PEARSON EDEXCEL INTERNATIONAL A LEVEL

BIOLOGY

Student Book 2

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TOPIC 5
ENERGY FLOW, ECOSYSTEMS AND THE ENVIRONMENT

TOPIC 6
MICROBIOLOGY, IMMUNITY AND FORENSICS

TOPIC 7
RESPIRATION, MUSCLES AND THE INTERNAL ENVIRONMENT

TOPIC 8
COORDINATION, RESPONSE AND GENE TECHNOLOGY

ABOUT THIS BOOK

This book is written for students following the Pearson Edexcel International Advanced Level (IAL) Biology specification. This book covers the second year of the International A Level (IAL) course.

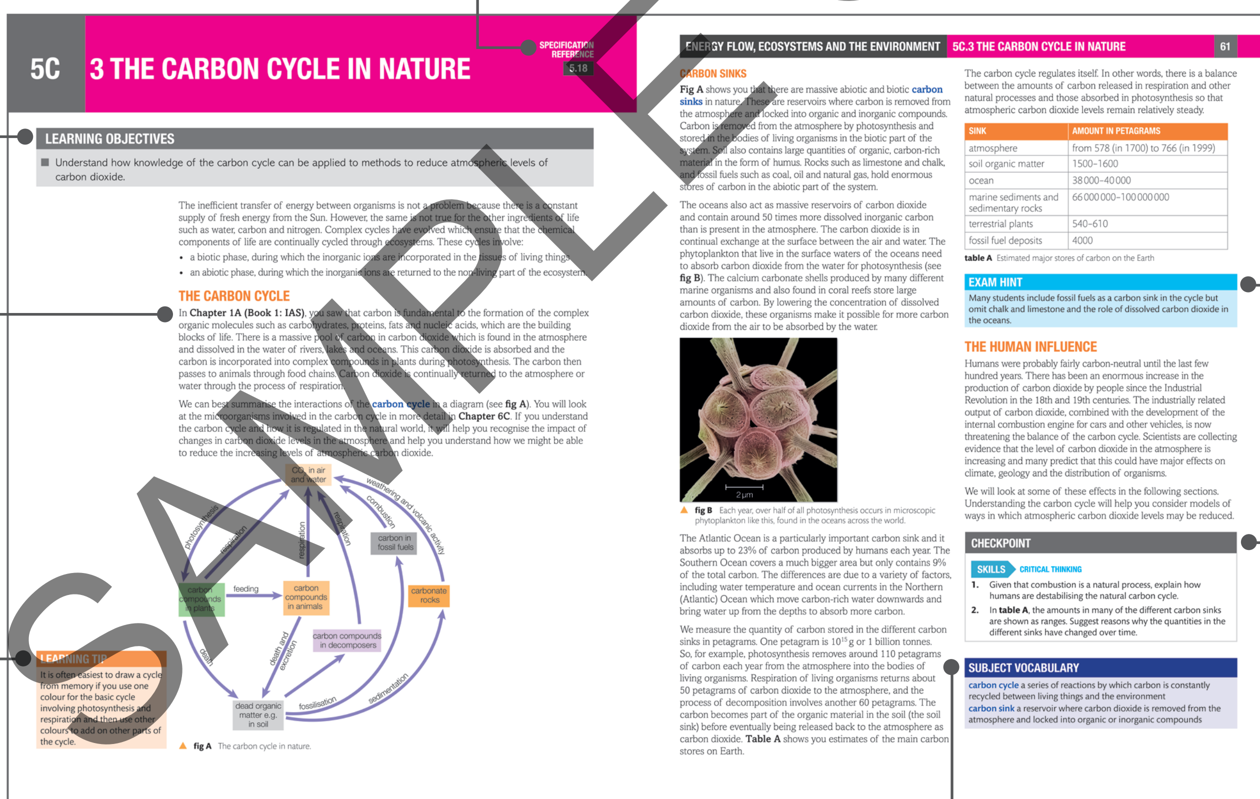
The book contains full coverage of IAL units (or exam papers) 4 and 5. Each unit in the specification has two topic areas. The topics in this book, and their contents, fully match the specification. You can refer to the Assessment Overview on pages x–xi for further information. Students can prepare for the written Practical Skills Paper (unit 6) with the support of the IAL Biology Lab Book (see pages viii and ix of this book).

Each Topic is divided into chapters and sections to break the content down into manageable chunks. Each section features a mix of learning and activities supported by the features explained below.

Learning objectives
Each chapter starts with a list of key assessment objectives. **Cross references** to previous or following Student Book content help you navigate course content.

Specification reference
The exact specification references covered in the section are provided.

Exam hints
Tips on how to answer exam-style questions and guidance for exam preparation, including how to respond to **command words**.



5C 3 THE CARBON CYCLE IN NATURE

SPECIFICATION REFERENCE 5.18

LEARNING OBJECTIVES

- Understand how knowledge of the carbon cycle can be applied to methods to reduce atmospheric levels of carbon dioxide.

The inefficient transfer of energy between organisms is not a problem because there is a constant supply of fresh energy from the Sun. However, the same is not true for the other ingredients of life such as water, carbon and nitrogen. Complex cycles have evolved which ensure that the chemical components of life are continually cycled through ecosystems. These cycles involve:

- a biotic phase, during which the inorganic ions are incorporated in the tissues of living things
- an abiotic phase, during which the inorganic ions are returned to the non-living part of the ecosystem.

THE CARBON CYCLE

In **Chapter 1A (Book 1: IAS)**, you saw that carbon is fundamental to the formation of the complex organic molecules such as carbohydrates, proteins, fats and nucleic acids, which are the building blocks of life. There is a massive pool of carbon in carbon dioxide which is found in the atmosphere and dissolved in the water of rivers, lakes and oceans. This carbon dioxide is absorbed and the carbon is incorporated into complex compounds in plants during photosynthesis. The carbon then passes to animals through food chains. Carbon dioxide is continually returned to the atmosphere or water through the process of respiration.

We can best summarise the interactions of the **carbon cycle** in a diagram (see **fig A**). You will look at the microorganisms involved in the carbon cycle in more detail in **Chapter 6C**. If you understand the carbon cycle and how it is regulated in the natural world, it will help you recognise the impact of changes in carbon dioxide levels in the atmosphere and help you understand how we might be able to reduce the increasing levels of atmospheric carbon dioxide.

fig A The carbon cycle in nature.

LEARNING TIP

It is often easiest to draw a cycle from memory if you use one colour for the basic cycle involving photosynthesis and respiration and then use other colours to add on other parts of the cycle.

ENERGY FLOW, ECOSYSTEMS AND THE ENVIRONMENT

CARBON SINKS

Fig A shows you that there are massive abiotic and biotic **carbon sinks** in nature. These are reservoirs where carbon is removed from the atmosphere and locked into organic and inorganic compounds. Carbon is removed from the atmosphere by photosynthesis and stored in the bodies of living organisms in the biotic part of the system. Soil also contains large quantities of organic, carbon-rich material in the form of humus. Rocks such as limestone and chalk, and fossil fuels such as coal, oil and natural gas, hold enormous stores of carbon in the abiotic part of the system.

The oceans also act as massive reservoirs of carbon dioxide and contain around 50 times more dissolved inorganic carbon than is present in the atmosphere. The carbon dioxide is in continual exchange at the surface between the air and water. The phytoplankton that live in the surface waters of the oceans need to absorb carbon dioxide from the water for photosynthesis (see **fig B**). The calcium carbonate shells produced by many different marine organisms and also found in coral reefs store large amounts of carbon. By lowering the concentration of dissolved carbon dioxide, these organisms make it possible for more carbon dioxide from the air to be absorbed by the water.

2 µm

fig B Each year, over half of all photosynthesis occurs in microscopic phytoplankton like this, found in the oceans across the world.

The Atlantic Ocean is a particularly important carbon sink and it absorbs up to 23% of carbon produced by humans each year. The Southern Ocean covers a much bigger area but only contains 9% of the total carbon. The differences are due to a variety of factors, including water temperature and ocean currents in the Northern (Atlantic) Ocean which move carbon-rich water downwards and bring water up from the depths to absorb more carbon.

We measure the quantity of carbon stored in the different carbon sinks in petagrams. One petagram is 10^{15} g or 1 billion tonnes. So, for example, photosynthesis removes around 110 petagrams of carbon each year from the atmosphere into the bodies of living organisms. Respiration of living organisms returns about 50 petagrams of carbon dioxide to the atmosphere, and the process of decomposition involves another 60 petagrams. The carbon becomes part of the organic material in the soil (the soil sink) before eventually being released back to the atmosphere as carbon dioxide. **Table A** shows you estimates of the main carbon stores on Earth.

5C.3 THE CARBON CYCLE IN NATURE 61

The carbon cycle regulates itself. In other words, there is a balance between the amounts of carbon released in respiration and other natural processes and those absorbed in photosynthesis so that atmospheric carbon dioxide levels remain relatively steady.

SINK	AMOUNT IN PETAGRAMS
atmosphere	from 578 (in 1700) to 766 (in 1999)
soil organic matter	1500–1600
ocean	38 000–40 000
marine sediments and sedimentary rocks	66 000 000–100 000 000
terrestrial plants	540–610
fossil fuel deposits	4000

table A Estimated major stores of carbon on the Earth

EXAM HINT

Many students include fossil fuels as a carbon sink in the cycle but omit chalk and limestone and the role of dissolved carbon dioxide in the oceans.

THE HUMAN INFLUENCE

Humans were probably fairly carbon-neutral until the last few hundred years. There has been an enormous increase in the production of carbon dioxide by people since the Industrial Revolution in the 18th and 19th centuries. The industrially related output of carbon dioxide, combined with the development of the internal combustion engine for cars and other vehicles, is now threatening the balance of the carbon cycle. Scientists are collecting evidence that the level of carbon dioxide in the atmosphere is increasing and many predict that this could have major effects on climate, geology and the distribution of organisms.

We will look at some of these effects in the following sections. Understanding the carbon cycle will help you consider models of ways in which atmospheric carbon dioxide levels may be reduced.

CHECKPOINT

SKILLS CRITICAL THINKING

1. Given that combustion is a natural process, explain how humans are destabilising the natural carbon cycle.
2. In **table A**, the amounts in many of the different carbon sinks are shown as ranges. Suggest reasons why the quantities in the different sinks have changed over time.

SUBJECT VOCABULARY

carbon cycle a series of reactions by which carbon is constantly recycled between living things and the environment
carbon sink a reservoir where carbon dioxide is removed from the atmosphere and locked into organic or inorganic compounds

Learning Tips
These help you to focus your learning and avoid common errors.

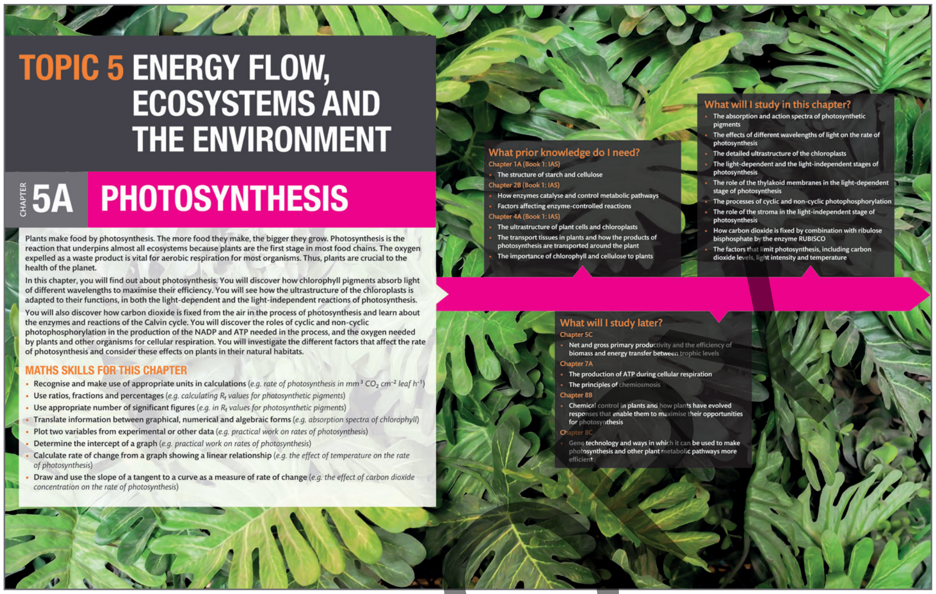
Worked examples show you how to work through questions and set out calculations.
Did you know? boxes present interesting facts to help you remember key concepts.

