Bio Factsheet

Number 81

Gas Exchange in Plants

This Factsheet covers the relevant AS syllabus content of the major examination boards.
By studying this Factsheet candidates will gain a knowledge and understanding of:
- **Fick's Law and leaf structure.**
- **stomata and stomatal mechanism.**
- **gas exchange in leaves.**
- **gas exchange in other plant organs.**

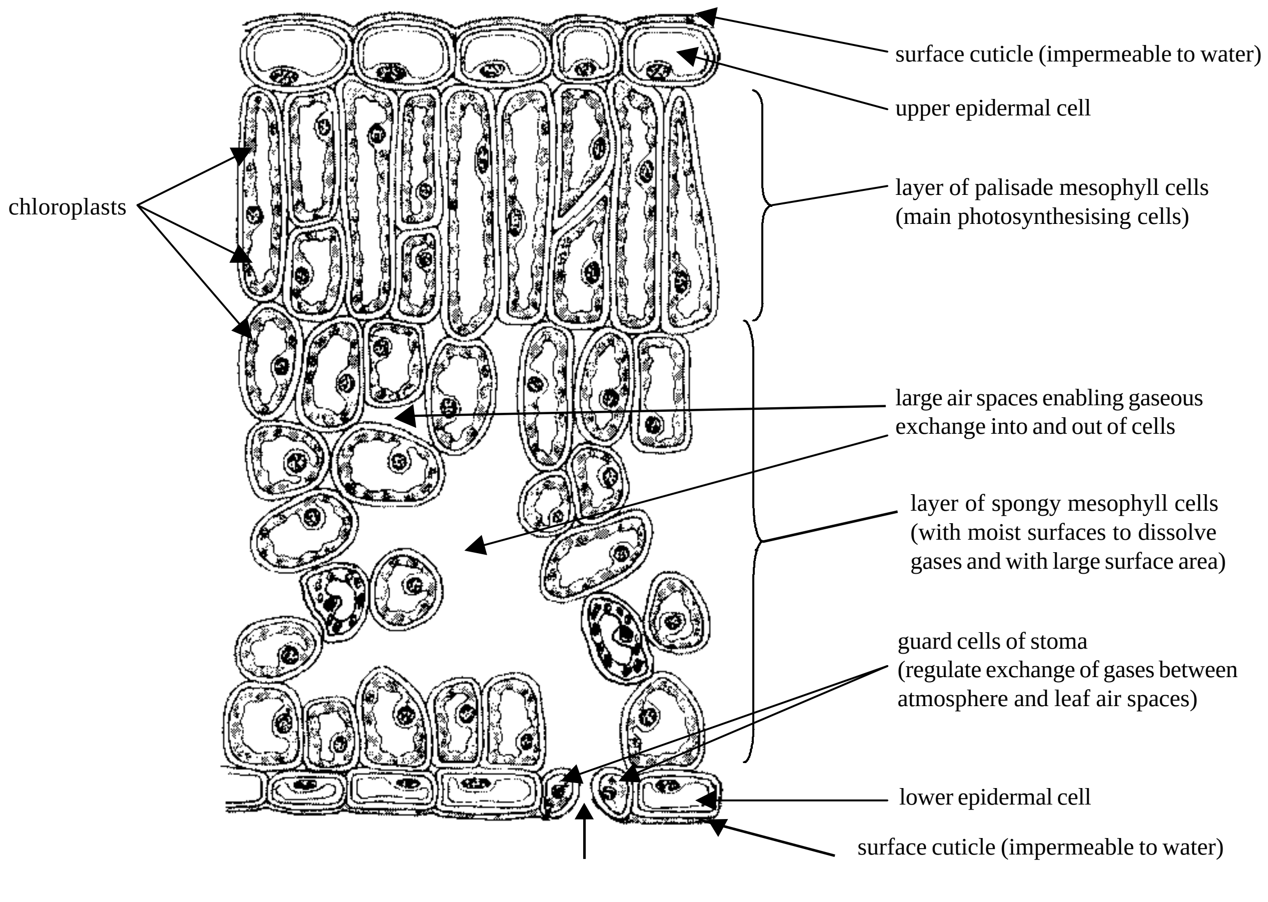
Introduction

Like all other organisms, flowering plants require a constant supply of energy. Most of this energy is supplied by the process of aerobic respiration of carbohydrate, some by anaerobic respiration. Most flowering plants are autotrophs, manufacturing carbohydrate from carbon dioxide and water by the process of photosynthesis. Both respiration and photosynthesis require a constant supply of gases and a means of disposing of any gaseous waste products. The most obvious source and sink for these gases, for terrestrial plants, is the atmosphere. The problem is this: adaptations which increase the efficiency of gas exchange also increase the rate of water loss, hence increase the chance of the plant dying from desiccation (plants need water for metabolic processes and for turgidity). Flowering plants have evolved to overcome this conflict.

All living cells in all parts of a plant must respire and therefore need to exchange respiratory gases, but by far the most active gas exchange in terrestrial flowering plants, takes place through their leaves. Leaves are especially adapted to enable efficient gas exchange, yet at the same time avoid excessive water loss. The structure of a typical dicotyledonous leaf is shown in Fig 1.

> ***Exam hint –*** *Examiners frequently require candidates to relate the structure of the leaf to the leaf functions. The specifications only require candidates to know dicotyledonous leaves.*

Fig 1. Vertical section through a typical dicotyledonous leaf



Fick's Law and leaf structure

Gases pass in and out of a leaf by diffusing down concentration gradients.

