CHAPTER 12 PLANT SYSTEMS FOR LIFE

By the end of this chapter you will have covered the following material.

Science Understanding

- In plants, gases are exchanged via stomata and the plant surface; their movement within the plant by diffusion does not involve the plant transport system (ACSBL059)
- In plants, transport of water and mineral nutrients from the roots occurs via xylem involving root pressure, transpiration and cohesion of water molecules; transport of products of photosynthesis and some mineral nutrients occurs by translocation in the phloem (ACSBL060)

Figure 12.1 ▶ 'Centurion' in Tasmania is an example of *E. regnans*, the tallest flowering plant species in the world


Forestry Tasmania, photo by David Mannes

The redwoods, or Sequoias, of California are famous for being among the tallest trees in the world. There is one redwood in California recorded at 115 m. The tallest flowering tree species in the world is *Eucalyptus regnans*. Known as mountain ash in Victoria and swamp gum in Tasmania, there is one specimen a few kilometres from Hobart that is 101 m tall. Aptly named 'Centurion', this particular swamp gum is estimated to be around 400 years old. At some stage in its life the crown appears to have snapped off and regrown. Because redwoods are classified as conifers, Centurion currently represents the tallest flowering plant, the tallest hardwood tree and the tallest eucalypt in the world. One of the greatest physiological challenges for tall trees is how to draw water and nutrients from the roots to the canopy. This requires the tree to lift many kilograms of water through vertical distances of 50–100 m against the force of gravity.

Plant structure and function

See Chapter 10 for more information of the types of cells, organs and systems found in plants.

While plants do not possess all of the same systems that multicellular animals do, they have specialised cells that make up **tissues** with specific functions to assist in their survival. Again, the individual cells are organised into tissues (such as photosynthetic tissue), which form the organs (such as the leaf) of the plant body. Each of these tissues is specialised to perform important functions that support the life of the organism. These include obtaining energy, producing organic compounds, distributing materials, removing wastes and exchanging gases. The structure of a vascular plant ensures that each organ – the leaves, stem, roots, flowers and seeds – receives what it needs. The organs are grouped as systems. In plants there are two systems: the shoot system and the root system.

1 The shoot system is comprised of all parts of the plant found above ground. It is responsible for the transportation of resources, the absorption of oxygen and carbon dioxide, reproduction and carrying out photosynthesis in leaves.
2 The root system is below ground and is responsible for absorbing water and nutrients from the soil.

Non-vascular plants

The first plants to colonise land lacked specialised support systems. Mosses do not have vascular tissue and generally are restricted to moist environments. They are small plants, usually no taller than 20 cm. Although they do have root-like, stem-like and leaf-like structures, these do not contain xylem and phloem. They are able to dry out almost completely, and then revive after absorbing moisture. Their root-like structures, **rhizoids**, are elongated cells that attach the plant to the soil and serve as absorptive structures. Mosses also have a cuticle that prevents water loss from above-ground parts.

Liverworts are even simpler than mosses, and belong to the group known as **bryophytes**. They are found only in moist environments and have photosynthetic cells. Liverworts have no roots, stem or leaves as such. They have rhizoids like the mosses; however, they do not grow beyond the flat sheet of cells and look like plastic spots on the surface of wet rocks. They are unable to grow in areas that do not have a lot of moisture.


Alamy/Robert Clay

▲ Figure 12.2 Liverworts are non-vascular plants with thin, simple leaves and no roots.

Vascular tissue

The features of various kinds of multicellular plants may differ but their structure and organisation enable them to function as a whole. In many plants, structural adaptations to dry land conditions include altered root and shoot systems, waxy cuticles, stomata, **vascular tissues** and lignin-reinforced tissues. These types of plants came to dominate the landscape as they survived even the harshest and driest land conditions.

In a vascular plant, there are specialised cells and tissues that distribute organic compounds, water, minerals and gases around the plant. Vascular tissue is involved in the transport of substances in plants. Vascular tissue is composed of two different types of tissues: **xylem** and **phloem**. Xylem is responsible for the transport of water, along with **nutrients** and minerals, absorbed from the soil through the root system. It is made up of two types of cells: **tracheids** and **vessel elements**. These tissues consist of tubular, elongated cells that allow water to pass freely. As xylem cells mature, they die, leaving behind hollow cells supported by the remaining cell walls. These are ideally suited to the transport of water. The dead xylem tissue forms the woody part of many plant stems. Wood is composed entirely of xylem tissue and provides the main support for most large plants such as trees.

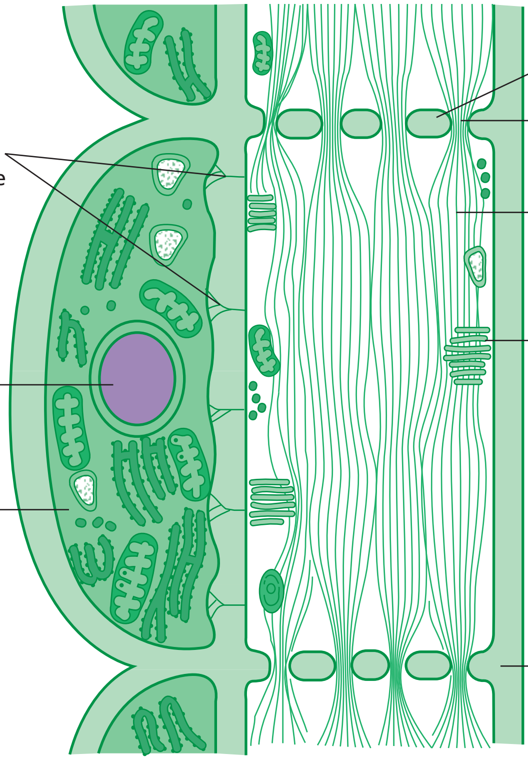
Xylem carries water and dissolved nutrients from the roots to the rest of the plant.

Phloem is conductive tissue composed of thin-walled cells that transport sugars, in the form of sucrose, and other plant products from one part of a plant to another. Unlike mature xylem cells, which are dead, phloem cells are living. There are two types of phloem cells: **sieve tube cells** and **companion cells**. Sieve tube cells are long, thin phloem cells that have large pores through the cell walls at either end. These cells have no nuclei, mitochondria or vacuoles. The sieve tube cells are arranged end-to-end into sieve tubes.

The sieve tube cells share cytoplasm. As a result, each sieve tube forms a channel through which sugars and other plant products can flow. Companion cells are phloem cells that are found alongside the sieve tubes. Companion cells have a cell nucleus and other cell organelles that are lacking in the sieve tube cells. They control the activities of the sieve tube cells. In trees, the phloem is the innermost part of the bark.

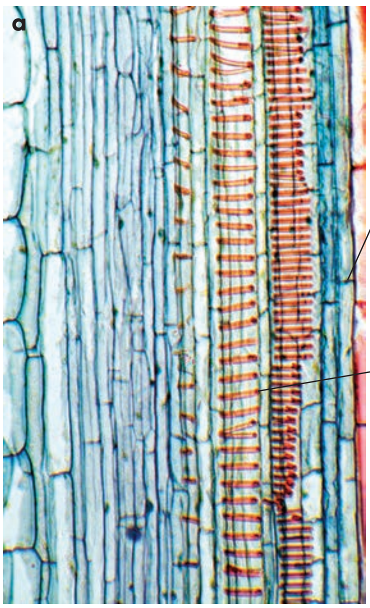
Phloem transports sugars and other plant products from where they are produced, often in the leaves, to the rest of the plant.

Figure 12.3 ▶
Sieve tube elements showing the arrangement of sieve tube cells, with the sieve plates connecting the cells, and companion cells

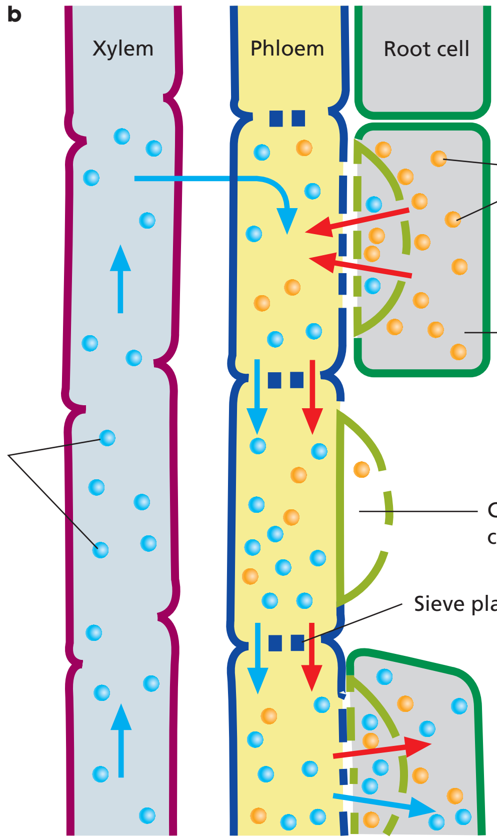


Adapted from Cowes, F. A. L. & Juniper, B. E. (1968) *Plant Cells*, Blackwell Scientific, Oxford.

Figure 12.4 ▼
a) A micrograph image of a longitudinal section of a stem, showing both xylem and phloem
b) Schematic diagram of phloem tissue, showing the movement of water (blue arrows) and sugars (red arrows). Sugar is moved into the sieve tube cells against a concentration gradient. This causes water to move from the xylem by osmosis into the sieve tube cells.



Getty Images/SPL/Dr Keith Wheeler



The functioning plant

As with any living organism, the eucalypt has specific processes to ensure the inputs are maximised; and then outputs are either utilised or removed. In plants, the processes occur within the individual cells.