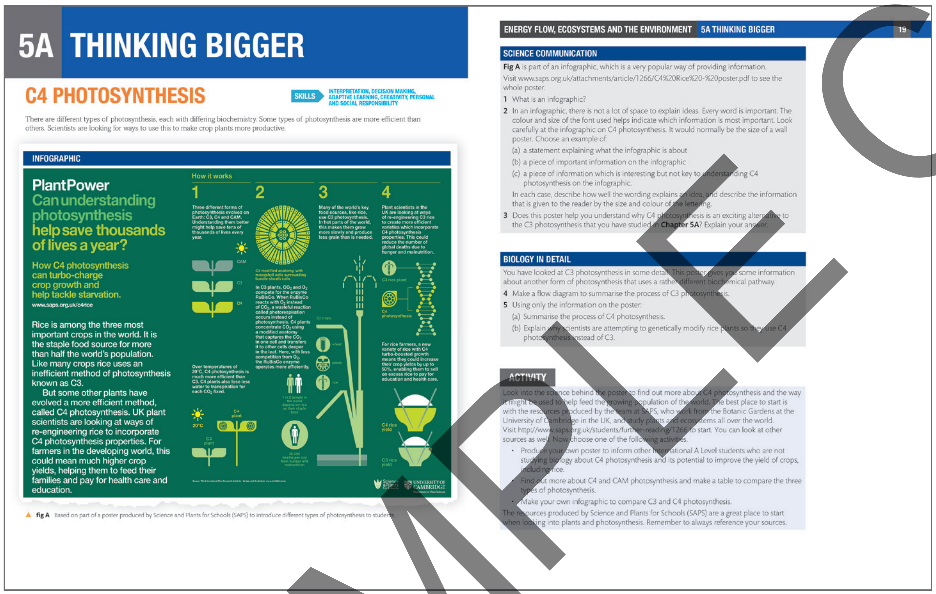
Subject vocabulary
Key terms are highlighted in blue in the text. Clear definitions are provided at the end of each section for easy reference, and are also collated in the **glossary** at the back of the book.

Checkpoint
Questions at the end of each section check understanding of the key learning points. Certain questions allow you to develop **skills** which will be valuable for further study and in the workplace.

You should be able to put every stage of your learning in context, chapter by chapter.

- Links to other areas of Biology include previous knowledge that is built on in the chapter, and areas of knowledge and application that you will cover later in your course.
- Maths knowledge required is detailed in a handy checklist. If you need to practise the maths you need, you can use the **Maths Skills** reference at the back of the book as a starting point.

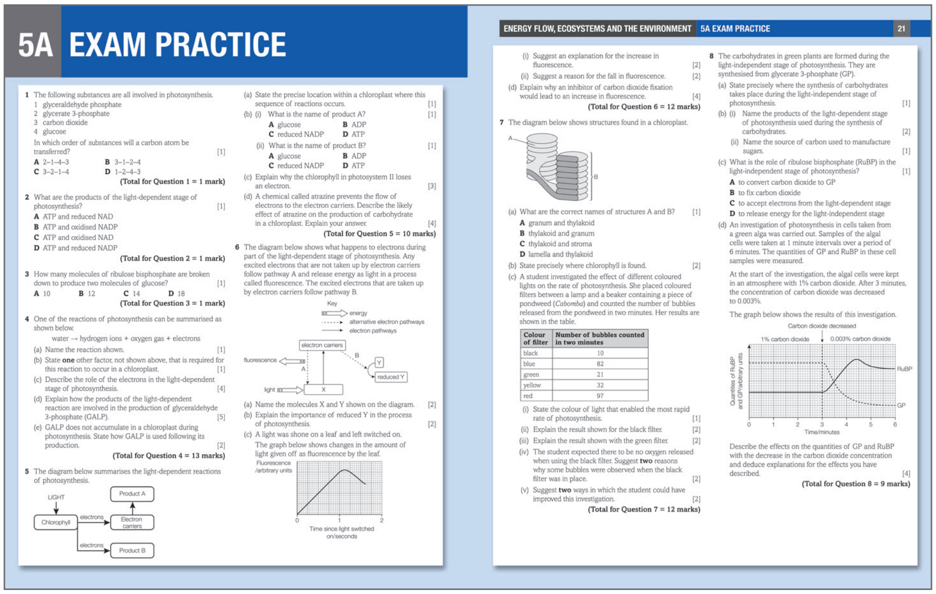




Thinking Bigger
At the end of most chapters there is an opportunity to read and work with real-life research and writing about science.

The activities help you to read authentic material that's relevant to your course, analyse how scientists write, think critically and consider how different aspects of your learning piece together.

These Thinking Bigger activities focus on **key transferable skills**, which are an important basis for key academic qualities.



Exam Practice
Exam-style questions at the end of each chapter are tailored to the Pearson Edexcel specification to allow for practice and development of exam-writing technique. They also allow for practice responding to the 'command words' used in the exams (see the **command words glossary** at the back of this book).

The **Preparing for your exams** section at the end of the book includes **sample answers** for different question types, with comments about the strengths and weaknesses of the answers.

PRACTICAL SKILLS

Practical work is central to the study of biology. The second year of the Pearson Edexcel International Advanced Level (IAL) Biology course includes nine Core Practicals that link theoretical knowledge and understanding to practical scenarios.

Your knowledge and understanding of practical skills and activities will be assessed in all exam papers for the IAL Biology qualification.

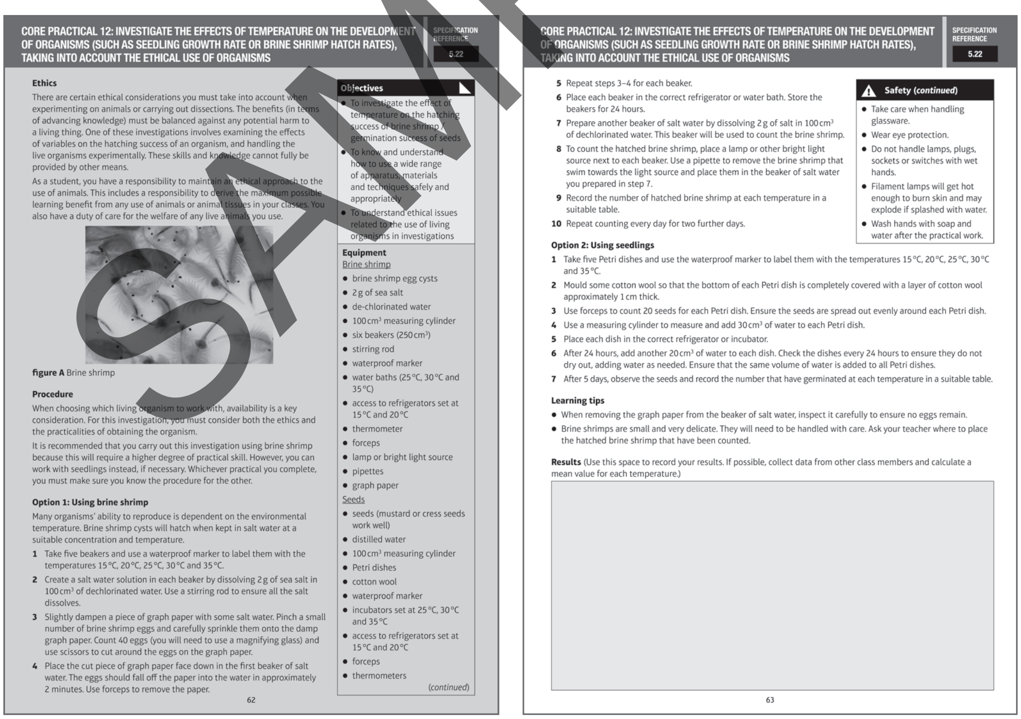
- Papers 4 and 5 will include questions based on practical activities, including novel scenarios.
- Paper 6 will test your ability to plan practical work, including risk management and selection of apparatus.

In order to develop practical skills, you should carry out a range of practical experiments related to the topics covered in your course.

STUDENT BOOK TOPIC	IA2 CORE PRACTICALS	
TOPIC 5 **ENERGY FLOW, ECOSYSTEMS AND THE ENVIRONMENT**	**CP10**	Investigate the effects of light intensity, light wavelength, temperature and availability of carbon dioxide on the rate of photosynthesis using a suitable aquatic plant.
	CP11	Carry out a study of the ecology of a habitat, such as using quadrats and transects to determine the distribution and abundance of organisms, and measuring abiotic factors appropriate to the habitat.
	CP12	Investigate the effects of temperature on the development of organisms (such as seedling growth rate or brine shrimp hatch rates), taking into account the ethical use of organisms.
TOPIC 6 **MICROBIOLOGY, IMMUNITY AND FORENSICS**	**CP13**	Investigate the rate of growth of microorganisms in a liquid culture, taking into account the safe and ethical use of organisms.
	CP14	Investigate the effect of different antibiotics on bacteria.
TOPIC 7 **RESPIRATION, MUSCLES AND THE INTERNAL ENVIRONMENT**	**CP15**	Use an artificial hydrogen carrier (redox indicator) to investigate respiration in yeast.
	CP16	Use a simple respirometer to determine the rate of respiration and RQ of a suitable material.
	CP17	Investigate the effects of exercise on tidal volume, breathing rate, respiratory minute ventilation, and oxygen consumption using data from spirometer traces.
TOPIC 8 **COORDINATION, RESPONSE AND GENE TECHNOLOGY**	**CP18**	Investigate the production of amylase in germinating cereal grains.

In the **Student Book**, the Core Practical specification is supplied in the relevant sections.

Practical Skills
Practical skills boxes explain techniques or apparatus used in the Core Practicals, and also detail useful skills and knowledge gained in other related investigations.



This Student Book is accompanied by a **Lab Book**, which includes instructions and writing frames for the Core Practicals for students to record their results and reflect on their work.

Practical skills checklists, practice questions and answers are also provided.

The Lab Book records can be used as preparation and revision for the Practical Skills Papers.

ASSESSMENT OVERVIEW

The following tables give an overview of the assessment for Pearson Edexcel International Advanced Level course in Biology. You should study this information closely to help ensure that you are fully prepared for this course and know exactly what to expect in each part of the examination. More information about this qualification, and about the question types in the different papers, can be found on page 314 of this book.

PAPER / UNIT 4	PERCENTAGE OF IA2	PERCENTAGE OF IAL	MARK	TIME	AVAILABILITY
ENERGY, ENVIRONMENT, MICROBIOLOGY AND IMMUNITY Written examination Paper code WBI14/01 Externally set and marked by Pearson Edexcel Single tier of entry	40%	20%	90	1 hour 45 minutes	January, June and October First assessment : January 2020
PAPER / UNIT 5	**PERCENTAGE OF IA2**	**PERCENTAGE OF IAL**	**MARK**	**TIME**	**AVAILABILITY**
RESPIRATION, INTERNAL ENVIRONMENT, COORDINATION AND GENE TECHNOLOGY Written examination Paper code WBI15/01 Externally set and marked by Pearson Edexcel Single tier of entry	40%	20%	90	1 hour 45 minutes	January, June and October First assessment : June 2020
PAPER / UNIT 6	**PERCENTAGE OF IA2**	**PERCENTAGE OF IAL**	**MARK**	**TIME**	**AVAILABILITY**
PRACTICAL SKILLS IN BIOLOGY II Written examination Paper code WBI16/01 Externally set and marked by Pearson Edexcel Single tier of entry	20%	10%	50	1 hour 20 minutes	January, June and October First assessment : June 2020

ASSESSMENT OBJECTIVES AND WEIGHTINGS

ASSESSMENT OBJECTIVE	DESCRIPTION	% IN IAS	% IN IA2	% IN IAL
A01	Demonstrate knowledge and understanding of science	36–39	31–34	34–37
A02	(a) Application of knowledge and understanding of science in familiar and unfamiliar contexts.	34–36	33–36	33–36
	(b) Analysis and evaluation of scientific information to make judgments and reach conclusions.	9–11	14–16	11–14
A03	Experimental skills in science, including analysis and evaluation of data and methods	17–18	17–18	17–18

RELATIONSHIP OF ASSESSMENT OBJECTIVES TO UNITS

UNIT NUMBER	ASSESSMENT OBJECTIVE (%)			
	A01	A02 (A)	A02 (B)	A03
UNIT 1	17–18	17–18	4.5–5.5	0
UNIT 2	17–18	17–18	4.5–5.5	0
UNIT 3	2–3	0	0	17–18
TOTAL FOR INTERNATIONAL ADVANCED SUBSIDIARY	**36–39**	**34–36**	**9–11**	**17–18**

UNIT NUMBER	ASSESSMENT OBJECTIVE (%)			
	A01	A02 (A)	A02 (B)	A03
UNIT 1	8.5–9.0	8.5–9.0	2.2–2.8	0
UNIT 2	8.5–9.0	8.5–9.0	2.2–2.8	0
UNIT 3	1–1.5	0	0	17–18
UNIT 4	7.3–7.8	8.4–8.9	3.6–4.0	0
UNIT 5	7.3–7.8	8.4–8.9	3.6–4.0	0
UNIT 6	1–1.5	0	0	8.8–9.2
TOTAL FOR INTERNATIONAL ADVANCED LEVEL	**34–37**	**33–36**	**11–14**	**17–18**

TOPIC 5 ENERGY FLOW, ECOSYSTEMS AND THE ENVIRONMENT

CHAPTER 5A PHOTOSYNTHESIS

Plants make food by photosynthesis. The more food they make, the bigger they grow. Photosynthesis is the reaction that underpins almost all ecosystems because plants are the first stage in most food chains. The oxygen expelled as a waste product is vital for aerobic respiration for most organisms. Thus, plants are crucial to the health of the planet.