> ***Remember*** - *diffusion is the net movement of particles (molecules or ions), from a region of high concentration to one of lower concentration.*

Diffusion is the result of the random movement of particles. Increasing the temperature of the particles increases the rate at which they move and therefore the rate at which they diffuse. Three other factors significantly affect the rate of diffusion:

(a) the surface area over which diffusion occurs,
(b) the difference in concentration of the gas across the surface (concentration gradient) and
(c) the distance over which the gas has to diffuse (length of diffusion path).

Increasing the value of (a) and (b) and decreasing the value of (c) increases the rate of diffusion.

> ***Remember*** - ***Fick's law*** *considers the way these three factors relate to the rate of diffusion. This law states that:*
>
> *the **rate of diffusion** is proportional to* $\frac{\text{surface area} \times \text{difference in concentration}}{\text{length of diffusion path}}$

The leaves of most land plants are typically flattened, offering a large external surface for light absorption and large internal surface for gas exchange. They are usually thin in cross section. The gas exchange surface within a leaf is made up of the combined surfaces of all the cells that are in contact with air in the air spaces. This gives a very large surface area and a short diffusion path, both features that, according to Fick's law, favour a rapid diffusion.

Exchange of gases takes place between the damp surface of the mesophyll cells and the air contained within the intercellular air spaces. The surface of a leaf is bound by epidermal cells covered by a waxy cuticle to prevent dehydration. Pores, known as stomata, are found mainly in the lower epidermis. Stomata allow the air in the intercellular air spaces of the leaf to communicate with the atmosphere outside. When they close, water loss and gas exchange are reduced.

Stomata and stomatal mechanism

The structure of a stoma is shown in Fig 2.