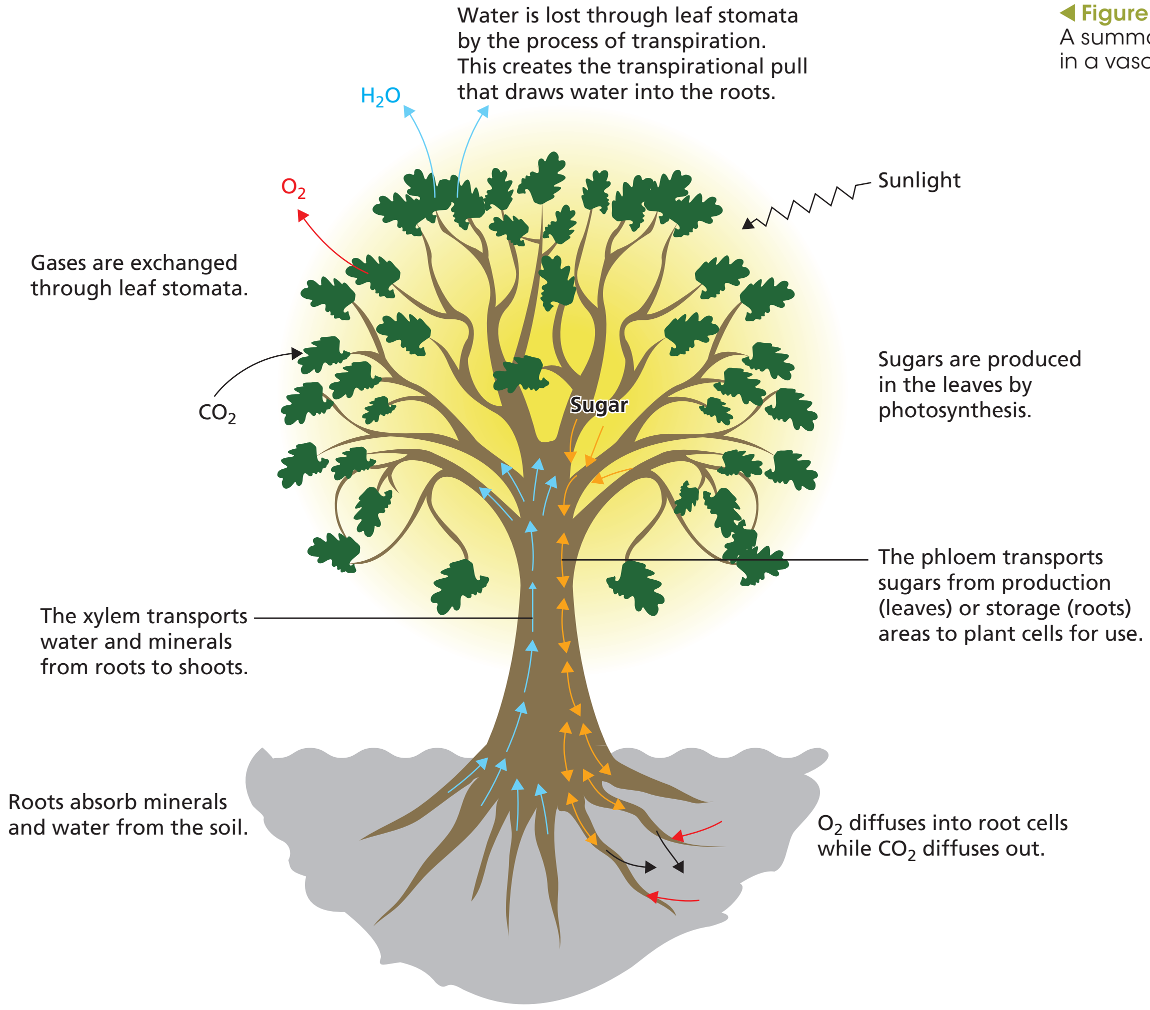


Figure 12.5
A summary of transport in a vascular plant

Two processes that take place in plant cells are photosynthesis and cellular respiration. In order for photosynthesis to occur, the necessary inputs need to reach the leaves: the photosynthetic organs of the plant. Apart from water and carbon dioxide, the leaves also need maximum exposure to available sunlight. The best position for a leaf on a plant is high above the ground and at the uppermost tip of the plant at the end of the stem. The organic substances produced in photosynthesis then need to be distributed to where they are either used or stored.

Photosynthesis and respiration are discussed in Chapter 9.

QUESTION SET 12.1

Remembering

1 List the essential requirements of a large plant, such as a eucalypt. Name the processes that need these requirements.

Understanding

2 Explain the processes involved in the movement of sucrose around a plant.
3 Create a table that compares the structure and function of the xylem and phloem vessels.
4 Explain how it is possible for dead cells to perform useful functions. Include two examples.

Transporting water

See Chapter 11 for more on transport systems in animals.

The evolution of land-based plants depended on the evolution of systems for transporting resources from one part of the plant to another. Plants and animals have some similar basic functional demands. They all need to transport materials, such as sugars and other nutrients, from one part of the body to another. All except the most primitive animals have transport systems based on muscular systems. All animals, except sponges, have some transport or circulatory system that utilises the mechanical action of muscle tissue. Plants lack muscle tissue and therefore depend on completely different methods of transportation.

All plants need to be able to get water to their leaves. Water is absorbed initially by the roots and moves against the pull of gravity through the stem to the leaves. When we look at how that occurs, we find the plant is best serviced by a one-way water movement system – the xylem.

The root system

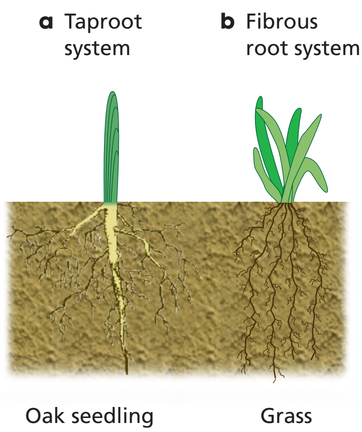


Figure 12.6 ▲ A typical a) taproot and b) fibrous root system

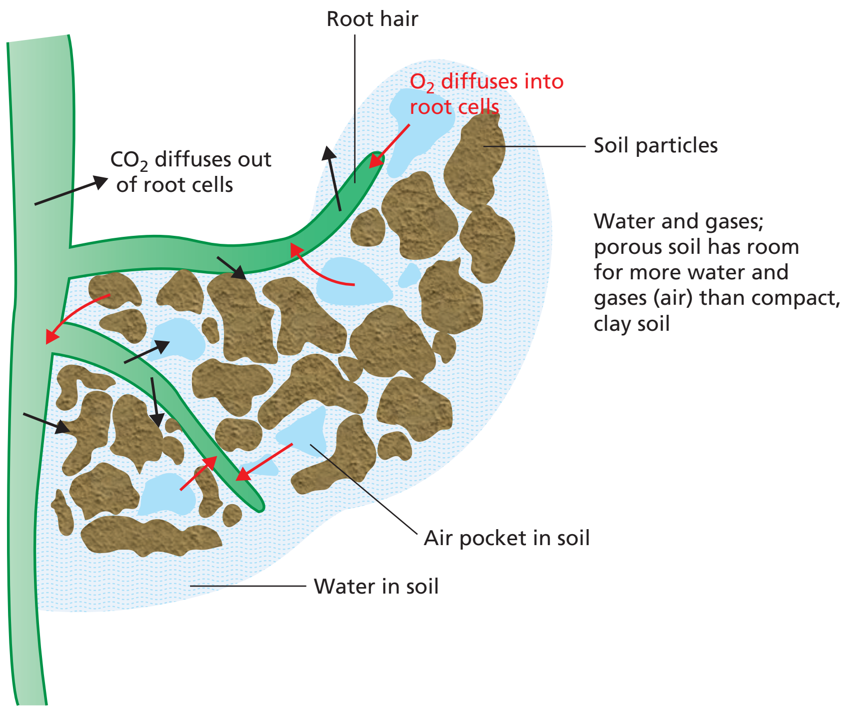
So how does the water in the ground reach the uppermost leaves of the plant? Some of these leaves can be more than 100 m above the ground. Part of the answer lies hidden below ground, in the plant's root system. Sometimes the root system is often larger than the plant's entire shoot system.

The roots of a plant have several functions. They absorb water and minerals from the soil, support and anchor the plant and, in many plants, they are the main storage tissue. Roots may take many forms, but the two most common are **taproots** and **fibrous roots**.

Taproots have a large, tapering main root that has only slender, short side branches. Taproots are found in plants such as eucalypts, daisies and orchids, and are able to push vertically through soil to reach water. Fibrous roots have many smaller roots of about equal size that grow out from the bottom of the plant stem. Although fibrous roots do not grow deeply, they hold the soil in place, preventing erosion. They are often used as colonising plants in coastal areas where wind and water erode the sand from the foreshore. Grasses have fibrous roots.

As well as anchoring the plant, the roots provide the surface through which water is taken up. This surface area is greatly increased by the presence of thousands of **root hairs**, just behind the tip of the root. A plant's root hairs present an enormous surface area across which water is absorbed. This can be up to 130 times greater than the surface area of its shoot system.

Figure 12.7 ▶ Gas exchange across root hairs in soil



Each root hair is a slender extension of each root epidermal cell that makes up the **epidermis**. These extensions increase the surface area for water absorption. The root hairs penetrate between the soil particles and are in close contact with the soil water. Because the epidermal cell has just a cell wall and a plasma membrane, the water can easily move from the soil into it. The root hairs are generally found just behind the root tip. Here they take up water six times faster than regions that are further back on the root.

