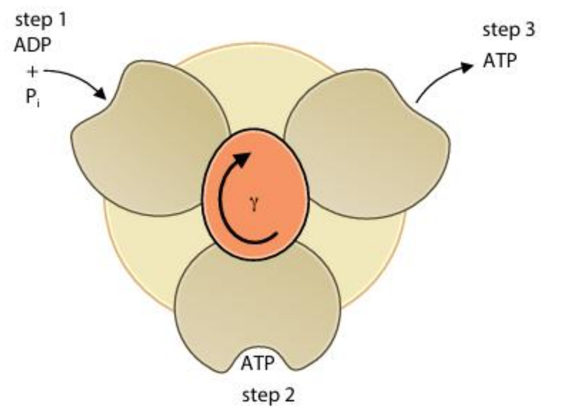


Figure 12.6 Transverse section (TS) of ATP synthase showing its activity.

The role of ATP in active transport

Active transport is the movement of molecules or ions across a partially permeable membrane against a concentration gradient. Energy is needed, from ATP, to counteract the tendency of these particles to move by diffusion down the gradient.

Respiration

Respiration is a process in which organic molecules act as a fuel.

Glucose breakdown can be divided into four stages: glycolysis, the link reaction, the Krebs cycle and oxidative phosphorylation (Figure 12.7).

The glycolytic pathway

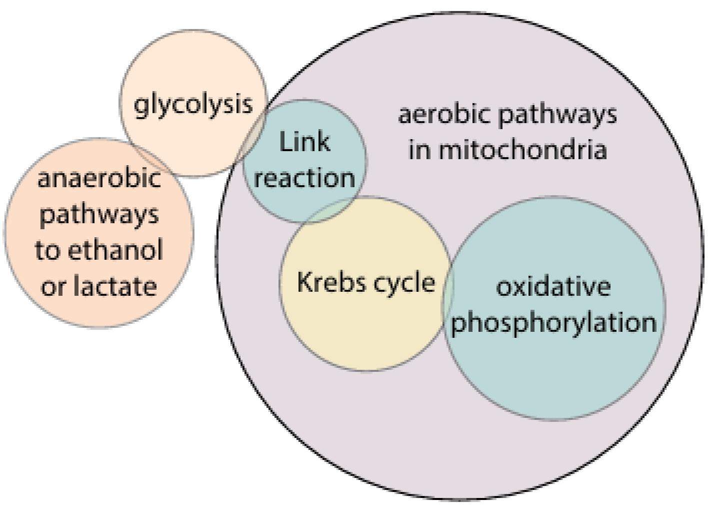


Figure 12.7 The sequence of events in respiration.

Glycolysis is the splitting, or lysis, of glucose. It is a multi-step process in which a glucose molecule with six carbon atoms is eventually split into two molecules of pyruvate, each with three carbon atoms.

The hydrogens carried by reduced NAD can easily be transferred to other molecules and are used in oxidative phosphorylation to generate ATP (page 273).

The link reaction

Pyruvate passes by active transport from the cytoplasm, through the outer and inner membranes of a mitochondrion and into the mitochondrial matrix. Here it is decarboxylated (this means that carbon dioxide is removed), dehydrogenated (hydrogen is removed) and combined with coenzyme A (CoA) to give acetyl coenzyme A.

$$\text{pyruvate} + \text{CoA} + \text{NAD} \rightleftharpoons \text{acetyl CoA} + CO_2 + \text{reduced NAD}$$

The Krebs cycle

The Krebs cycle (also known as the citric acid cycle or tricarboxylic acid cycle) was discovered in 1937 by Hans Krebs. It is shown in Figure 12.9.

The Krebs cycle is a closed pathway of enzyme controlled reactions.

■ ■ Acetyl coenzyme A combines with a four-carbon compound (oxaloacetate) to form a six-carbon compound (citrate).

■ ■ The citrate is decarboxylated and dehydrogenated in a series of steps, to yield carbon dioxide, which is given off as a waste gas, and hydrogens which are accepted by the carriers NAD and FAD (page 275).

■ ■ Oxaloacetate is regenerated to combine with another acetyl coenzyme A.

Oxidative phosphorylation and the electron transport chain

In the final stage of aerobic respiration, oxidative phosphorylation, the energy for the phosphorylation of ADP to ATP comes from the activity of the electron transport chain. Oxidative phosphorylation takes place in the inner mitochondrial membrane (Figure 12.10).

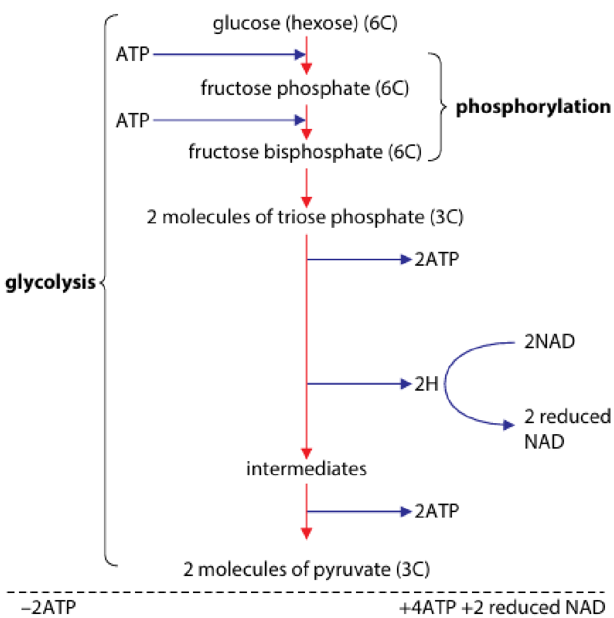


Figure 12.8 The glycolytic pathway.

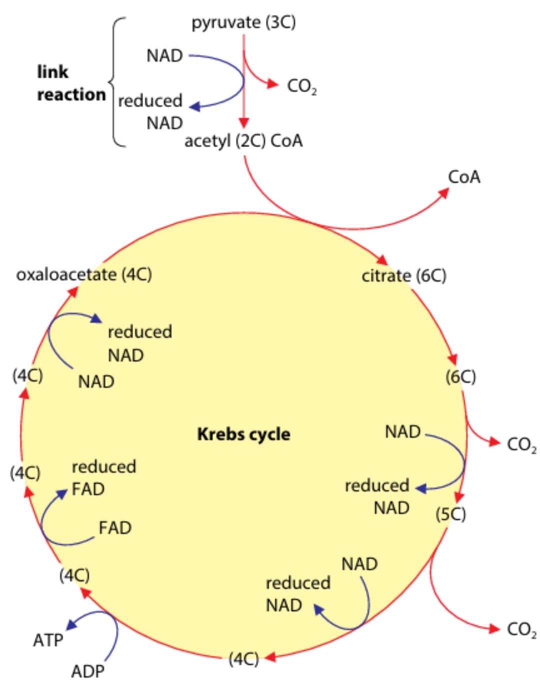


Figure 12.9 The link reaction and the Krebs cycle.