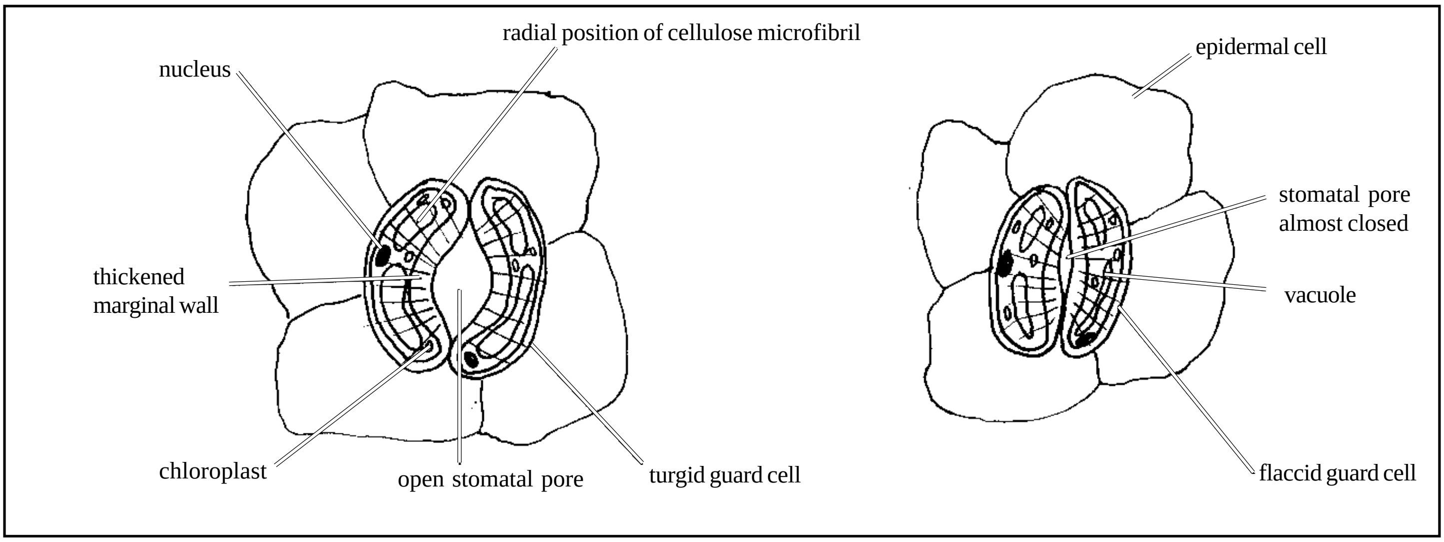
Most cells change shape in a regular way when they experience turgor changes. Guard cells are unusual in that the wall adjacent to the partner guard cell does not move outward as one might expect when the cell inflates with water. This particular wall is thicker, more rigid than the others and resists the stretching effect. Cellulose micro-fibrils occur in the walls of guard cells. They are aligned along what would be the radii of a circle whose centre would be the centre of the stomatal pore. The micro-fibrils act like guy-ropes, anchoring the wall adjacent to the pore to the others. As the thinner walls are stretched outwards as turgor increases, the 'pore-walls' are dragged apart, opening the pore. The size of the pore depends on the state of turgor experienced by the guard cells. At full turgor the pore is kept wide open, closing only when turgor is lost.

> ***Remember*** – *guard cells contain chloroplasts, enabling them to photosynthesise, whereas epidermal cells do not contain chloroplasts. Thus the epidermis is transparent and allows light to reach the mesophyll cells.*

Guard cells are sensitive to carbon dioxide concentration and water availability. When the carbon dioxide concentration of the intercellular spaces in the leaf starts to decrease, the guard cells tend to show an increase in turgor and the stomata open. This will occur when photosynthesis starts up at dawn, removing respiratory carbon dioxide from the intercellular spaces. As it gets dark, photosynthesis slows, carbon dioxide levels rise and the stomata close. However there are some species that open and close their stomata in a set pattern, irrespective of light and carbon dioxide concentrations. Some species of plants (for example, cacti) show inverted stomatal rhythms, opening at night and closing during the day. Water availability also has a controlling influence. If the plant is losing more water than it can take up, then the guard cells lose turgor and the stomatal pores are closed whatever the light and carbon dioxide levels happen to be.