In this chapter, you will find out about photosynthesis. You will discover how chlorophyll pigments absorb light of different wavelengths to maximise their efficiency. You will see how the ultrastructure of the chloroplasts is adapted to their functions, in both the light-dependent and the light-independent reactions of photosynthesis.

You will also discover how carbon dioxide is fixed from the air in the process of photosynthesis and learn about the enzymes and reactions of the Calvin cycle. You will discover the roles of cyclic and non-cyclic photophosphorylation in the production of the NADP and ATP needed in the process, and the oxygen needed by plants and other organisms for cellular respiration. You will investigate the different factors that affect the rate of photosynthesis and consider these effects on plants in their natural habitats.

MATHS SKILLS FOR THIS CHAPTER

- **Recognise and make use of appropriate units in calculations** (*e.g. rate of photosynthesis in* mm^3 CO_2 cm^{-2} *leaf* h^{-1})
- **Use ratios, fractions and percentages** (*e.g. calculating* R_f *values for photosynthetic pigments*)
- **Use appropriate number of significant figures** (*e.g. in* R_f *values for photosynthetic pigments*)
- **Translate information between graphical, numerical and algebraic forms** (*e.g. absorption spectra of chlorophyll*)
- **Plot two variables from experimental or other data** (*e.g. practical work on rates of photosynthesis*)
- **Determine the intercept of a graph** (*e.g. practical work on rates of photosynthesis*)
- **Calculate rate of change from a graph showing a linear relationship** (*e.g. the effect of temperature on the rate of photosynthesis*)
- **Draw and use the slope of a tangent to a curve as a measure of rate of change** (*e.g. the effect of carbon dioxide concentration on the rate of photosynthesis*)

What prior knowledge do I need?

Chapter 1A (Book 1: IAS)

- The structure of starch and cellulose

Chapter 2B (Book 1: IAS)

- How enzymes catalyse and control metabolic pathways
- Factors affecting enzyme-controlled reactions

Chapter 4A (Book 1: IAS)

- The ultrastructure of plant cells and chloroplasts
- The transport tissues in plants and how the products of photosynthesis are transported around the plant
- The importance of chlorophyll and cellulose to plants

What will I study in this chapter?

- The absorption and action spectra of photosynthetic pigments
- The effects of different wavelengths of light on the rate of photosynthesis
- The detailed ultrastructure of the chloroplasts
- The light-dependent and the light-independent stages of photosynthesis
- The role of the thylakoid membranes in the light-dependent stage of photosynthesis
- The processes of cyclic and non-cyclic photophosphorylation
- The role of the stroma in the light-independent stage of photosynthesis
- How carbon dioxide is fixed by combination with ribulose bisphosphate by the enzyme RUBISCO
- The factors that limit photosynthesis, including carbon dioxide levels, light intensity and temperature

What will I study later?

Chapter 5C

- Net and gross primary productivity and the efficiency of biomass and energy transfer between trophic levels

Chapter 7A

- The production of ATP during cellular respiration
- The principles of chemiosmosis

Chapter 8B

- Chemical control in plants and how plants have evolved responses that enable them to maximise their opportunities for photosynthesis

Chapter 8C

- Gene technology and ways in which it can be used to make photosynthesis and other plant metabolic pathways more efficient

SPECIFICATION REFERENCE 5.2

5A 1 THE IMPORTANCE OF ATP

LEARNING OBJECTIVES

- Understand how photophosphorylation of ATP requires energy and that hydrolysis of ATP provides an immediate supply of energy for biological processes.

Energy is essential to life. If the supply of energy to the cells of a living organism fails for any reason, the organism will die. Very large amounts of energy continually flow through the biosphere and organisms can be classified according to how they get their energy. **Autotrophic** organisms make organic compounds from carbon dioxide. Most of them do this by **photosynthesis**: they capture energy from the Sun and transfer it into chemical energy in the bonds of organic molecules such as glucose and starch. These compounds are used as an energy source by the organism, and as the building blocks of other important molecules such as proteins. Plants, algae and some bacteria are the main photosynthetic organisms (see **fig A**). There are a few autotrophic bacteria that are not photosynthetic. They use energy from chemical reactions to synthesise their food. **Heterotrophic** organisms generally eat plants or other animals which have eaten plants. They use the products of photosynthesis indirectly for making necessary molecules, and as fuels to supply energy for activities. The Sun is thus the ultimate source of energy for almost all organisms.

LEARNING TIP

Remember that light is the source of energy for photosynthesis. It is, therefore, the original source of energy for almost all living processes.

fig A The ability of plants to trap and use energy from the Sun in photosynthesis supports almost all life on Earth.

ATP: THE ENERGY SOURCE FOR THE CELL

Making chemical bonds needs an input of energy. Chemical bonds are constantly being broken in the cells of any living organism. Energy has to be constantly available in an accessible form, ready for use instantly in a multitude of different reactions. One molecule is believed to be the universal energy supplier in cells. It is found in all living organisms in exactly the same form. Anything that interferes with its production or breakdown is fatal to the cell and, ultimately, the organism. This remarkable compound is called **adenosine triphosphate (ATP)**. **Fig B** shows the structure of ATP.

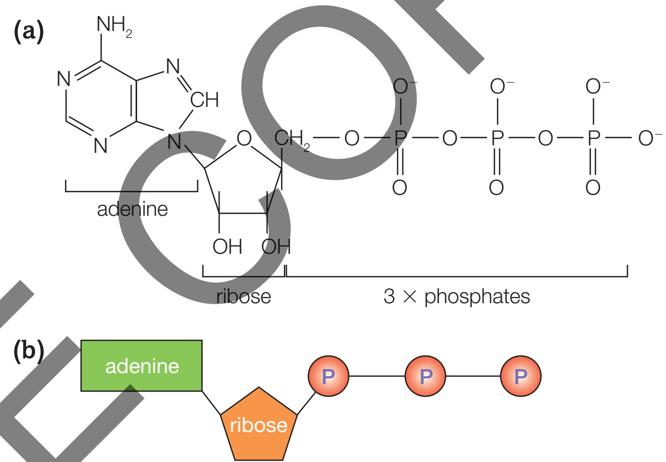


fig B ATP is a nucleotide with three phosphate groups attached. It is the energy stored in the phosphate bonds, particularly the end one, which is made available to cells to use to make or break bonds. (a) Structural formula of ATP (some hydrogen atoms have been omitted for simplicity). (b) Simplified diagram of an ATP molecule.

When energy is needed, the third phosphate bond can be broken by a hydrolysis reaction. This is catalysed by the enzyme **ATPase**. The result of this hydrolysis is **adenosine diphosphate (ADP)**, a free inorganic phosphate group (P_i) and energy (see **fig C**). About 34 kJ of energy is released per mole of ATP hydrolysed. Some of this energy is lost as heat and is wasted. The rest is used for any biological activity in the cell which requires energy. Examples include active transport (see **Section 2A.4 (Book 1: IAS)**), anabolic reactions in which large molecules are built up from smaller ones, and muscle contraction (see **Chapter 7B**).

EXAM HINT

Remember that synthesising ATP is a condensation reaction and breakdown of ATP is a hydrolysis reaction. There is a close link to similar reaction studies in **Chapter 1A (Book 1: IAS)**.

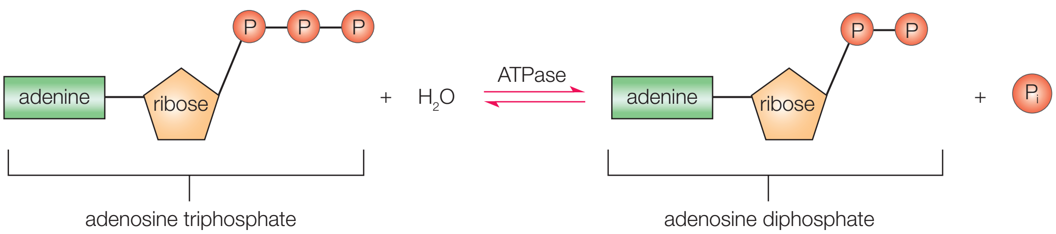


fig C When ATP is hydrolysed (broken down) to ADP + P_i (left ⟶ right on the diagram), energy is made available for cellular reactions. When ATP is synthesised (made) from ADP and P_i in the reverse reaction, the same amount of energy is absorbed. This energy comes from cellular respiration.

LEARNING TIP

Don't forget that all organisms, including plants, respire all the time.

The breakdown of ATP into ADP and phosphate is a reversible reaction. ATP can be synthesised (made) from ADP and a phosphate group. This synthesis reaction is also catalysed by the enzyme ATPase and it requires an input of energy (34 kJ per mole of ATP produced). The energy needed to drive the synthesis of ATP usually comes from catabolic (breakdown) reactions or **reduction/oxidation reactions (redox reactions)**. As a result, an ATP molecule provides an immediate supply of energy for your cells, ready for use when needed (see **fig D**).

EXAM HINT

You can use the acronym OILRIG to help you remember the meanings of oxidation and reduction: Oxidation Is Loss, Reduction Is Gain.

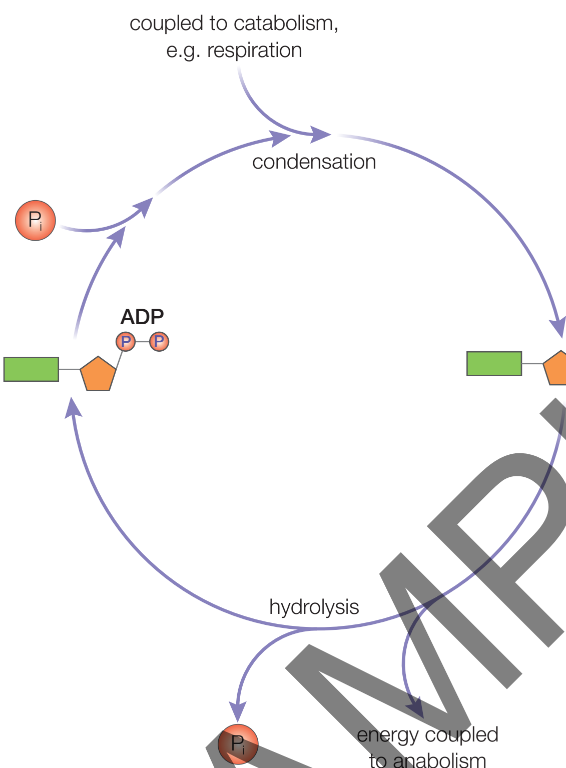


fig D The energy released in catabolic reactions is used to drive the production of ATP. ATP acts as a store of energy which is released when it is needed for cell functions, including anabolic reactions, when large molecules are built up from smaller ones. This results in the formation of ADP and inorganic phosphate which can be resynthesised into ATP.

MAKING ATP: THE ELECTRON TRANSPORT CHAIN

There are two main ways in which ATP is formed from ADP and inorganic phosphate in the cell. One is using energy released from the catabolic reactions which take place, for example, in cellular respiration. However, the main way in which ATP is synthesised is by the removal of hydrogen atoms from several of the intermediate compounds in a metabolic pathway.

When two hydrogen atoms are removed from a compound, they are collected by a hydrogen carrier or acceptor. The acceptor is reduced. Electrons from the hydrogen atoms are then transferred along a series of carriers known as an **electron transport chain**. The components of the chain are reduced when they receive the electrons, and oxidised again when they transfer the electrons to the next part of the chain. These redox reactions each release a small amount of energy which is used to drive the synthesis of a molecule of ATP. In this way, the energy is readily available for use when it is needed in the cell. You will learn more about the production of ATP later (see **Chapter 7A**).

CHECKPOINT

SKILLS CREATIVITY

SKILLS CRITICAL THINKING

1. (a) The breakdown reaction of ATP to ADP + P_i is described as reversible. Explain what this means.
   (b) Both the formation and the breakdown of ATP are controlled by the same enzyme. State the name of this enzyme.
2. ATP is the universal energy supply molecule in living things. Explain how ATP is suited for this role in the cells.
3. Some people describe photosynthesis as the most important reaction in living organisms. Give one reason why it might be, and one reason why not.

SUBJECT VOCABULARY

autotrophic organisms that make complex organic compounds from simple compounds in the environment
photosynthesis the process by which living organisms, particularly plants and algae, capture the energy of the Sun using chlorophyll and use it to convert carbon dioxide and water into simple sugars
heterotrophic organisms that obtain complex organic molecules by feeding on other living organisms or their dead remains
adenosine triphosphate (ATP) a nucleotide that acts as the universal energy supply in cells. It is made up of the base adenine, the pentose sugar ribose and three phosphate groups
ATPase the enzyme which catalyses the formation and breakdown of ATP, depending on the conditions
adenosine diphosphate (ADP) a nucleotide formed when a phosphate group is removed from ATP, releasing energy to drive reactions in the cell
reduction/oxidation reactions (redox reactions) reactions in which one reactant loses electrons (is oxidised) and another gains electrons (is reduced)
electron transport chain a series of electron-carrying compounds along which electrons are transferred in a series of oxidation/reduction reactions, driving the production of ATP

5A 2 CHLOROPLASTS AND CHLOROPHYLL

SPECIFICATION REFERENCE

5.1 5.5 5.6 5.7

LEARNING OBJECTIVES

- Understand the overall reaction of photosynthesis as requiring energy from light to split apart the strong bonds in water molecules, storing the hydrogen in a fuel (glucose) by combining it with carbon dioxide and releasing oxygen into the atmosphere.
- Understand the structure of chloroplasts in relation to their role in photosynthesis.
- Understand what is meant by the terms *absorption spectrum* and *action spectrum*.
- Understand that chloroplast pigments can be separated using chromatography and the pigments identified using R_f values.