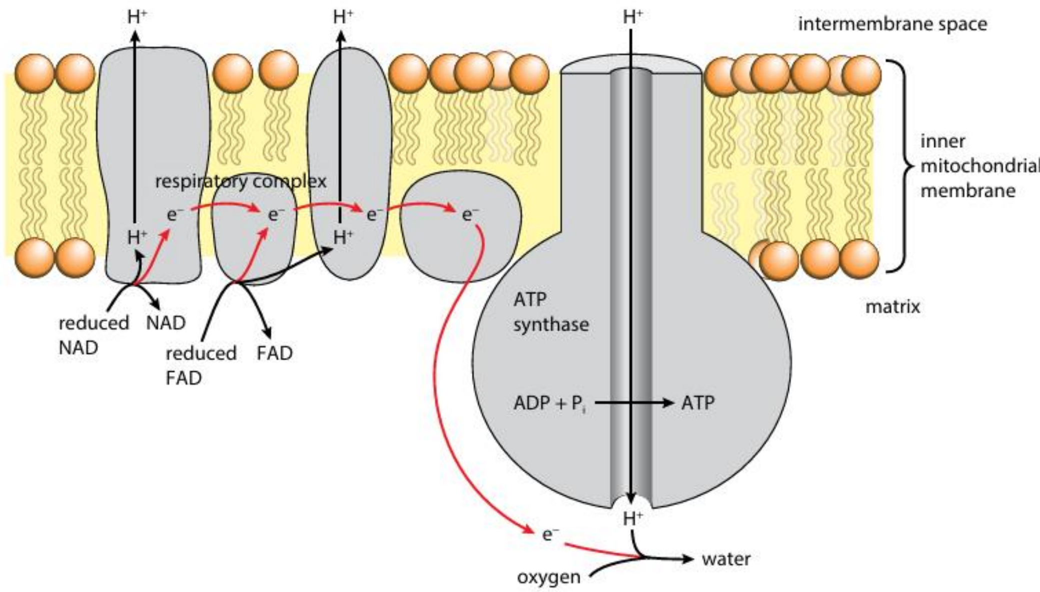


Figure 12.10 Oxidative phosphorylation: the electron transport chain.

The respiration pathway involves the transfer of glucose molecules through a respiratory complex of membrane proteins. These proteins, arranged in an energy gradient, release energy to move protons from the matrix of the mitochondrion into the intermembrane space. The protons then pass through protein channels in the inner membrane, using their electrical potential energy to synthesize ATP. Three molecules of ATP can be produced from each molecule of reduced NAD and two molecules from each molecule of reduced FAD, but about 25% of the total energy yield is used for transporting ADP and ATP.

	ATP used	**ATP made**	**Net gain in ATP**
glycolysis	–2	4	+2
link reaction	0	0	0
Krebs cycle	0	2	+2
oxidative phosphorylation	0	28	+28
Total	**–2**	**34**	**+32**

Table 12.1 Balance sheet of ATP use and synthesis for each molecule of glucose entering respiration.

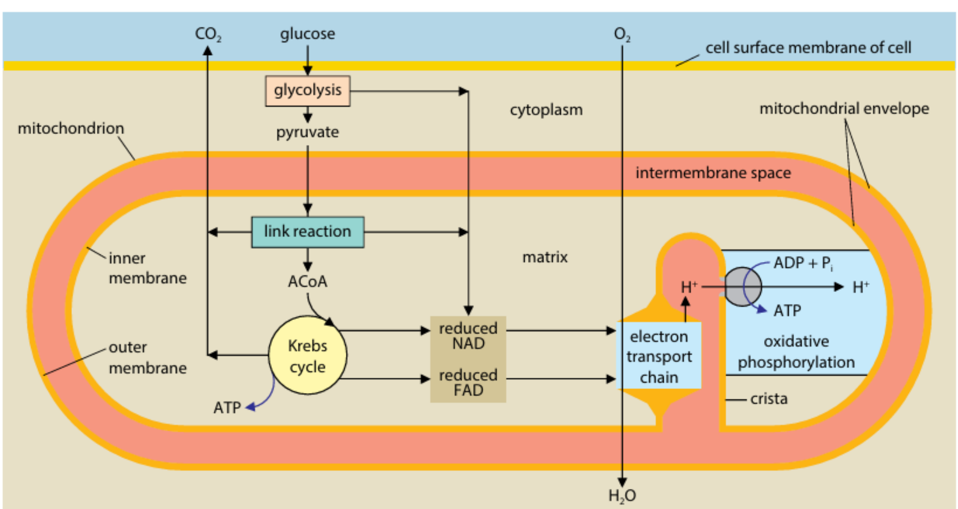


Figure 12.11 The sites of the events of respiration in a cell. ACoA = acetyl coenzyme A.

Hydrogen carrier molecules

NAD is made of two linked nucleotides (Figure 12.12). Both nucleotides contain ribose. One nucleotide contains the nitrogenous base adenine. The other has a nicotinamide ring, which can accept a hydrogen ion and two electrons, thereby becoming reduced.

$$NAD + 2H \rightleftharpoons \text{reduced } NAD$$
$$NAD^+ + 2H \rightleftharpoons NADH^+ + H^+$$

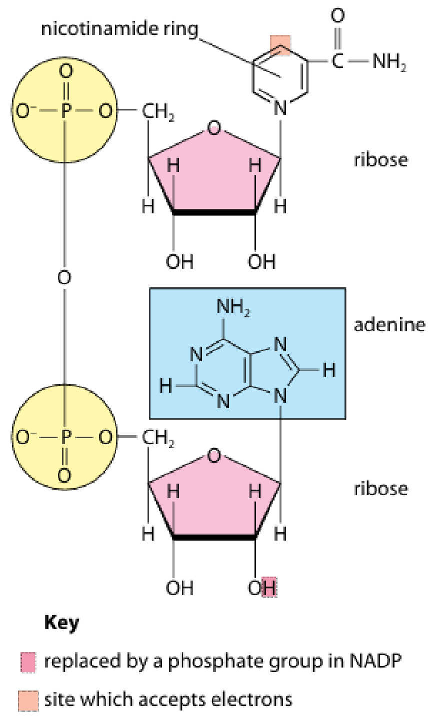


Figure 12.12 NAD (nicotinamide adenine dinucleotide). You do not need to learn the structure of this molecule, but may like to compare it with the units that make up DNA and RNA.