Plant physiologists suggest that the control mechanism, for these turgor changes involves controlled changes in the concentrations of potassium ions and glucose in the guard cells. It is suggested that hydrogen ions are actively pumped out of the guard cells and as a result potassium ions diffuse in from the surrounding cells. At the same time, starch manufactured by photosynthesis in the guard cells is hydrolysed to form glucose which is then metabolised to malate ions, which are negatively charged. These balance the positive charge of the potassium ions. The increased concentration of the potassium and malate ions lowers the water potential of the guard cell sap and so water is taken in from surrounding cells by osmosis. The guard cells show an increase in turgor as a result, and the stomatal pores are opened. How the potassium pumps are switched on and off to control these changes is not fully understood as yet, but presumably, it is likely that carbon dioxide concentration and light intensity are influential factors.

Fig 2. Surface views of a stoma in open and closed states



Gas exchange in leaves

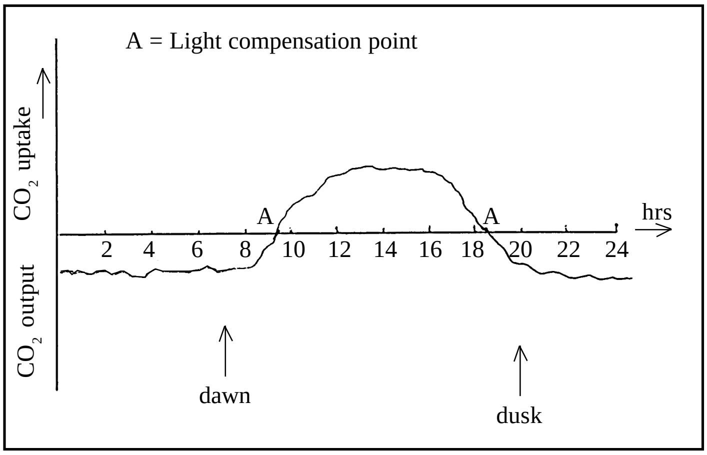
Three processes occur in the leaves of flowering plants that involve the exchange of gases with the atmosphere: respiration, photosynthesis and transpiration.

Transpiration is the process during which water vapour is lost from the shoot system of a flowering plant to the atmosphere. Water diffuses from the moist exchange surface, provided by the spongy mesophyll tissues of leaves, into intercellular air spaces. Air in these spaces will be highly saturated. Water vapour passes down a diffusion gradient, out of the leaves through stomata and into the atmosphere.

***Remember** – the water is supplied to the leaf from the xylem vessels which transport water from the roots.*

Fig 3 illustrates the carbon dioxide exchange pattern of leaves over a 24 hour period.

Fig 3. Exchange of carbon dioxide by mesophyll cells over a 24 hour period



***Exam hint** – Questions are commonly set on compensation points. The compensation point is the **light intensity** at which the rate of carbon dioxide use in photosynthesis is exactly balanced by the rate of carbon dioxide release by respiration. At this light intensity there will be no net uptake or release of carbon dioxide by the leaf.*

All plant cells must respire continuously to stay alive. The oxygen that leaf cells require is present in intercellular air spaces. Oxygen diffuses down a diffusion gradient from the air space into the cytoplasm and mitochondria of the cells. Respiratory carbon dioxide passes in the opposite direction. Those cells in a leaf that contain chlorophyll are able to photosynthesise. These cells obtain the carbon dioxide they require from the intercellular air spaces of the leaf and dump waste oxygen into them. Once more the gas exchange surface will be the surfaces of the cells involved and the direction of exchange will be determined by concentration gradients of the gases.