Photosynthesis is the process used by living organisms, particularly plants, to capture the energy of the Sun using chlorophyll and use it to convert carbon dioxide and water into simple sugars. This equation summarises photosynthesis:

$$\text{carbon dioxide} + \text{water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{glucose} + \text{oxygen} \qquad \Delta H \approx +2880\,\text{kJ}$$

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{light energy}} C_6H_{12}O_6 + 6O_2 \qquad \Delta H \approx +2880\,\text{kJ}$$

The energy from light is used to break the strong H–O bonds in the water molecules. The hydrogen which is released is combined with carbon dioxide to form a fuel for the cells (glucose). Oxygen is released into the atmosphere as a waste product of this process.

Simple models of photosynthesis such as the equation above show a one-step process. They include the most important points of the process and make it relatively easy to understand. But the whole process is extremely complex. You will learn some of the details of the process in this section.

The structure of plants has evolved around the process of photosynthesis. The different parts of the plant are adapted for efficiently obtaining the raw materials carbon dioxide and water, and for trapping as much sunlight as possible.

LEARNING TIP

The processes of photosynthesis and cellular respiration are closely linked.

Photosynthesis takes in energy and uses carbon dioxide and water to synthesise glucose and oxygen. It is endothermic.

Aerobic respiration uses glucose and oxygen to produce energy in the form of ATP for the cell, with carbon dioxide and water as the waste products. It is exothermic. You will learn more about aerobic respiration in **Chapter 7A**.

THE IMPORTANCE OF CHLOROPLASTS

Chloroplasts are relatively large organelles found in the cells of the green parts of plants (see **fig A**). An average green plant cell contains 10–50 chloroplasts which are uniquely adapted for the process of photosynthesis (see **Section 4A.2 (Book 1: IAS)**). Each chloroplast is surrounded by an outer and an inner membrane with a space between the two, known as the **chloroplast envelope**. Inside the chloroplast is a system of membranes that are arranged in layers called **grana**. A single granum is made up of layers of membrane discs known as **thylakoids**. This is where the green pigment chlorophyll is found. The pigment molecules are arranged on the membranes in the best possible position for capturing light energy. Electron micrographs show that the granal membranes are covered in particles. Scientists think these particles are involved in ATP synthesis. The grana are joined together by **lamellae**, which are extensions of the thylakoid membranes. These lamellae connect two or more grana. The lamellae act as a skeleton inside the chloroplast, maintaining a distance between the grana so that they receive the maximum light and function as efficiently as possible.

The membrane layers are surrounded by a matrix called the **stroma**. The stroma contains all the enzymes needed to complete the process of photosynthesis and produce glucose. Glucose can then be used in cellular respiration, converted to starch for storage or used as an intermediate for the synthesis of other organic compounds such as amino acids and lipids.

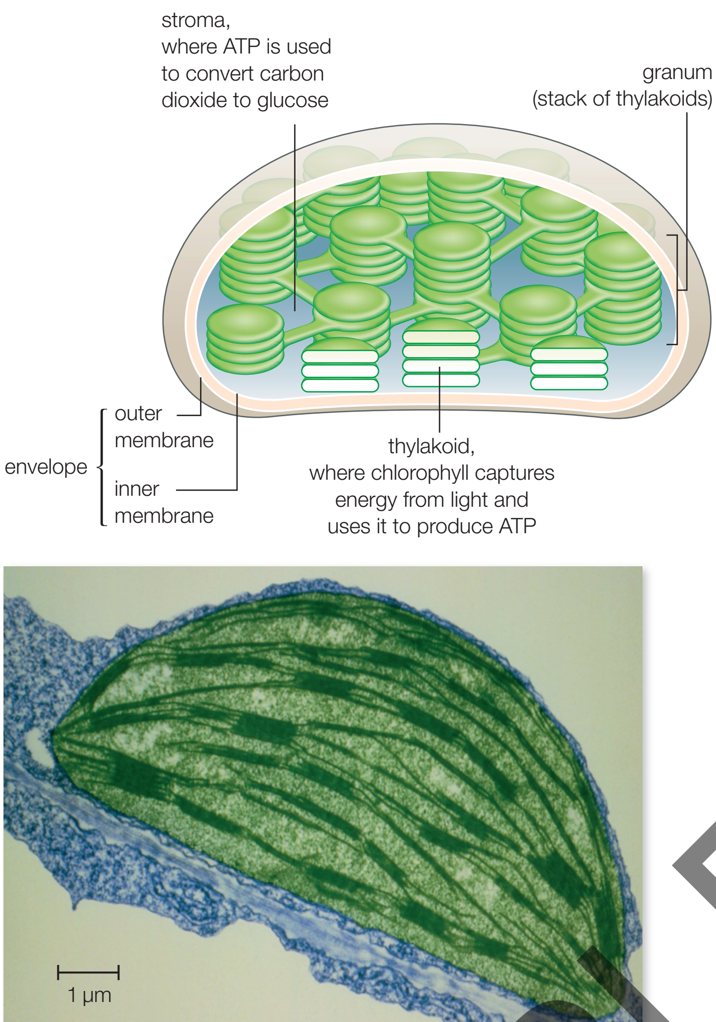


fig A Evidence from electron micrographs has helped scientists to produce a realistic and complex model demonstrating how the structure of a chloroplast is adapted to its functions in photosynthesis.

EXAM HINT

Make sure you spell *stroma* correctly. Do not confuse it with *stoma*.

LEARNING TIP

A good way to recall and record the details of chloroplast structure is to draw a diagram and annotate it fully. You need to write brief but detailed notes around the diagram, not just labels.

CHLOROPHYLL

Chlorophyll is the other major adaptation of the chloroplasts. It is a light-capturing, photosynthetic pigment. Chlorophyll is not a single molecule. It is a mixture of closely related pigments. These include **chlorophyll *a*** (blue-green), **chlorophyll *b*** (yellow-green), the chlorophyll **carotenoids** (orange carotene and yellow xanthophyll) and also a grey pigment **phaeophytin**, which is a breakdown product of the others. Chlorophyll *a* is found in all photosynthesising plants and in the highest quantity of the five pigments. The other pigments are found in varying proportions in different plants. These differences give the leaves of plants their great variety of different greens. Each of the pigments absorbs and captures light from particular areas of the light spectrum. As a result, much more of the energy from the light falling on the plant can be used than if only one pigment was involved.

The different photosynthetic pigments can be demonstrated in a number of ways.

ABSORPTION SPECTRA AND ACTION SPECTRA

The **absorption spectrum** describes the different amounts of light of different wavelengths that a photosynthetic pigment absorbs. It is usually represented as a graph. We can find the absorption spectra of the different photosynthetic pigments by measuring their absorption of light of differing wavelengths (see **fig B**). It is also possible to produce an absorption spectrum for whole chloroplasts, with all the photosynthetic pigments combined.

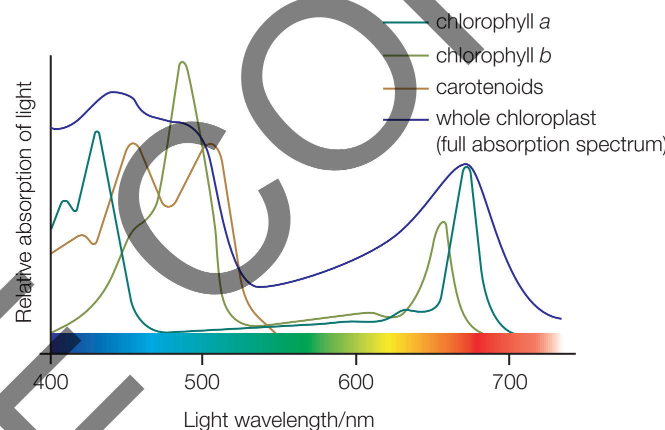


fig B The different photosynthetic pigments absorb light of different wavelengths. This enables the plant to use more of the available light.

You can compare the rate of photosynthesis with the wavelength of light. The first person to do this was T.W. Engelmann in the late 1800s. He placed a strand of a filamentous alga in light of different wavelengths. He used bacteria that move towards oxygen to show where most oxygen was released, because this is directly related to the amount of photosynthesis occurring. In this way, he achieved an **action spectrum**, which is a way of demonstrating the rate of photosynthesis according to the wavelength of light (see **fig C**).

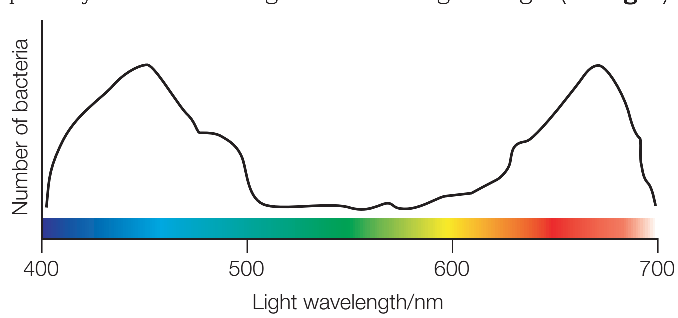


fig C Engelmann's first action spectrum was developed using numbers of bacteria to show where photosynthesis was occurring.

Modern action spectra use electronic data logging instead of bacterial movements to measure the rate of photosynthesis at different wavelengths of light. However, the action spectra they produce still compare the rate of photosynthesis to the wavelength of light. Action spectra show us that the rate of photosynthesis is very closely related to the combined absorption spectrum of all the photosynthetic pigments in a plant, as you can see in **fig D**. This demonstrates that having different photosynthetic pigments makes a much bigger portion of light available to plants and therefore gives them an adaptive advantage.

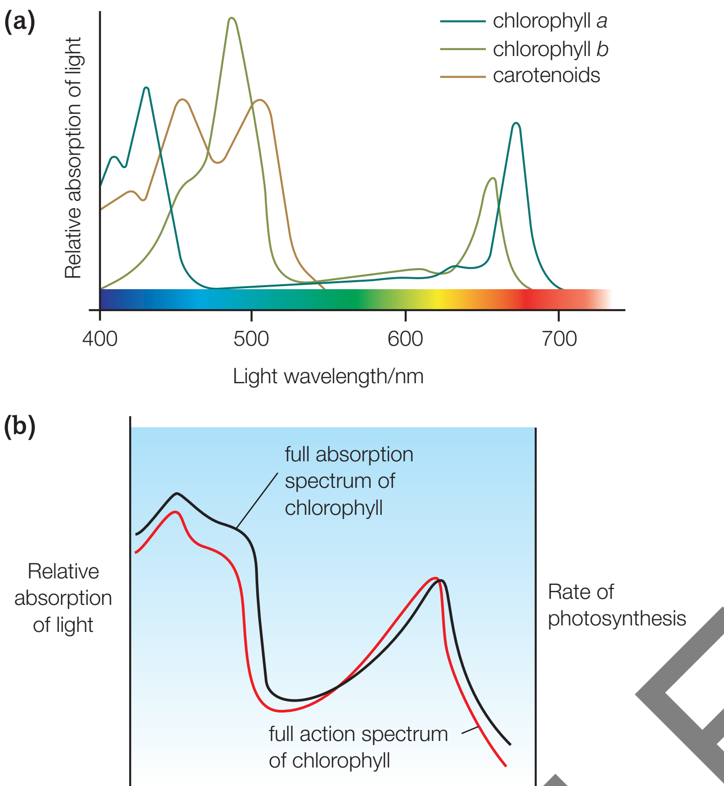


fig D Here you can see (a) the absorption spectrum of the individual photosynthetic pigments compared with (b) the absorption spectrum and action spectrum of chlorophyll in a chloroplast. This shows the advantage of having more than one pigment available to absorb the light.

EXAM HINT

Remember that different proportions of the photosynthetic pigments will produce a different colour of leaf; this can be a major adaptation to habitat. For example, many aquatic plants are red or brown. These colours absorb the blue light that penetrates water easily.

CHROMATOGRAPHY

Plants look green. If you extract the pigments from a plant by grinding up leaves with propanone and then filtering, the filtrate looks green. So how can you show that there are several different pigments? The answer is by chromatography using paper or silica gel. The pigments travel up the solid medium at different speeds and are readily separated using a suitable solvent (see **fig E**).