Beneath the epidermis, large, thin-walled **parenchyma** cells make up the cortex that constitutes the main root body. In the centre, there is a core of vascular tissue that consists of several groups of xylem cells (made of **lignin**) between which are distinct groups of phloem cells. The vascular tissues are arranged in such a way that, as the root grows into the soil, the vascular tissue also extends down the centre of the root, enabling the transportation of materials. These two tissues have distinctive parts to play in transporting materials and in many plants they also strengthen the root system.

Water and dissolved minerals enter the root from the soil by the process of **osmosis** in the case of water molecules, and by diffusion and **active transport** in the case of dissolved ions. Once inside the root hair, the water moves to the parenchyma cells and into the xylem vessel via pits in the cell walls. The force of the water entering the root and 'pushing' its way into the cells creates pressure. If the stem of a plant is severed, the cut end will exude copious amounts of water for some time. This suggests that there is a force pushing water up the stem from the roots. This force is known as **root pressure**, as discovered by Stephen Hales in 1727. Hales found that root pressure could be responsible for raising water to a height of over 6.4 m in a vine. This forces water into the plant and works to ensure that the water and minerals reach the vascular tissue of the stem. There are, in fact, more processes involved in moving water from roots to leaves than just root pressure.

Water and dissolved minerals enter the root from the soil by the process of osmosis in the case of water molecules, and diffusion and active transport in the case of dissolved ions.

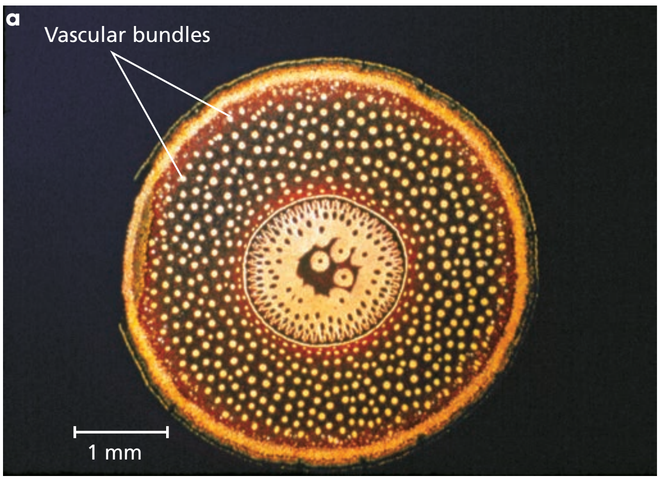
The shoot system

Water and dissolved minerals continue their journey to the leaves via the stem of the plant. In order to understand how this happens, we must first look at the internal structure of the stem; in particular, the vascular tissues.

The structure of the specialised tissues and their arrangement in the stem makes it possible for water and mineral ions to move upwards, sometimes to great heights. These tissues, along with phloem tissue, are grouped into a series of **vascular bundles**, each rather like an electric cable in the stem. In the **dicotyledon** eucalypt, for example, the vascular bundles are arranged in a ring towards the outside of the trunk. In **monocotyledon** plants such as lilies and grasses, they are scattered randomly throughout the stem (Figure 12.8). The veins visible on a leaf are vascular bundles.

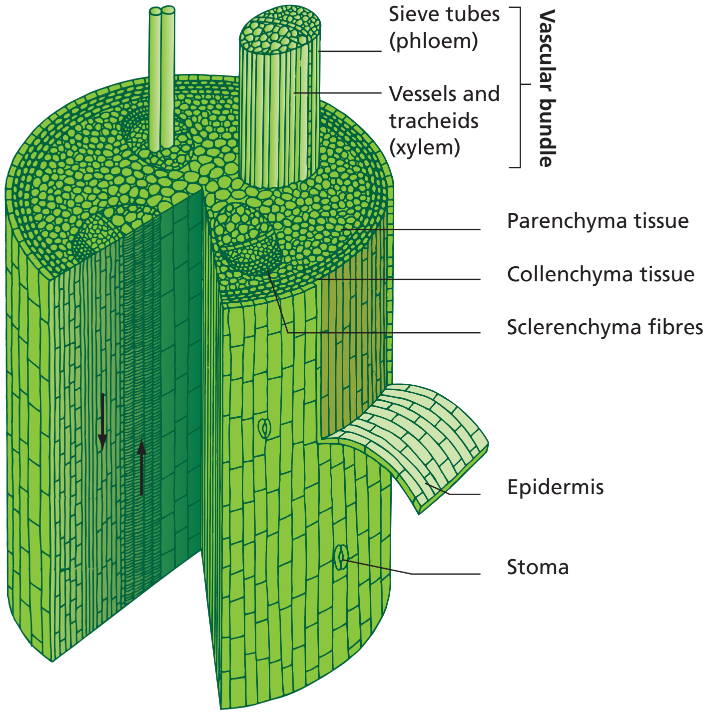
▼ **Figure 12.8** Cross-sections of vascular bundles in a) monocotyledon and b) dicotyledon stems. The xylem and phloem transport different resources.

Getty Images/SPL/Richard Kirby, David Spears Ltd



Getty Images/SPL/Steve Gschmeissner

Figure 12.9 ▶ Internal structure of a plant stem showing the arrangement of xylem and phloem. This diagram shows the general arrangement in dicotyledon plants, such as eucalypts and other non-grass plants.



NEVER LOOK AT TREES THE SAME WAY AGAIN

Learn more about exactly how trees, especially very tall trees, use the process of transpiration to obtain the water they need … and don't need.

The way water moves through a plant, specifically through the roots and stem to the leaves, involves many connected processes. We have looked at root pressure created when water enters the plant cells, but what aids the movement of water up the stem as root pressure is reduced?

If you examine a glass of water, you can observe how water is curved up against the sides of the glass. It is easy to see this effect in a measuring cylinder. It can be explained by **adhesion**, the forces of attraction between water molecules and the molecules that make up the sides of the container. The narrower the tube the water is in, the further the molecules reach up the side. Xylem vessels are very narrow, so water is able to climb some distance up these tubes. However, the problem is not only how to hold up the column of water, but also how to prevent it from breaking in the middle. What is responsible for this? Forces of attraction between the water molecules themselves help to pull the molecules up the narrow xylem vessel. This is **cohesion**. But there is another problem. If you suck water up a straw too hard, the walls of the straw will collapse and the column of water breaks. In the xylem, the thickened, lignified walls normally prevent this from happening. The tension in the xylem of a eucalypt is extreme, but the strength of the water columns must be sufficient or tall trees would not be able to exist. Therefore, following the reduction of root pressure, the combined forces of adhesion and cohesion ensure the continuous column of water movement through the xylem tissue in the stem of the plant.

The continuous column of water through the plant is known as the **transpiration stream**. This constant upwards movement is driven by the evaporation of water from the leaves: **transpiration**. Continuous columns of water therefore hang from the top of the plant, from the leaves, down through the xylem to the roots. The force that holds them there is generated by the Sun, evaporating water from the leaf to the atmosphere, and by the forces that act on the water in the stem. This process, where the water is pulled up large vertical distances through the xylem, is called **transpirational pull**.

Water and minerals are moved through xylem due to a combination of root pressure and transpirational pull. Adhesion and cohesion assist with this journey.

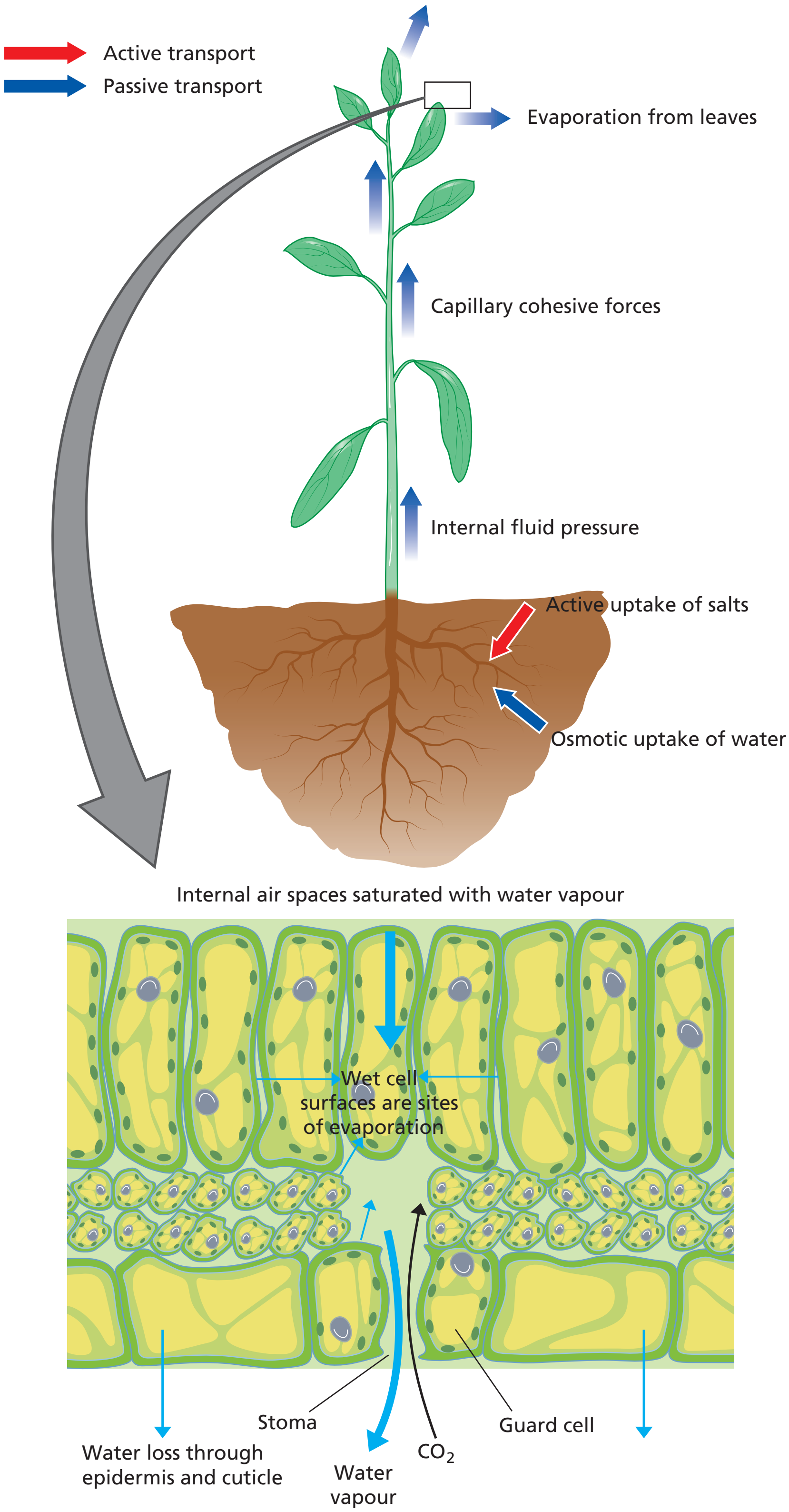


Figure 12.10
The process of transpiration in plants. The process is solar powered.