Mitochondrial structure and function

In eukaryotic organisms, the mitochondrion is the site of the Krebs cycle and the electron transport chain. Mitochondria are rod-shaped or filamentous organelles about 0.5–1.0 µm in diameter. Time-lapse photography shows that they are not rigid, but can change their shape.

The inner membrane is studded with tiny spheres, about 9 nm in diameter, which are attached to the inner membrane by stalks (Figure 12.14). The spheres are the enzyme **ATP synthase**

Figure 12.13 Transmission electron micrograph of a mitochondrion from a pancreas cell (×15 000).

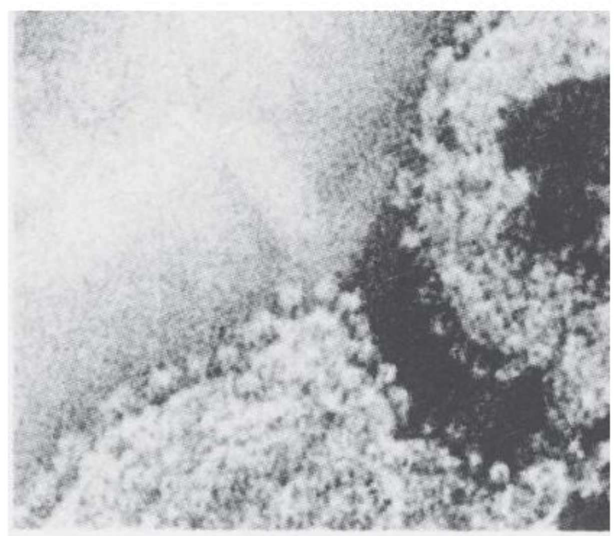


Figure 12.14 Transmission electron micrograph of ATP synthase particles on the inner membrane of a mitochondrion (×400 000).

Respiration without oxygen

When free oxygen is not present, hydrogen cannot be disposed of by combination with oxygen. The electron transfer chain therefore stops working and no further ATP is formed by oxidative phosphorylation.

These reactions 'buy time'. They allow the continued production of at least some ATP even though oxygen is not available as the hydrogen acceptor. However, as the products of anaerobic reaction, ethanol or lactate, are toxic, the reactions cannot continue indefinitely.

When exercise stops, the person continues to breathe deeply and absorb oxygen at a higher rate than when at rest. This post-exercise uptake of extra oxygen, which is 'paying back' the oxygen deficit, is called the oxygen debt. The oxygen is needed for:

■ ■ conversion of lactate to glycogen in the liver

■ ■ reoxygenation of haemoglobin in the blood

■ ■ a high metabolic rate, as many organs are operating at above resting levels.

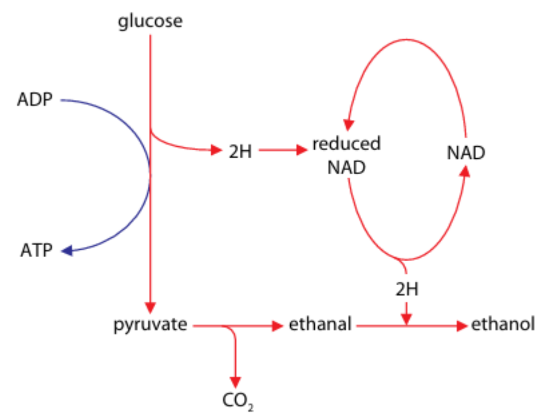


Figure 12.15 Alcoholic fermentation.

Respiratory substrates

Although glucose is the essential respiratory substrate for some cells such as neurones in the brain, red blood cells and lymphocytes, other cells can oxidise lipids and amino acids

Energy values of respiratory substrates

Most of the energy liberated in aerobic respiration comes from the oxidation of hydrogen to water when reduced NAD and reduced FAD are passed to the electron transport chain.

The energy liberated by oxidising the substrate can be determined from the rise in temperature of a known mass of water in the calorimeter. Typical energy values are shown in Table 12.2.

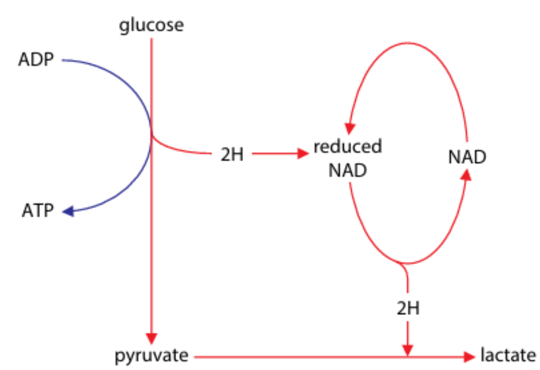


Figure 12.16 Lactic fermentation.

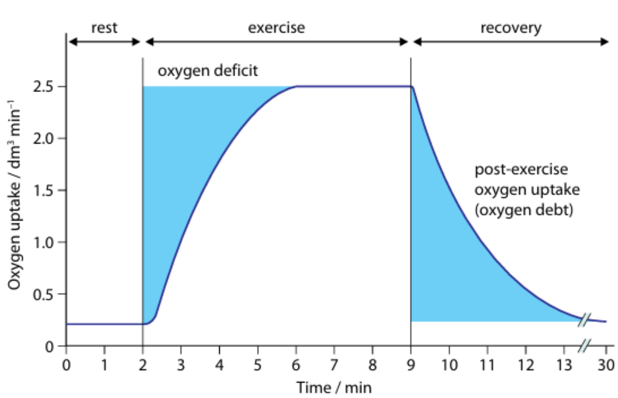


Figure 12.17 Oxygen uptake before, during and after strenuous exercise.