***Exam hint** – do not make the elementary but common mistake of saying that plants photosynthesise by day and respire at night. Plants respire all the time.*

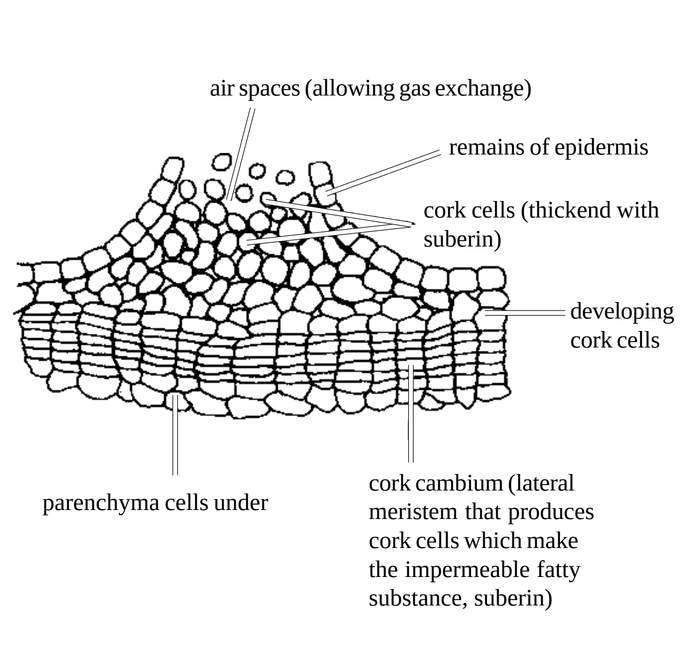
Because both respiration and photosynthesis use the same gas exchange surfaces and intercellular air spaces as sources and sinks for the same pair of gases, the overall result must depend on the relative rates of the two processes.

Photosynthesis requires light to proceed; respiration is continuous whether light is present or not. When photosynthesis starts, the carbon dioxide being produced by respiration, and that already present in the intercellular spaces from earlier respiratory activity, is likely to be enough to meet its carbon dioxide demands. However as the rate of photosynthesis increases, demand exceeds supply. Lowered concentrations of carbon dioxide trigger turgor changes in the guard cells of stomata (see above) and the stomatal pores are opened. Carbon dioxide diffuses from the atmosphere into the leaf and this extra demand is met. During the hours of darkness, oxygen for respiration is obtained from the air spaces, diffusing across cell membranes to the mitochondria. The cuticle of the leaf is not totally impermeable to oxygen and because atmospheric oxygen levels are so high, oxygen can diffuse through it and even through the closed stomata. This means that the large air spaces of the leaf and other parts of the plant can gain some oxygen at night. However, as the rate of photosynthesis increases, oxygen produced by the process eventually provides enough to maintain respiratory activity, replenishing oxygen levels in the air spaces. Photosynthetic rate exceeds respiratory rate for part of the day. This compensates for those periods when photosynthesis cannot take place but respiration can. When the rate of photosynthesis exceeds the rate of respiration, excess oxygen diffuses across the exchange surface, into the air spaces, and down diffusion gradients through stomatal pores into the atmosphere.

Gas exchange in other plant organs.

Plants are not as active as animals. This means that plants can maintain a full rate of respiration and live successfully with much lower oxygen concentrations. This is of particular significance to roots and stems. Roots obtain their oxygen from the air spaces between soil particles, but this tends to be in short supply owing to respiratory activity of not only the roots in question, but also those of other plants, and the respiratory activity of soil animals and microorganisms. When it rains the situation is made worse because the air is displaced by water and in poorly drained soils, totally replaced by it. Roots then rely on intercellular air spaces, linked throughout the plant, to act as sources of oxygen and sinks for respiratory carbon dioxide or are obliged to respire anaerobically. Herbaceous stem tissues obtain their oxygen from large air spaces or directly by diffusion through the cuticle from the atmosphere. Woody stems are bounded by bark. Bark is impermeable to water and respiratory gases. Special structures called lenticels occur. These are formed from groups of loosely packed surface cells that allow air to penetrate below the surface permitting exchange of gases in both directions. Fig 4 shows a vertical section through a lenticel.