When a plant loses more water through transpiration than it takes up through its roots, it wilts and is said to suffer from water stress. The loss of water from the leaves raises the tension of the water columns in the xylem, and the **water potential** gradient from the soil to the xylem increases. As a result, the roots remove increasingly more water from the soil. Once the flow of the water to the roots slows down, pores in the leaves called **stomata** close rapidly, thereby reducing water loss to a minimum.

EXPERIMENT 12.1

PLANT TRANSPORT SYSTEMS

Water is an essential requirement for photosynthesis to occur. As photosynthesis mostly occurs in the leaves of plants, water and the substances dissolved within it move through vascular plants in the xylem, from the roots to the leaves. Xylem consists of hollow cells of tracheids and vessels. Sugars, in the form of the disaccharide sucrose, and other nutrients move in the phloem. The phloem is made up of sieve tube cells and companion cells.

Aim

To examine how water is transported through a celery stalk and leaves

Materials

Each group will require:

- stick of celery that has been standing in red food dye or eosin for several hours, cut 2 cm from its base
- single-edged razor blade
- microscope, stereo microscope or hand lens
- microscope slides and coverslips
- mounted needles (optional)
- millimetre ruler, transverse and longitudinal stem sections of *Helianthus* (for Taking it Further)

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Razor blades are sharp and can easily cut skin.	Handle razor blades carefully and report any injuries to your teacher immediately.
Food in the lab can be contaminated.	Do not eat the celery.

Procedure

1 Remove the celery from the coloured solution.
2 Examine the stalk and leaves for spread of the dye; holding them up to the light may help. Observe the areas where the dye is concentrated. Draw the distribution of dye in the leaf.
3 Cut thin transverse sections (1 mm) across the stem and branch (and leaf if possible). Arrange the sections onto a microscope slide.
4 Examine the sections under low power and make diagrams showing the distribution of the dye.
5 Cut another 1–2 mm piece of stem.
6 Use the razor blade to cut out a small piece of the area coloured by the dye and put this on a microscope slide.

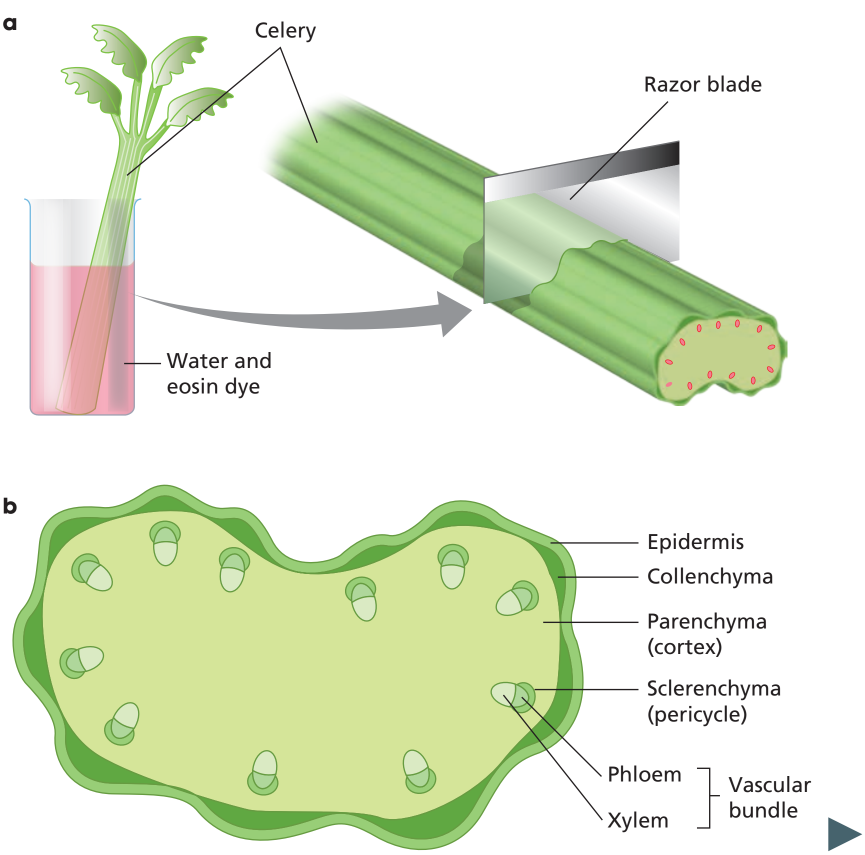


Figure 12.11 ▶ Movements of materials in xylem: a) experiment using celery to show the movement of materials in xylem; b) transverse section through celery stem showing tissue distribution (light microscope view)

7 Use a couple of razor blades or mounted needles to tease the piece of tissue apart.
8 Add a coverslip, using a drop of water if the tissue is becoming dry.
9 Use low power, then high power to find 'spirals' or 'coils'. Draw these structures.

Discussion

1 Describe how the dye is distributed in the plant. Has the whole stem turned a little pink or is the dye found in particular places? Explain your answer.
2 Discuss the assumption that the dye shows us where the xylem is.
3 Suggest what causes the dye to travel to the leaves.
4 If a stem is placed in Indian ink, which is a mixture of small particles rather than a solution (which the red dye is), the colour does not reach the leaves. Explain why this would be the case.
5 a Name the types of cells that the coils and spirals you should have seen are found around.
 b Identify what the spirals are made of.
 c The spirals have functions equivalent to those of the spirals of cartilage around the trachea. Suggest their functions.

Taking it further

1 Examine prepared slides of transverse and longitudinal stem sections of *Helianthus* (sunflower) or another suitable plant. If the slide has been prepared with toluidine blue, lignin will be stained a greenish-blue colour; unlignified cell walls tend to stain a reddish-purple. Alternative stains may make the lignin a reddish colour.
 a Draw some diagrams from the longitudinal and cross-sections, showing where the regions of xylem (lignified areas) and phloem are. You should also be able to draw other types of spirals and coils.
 b In the phloem you may be able to find some sieve plates, sieve tubes (same diameter as the sieve plates) and companion cells (smaller). Draw and label all these.

QUESTION SET 12.2

Remembering

1 List the main functions of both roots and stems. Identify the functions both perform. Determine which function roots perform almost exclusively.
2 List the features of the xylem that make it effective in transporting water around the plant.

Understanding

3 Explain the forces that enable water in a xylem vessel to reach the top of a tree.
4 Explain where the energy for transpiration originates.

Gas exchange

Oxygen and carbon dioxide are exchanged locally throughout the plant. This means that they do not need to be transported from one part of the plant to another. Gas exchange in plants occurs entirely through the process of passive diffusion. The structure of leaves is well adapted to achieve this. They may be large but are always flat, maximising the surface area available in comparison to the relatively small volume of each leaf. Leaves contain open air spaces within the leaf. These provide even greater surface area and allow the gases to move freely through much of the leaf without having to pass through cells.

The movement of gases in leaves depends on simple diffusion and happens locally over short distances. No transport system is used.

The entry of carbon dioxide and oxygen through the epidermis is essential for photosynthesis and cellular respiration. However, another problem arises when water evaporates from the leaf when the stomata are open during the heat of the day. The presence of stomatal pores that can open and close is a remarkable adaptation that solves this problem. Numerous stomata are found on the lower epidermis. The upper epidermis may have some also but there are usually much fewer than the lower epidermis.

In many broadleaf plants, the stomata are found mostly on the underside of the leaf. Australian eucalypts tend to have leaves that hang vertically and these leaves have many stomata on both surfaces. This helps minimise exposure to the hot midday sun. Plants that float on water generally have stomata only on their upper surfaces, while plants that grow under water may have no stomata at all.

Each stomatal pore, or stoma, is bordered by **guard cells**, a pair of crescent-shaped cells. A stoma opens when guard cells absorb water, and closes when they lose water. As a result, stomata tend to be open when a plant is experiencing moist conditions, and closed when a plant is experiencing dry conditions. When oxygen or carbon dioxide enters the leaf and arrives at the cell surface, it dissolves in solution on the moist cell membrane. Here it diffuses directly across the cell wall and plasma membrane into the cell.

OPEN, SHUT THEM

Watch the video and animation to see how the action of guard cells leads to the opening and closing of stomata.