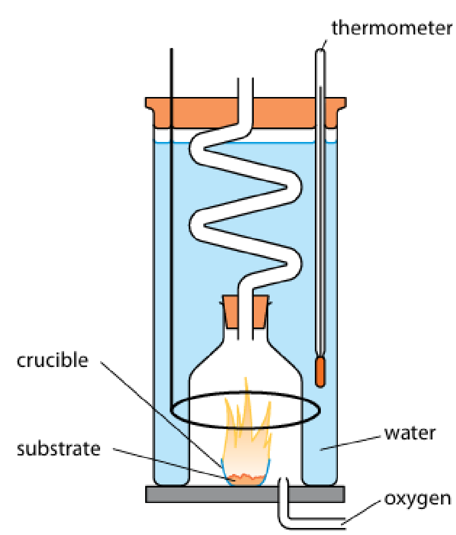


Figure 12.18 A simple calorimeter in which the energy value of a respiratory substrate can be measured.

Respiratory substrate	Energy density / kJ g^{-1}
carbohydrate	15.8
lipid	39.4
protein	17.0

Table 12.2 Typical energy values.

Respiratory quotient (RQ)

The overall equation for the aerobic respiration of glucose shows that the number of molecules, and hence the volumes, of oxygen used and carbon dioxide produced are the same:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

$$RQ = \frac{\text{volume of carbon dioxide given out in unit time}}{\text{volume of oxygen taken in in unit time}}$$

Or, from an equation,

$$RQ = \frac{\text{moles or molecules of carbon dioxide given out}}{\text{moles or molecules of oxygen taken in}}$$

For the aerobic respiration of glucose:

$$RQ = \frac{CO_2}{O_2} = \frac{6}{6} = 1.0$$

When the fatty acid oleic acid (from olive oil) is respired aerobically, the equation is:

$$C_{18}H_{34}O_2 + 25.5O_2 \rightarrow 18CO_2 + 17H_2O + \text{energy}$$

For the aerobic respiration of oleic acid:

$$RQ = \frac{CO_2}{O_2} = \frac{18}{25.5} = 0.7$$

Typical RQs for the aerobic respiration of different substrates are shown in Table 12.3.

Respiratory substrate	Respiratory quotient (RQ)
carbohydrate	1.0
lipid	0.7
protein	0.9

Table 12.3 Respiratory quotients of different substrates.

Adaptations of rice for wet environments

Although rice can grow in dry conditions, it is often grown in 'paddies' – fields where the ground is intentionally f looded. Rice can tolerate growing in water, whereas most of the weeds that might compete with it are not able to do so (Figure 12.20).

Some varieties of rice respond to flooding by growing taller. As the water rises around them, they keep growing upwards so that the top parts of their leaves and flower spikes are always held above the water.

Figure 12.20 Rice growing in Madagascar. The blocks of rice were planted at different times and are at different stages of growth.

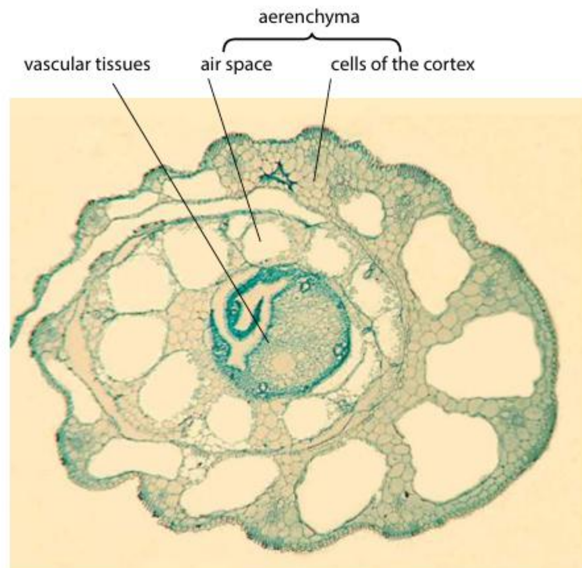


Figure 12.21 Photomicrograph of a cross-section of a rice stem near its tip, with a leaf base around it. Lower down, the stem is completely hollow (×140).

Chapter 13: Photosynthesis

An energy transfer process

As you have seen at the beginning of Chapter 12, the process of photosynthesis transfers light energy into chemical potential energy of organic molecules. This energy can then be released for work in respiration (Figure 12.2).

An outline of the process

Photosynthesis is the trapping (fixation) of carbon dioxide and its subsequent reduction to carbohydrate, using hydrogen from water. It takes place inside chloroplasts (Figure 13.2)

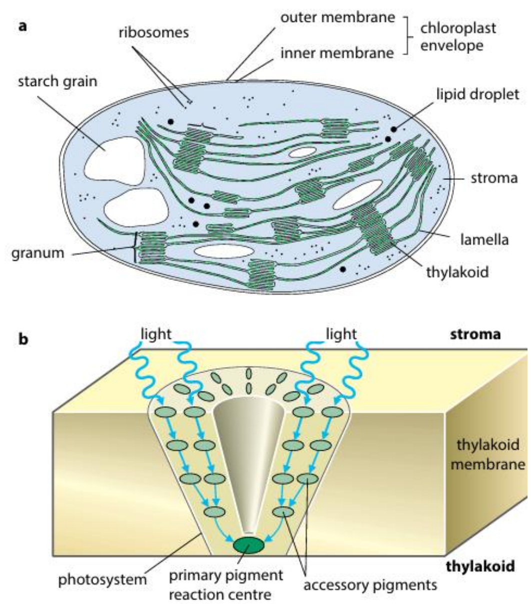


Figure 13.2 **a** A diagram of a chloroplast. **b** A photosystem: a light-harvesting cluster of photosynthetic pigments in a chloroplast thylakoid membrane. Only a few of the pigment molecules are shown.

An overall equation for photosynthesis in green plants is:

$$\underset{\text{carbon dioxide}}{nCO_2} + \underset{\text{water}}{nH_2O} \xrightarrow{\text{light energy in the presence of chlorophyll}} \underset{\text{carbohydrate}}{(CH_2O)n} + \underset{\text{oxygen}}{nO_2}$$

Hexose sugars and starch are commonly formed, so the following equation is often used:

$$\underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} \xrightarrow{\text{light energy in the presence of chlorophyll}} \underset{\text{carbohydrate}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2}$$

T h e photosynthetic pigments involved fall into two categories: primary pigments and accessory pigments. T h e pigments are arranged in light-harvesting clusters called photosystems of which there are two types, I and II. In a photosystem, several hundred accessory pigment molecules surround a primary pigment molecule, and the energy of the light absorbed by the different pigments is passed to the primary pigment (Figure 13.2b)

The light dependent reactions of photosynthesis

The light dependent reactions include the splitting of water by photolysis to give hydrogen ions (protons) and the synthesis of ATP in photophosphorylation.