Fig 4. Vertical section through a lenticel



Practice Questions

1. The equation below represents Fick's Law of diffusion across membranes:

$$J = DA \frac{\Delta c}{\Delta x}$$

where J = net rate of diffusion
D = diffusion constant of the dissolved solute
A = surface area of the membrane
Δc = concentration difference across the membrane
Δx = thickness of the membrane

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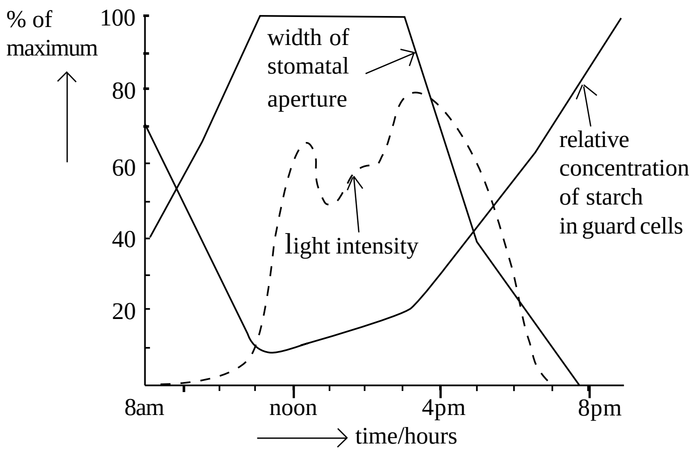
(a) Explain why, with reference to Fick's Law, a typical dicotyledonous leaf favours a high rate of diffusion and an efficient gas exchange. 4

(b) Suggest why lenticels only take up oxygen and give out carbon dioxide. 2

Total 6

2. The graph below shows results of investigations into the mechanism of stomatal opening.



(a) Describe the relationship between stomatal aperture width and starch concentration.
(i) Between 8.00 am and noon. 1
(ii) Between 4.00 pm and 8.00 pm. 1

(b) (i) Using information from the graph and your own knowledge, suggest a mechanism for stomatal opening. 5
(ii) What is meant by the term inverted stomatal rhythm? 1

Total 8

3. (a) Describe the gas exchange surface in the leaf. 3

(b) How do leaf cells get oxygen when the stomata are closed? 3

(c) Roots absorb some ions by active transport. This requires a supply of respiratory ATP. How do root cells obtain the oxygen essential for this process? 3

Total 9

Answers

Semi colons indicate marking points.

1. (a) (palisade) mesophyll cells provide a huge surface area for exchange;
when A is large then J/net rate of diffusion must be large;
leaf is thin so Δx is small thus J/net rate of diffusion is large;
if J is large then gas exchange must be fast/ efficient; 4

(b) lenticels only occur in (woody) stems which do not photosynthesise/use CO_2;
but stem tissues do respire and so require oxygen and give out carbon dioxide; 2

Total 6

2. (a) (i) stomatal width increases as starch concentration decreases; 1
(ii) stomatal width decreases as starch concentration increases; 1

(b) (i) as light intensity increases starch is converted to sugars;
increased sugar concentration reduces water potential of guard cells;
water enters osmotically causing guard cells to swell;
due to uneven guard cell wall thickening the swelling causes the stomatal pore to open;
hydrogen ions also pumped out of guard cell and replaced by uptake of potassium ions;
sugars converted to negative malate ions which neutralise/ balance the positive potassium ions;
accumulation of malate and potassium ions also reduce water potential of guard cells; max 5

(ii) stomata open at night/closed during day; 1

Total 8

3. (a) large surface area of cells (in contact with air spaces);
wet cell surfaces to dissolve gases;
ref to spongy mesophyll and palisade mesophyll; 3

(b) diffuses slowly through cuticle;
and closed stomata;
some oxygen already present in air spaces (as photosynthetic by-product during light); 3

(c) air between soil particles contains oxygen;
oxygen diffuses through the root surface cells/particularly through root hair cells;
cells also obtain oxygen from intercellular air spaces in the root; 3

Total 9

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