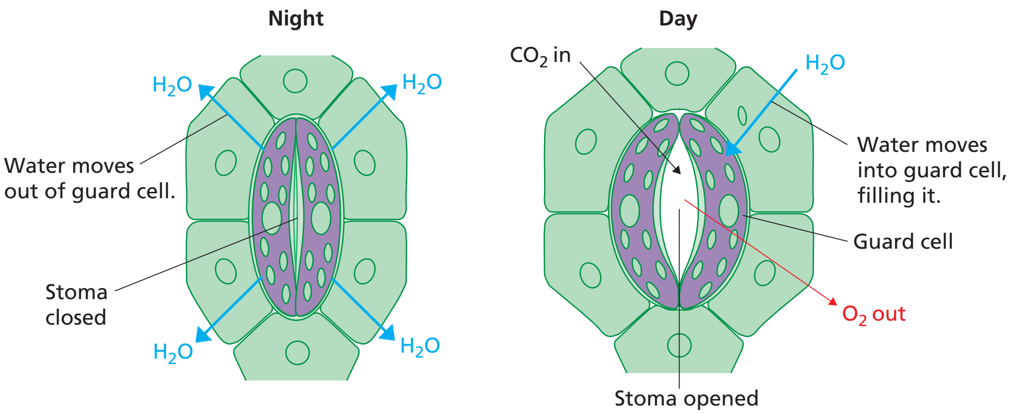


Figure 12.12 ▶ A schematic diagram of a stoma: the opening is surrounded by two guard cells, which can change shape to control the size of the opening. a) When the stomata are closed, the leaf is sealed off from the outside. b) When the stomata are open, gases, including CO_2, are able to enter the leaf while water vapour and oxygen gas escape. The movement of the guard cells occurs because of changes in turgor.

The timing of the opening and closing of stomata depends on a number of environmental factors. Under natural conditions, stomata open at daybreak and close at night, so light appears to be the main factor that initiates opening. Other conditions, however, can override the effects of light. For example, on a warm sunny day as the temperature increases, more and more water vapour is lost through the open stomata. If the water loss exceeds the uptake of water from the soil, the water content of the plant falls. Eventually, the guard cells will begin to lose their water and the stomata will close. Under conditions of decreased water availability, photosynthesis may be reduced and the concentration of carbon dioxide inside the leaf will rise. This also causes the stomata to close and no further carbon dioxide will diffuse into the plant. Conversely, a fall in the internal concentration of carbon dioxide can cause the stomata to open, allowing carbon dioxide to diffuse into the plant.

High levels of humidity can also affect the stomata. If the air is saturated with water vapour, the rate of water loss from the leaf cells is reduced, enabling the stomata to remain open. When the stomata are open, however, water is also lost through them as water vapour. If water is lost in excess, the plant wilts. Plants need to balance their gaseous requirements with their ability to withstand water loss.

In situations of severe water stress, such as in a drought, the guard cells may lose water during the day and close the stomata. While this reduces the loss of water it also cuts off the supply of CO_2. This restricts the capacity of the leaf to carry out photosynthesis, thus restricting the overall growth of the plant during these environmental conditions.

A few plants have evolved mechanisms of storing carbon compounds for later use, allowing them greater control over when and under what conditions they open their stomata. These plants, such as pineapples and many cactuses and orchids, have evolved mechanisms whereby they can open their stomata during the evening, when it is cooler, and effectively store CO_2 for use in photosynthesis in the daytime. They are able to close their stomata during the hottest part of the day.

As all living cells in a plant respire, they all need to exchange gases with their environment. Oxygen diffuses into the cells of the roots of plants and carbon dioxide diffuses out through the root hairs. Root cells require large amounts of oxygen for respiration to provide energy for the active uptake of minerals. If sufficient oxygen is not available for aerobic respiration, such as in waterlogged areas, some plants can revert to anaerobic respiration: respiration in the absence of oxygen. Most plants, however, are not adapted to do this and persistent waterlogging will cause the plant to die.

Plants absorb and release gases, including oxygen and carbon dioxide, via stomata and the plant surface.

QUESTION SET 12.3

Remembering

1 Distinguish between stoma, stomata and guard cells.

2 Name the three gases that are exchanged in and out of stomata.

3 Recall the process by which gases move in and out of leaf cells. Compare this to how gases are transferred in root cells.

Understanding

4 Identify the origin and use of each of the three gases that move in and out of the leaf cell.

5 a Applying petroleum jelly to the leaf surface can be used to plug the stomata. Predict how putting petroleum jelly on a plant's leaves would affect the rates of transpiration and photosynthesis.

b Discuss which factors you would need to control to test your predictions.

Obtaining and transporting nutrients

Eucalypts, like all flowering plants, require a variety of mineral elements in addition to carbon dioxide and water. These minerals are absorbed as the appropriate ions from the surrounding water in the case of aquatic plants, and from the soil water in the case of terrestrial plants. Minerals are actively transported, or pumped, into the root hairs and other surface cells in the young or growing parts of the root. The ions then move between cells through the **plasmodesmata**, or junctions between cells. Once inside the vessels and tracheids, the ions are carried up the stem along with the water in the transpiration stream.

Once the mineral ions reach the leaf they are used to produce more chlorophyll, proteins, carbohydrates and other materials. Plants that do not receive sufficient amounts of mineral ions often suffer from deficiency diseases, which can be seen as yellowing of leaves, small leaves or stunted growth.

The distinction between food and nutrients can be confusing, because in animals they are essentially gained from the same source: the food we eat. In this context, food refers to molecules that are processed through digestion and cellular respiration to provide energy to power cellular processes. Nutrients refer to other substances such as minerals and vitamins. Plant nutrients generally refer to soluble minerals and salts, such as sodium, potassium and phosphorus. These are required for the complex chemistry that runs every cell. They do not provide energy to the cell.

Case study

Algae architecture

The first algae-powered building in the world opened in Hamburg, Germany in 2013. A group of architecture and engineering firms collaborated to meet the challenge of designing more sustainable, low-energy-use buildings. Their solution, the Bio Intelligence Quotient (BIQ) House, took 3 years of research and development but resulted in a functioning 'green' building.

A 'bio-adaptive algae façade', made up of a double layer of 129 'SolarLeaf' vertical glass panels filled with 24 litres of algae and liquid, stretches along the front of two sides of the building. These shiny green living panels function in a number of ways. They form a layer of insulation against sound, heat and cold. As a functioning closed system, the algae behind the glass photosynthesise and convert solar energy into heat. The algae also take up carbon dioxide, produce oxygen and produce biomass and heat energy. Each algal cell can photosynthesise in this unicellular species, so they can grow and produce biomass approximately 10 times faster than larger, multicellular plants. This biomass is harvested to produce biofuel to heat the building.

Within the first year of going live, the algae façade has reached a conversion efficiency total of about 58% (converting sunlight captured into energy). This project marks the beginning of future designs for zero-energy and zero-carbon buildings.

IBA-Hamburg GmbH/Johannes Arlt

Figure 12.13 ▲
The algae-powered Bio Intelligence Quotient House in Hamburg, Germany

Questions

1 Identify the ways in which the engineers and architects have 'copied' from plant structures and function.
2 The glass panels were described as a closed system. Assess whether or not this is possible and explain your answer. Create a diagram to illustrate your explanation.
3 Predict other ways in which the concept of modelling designs based on plant structure and function could be applied.
4 Evaluate whether or not you think algae-based architecture is a beneficial application of scientific knowledge.

Special methods of obtaining minerals and nutrients

Some soils are low in or lack mineral ions, and plants living in them have special means of obtaining essential elements. For example, the roots of many plants that live in **humus-rich soil** and are deficient in mineral ions possess a mycorrhiza, an association between their roots and a fungus. The fungus has the effect of increasing the absorbing area of the root. In some cases the fungus is located on the surface of their root, in others cases it is internal; either way it has the ability to break down the humus into soluble nutrients, some of which are absorbed and used by the plant.

Another special adaptation is seen in legumes such as peas, beans and clover that contain **nitrogen-fixing bacteria** in their roots. Plants living in nitrogen-deficient soil sometimes resort to carnivorous methods and are able to digest animal matter to obtain their nitrogen requirements. Pitcher plant species occur around the world in tropical forests and northern bogs. Each species has evolved in a habitat where particular minerals are hard to come by. The Australian pitcher plant (*Cephalotus follicularis*) is a native of the swampy, damp terrain of the South-West region of Western Australia. This vascular plant cannot grow properly without certain mineral ions, and these happen to be scarce in the soggy soils where it lives. However, plenty of insects fly in from neighbouring regions. Nectar oozes from the edges of the pitcher-shaped leaf and entices insects to land on the leaf. The insects slip into the bottom of the pitcher when they land on downward-facing hairs, and liquid in the bottom of the tube contains enzymes that digest the animal. The products of digestion, which contain nitrogen, are absorbed into the leaf and transported through the phloem to wherever they are required in the plant.