Cyclic photophosphorylation

Cyclic photophosphorylation involves only photosystem I. Light is absorbed by photosystem I and is passed to the primary pigment. An electron in the chlorophyll molecule is excited to a higher energy level and is emitted from the chlorophyll molecule. Th is is called photoactivation.

Non-cyclic photophosphorylation

Non-cyclic photophosphorylation involves both photosystems in the so-called 'Z scheme' of electron fl ow (Figure 13.3). Light is absorbed by both photosystems and excited electrons are emitted from the primary pigments of both reaction centres.

Photolysis of water

Photosystem II includes a water-splitting enzyme that catalyses the breakdown of water:

$$H_2O \rightarrow 2H^+ + 2e^- + \tfrac{1}{2}O_2$$

Oxygen is a waste product of this process. Th e hydrogen ions combine with electrons from photosystem I and the carrier molecule NADP to give reduced NADP.

$$2H^+ + 2e^- + NADP \rightarrow \text{reduced NADP}$$

The Hill reaction

Redox reactions are oxidation–reduction reactions and involve the transfer of electrons from an electron donor (reducing agent) to an electron acceptor (oxidising agent). Sometimes hydrogen atoms are transferred, so that dehydrogenation is equivalent to oxidation.

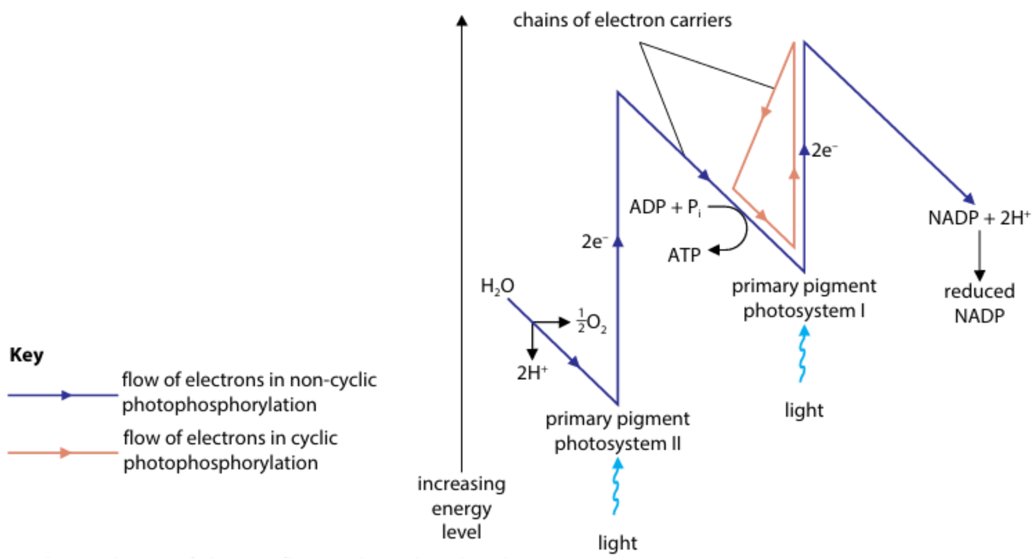


Figure 13.3 The 'Z scheme' of electron flow in photophosphorylation.

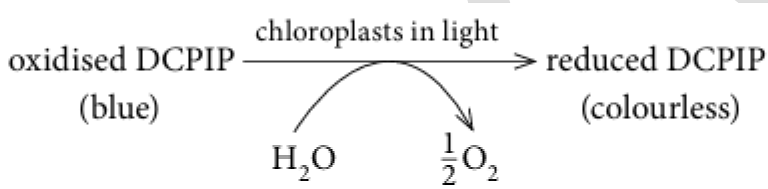


Figure 13.4 shows classroom results of this reaction.

The light independent reactions of photosynthesis

The fixation of carbon dioxide is a light independent process in which carbon dioxide combines with a five carbon sugar, ribulose bisphosphate (RuBP), to give two molecules of a three-carbon compound, glycerate 3-phosphate (GP). (This compound is also sometimes known as PGA.)

Chloroplast structure and function

In eukaryotic organisms, the photosynthetic organelle is the **chloroplast**. In dicotyledons, chloroplasts can be seen with a light microscope and appear as biconvex discs about 3–10 µm in diameter. There may be only a few chloroplasts in a cell or as many as 100 in some palisade mesophyll cells.

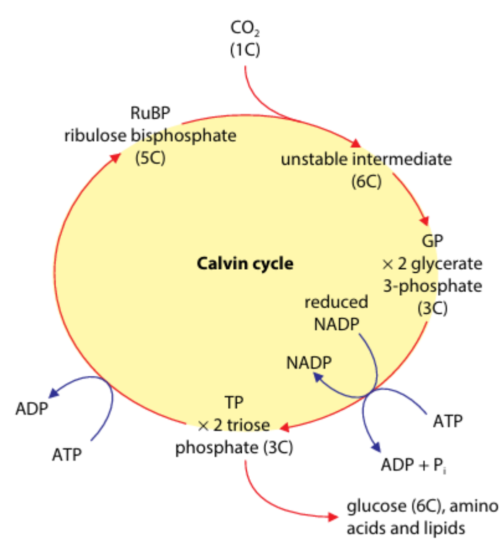


Figure 13.5 The Calvin cycle.

The membrane system is the site of the light dependent reactions of photosynthesis. It consists of a series of flattened fluid-filled sacs, or thylakoids, which in places form stacks, called **grana**, that are joined to one another by membranes.

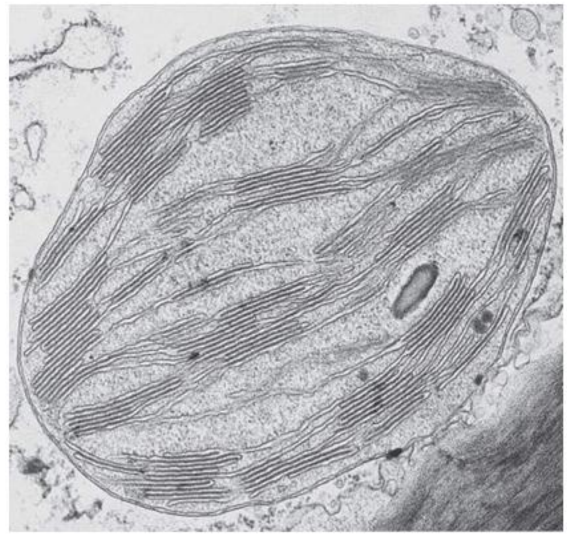


Figure 13.6 Transmission electron micrograph of a chloroplast from *Potamogeton* leaf (×27 000). See also Figure 1.29.