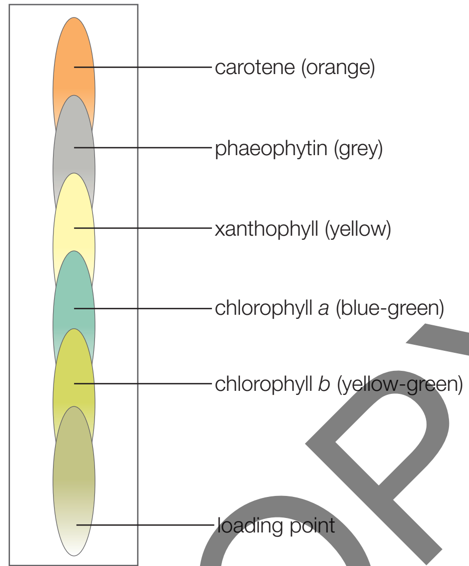


fig E Chromatogram of chlorophyll extracted from a plant showing five photosynthetic pigments.

Once you have conducted chromatography on the photosynthetic pigments you can determine their **R_f values** and compare them to the R_f values of known pigments in the same solvent. It is important to compare R_f values using the same solvent because the pigments can have very different values with different solvents. The R_f value is the ratio of the distance travelled by the pigment to the distance travelled by the solvent alone (see **fig F**). The R_f value is always between 0 and 1 and this is how you can calculate it:

$$R_f \text{ value} = \frac{\text{distance travelled by solute (photosynthetic pigment)}}{\text{distance travelled by solvent}}$$

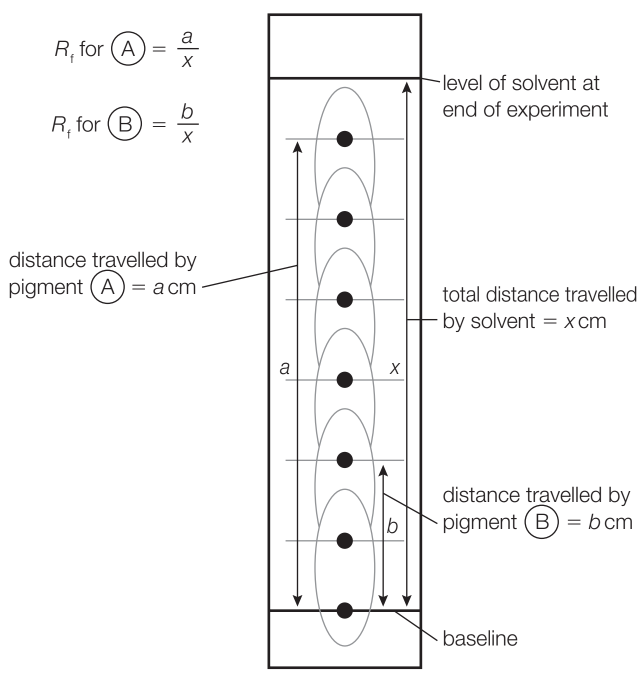


fig F This example shows a method for calculating the R_f values for two photosynthetic pigments on a silica gel chromatogram.

PHOTOSYNTHETIC PIGMENT	R_f VALUE FOR SPINACH LEAVES EXTRACTED WITH HEXANE AND CHROMATOGRAPHED WITH 3:1:1 PETROLEUM ETHER-PROPANONE-CHLOROFORM SOLVENT ON SILICA GEL
carotene	0.98
chlorophyll *a*	0.59
chlorophyll *b*	0.42
phaeophytin	0.81
xanthophyll 1	0.28
xanthophyll 2	0.15

table A Photosynthetic pigments and their R_f values

PHOTOSYSTEMS

The photosynthetic pigments absorb light in two distinct chlorophyll complexes known as **photosystem I (PSI)** and **photosystem II (PSII)**. Each system contains a different combination of chlorophyll pigments and therefore absorbs light in a slightly different area of the spectrum (wavelength 700 nm for PSI and 680 nm for PSII). Electron micrographs have revealed that the different photosystems are differently sized particles attached to the membranes in the chloroplasts. PSI particles are mainly on the intergranal lamellae, whereas PSII particles are on the grana themselves. They have different functions in photosynthesis, as you will see later.

CHECKPOINT

SKILLS CRITICAL THINKING

SKILLS ANALYSIS

1. (a) Chloroplasts are not present in all plant cells. Explain why not.
   (b) Summarise the adaptations of chloroplasts for their role in photosynthesis, including the role of membranes.
2. Explain, using the data in **fig B**, why plant leaves usually appear green.
3. Measure the distances travelled by the solute and solvent and calculate the R_f values for the pigments labelled A and B in **fig F**. Identify these two pigments, assuming they were extracted with hexane and chromatographed with 3:1:1 petroleum ether–propanone–chloroform solvent on silica gel.

SUBJECT VOCABULARY

chloroplast envelope the outer and inner membranes of a chloroplast including the intermembrane space
grana layers of thylakoid membranes within a chloroplast
thylakoids membrane discs found in the grana of a chloroplast
lamellae extensions of the thylakoid membranes which connect two or more grana and act as a supporting skeleton in the chloroplast; they maintain a working distance between the grana so that these receive the maximum light and function as efficiently as possible
stroma the matrix which surrounds the grana and contains all the enzymes needed to complete the process of photosynthesis and produce glucose
chlorophyll *a* a blue-green photosynthetic pigment, found in all green plants
chlorophyll *b* a yellow-green photosynthetic pigment
carotenoids photosynthetic pigments consisting of orange carotene and yellow xanthophyll
phaeophytin a grey pigment which is produced by the breakdown of the other photosynthetic pigments
absorption spectrum a graph showing the amount of light absorbed by a pigment against the wavelength of the light
action spectrum a graph demonstrating the rate of photosynthesis against the wavelength of light
R_f value the ratio of the distance travelled by the pigment to the distance travelled by the solvent alone when pigments are separated by chromatography
photosystem I (PSI) a combination of chlorophyll pigments which absorbs light of wavelength 700 nm and is involved in cyclic and non-cyclic photophosphorylation
photosystem II (PSII) a combination of chlorophyll pigments which absorbs light of wavelength 680 nm and is involved only in non-cyclic photophosphorylation

3 THE BIOCHEMISTRY OF PHOTOSYNTHESIS

SPECIFICATION REFERENCE 5.3 5.4(i) 5.4(ii) CP10

LEARNING OBJECTIVES

- Understand the light-dependent reactions of photosynthesis, including how light energy is trapped by exciting electrons in chlorophyll and the role of these electrons in generating ATP, reducing NADP in cyclic and non-cyclic photophosphorylation and producing oxygen through photolysis of water.
- Understand the light-independent reactions as reduction of carbon dioxide using the products of the light-dependent reactions (carbon fixation in the Calvin cycle, the role of GP, GALP, RuBP and RUBISCO).
- Know that the products of photosynthesis are simple sugars that are used by plants, animals and other organisms in respiration and the synthesis of new biological molecules (polysaccharides, amino acids, proteins, lipids and nucleic acids).

Photosynthesis is a two-stage process involving a complex series of reactions (see **fig A**). The reactions in the first stage only occur in light. The reactions of the second stage occur independently of light. The **light-dependent reactions** produce materials to be used in the **light-independent reactions**. The whole process occurs all the time during the hours of daylight. The light-independent reactions can continue when it is dark.

EXAM HINT

Do not refer to these as the light stage and the dark stage. The light-dependent reactions occur only when light is available. The light-independent reactions occur in both light and dark conditions.

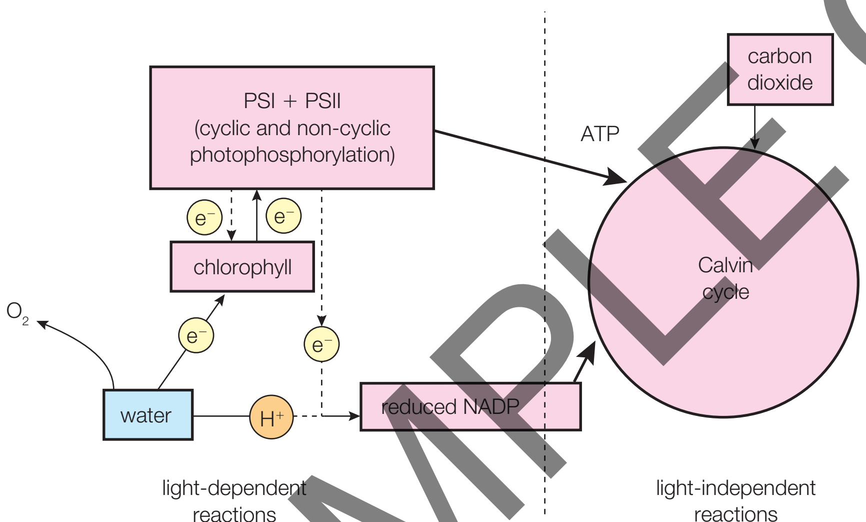


fig A A simplified summary of photosynthesis.

THE LIGHT-DEPENDENT STAGE OF PHOTOSYNTHESIS

The light-dependent stage of photosynthesis occurs on the thylakoid membranes of the chloroplasts. It has two main functions:

- to break up water molecules in a **photochemical reaction**, providing hydrogen ions to reduce carbon dioxide and produce carbohydrates in the light-independent stage
- to produce ATP, which supplies the energy to build carbohydrates (see **Section 5A.1**).

Light is a form of electromagnetic radiation and the smallest unit of light is a photon. When a photon of light hits a chlorophyll molecule, the energy is transferred to the electrons of the chlorophyll molecule. The electrons are excited and are raised to higher energy levels. If an electron is raised to a sufficiently high energy level, it leaves the chlorophyll molecule completely. The excited electron is collected by a carrier molecule called an electron acceptor and this results in the synthesis of ATP by one of two processes: **cyclic photophosphorylation** and **non-cyclic photophosphorylation**. Both these processes occur at the same time and, in both cases, ATP is formed as the excited electron is transferred along an electron transport chain. In non-cyclic photophosphorylation, reduced NADP is also produced.

LEARNING TIP

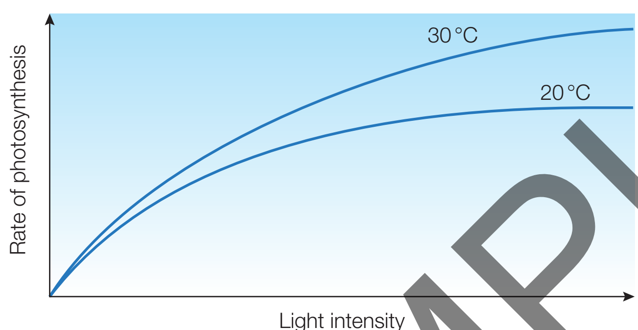
Here, phosphorylation means adding a phosphate group to ADP. There are a number of different ways that phosphorylation can be achieved. Photophosphorylation occurs during photosynthesis; it can be cyclic or non-cyclic. Oxidative phosphorylation occurs in respiration; it involves electron transport chains and oxygen as the final electron acceptor. Oxidative phosphorylation can also occur by direct substrate-level reactions which occur mostly in anaerobic respiration.

DID YOU KNOW?

A two-stage process

How do we know that photosynthesis is a two-stage process? There are several pieces of evidence for this current model.

1 Photochemical reactions obtain the energy they need from light, so temperature should not affect the rate of the reaction. However, when the rate of photosynthesis is investigated experimentally, temperature can be shown to have a clear effect (see **fig B**). Initially, photochemical (light-dependent) reactions limit the rate of the overall process and so temperature has no effect. However, once there is plenty of available light, the process seems to be limited by temperature-sensitive reactions. This shows there are two distinct phases to photosynthesis, one dependent on light and the other controlled by temperature-sensitive enzymes.

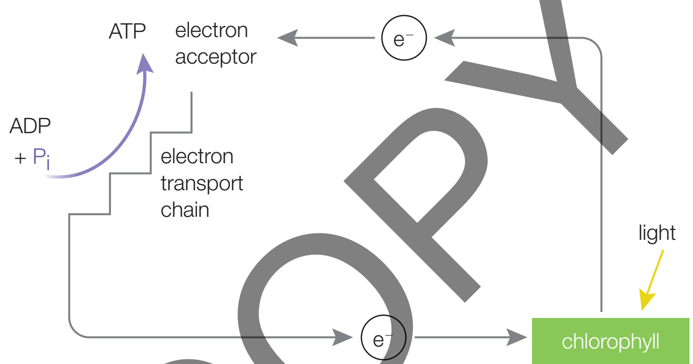


▲ **fig B** The effect of temperature on the rate of photosynthesis shows that two different processes are involved.

2 A plant that is exposed to alternating periods of dark and light forms more carbohydrate than a plant in continuous light. How can we explain this? The light-dependent reactions produce a chemical that feeds into the light-independent stage. In continuous light, this chemical accumulates, because the light-independent stage is not as fast as the light-dependent stage. The increasing concentration of this chemical inhibits the enzymes which control the light-independent reactions that make carbohydrates. A period of darkness allows all of the products of the light stage to be converted into carbohydrate without their concentration becoming too high. This system is very efficient in a natural environment with periods of light and dark (day and night). Scientists have been able to isolate regions of the chloroplast with newly developed techniques. The reactions occurring on the grana have been shown to depend on the presence of light, whereas those in the stroma do not.