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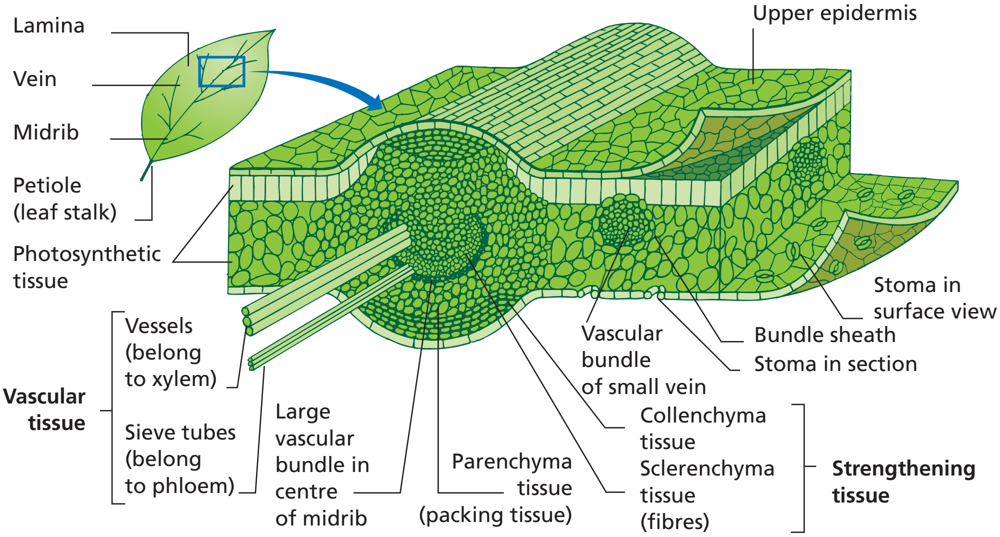
▲ **Figure 12.14**
The carnivorous pitcher plant, *Nepenthes* spp.

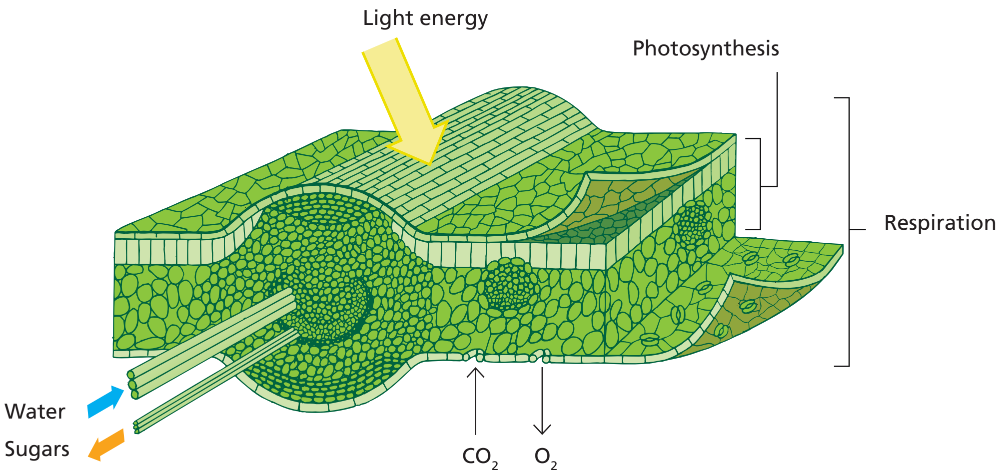
Leaf structure and function

The process of photosynthesis at the cellular level has been dealt with earlier, but how does the structure of the leaf enable its photosynthetic cells to function efficiently?



Roberts, M., Reiss, M. & Monger, G. (1993) Biology: Principles and Processes. Thomas Nelson. New edition released as Advanced Biology (Nelson Thornes, 2000). © Micheal Roberts, Michael Reiss and Grace Monger 1993, 2000. Reprinted by permission of Oxford University Press.

◀ **Figure 12.15**
Diagram of a eucalypt leaf showing tissues and structures



◀ **Figure 12.16**
Eucalypt leaf showing inputs, processes and outputs

Leaves are perfectly designed to capture light energy. Their location and orientation ensures uninterrupted exposure to the Sun. They are generally thin and flat and collectively present a large surface area to the light, therefore maximising the photosynthetic rate. Being thin and flat makes the leaves liable to sag, but their shape is maintained by the **turgor** of the living cells inside them, and by the midrib and veins that are well-supplied with strengthening tissue. The midrib and veins consist of vascular tissue – the xylem and the phloem.

The large surface area of leaves, while allowing maximum photosynthesis, also increases evaporative water loss. This problem is overcome in some plants by the presence of an impermeable waxy cuticle on the leaf surface.

WOW

Giant water lily

Despite its size, the leaves of a giant water lily are still only millimetres thick due to the limitations of passive transport of gases from the surrounding water and air. These lily leaves can grow to almost 3 m in diameter and can support up to 136 kg (more than the average adult human)!

Figure 12.17 ▶
A giant water lily from South America

Leaves of rainforest plants show a great variation in size and shape. When looking at which level within the rainforest the leaf occurs, you get an idea of how much light it receives. For example, plants that grow on the ground receive very little, if any, direct sunlight, and mainly collect filtered light. They still need to photosynthesise in order to provide both the energy and the nutrients the plant needs to survive. These plants often have very large, flat leaves, thus increasing the surface area available for the absorption of light.

Leaves of plants in the canopy, however, have different problems to overcome. Their exposure to sunlight is unlimited, and the biggest threat to the wellbeing of the leaf is over-exposure and the hazards that this brings. The leaves are very small, often hang vertically (limiting the amount of sunlight that strikes them directly), and point towards the trunk of the tree, so that any water is directed down the trunk to the roots of the plant.

Stomata are small pores that provide openings through the epidermis and cuticle. If we study the diagram of the leaf structure (Figure 12.15), the location of stomata in the leaves allows for the diffusion of carbon dioxide, an essential component of photosynthesis, into the photosynthetic tissue. You will notice that each photosynthetic cell is not far from vascular tissue, and also that there is a large number of air spaces among the cells. This design ensures the entry and movement of the required water from the soil as well as carbon dioxide from the atmosphere.

The inside of the leaf has two types of cells that contain chloroplasts. Those immediately beneath the upper epidermis, called the **palisade cells**, are elongated with their long axes perpendicular to the surface. They are separated from each other by narrow air spaces and are densely packed with chloroplasts to maximise light absorption beneath the transparent epidermis. The palisade cells collectively form the palisade mesophyll that may be one or several cells thick. Between the palisade layer and the lower epidermis are the spongy **mesophyll cells**. These cells are irregular in shape and arrangement. They also contain chloroplasts, but fewer than the palisade cells, which is why the lower side of a leaf usually looks paler than the upper side. If the plant is well supplied with water, the thin cellulose walls of the spongy mesophyll cells are permanently saturated with moisture. Between the spongy mesophyll are large air spaces that are linked with each other and with the narrower air spaces between the palisade cells. This system of air spaces allows gases to diffuse freely between the cells within the leaf.

It is because of these various structures that the leaf is the organ best suited to photosynthesis. Its location allows more sunlight to strike its upper epidermis, so the more closely packed palisade mesophyll cells absorb the most light energy. Moreover, because broader leaves offer a larger surface area than narrow leaves, they are more efficient at absorbing light and allowing the transfer of water and gases across the membranes. The stomata allow for the diffusion of carbon dioxide and oxygen into and out of the plant cells. The vascular tissues allow for the transport of water, minerals and organic compounds throughout the plant. Every leaf cell is close enough to the vascular tissues of the plant to ensure they are adequately supplied with water via osmosis.

EXPERIMENT 12.2

LEAF STRUCTURE

Most plants obtain their requirements either through their roots or their leaves. The roots obtain water and mineral ions for distribution around the plant via the xylem. The leaves are the primary site of photosynthesis in the plant and have developed to become highly specialised in structure.

Leaves are made of an outermost layer of cells called the epidermis. Epidermal cells produce a waxy substance that forms a cuticle, which is impermeable to water and gas. Stomata are found in the epidermis, and allow gas exchange and transpiration to occur due to the function of specialised guard cells that open and close the stomata.

Inside the leaf are layers of cells packed with chloroplasts that utilise sunlight for the process of photosynthesis. The water needed for photosynthesis is brought to the leaves from the roots in the xylem, and the sugars produced are carried away in the phloem.

Aim

To observe the structure of a typical green leaf and relate the structure to the functions that it performs

Materials

- fresh, small, broad leaves of herbaceous plants such as broad beans, geraniums or impatiens
- single-edged razor blades
- monocular microscope
- two slides and coverslips
- carrot tissue, about 2 cm wide by 5 cm long
- white tile
- fine brush
- Petri dish of water
- ruler
- magnifying glass wall or hand lens
- *Eucalyptus* leaves, video microscope and digital camera (for Taking It Further)

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Razor blades are sharp and can easily cut skin.	Handle razor blades carefully and report any injuries to your teacher immediately.

Procedure

Part A: Leaf structure

1 Using a hand lens or magnifying glass, examine the structure of the leaf closely while holding it up towards the light. In particular, focus your attention on the arrangements of veins throughout the leaf. Record your estimate of how far most parts of the leaf would be from the nearest vein (in mm).

Part B: Preparation of a transverse section of a leaf

1 If the leaf is thin, fit it into a vertical slit made down the centre of the carrot tissue (Figure 12.19). This will provide a firm position while the sections are cut. Trim the leaf, making sure you use a knife or old razor blades for all trimming. Use a new blade only for cutting sections.