Factors necessary for photosynthesis

You can see from the equation on page 288 that certain factors are necessary for photosynthesis to occur, namely the presence of a suitable photosynthetic pigment, a supply of carbon dioxide, water and light energy.

Factors affecting the rate of photosynthesis '

The main external factors affecting the rate of photosynthesis are light intensity and wavelength, temperature and carbon dioxide concentration.

At low light intensity, increasing the temperature has little effect on the rate of photosynthesis.

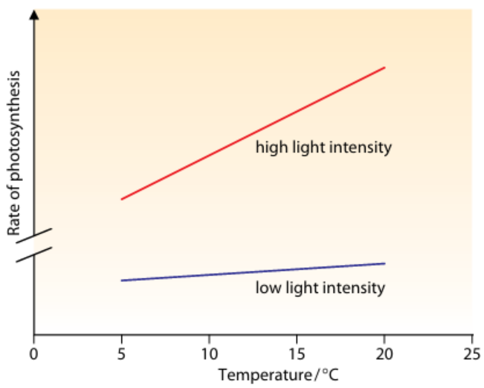


Figure 13.8 The rate of photosynthesis at different temperatures and constant light intensities.

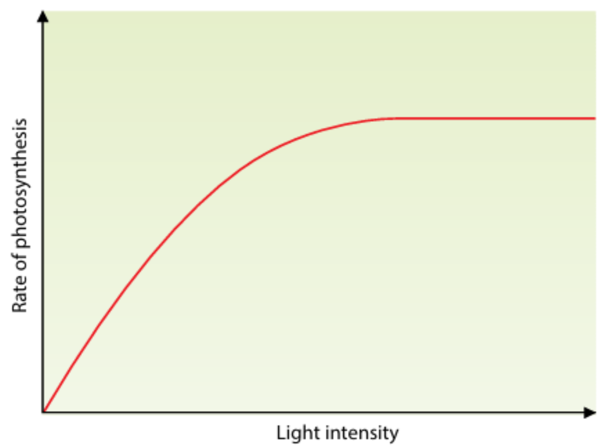


Figure 13.7 The rate of photosynthesis at different light intensities and constant temperature.

Limiting factors

The rate of any process which depends on a series of reactions is limited by the slowest reaction in the series. In biochemistry, if a process is affected by more than one factor, the rate will be limited by the factor which is nearest its lowest value.

The number of bubbles of gas (mostly oxygen) produced in unit time from a cut stem of the plant can be counted in different conditions. Alternatively, the gas can be collected and the volume produced in unit time can be measured. This procedure depends on the fact that the rate of production of oxygen is a measure of the rate of photosynthesis.

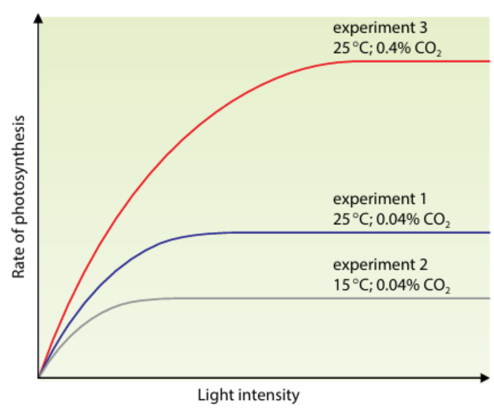


Figure 13.9 The rate of photosynthesis at different temperatures and different carbon dioxide concentrations. (0.04% CO_2 is about atmospheric concentration.)

Growing plants in protected environments

An understanding of the effect of environmental factors on the rate of photosynthesis allows their management when crops are grown in protected environments, such as glasshouses. The aim is to increase the yield of the crop concerned.

C4 plants

In the light independent stage of photosynthesis, you may remember that carbon dioxide combines with RuBP to form a six-carbon compound, which immediately splits to form two three-carbon molecules (page 290). Plants that do this are called C3 plants.

Avoiding photorespiration

Why do tropical grasses need to do something different from other plants in the light independent stage of photosynthesis? The reason is a problem with the enzyme rubisco. This enzyme catalyses the reaction of carbon dioxide with RuBP.

Carbon dioxide is absorbed by another group of cells, the mesophyll cells, which are in contact with air (Figure 13.13). The **mesophyll** cells contain an enzyme called PEP carboxylase, which catalyses the combination of carbon dioxide from the air with a three-carbon substance called **phosphoenolpyruvate**, or PEP. The compound formed from this reaction is oxaloacetate (Figure 13.14).

Figure 13.11 Photomicrograph of a section through a leaf of maize (×125).

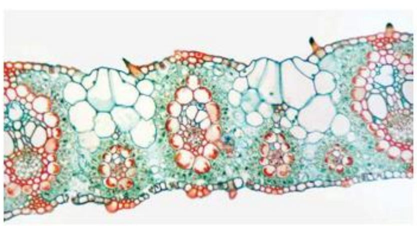


Figure 13.12 Photomicrograph of a section through a leaf of sugar cane (×120).

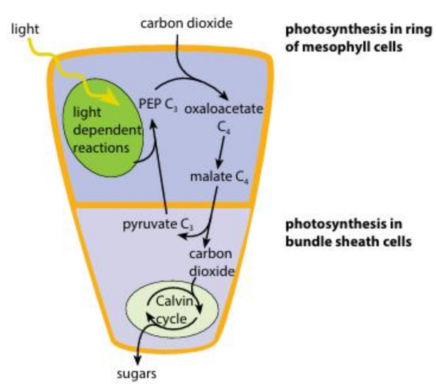


Figure 13.14 C4 photosynthesis.

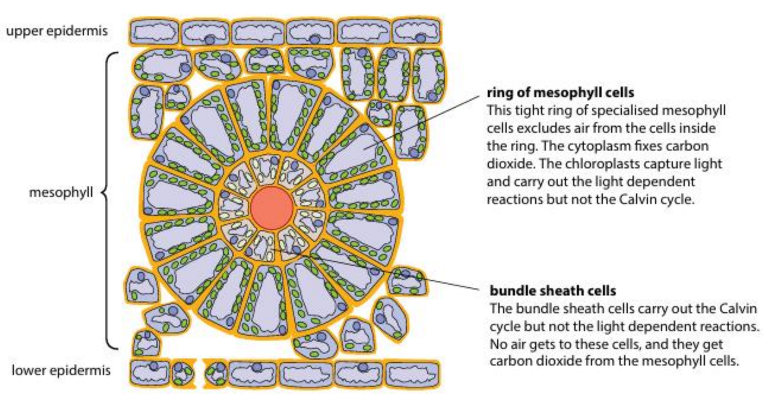


Figure 13.13 Tissues surrounding a vascular bundle of a C4 leaf.