CYCLIC PHOTOPHOSPHORYLATION

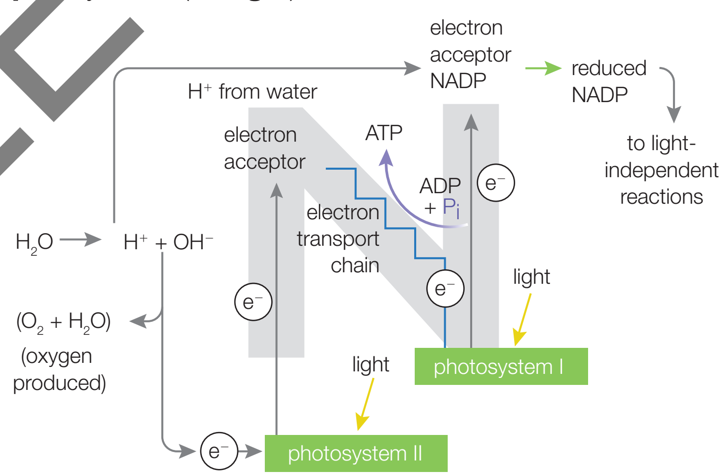
Cyclic photophosphorylation involves only photosystem I (PSI) and drives the production of ATP. When light hits a chlorophyll molecule in PSI, a light-excited electron leaves the molecule. It is collected by an electron acceptor and transferred directly along an electron transport chain to produce ATP. When an electron returns to the chlorophyll molecule in PSI, it can then be excited in the same way again (see **fig C**).



▲ **fig C** Cyclic photophosphorylation

NON-CYCLIC PHOTOPHOSPHORYLATION

During non-cyclic photophosphorylation, water molecules are broken down, providing hydrogen ions to reduce NADP. ATP is also produced. The process involves both photosystem I and photosystem II (see **fig D**).



▲ **fig D** Non-cyclic photophosphorylation: one electron leaves a chlorophyll molecule in PSI and moves into the light-independent stage of the process. A different electron is returned to PSI from PSII by an electron transport chain thus driving the production of more ATP.

In the light, photons constantly hit chlorophyll molecules in both PSI and PSII. This excites the electrons to a higher level. They are, therefore, lost from the chlorophyll molecule and collected by electron acceptors. An excited electron from PSII is collected by an electron acceptor and transferred along an electron transport chain to PSI, driving the synthesis of one molecule of ATP. PSI receives an electron to replace one that was lost to the light-independent reactions. Now the chlorophyll molecule in PSII is missing one electron and so it is unstable. The original electron cannot be returned to the chlorophyll because it has continued on to PSI. So another electron is needed to restore the chlorophyll to its original state. This electron comes from the breaking down of water molecules, a process that is known as **photolysis** because it depends on light. Water molecules dissociate (break down) spontaneously into hydrogen (H^+) ions and hydroxide (OH^-) ions. As a result, there are many hydrogen and hydroxide ions in every part of the cell, including in the chloroplasts. These ions are used to replace the lost electrons from chlorophyll. Once the chlorophyll molecule in PSII has received an electron it is restored to its original state, ready to be excited again when hit by another photon of light.

At the same time, electrons in PSI are also being excited by light and collected by an electron acceptor. Electrons are transferred along an electron transport chain and collected by the electron acceptor, nicotinamide adenine dinucleotide phosphate (NADP). The NADP also collects a hydrogen ion from the dissociated water to form reduced NADP.

The reduced NADP and ATP which are produced during non-cyclic photophosphorylation provide the source of reducing power and energy respectively in the light-independent reactions of photosynthesis to make glucose.

Photosynthesis is a reaction that occurs millions of times in every chloroplast. This means that many hydrogen ions are removed by NADP, and many hydroxide ions remain. The hydroxide ions react together to form oxygen and water. Electrons are freed as a result of the reaction and are absorbed by chlorophyll. Four chlorophyll molecules regain electrons in the production of one molecule of oxygen:

$$4OH^- - 4e^- \text{ (lost to chlorophyll)} \rightarrow O_2 + 2H_2O$$

EXAM HINT

Make sure you are clear about the differences between PSI and PSII.

Remember that both photosystems need light. Do not confuse PSI and PSII with the light-dependent and light-independent stages of photosynthesis.

THE LIGHT-INDEPENDENT STAGE OF PHOTOSYNTHESIS

The light-independent stage of photosynthesis uses the reducing power (reduced NADP) and ATP produced by the light-dependent stage to build carbohydrates. This stage consists of a series of reactions known as the **Calvin cycle** and occurs in the stroma of the chloroplast. A series of small steps results in the reduction of carbon dioxide from the air leading to the synthesis of carbohydrates (see **fig E**). Each stage of the cycle is controlled by enzymes.

THE CALVIN CYCLE

In the first step of the Calvin cycle, carbon dioxide from the air combines with the 5-carbon compound **ribulose bisphosphate (RuBP)** in the chloroplasts. The carbon dioxide is said to be fixed, so this process is known as carbon fixation. This vital step needs the enzyme **ribulose bisphosphate carboxylase/oxygenase (RUBISCO)**. Research has shown that RUBISCO is the rate-limiting enzyme in the process of photosynthesis.

Theoretically, the result of the reaction between RuBP and carbon dioxide is a 6-carbon compound. Scientists are convinced that this theoretical compound exists but it is highly unstable and it has never been isolated. It immediately separates into two molecules of **glycerate 3-phosphate (GP)**, a 3-carbon compound. GP is then reduced (hydrogen is added) to form **glyceraldehyde 3-phosphate (GALP)**, a 3-carbon sugar. The hydrogen for this reduction comes from reduced NADP, and the energy required comes from ATP; both of these are produced in the light-dependent stage.

Much of the 3-carbon GALP follows a series of steps to replace the RuBP needed in the first step of the cycle. However, some 3-carbon GALP is synthesised into the 6-carbon sugar glucose or transferred directly into the glycolysis pathway. In this pathway, it may be used for the synthesis of other molecules needed by the plant (see next page). The reactions of the Calvin cycle occur in both the light and the dark. These reactions only stop in the dark when no products of the light reaction remain, that is to say, no reduced NADP or ATP is available in the chloroplasts. The reactions of the Calvin cycle are summarised in **fig E**, and the whole process of photosynthesis is put together in **fig F**.

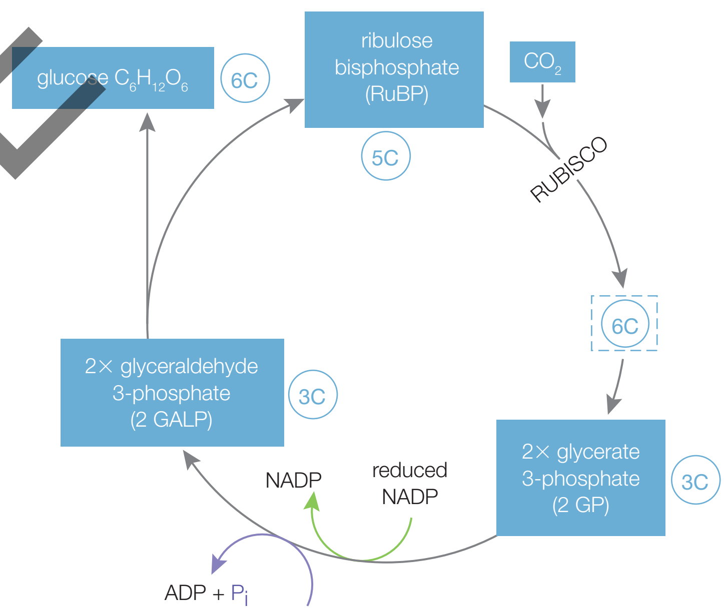
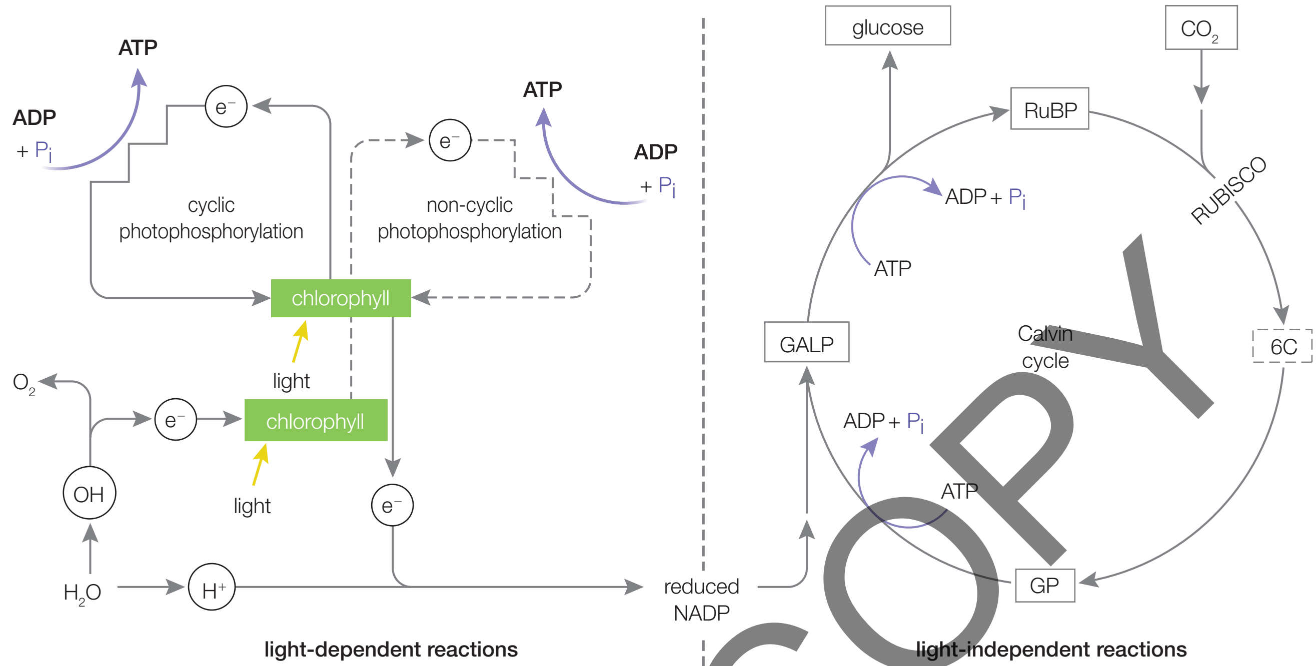


fig E The Calvin cycle: the products of the light-dependent stage of photosynthesis are used in a continuous cycle to fix carbon dioxide. The end result is new carbohydrates.

EXAM HINT

The Calvin cycle is very complex. This is a simplified version with all the detail you need. Each step is controlled by enzymes. Therefore, the rate of the whole cycle is affected by the factors that affect enzyme activity. Remember that you need to be ready to make use of the knowledge you learned at IAS to help answer questions.



▲ **fig F** The full process of photosynthesis occurs continuously in plants when they are exposed to light.

DID YOU KNOW?

RUBISCO and photorespiration

RUBISCO makes up about 30% of the total protein of a leaf, so it is probably the most common protein on Earth. It is also possibly the most important enzyme because of its role in fixing carbon dioxide during photosynthesis. But RUBISCO is very inefficient. The active site cannot distinguish between the carbon–oxygen double bonds of carbon dioxide molecules and the oxygen–oxygen double bonds of oxygen molecules. As a result, both molecules compete for the active site of the enzyme (see **Section 2B.2 (Book 1: IAS)**). This is called competitive inhibition.

RUBISCO functions as a carboxylase in high levels of carbon dioxide/relatively low oxygen. RUBISCO binds to the carbon dioxide and combines it with RuBP, producing two molecules of 3C GP which enter into the Calvin cycle.

RUBISCO functions as an oxygenase in low levels of carbon dioxide/relatively high oxygen. RUBISCO binds to the oxygen and combines it with RuBP to form one molecule of GP and one molecule of glycolate-2-phosphate. The glycolate-2-phosphate is converted into GP in a reaction that uses products of the Calvin cycle and ATP and releases carbon dioxide. This process is known as **photorespiration** because it uses oxygen and releases carbon dioxide.

Photorespiration wastes both carbon and energy. Fortunately for human beings, RUBISCO is attracted to carbon dioxide 80 times more than it is attracted to oxygen. However, in plants about 25% of the products of the Calvin cycle are lost in photorespiration. This means that in many plants, the efficiency of photosynthesis is reduced by 25%.

Why is RUBISCO so inefficient? All the evidence suggests that when RUBISCO evolved the atmosphere was high in carbon dioxide with very little oxygen. Because of this, photorespiration never occurred and there was no selection pressure against it. Even today, photorespiration is not a problem for plants because of our high oxygen/low carbon dioxide atmosphere. There is no selection pressure for the enzyme to evolve to become more specific to carbon dioxide. However, if RUBISCO became more efficient, our crop plants could become 25% more productive, which would be extremely useful to people.

USING THE PRODUCTS OF PHOTOSYNTHESIS

GALP is the primary end-product of the process of photosynthesis. It is the most important molecule for the synthesis of everything else needed in the plant. Some of the GALP is used directly in cellular respiration. You will learn more about this process in **Chapter 7A**. Some of the GALP produced in the Calvin cycle is used to produce glucose in a process called **gluconeogenesis**.