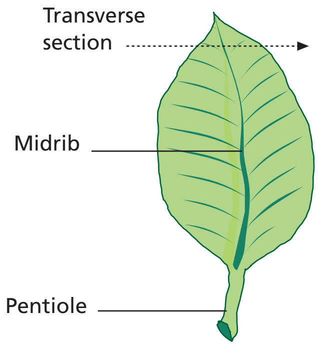


Figure 12.18
Transverse section of a leaf

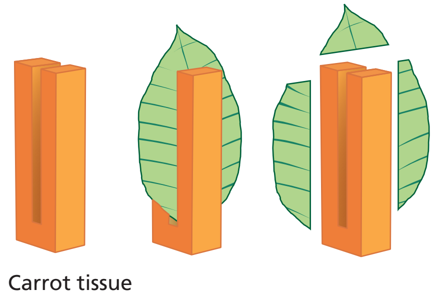


Figure 12.19
Using carrot as a support for cutting

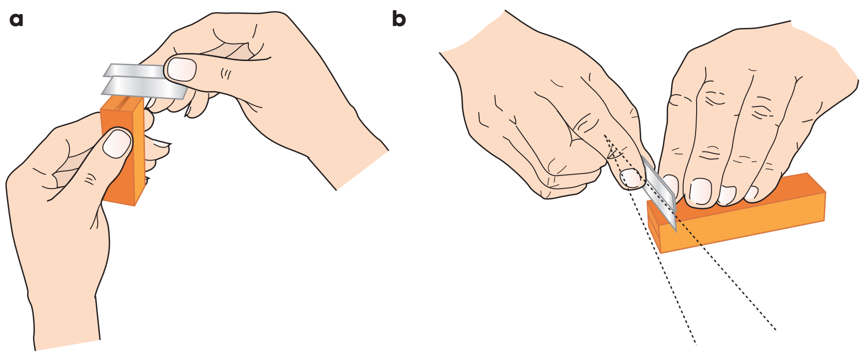


Figure 12.20
Two ways of cutting sections:
a) cutting towards you;
b) cutting across through the carrot and leaf at a slight angle to produce a very thin section at one end

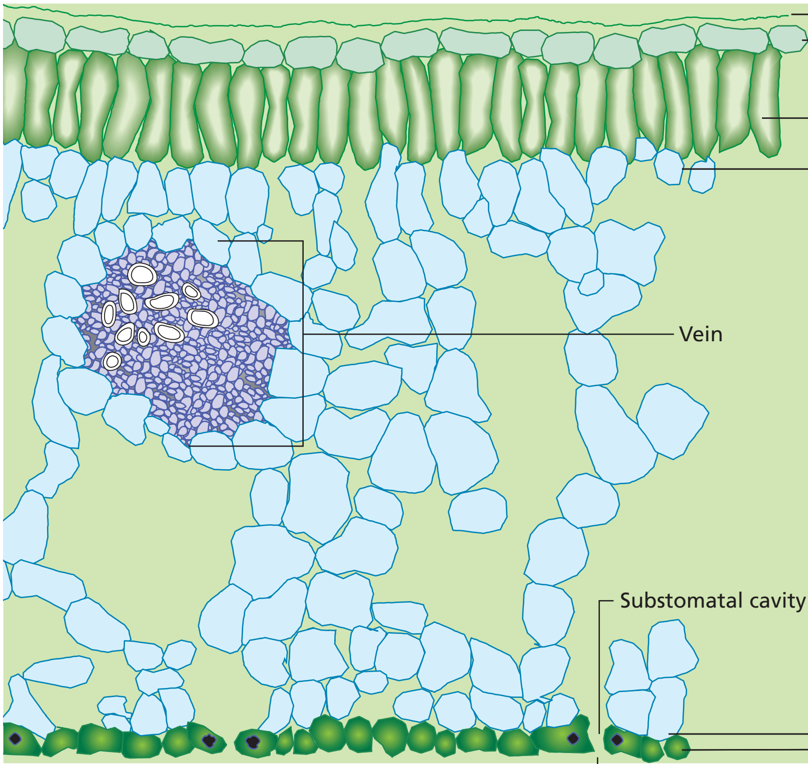
2 Cut very thin sections with the new razor as shown in Figure 12.20. Make sure that the carrot/leaf assembly is kept wet as well as the razor blade. This helps to minimise friction.
3 Float the cut sections off the blade into a Petri dish of water.
4 Choose one or two of the thinnest sections (those that are colourless and almost transparent in parts). You will only be able to see all the cells referred to in this activity if your section is very thin (a few cells thin). Transfer these sections with a moist fine brush (not with forceps, which may damage them) onto a drop of water on a microscope slide. Make sure that the section is sitting with the cut edge facing up. Lower a coverslip onto the section.
5 Examine the transverse section with the microscope. You could irrigate your section with iodine solution, following your teacher's instructions, to reveal any starch present.

Part C: Examining the transverse section of a leaf

1 Examine the transverse section of the leaf under low power. If you have difficulty getting it to sit on its cut edge, gently press on the coverslip and slide it a little. This will cause the leaf section to roll and twist a little on the slide, thus turning part of it on its side. Check with your teacher that you are viewing your leaf correctly.
2 Identify the layers of cells labelled in Figure 12.21 in your specimen: the upper and lower epidermis, and the palisade and spongy mesophyll cells. Identify a stoma and the space behind it called the substomatal cavity. Identify a vein (called a vascular bundle). Notice if there is a cuticle (a waxy layer) along the outer edge of the upper and lower epidermis.
3 Draw a labelled diagram showing the arrangements of the tissues in your section. Label all the cell layers that you can see.
4 Use the high power of the microscope to observe different cell shapes and contents, especially the large green chloroplasts. Draw diagrams of two or three cells of each tissue. Label the cell with all the parts that you can see (e.g. cell wall, chloroplasts).

Results and Discussion

1 Describe what you observed about the furthest distance any part of the leaf is from a vein. Suggest reasons why this may be so important for the survival of the cells within the leaf.
2 Compare the surface area of a leaf to its volume. Suggest what advantages this provides to leaf function. Suggest what disadvantages this provides to leaf function and how these are overcome.
3 Name cells within the leaf that seem to be mainly involved in photosynthesis. Describe where they are mostly situated. Explain how you came to your conclusions.
4 Compare the thickness of the cuticle on the upper and lower leaf surfaces. Account for any differences.



▲ **Figure 12.21**
A generalised cross-section of a leaf

5 Identify the layer of photosynthetic cells that has the most air spaces between its cells.

6 During photosynthesis, green cells in plants take up CO_2 and release O_2. Illustrate the pathway along which a green cell in the leaf could:
  a obtain carbon dioxide from the air.
  b lose oxygen to the air.
  c obtain water and mineral ions.

7 Explain how the external and cellular structure of a leaf assists it in carrying out the function of photosynthesis.

Taking it further

1 Make transverse sections of a *Eucalyptus* leaf and examine them under the microscope. How does this leaf differ from the soft herbaceous ones?

2 A video microscope can be used to view a prepared slide. A camera attached to the microscope could record an image of the leaf section.

3 Use a digital camera to record leaves of different sizes and shapes. Produce a multimedia presentation to show the range of leaves. Annotate with possible reasons for their different shapes and sizes.

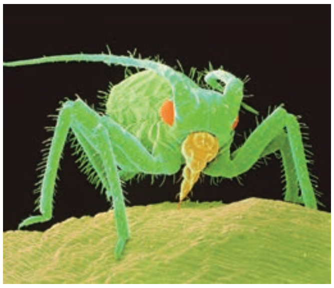
Distributing products of photosynthesis

Photosynthesis captures the energy the plant requires and packages it very neatly into packets of sugar. As outlined earlier, the energy contained in the sugar is required by the cells to function and to allow the whole plant to survive and thrive in its habitat. Now we must consider the transport of these packages. In particular, how are the sugars produced in photosynthesis moved from the leaves where they are formed to the parts of the plant where they are needed? All the cells that are unable to photosynthesise need a share of these materials, especially those in the roots, stem and branches where active transport, cell division and growth are taking place. Transport of energy-rich materials to these growing points is usually greatest when growth is prolific.

WOW

Effortless eating

Aphids are common pests in home gardens. They are often thought of as insects that suck sap from plants. In fact, aphids pierce the phloem directly with a tubular mouth part, and sap is forced into the aphid's digestive system due to the pressure in the phloem. No sucking is required.



Getty Images/SPL/Volker Steger

Figure 12.22 ▲ An aphid feeding

At times when more sugars are produced than can be used by the plant, many plants form tubers, bulbs or corms. Excess products of photosynthesis are transported to these for storage as starch until they are needed. When the next growing season arrives, the stored starch is converted into soluble form and transported to the growing points of the new plant.

Phloem and translocation

Translocation is the movement of sugars in solution through the plant. Sugars, usually in the form of sucrose, are actively transported against a concentration gradient (from high to low concentration) into the sieve cells. This requires energy. The energy for this comes from cellular respiration occurring in the mitochondria of the companion cells.

As the concentration of sugar in the phloem increases, water moves from the xylem by osmosis into the sieve cells. This increases the volume of liquid in the sieve cells, causing the sugary solution to move, usually down to the roots but also to new growth or to fruits, which may be higher up the plant. The sugar leaves the sieve tube cells for the cells where it is needed for cellular respiration, with water following again by osmosis. Unused or stored nutrients can also be translocated out of leaves of deciduous plants before the leaves are dropped in autumn.

Phloem sap is mostly a sugar solution; the sugar is sucrose in most species of plants. Phloem sap may contain up to 30% sucrose by weight, giving it a very syrupy consistency. It is also highly nutritious, which is very attractive to a range of sucking insects that feed on it.

Waste removal

Apart from the removal of unwanted gases via the stomata, deciduous plants can also store other wastes in leaves, which then drop off in autumn. Non-deciduous trees, such as mangroves, remove excess salt from their systems in this way, too. Plants that regularly lose their bark, such as the lemon-scented gum, can transfer unwanted material via the phloem to the bark before it is shed. Other wastes may be stored as insoluble crystals or dissolved in vacuoles. Woody plants can store some wastes in non-living tissue. The cell walls are used as a depository for toxic substances, some of which are modified to form lignin. Certain plants remove other wastes by exuding various resins, fats, waxes and complex organic chemicals, like the latex from rubber trees and milkweeds.

Alamy/Tim Graham

◀ **Figure 12.23** Trees lose wastes by shedding leaves or bark where wastes have been stored, as seen with this blue gum shedding bark.