Trapping light energy

Chloroplasts contain several different pigments, and these different pigments absorb different wavelengths of light. The photosynthetic pigments of higher plants form two groups: the chlorophylls (primary pigments) and the carotenoids (accessory pigments) (Table 13.1).

Group	Pigment	Colour
chlorophylls	chlorophyll *a* chlorophyll *b*	yellow-green blue-green
carotenoids	β carotene xanthophyll	orange yellow

Table 13.1 The colours of the commonly occurring photosynthetic pigments.

Chlorophylls absorb mainly in the red and blue violet regions of the light spectrum. They reflect green light, which is why plants look green. The structure of chlorophyll a is shown in Figure 13.15. The carotenoids absorb mainly in the blue-violet region of the spectrum

An absorption spectrum is a graph of the absorbance of different wavelengths of light by a pigment (Figure 13.16a).

If you illuminate a solution of chlorophyll a or b with ultraviolet light, you will see a red fluorescence. (In the absence of a safe ultraviolet light, you can illuminate the pigment with a standard fluorescent tube.)

You can calculate the R_f value for each pigment, using this equation:

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

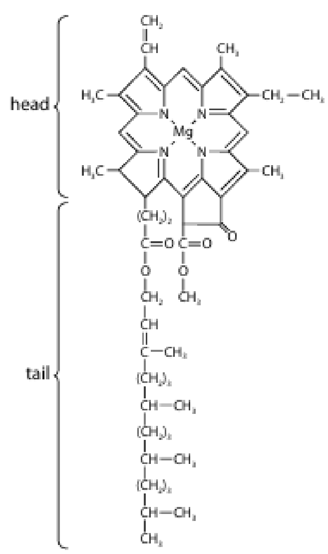


Figure 13.15 Structure of chlorophyll *a*. You do not need to learn this molecular structure.

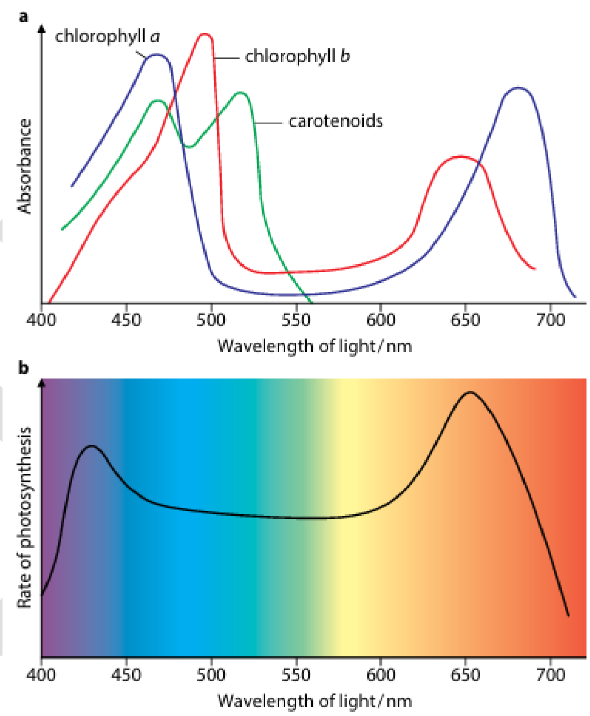


Figure 13.16 **a** Absorption spectra of chlorophylls *a* and *b*, and carotenoid pigments. **b** Photosynthetic action spectrum.

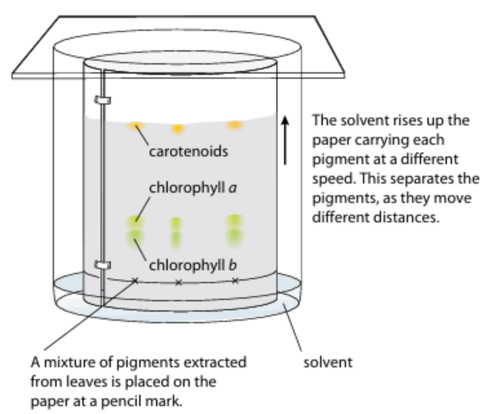
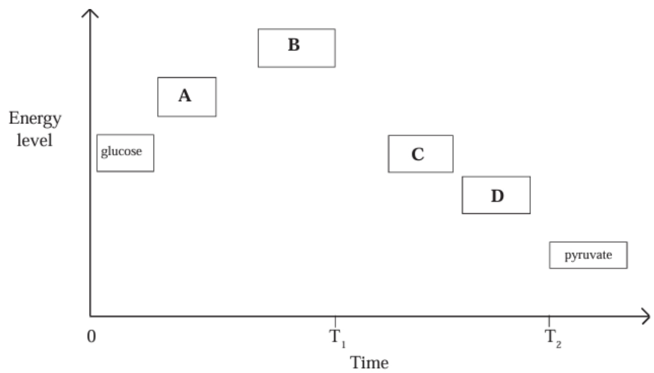


Figure 13.17 Chromatography of pigments in chloroplasts.

These will vary depending on the solvent used, but in general carotenoids have R_f values close to 1, chlorophyll *b* has a much lower R_f value and chlorophyll *a* has an R_f value between those of carotenoids and chlorophyll *b*.

Revision questions

1. The figure shows the energy changes which occur during one stage of cellular respiration. A, B, C and D are intermediate compounds.



(a)State where in the cell this stage would take place.

b)Suggest an explanation for the energy changes between,

(i) Time 0 to T1 :

(ii) Time T1 to T2 :

(c)In aerobic conditions what will be the immediate fate of the pyruvate?

(d)Outline the role of coenzymes in aerobic respiration.

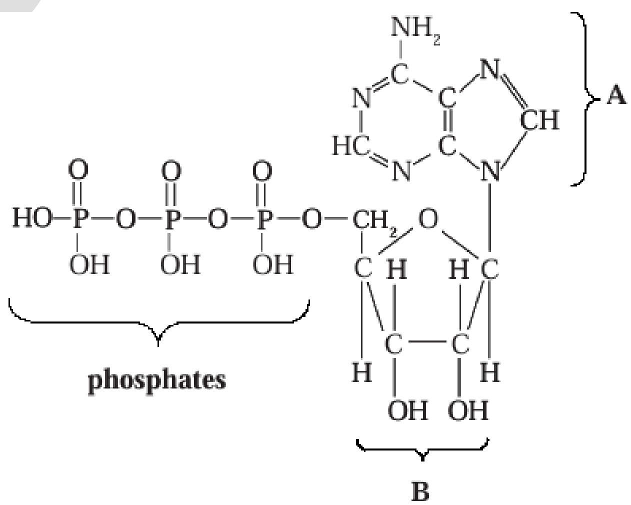
2. The diagram below shows the structure of ATP.