This glucose may be converted into disaccharides such as sucrose for transport round the plant; into polysaccharides such as starch for energy storage; and into cellulose for structural support (see **Sections 1A.2** and **1A.3 (Book 1: IAS)**).

The GALP that enters cellular respiration is used to provide energy in the form of ATP for the functions of the cell. Compounds from these pathways are also used as the building blocks of amino acids. The molecules combine with nitrates from the soil. GALP can also continue round the Calvin cycle and, in that case, it can combine with phosphates from the soil to produce nucleic acids.

Some of the GALP that enters the cellular respiration pathways is converted into a chemical called acetyl coenzyme A. This compound is then used to synthesise the fatty acids needed for the production of phospholipids for membranes, and lipids needed for storage and other functions within the plant.

GP is also part of this process, but GALP is regarded as the main molecule leading to the synthesis of all the other molecules needed by the plant (see **fig G**).

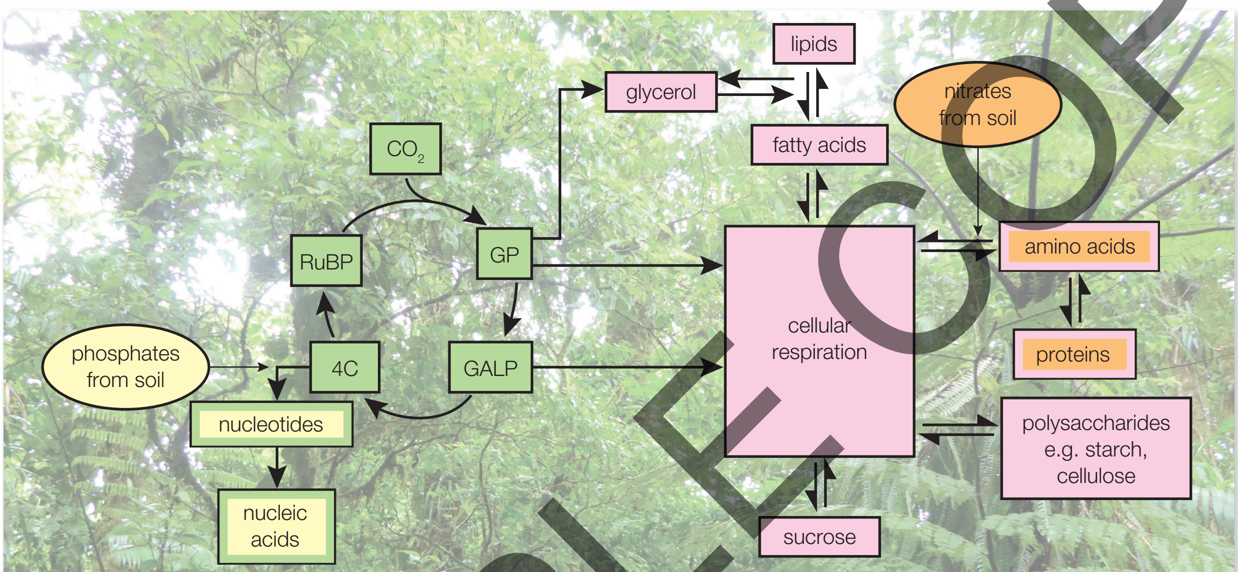


fig G The body of a plant is composed of many different chemicals. Most of these chemicals are formed from the products of photosynthesis.

LIMITING FACTORS IN PHOTOSYNTHESIS

When you understand the process of photosynthesis, you can see why certain factors affect the ability of a plant to photosynthesise. Photosynthesis is limited by the factor that is nearest to its minimum value.

LIGHT

Light intensity affects the amount of chlorophyll which is excited and, therefore, the amount of reduced NADP and ATP produced in the light-dependent stage of the process. If there is a low level of light, insufficient NADP and ATP will be produced to allow the reactions of the light-independent stage to progress at their maximum rate. Light is, therefore, the **limiting factor** for the process in this situation. Both the light intensity and the wavelength of the light falling on a plant will affect the rate of photosynthesis.

CARBON DIOXIDE

Carbon dioxide concentration is very important in photosynthesis. If there is not enough carbon dioxide available for fixing in the Calvin cycle, the reactions of photosynthesis cannot proceed at the maximum rate. Carbon dioxide concentration is, therefore, the limiting factor in this case. In natural environments, carbon dioxide concentration is the most common limiting factor of photosynthesis in plants. Changes in the concentration of carbon dioxide have a clear effect on the rate of photosynthesis (see **fig H**). When commercial growers of some fruits and vegetables grow their crops in greenhouses, they often supply extra carbon dioxide to the atmosphere to increase their production.

EXAM HINT

Always remember to refer to *light intensity* rather than *the amount of light*. When you describe the effect of light remember to state ‘as light intensity increases, the rate of photosynthesis increases’. It is not enough to say ‘light increases the rate of photosynthesis’.

EXAM HINT

Again, remember to refer to *the concentration of carbon dioxide*. If you are describing or explaining a relationship, remember to say ‘as carbon dioxide concentration increases … ’.

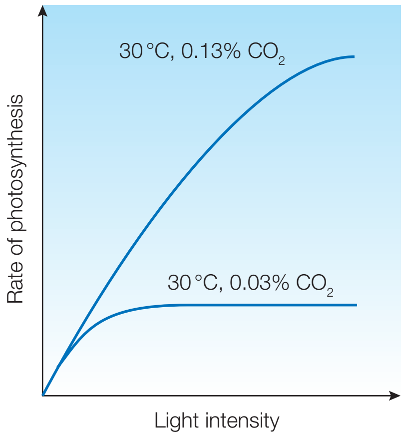


fig H The effect of carbon dioxide concentration as a limiting factor in photosynthesis.

TEMPERATURE

The other main factor which limits the rate of photosynthesis is temperature. All of the Calvin cycle reactions and many of the light-dependent reactions of photosynthesis are controlled by enzymes and are, therefore, sensitive to temperature (see **Section 2B.2 (Book 1: IAS)**). A plant can only photosynthesise rapidly when the temperature is in the right range, even if light and carbon dioxide levels are abundant. The rate of photosynthesis in a wild plant is often determined by a combination of these factors, some or all of them having a limiting effect on the process (see **fig I**).

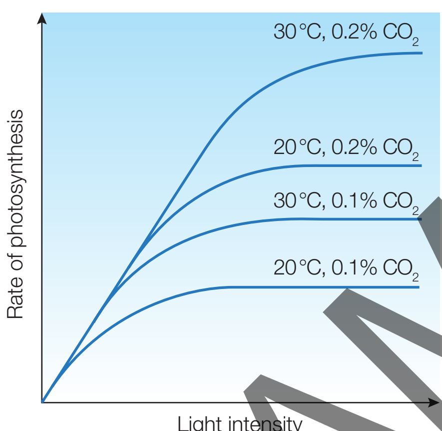


fig I Different factors interact to limit the rate of photosynthesis.

EXAM HINT

As part of your study of this topic, you will conduct **Core Practical 10: Investigate the effects of light intensity, light wavelengths, temperature and availability of carbon dioxide on the rate of photosynthesis**. Make sure you understand this practical well because your understanding of the experimental method may be assessed in your examination.

PRACTICAL SKILLS CP10

You will investigate the effect of different factors on the rate of photosynthesis in plants. You will have to use an aquatic plant to do this. It is very hard to measure the rate of photosynthesis in land plants, but aquatic plants release bubbles of oxygen gas which you can see in the water. You can:

- count the rate at which the bubbles are released in a given time interval and calculate the rate of photosynthesis in bubbles per minute
- collect the gas produced over a given time interval and calculate the rate of photosynthesis from the volume of gas produced per minute.

With both of these methods, you can then change the conditions for your plant. For example, you can change the wavelength of the light shining on the plant or you can change the temperature of the water the plant is in. By measuring any change in the rate of photosynthesis, you can observe the effect of different factors on how your water plant makes food.

Safety Note: Lights must not be splashed with water nor electric cables, plugs or sockets handled with wet hands. After handling plant materials, hands should be washed with soap and water.

PHOTOSYNTHESIS, LIMITING FACTORS AND REAL PLANTS

Photosynthesis and its limiting factors are relatively easy to investigate in the laboratory, but what happens in the real world?

Plants do not usually grow in pots in a controlled environment. They are found in woods, gardens, ponds, mountains, swamps, savannah and desert. How plants grow and the ecosystems that develop are controlled by competition between plants for the factors that can limit photosynthesis and growth. For example, carbon dioxide concentration does not generally vary much in the air, but plants compete for light and warmth. They also compete for the nutrients they need to convert carbohydrate into proteins and fats. Plants are adapted to get as much light as possible so that photosynthesis is not limited. For example, they can grow tall, spread their leaves, climb or develop large leaves. Methods of seed dispersal have also evolved to reduce competition by ensuring that seedlings do not develop in the shade of their parents. The biochemistry investigated in the artificial situation of the laboratory is extremely important to help us understand the lives of plants in their natural habitats.

CHECKPOINT

1. Make a table to compare what happens in cyclic and non-cyclic photophosphorylation.
2. Calvin cycle reactions are also known as the light-independent reactions of photosynthesis. Explain why this name is appropriate as well as being, in some ways, inaccurate.
3. Explain why GALP is sometimes referred to as *the primary product of photosynthesis*.
4. Greenhouses and polytunnels are used in many countries to change the conditions so farmers can grow high-value food crops and flowers as economically and quickly as possible. In many of these artificial growing environments, the light levels, temperature and carbon dioxide levels are carefully monitored and controlled. Explain this in terms of limiting factors.

SKILLS CREATIVITY

SUBJECT VOCABULARY

light-dependent reactions the reactions that take place in the light on the thylakoid membranes of the chloroplasts; the reactions produce ATP and break down water molecules in a photochemical reaction, providing hydrogen ions to reduce carbon dioxide and produce carbohydrates

light-independent reactions the reactions that use the reduced NADP and ATP produced by the light-dependent stage of photosynthesis in a pathway known as the Calvin cycle; this occurs in the stroma of the chloroplast and results in the reduction of carbon dioxide from the air to cause the synthesis of carbohydrates

photochemical reaction a reaction initiated by light

cyclic photophosphorylation a process that drives the production of ATP; light-excited electrons from PSI are taken up by an electron acceptor and transferred directly along an electron transport chain to produce ATP, with the electron returning to PSI

non-cyclic photophosphorylation a process involving both PSI and PSII in which water molecules are broken into smaller units using light energy to provide reducing power to make carbohydrates and at the same time produce more ATP

photolysis the breaking down of a molecule into smaller units using light

Calvin cycle a series of enzyme-controlled reactions that take place in the stroma of chloroplasts and result in the reduction of carbon dioxide from the air to bring about the synthesis of carbohydrate

ribulose bisphosphate (RuBP) a 5-carbon compound that combines with carbon dioxide from the air in the Calvin cycle to fix the carbon dioxide and form a 6-carbon compound

ribulose bisphosphate carboxylase/oxygenase (RUBISCO) a rate-controlling enzyme that catalyses the reaction between carbon dioxide/oxygen and ribulose bisphosphate

glycerate 3-phosphate (GP) a 3-carbon compound thought to be the result of breakdown of a theoretical highly unstable 6-carbon compound formed as a result of the reaction between RuBP and carbon dioxide in the Calvin cycle

glyceraldehyde 3-phosphate (GALP) a 3-carbon sugar produced in the Calvin cycle using reduced NADP and ATP from the light-dependent stage; GALP is the key product of photosynthesis and is used to replace the RuBP needed in the first step of the cycle, in glycolysis and the Krebs cycle, and in the synthesis of amino acids, lipids, etc. for the plant cells

photorespiration the alternative reaction catalysed by RUBISCO in a low carbon dioxide environment which uses oxygen and releases carbon dioxide, making photosynthesis less efficient

gluconeogenesis the synthesis of glucose from non-carbohydrates

limiting factor the factor needed for a reaction to progress that is closest to its minimum value

C4 PHOTOSYNTHESIS

SKILLS INTERPRETATION, DECISION MAKING, ADAPTIVE LEARNING, CREATIVITY, PERSONAL AND SOCIAL RESPONSIBILITY

There are different types of photosynthesis, each with differing biochemistry. Some types of photosynthesis are more efficient than others. Scientists are looking for ways to use this to make crop plants more productive.