QUESTION SET 12.4

Remembering

1 Name the essential nutrient that carnivorous plants are usually lacking. Describe how they make up for this deficit.
2 Suggest where the energy for translocation comes from.
3 List the features of the phloem that make it ideal as a transport system for nutrients.
4 Describe the main function of the leaf.
5 List the substances that enter leaves and are used for photosynthesis.

Understanding

6 Explain why plants require mineral ions. Suggest what would happen if they don't get sufficient amounts of these.
7 Describe what deciduous plants do before they drop their leaves. Discuss the benefit to a plant for it to drop leaves, bark or any other material.
8 Explain the function of each of the following terms.
   a Epidermis
   b Palisade mesophyll
   c Stomata
   d Spongy mesophyll
   e Guard cells

CHAPTER SUMMARY

- Plants depend on a supply of carbon dioxide and oxygen, which are mostly available in free air. Plants also depend on a supply of water and nutrients, which are mostly available in the soil.
- Plants transport water and nutrients through xylem and phloem, which are found together in vascular bundles and are powered by the processes of osmosis and water pressure.
- Xylem is a water-conducting tissue composed of tracheids and vessels. When xylem cells mature, they die.
- Phloem tissue transports sugars and other plant products around the plant. Sieve tube cells and companion cells are the living components of phloem.
- Roots absorb water and minerals from the soil, support and anchor a plant, and are often used for storage.
- Root hairs greatly increase the surface area for water absorption.
- Sugars and other plant products are transported through the phloem by a process called translocation.
- Water and minerals are absorbed into roots through a combination of osmosis, water pressure, and active uptake.
- Water and minerals, in xylem, are moved through a combination of root pressure and transpirational pull.
- Leaves and their distribution play a major role in the collection of light for photosynthesis.
- The structure of leaves is designed to allow maximum photosynthesis without a great loss of water.
- Gases are absorbed and utilised locally throughout many parts of the plant, and therefore do not require a transport system. Leaves are ideally structured in order to achieve this.
- Movement of gases in leaves depends on simple diffusion.
- Leaves and stems control the movement of gases by opening and closing stomata.
- As plants absorb CO_2 through their stomata, but they also lose water during this process.
- Sugars in solution move through a plant in the process called translocation. This requires energy.
- Plants remove wastes in a variety of ways such as dropping leaves or bark.

CHAPTER GLOSSARY

active transport the process whereby cells actively transport substances across a membrane from a low concentration to higher concentration of the substance; characterised by the fact that the process consumes energy

adhesion the strong forces that exist between water molecules and other substances, due to the polar nature of the water molecules

bryophyte the traditional name for a primitive group of land plants that lack true vascular tissues, including mosses and liverworts

cohesion refers to the strong forces that exist between water molecules

companion cell the type of cell situated next to the phloem sieve cells; provides most of the cell functions of the sieve tube cells, which lack most organelles

dicotyledon where the vascular bundles of plants are arranged in a ring towards the outside of the stem or trunk of the plant

epidermis the surface layer of plant or animal cells, generally responsible for separating and protecting the organism from its environment

fibrous root a small root that grows out from the bottom of the plant stem

guard cells pairs of cells surrounding and controlling the action of stomata

humus-rich soil the complex organic material resulting from the decomposition of plant and animal debris (detritus)

lignin found in xylem cells; provides strength and structure to the cell wall and plant

mesophyll cell the cell in the middle of leaves, packed with chloroplasts and essential for photosynthesis

monocotyledon where the vascular bundles are scattered randomly throughout the stem

nitrogen-fixing bacteria bacteria found in the roots of certain plants that are able to capture and use atmospheric nitrogen

nutrient a substance required by living organisms, generally including dissolved salts and vitamins in the case of animals, generally not including substances taken up to provide energy in animals

osmosis the movement of water across a selectively permeable membrane from regions of low solute concentration to high solute concentration

palisade cell an elongated cell packed with chloroplasts

parenchyma large, thin-walled cells that make up the cortex of the plant

phloem a vascular tissue in plants, mainly responsible for the transport of sugars from leaves to the rest of the plant; it is composed of living cells

plasmodesmata junctions between plant cells that allow the passage of ions into specific structures in the plant

rhizoid a thread-like structure resembling roots that anchors moss and liverwort plants to their substrate

root hair a tube-like outgrowth of a root epidermal cell that increases the surface area of the root; responsible for absorbing water and nutrients

root pressure the force that pushes water up the stem from the roots

sieve tube cell long and tubular plant cells without a nucleus that join to form sieve tubes, through which sugar and other solutes travel

stomata the openings in leaves, and some stems, that control the movement of gases into and out of the plant; singular is stoma (or sometimes stomate)

taproot the large, tapering main root of a plant that has slender, short, side branches

tissue a group of specialised cells working together to perform a specific function

tracheid a system of elongated cells in the xylem of plants, usually comprised of dead cells

translocation the movement of sugars through the phloem of plants

transpiration the loss of water from plants through evaporation

transpiration stream a continuous column of water that runs the length of the stem of a plant

transpirational pull the force arising from the evaporation of water from leaves and transmitted down the xylem

turgor the capacity of plant cells to be pressurised through the process of osmosis

vascular bundle a combined bundle of xylem and phloem tissues in plants

vascular tissue (in plants) the plant tissue devoted to the bulk transport of water, nutrients, sugars and other substances; comprising the xylem and phloem

vessel element one type of cell comprising xylem tissue of flowering plants; they have perforations at each end of the usually dead cells to allow the free flow of water

water potential the capacity of water to do work based on the kinetic energy of its individual molecules; the work is done as water moves across selectively permeable membranes through osmosis

xylem a vascular tissue in plants, mainly comprised of dead cells, responsible for the bulk transport of water and nutrients from the roots to the rest of the plant

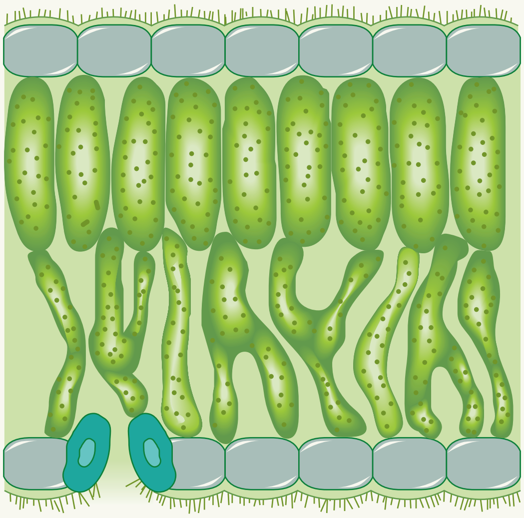
CHAPTER REVIEW QUESTIONS

Remembering

1 List the major resources that plants must exchange with their environment.
2 Name the two types of vascular tissues in plants.
3 Describe how vascular tissue is arranged in most plants.
4 List the factors in the external environment of a plant that would affect the rate of transpiration.
5 Describe the key adaptation of some tropical plants to limit water loss under high daytime temperatures.

Understanding

6 Outline the major difference between transport systems in animals and in plants.
7 Summarise the main characteristics and functions of the two types of vascular tissues in plants: xylem and phloem.
8 Using Figure 12.24, explain the pathway of oxygen and carbon dioxide through the leaf cells. Indicate what processes these gases would be used or produced in, and where these processes will occur.



◀ Figure 12.24

9 Explain why leaves tend to be flat and thin.
10 Discuss the importance of turgor to leaves.
11 Explain how sugars are moved through the phloem.
12 Explain why the function of the phloem depends on having xylem tissue nearby.
13 Explain how the absorption of carbon dioxide and the loss of water are controlled in leaves.
14 Explain how most plants respond to very high temperatures to limit the loss of water from leaves, and what effects this has on leaf function.
15 Describe how the structure of mosses and liverworts requires them to live in moist environments.

Applying

16 Plants are able to use oxygen produced in photosynthesis for the process of respiration and carbon dioxide produced in respiration for photosynthesis.
   a Suggest under what circumstances the plant would be able to supply its own gaseous requirements.
   b Predict when the plant would need to take in oxygen or carbon dioxide from the outside environment.
   c Explain why a plant will lose weight when kept in the dark.
17 If stomata could be manipulated to always stay open, predict the effect on a plant. Suggest what would happen to a plant if stomata always stayed shut.
18 Aphids are often regarded as sucking insects. Explain why aphids do not actually need to suck when they feed.

19 Suggest what the energy source is for the following processes.
  a The transport of water from the roots to the crown of a tall tree
  b The transport of sugars from the leaf to other parts of a tree
20 Discuss which characteristic of mosses limits how large they can grow.

Analysing

21 When transplanting plants from one place to another, it is important to take some of the natural soil still clinging to its roots. Suggest reasons for this, given what you have learned about mycorrhizae and root hairs.
22 Explain how the uptake of mineral ions differs from the uptake of water from the soil.
23 In most plants, the xylem is mostly comprised of dead tissue while phloem is always comprised of living cells. Account for this difference in terms of the different mechanisms used to move substances through the xylem and phloem vascular systems.

Evaluating

24 Transpiration has been described as a 'necessary evil'. Explain the costs and benefits of transpiration to a plant.
25 A certain plant is shown to have fungus growing around its roots. The plant seems to be growing better than other plants without the fungus. Suggest reasons why this may be the case.

Creating

26 Plants are continually losing water as they open their stomata to absorb carbon dioxide. Consider and discuss how the rising levels of carbon dioxide in the atmosphere, due to human activity, might affect plants.
27 Consider the type of plants that would be suitable to establish in a harsh Australian outback garden. Propose the plant features you would select. Discuss the adaptations the plants would need in order to survive in the environment of very high light levels and high temperatures.