(a)Name each of the components:

(b)The table shows the relative energy levels of common phosphate-containing metabolites

(i) Suggest why ADP and ATP are effective energy carrier molecules.

(ii) Suggest why high levels of creatine phosphate are found in striated muscle tissues



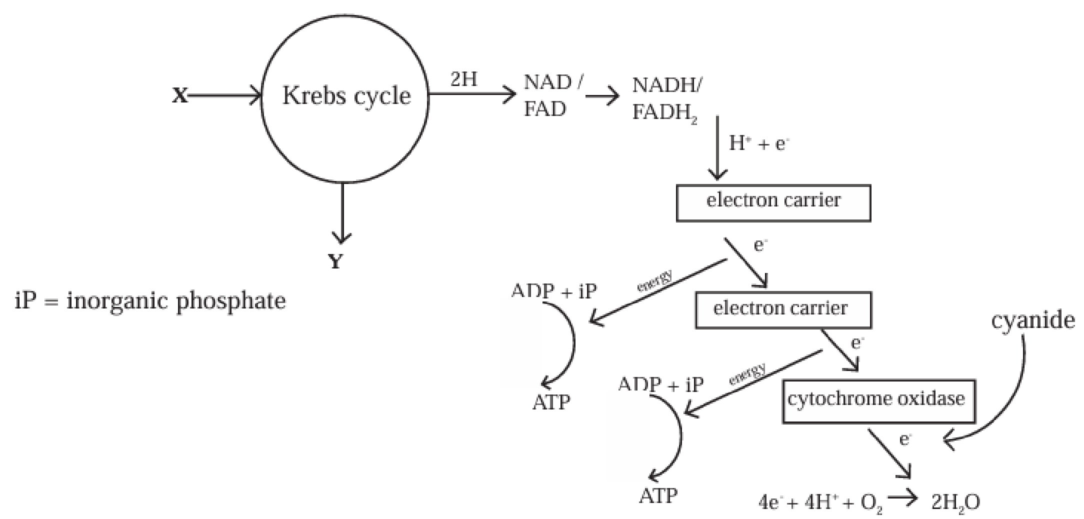
Metabolite	Relative Energy
Creatine phosphate	very high
Adenosine triphosphate Adenosine diphosphate Glucose-1-phosphate	Intermediate
Glucose-6-phosphate	Low

3. ATP is produced in both chloroplasts and mitochondria. The table below compares the process of ATP production in these organelles. Complete the table with a tick (ü) in the appropriate box if the statement is true for ATP production in each organelle and a cross (×) if the statement is incorrect.

Statement	Chloroplast	Mitochondrion
Electrons are excited by photons		
Electrons pass through carriers		
Involves oxidative photophosphorylation		
ATP produced from ADP and phosphate		
Occurs in day and night		

4.

Cyanide is a metabolic poison. Cyanide ions (CN^-) bind to cytochrome oxidase which is the final carrier in the electron transport chain. This is shown in the figure below.



(a)Name substances X and Y.

(b)State precisely where in the cell:

(i) The Krebs cycle occurs

(ii) electron carriers are situated

(c)Explain the term 'coupled redox reaction'

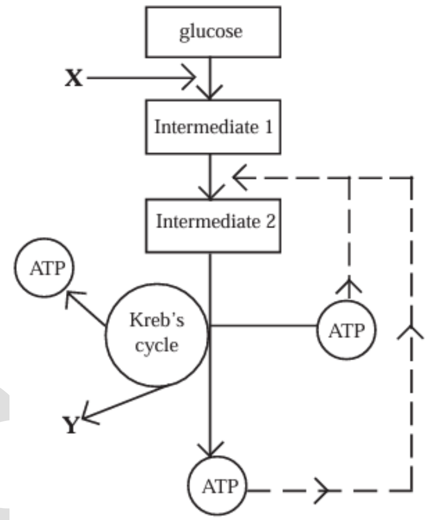
(d)Suggest why cyanide poisoning victims suffer from severe ATP shortage.

5. The diagram shows the sequence of events involved in glycolysis and Krebs cycle.

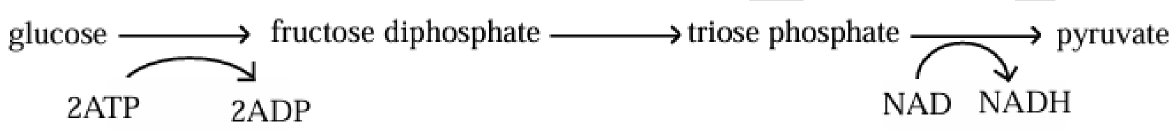
(a)Name the substances X and Y.

(b)State where in the cell the processes of glycolysis and Krebs cycle occur.

(c)Use the information in the diagram to explain the term 'feedback inhibition'



6. The equation shows some of the stages in the process of glycolysis



(a)Where in the cell does glycolysis occur?

(b)Explain why ATP molecules are used in the first stage of glycolysis

(c)What type of chemical reaction is involved in the conversion of triose phosphate to pyruvate?

d)How is NADH reoxidised in anerobic conditions in:

(i) animals?

(ii) yeast ?..........

(e)Outline the process of oxidative phosphorylation

7. The table below summarises the process of cellular respiration. Complete the table by filling in the gaps.

Stage	Site	Oxygen Needed?	What Happens?
Glycolysis			Glucose is converted to .... Hydrogen is removed and is passed to the electron carriers.
	Matrix of Mitochondria	Yes	Pyruvate enters mitochondrion, is decarboxylated, dehydrogenated and combines with coenzyme A to give acetyl coenzyme A. The hydrogen which is removed is passed to the electron carriers.
			A cyclical series of reactions during which hydrogen is passed to the electron carriers, carbon dioxide is removed and a starting reactant is regenerated.
Electron Transfer Chain		Yes	The hydrogen from the respiratory reactions is split to release electrons. These pass through carriers and generate .... The hydrogen reforms and is combined with oxygen to release water.