INFOGRAPHIC

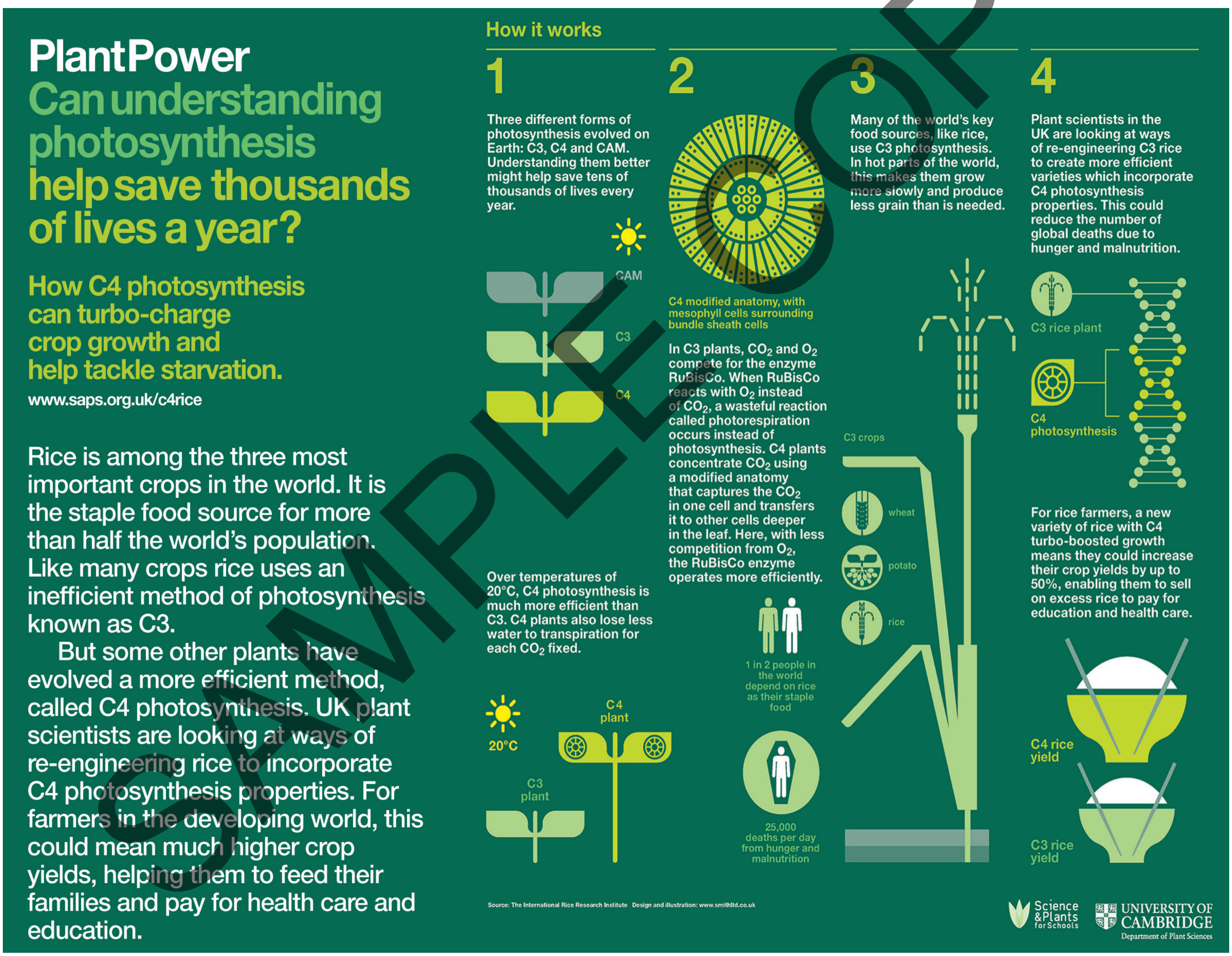


fig A Based on part of a poster produced by Science and Plants for Schools (SAPS) to introduce different types of photosynthesis to students.

SCIENCE COMMUNICATION

Fig A is part of an infographic, which is a very popular way of providing information.

Visit www.saps.org.uk/attachments/article/1266/C4%20Rice%20-%20poster.pdf to see the whole poster.

1 What is an infographic?

2 In an infographic, there is not a lot of space to explain ideas. Every word is important. The colour and size of the font used helps indicate which information is most important. Look carefully at the infographic on C4 photosynthesis. It would normally be the size of a wall poster. Choose an example of:

(a) a statement explaining what the infographic is about

(b) a piece of important information on the infographic

(c) a piece of information which is interesting but not key to understanding C4 photosynthesis on the infographic.

In each case, describe how well the wording explains an idea, and describe the information that is given to the reader by the size and colour of the lettering.

3 Does this poster help you understand why C4 photosynthesis is an exciting alternative to the C3 photosynthesis that you have studied in **Chapter 5A**? Explain your answer.

BIOLOGY IN DETAIL

You have looked at C3 photosynthesis in some detail. This poster gives you some information about another form of photosynthesis that uses a rather different biochemical pathway.

4 Make a flow diagram to summarise the process of C3 photosynthesis.

5 Using only the information on the poster:

(a) Summarise the process of C4 photosynthesis.

(b) Explain why scientists are attempting to genetically modify rice plants so they use C4 photosynthesis instead of C3.

ACTIVITY

Look into the science behind the poster to find out more about C4 photosynthesis and the way it might be used to help feed the growing population of the world. The best place to start is with the resources produced by the team at SAPS, who work from the Botanic Gardens at the University of Cambridge in the UK, and study plants and ecosystems all over the world.
Visit http://www.saps.org.uk/students/further-reading/1266 to start. You can look at other sources as well. Now choose one of the following activities.

- Produce your own poster to inform other International A Level students who are not studying biology about C4 photosynthesis and its potential to improve the yield of crops, including rice.
- Find out more about C4 and CAM photosynthesis and make a table to compare the three types of photosynthesis.
- Make your own infographic to compare C3 and C4 photosynthesis.

The resources produced by Science and Plants for Schools (SAPS) are a great place to start when looking into plants and photosynthesis. Remember to always reference your sources.

5A EXAM PRACTICE

1 The following substances are all involved in photosynthesis.

1 glyceraldehyde phosphate
2 glycerate 3-phosphate
3 carbon dioxide
4 glucose

In which order of substances will a carbon atom be transferred? [1]

A 2–1–4–3 **B** 3–1–2–4
C 3–2–1–4 **D** 1–2–4–3

(Total for Question 1 = 1 mark)

2 What are the products of the light-dependent stage of photosynthesis? [1]

A ATP and reduced NAD
B ATP and oxidised NADP
C ATP and oxidised NAD
D ATP and reduced NADP

(Total for Question 2 = 1 mark)

3 How many molecules of ribulose bisphosphate are broken down to produce two molecules of glucose? [1]

A 10 **B** 12 **C** 14 **D** 18

(Total for Question 3 = 1 mark)

4 One of the reactions of photosynthesis can be summarised as shown below.

water → hydrogen ions + oxygen gas + electrons

(a) Name the reaction shown. [1]

(b) State **one** other factor, not shown above, that is required for this reaction to occur in a chloroplast. [1]

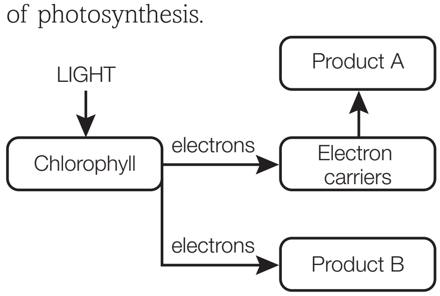
(c) Describe the role of the electrons in the light-dependent stage of photosynthesis. [4]

(d) Explain how the products of the light-dependent reaction are involved in the production of glyceraldehyde 3-phosphate (GALP). [5]

(e) GALP does not accumulate in a chloroplast during photosynthesis. State how GALP is used following its production. [2]

(Total for Question 4 = 13 marks)

5 The diagram below summarises the light-dependent reactions of photosynthesis.



(a) State the precise location within a chloroplast where this sequence of reactions occurs. [1]

(b) (i) What is the name of product A? [1]

A glucose **B** ADP
C reduced NADP **D** ATP

(ii) What is the name of product B? [1]

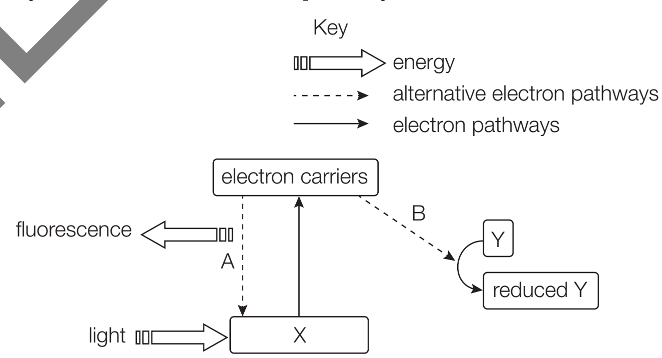
A glucose **B** ADP
C reduced NADP **D** ATP

(c) Explain why the chlorophyll in photosystem II loses an electron. [3]

(d) A chemical called atrazine prevents the flow of electrons to the electron carriers. Describe the likely effect of atrazine on the production of carbohydrate in a chloroplast. Explain your answer. [4]

(Total for Question 5 = 10 marks)

6 The diagram below shows what happens to electrons during part of the light-dependent stage of photosynthesis. Any excited electrons that are not taken up by electron carriers follow pathway A and release energy as light in a process called fluorescence. The excited electrons that are taken up by electron carriers follow pathway B.

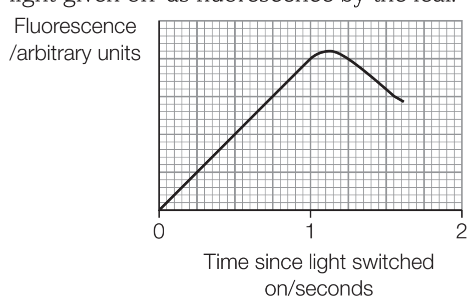


(a) Name the molecules X and Y shown on the diagram. [2]

(b) Explain the importance of reduced Y in the process of photosynthesis. [2]

(c) A light was shone on a leaf and left switched on.

The graph below shows changes in the amount of light given off as fluorescence by the leaf.



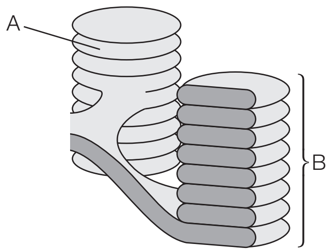
(i) Suggest an explanation for the increase in fluorescence. [2]

(ii) Suggest a reason for the fall in fluorescence. [2]

(d) Explain why an inhibitor of carbon dioxide fixation would lead to an increase in fluorescence. [4]

(Total for Question 6 = 12 marks)

7 The diagram below shows structures found in a chloroplast.



(a) What are the correct names of structures A and B? [1]

A granum and thylakoid

B thylakoid and granum

C thylakoid and stroma

D lamella and thylakoid

(b) State precisely where chlorophyll is found. [2]

(c) A student investigated the effect of different coloured lights on the rate of photosynthesis. She placed coloured filters between a lamp and a beaker containing a piece of pondweed (*Cabomba*) and counted the number of bubbles released from the pondweed in two minutes. Her results are shown in the table.

Colour of filter	Number of bubbles counted in two minutes
black	10
blue	82
green	21
yellow	32
red	97

(i) State the colour of light that enabled the most rapid rate of photosynthesis. [1]

(ii) Explain the result shown for the black filter. [2]

(iii) Explain the result shown with the green filter. [2]

(iv) The student expected there to be no oxygen released when using the black filter. Suggest **two** reasons why some bubbles were observed when the black filter was in place. [2]

(v) Suggest **two** ways in which the student could have improved this investigation. [2]

(Total for Question 7 = 12 marks)

8 The carbohydrates in green plants are formed during the light-independent stage of photosynthesis. They are synthesised from glycerate 3-phosphate (GP).

(a) State precisely where the synthesis of carbohydrates takes place during the light-independent stage of photosynthesis. [1]

(b) (i) Name the products of the light-dependent stage of photosynthesis used during the synthesis of carbohydrates. [2]

(ii) Name the source of carbon used to manufacture sugars. [1]

(c) What is the role of ribulose bisphosphate (RuBP) in the light-independent stage of photosynthesis? [1]

A to convert carbon dioxide to GP

B to fix carbon dioxide

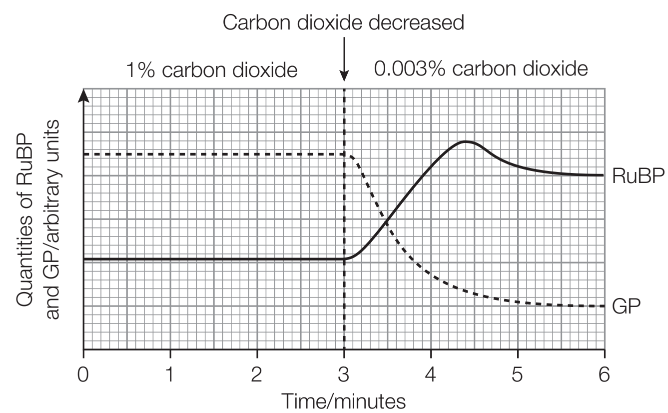
C to accept electrons from the light-dependent stage

D to release energy for the light-independent stage

(d) An investigation of photosynthesis in cells taken from a green alga was carried out. Samples of the algal cells were taken at 1 minute intervals over a period of 6 minutes. The quantities of GP and RuBP in these cell samples were measured.

At the start of the investigation, the algal cells were kept in an atmosphere with 1% carbon dioxide. After 3 minutes, the concentration of carbon dioxide was decreased to 0.003%.

The graph below shows the results of this investigation.



Describe the effects on the quantities of GP and RuBP with the decrease in the carbon dioxide concentration and deduce explanations for the effects you have described. [4]

(Total for Question 8 = 9 marks)