TRANSPORT OF MATERIALS IN PLANTS

Plants require adequate supply of CO_2, O_2, mineral salts and water for normal growth. Lower plants like algae move materials in and out of their bodies by diffusion and active transport because they have a large surface area to volume ratio. Higher plants have a vascular system which helps in translocation.

The vascular tissues have several adaptations to perform their functions.

Adaptations of the xylem tissue

1. Has long cells joined end to end in order to form a continuous column for the flow of water.
2. End walls break down to form an uninterrupted structure to ensure smooth flow of water from vessels to leaves in tracheid. Where end walls are not present, large pits are formed to reduce the resistance to flow.
3. There are pits at particular places where lignin is deposited. These pits allow natural flow of water where this is necessary to prevent air bubbles from blocking the vessels.
4. Deposition of cellulose walls with lignin increases the adhesive forces between water molecules and the tissue wall and it enables water to raise up by capillarity.
5. The xylem tissue especially the vessels have very narrow lumen of about 0.01-0.02mm in diameter. This increases capillarity forces for the uptake of water.
6. Each xylem element has a wall made up cellulose and lignin. Lignin is water proof and a very strong material which helps in maintaining water inside the xylem element.

Adaptations of the phloem to its function

The phloem has tissues that are well adapted to movement of materials in the following ways:

1. Possess cytoplasmic strands over which materials can flow.
2. Possess end walls called sieve plates which are perforated by numerous pores to allow passage of substances from one sieve element to the next.
3. The cytoplasm of the sieve elements is structurally simple with no or few organelles like endoplasmic reticulum. This provides large space for the movement of materials.
4. Besides each sieve element is a companion cell which possesses nucleus, mitochondria, endoplasmic reticulum, etc., which is a site for intense metabolism. The mitochondria provides the energy required.
5. Cells have plasmadesmata pits that allow movement of materials between sieve elements.
6. The phloem tissue in leaves have transfer cells responsible for moving products of photosynthesis from the mesophyll cells to the sieve tubes.

THE UPTAKE OF WATER:

ABSORPTION

The uptake of water by the roots is mainly done by the root hairs which are extensions of epidermal cells in the piliferous region of the root. Here the epidermis is freely permeable to water (but selectively permeable to inorganic ions). The root hairs serve to increase the surface area and are adapted for absorption by;

- Lacking a cuticle (hence making them freely permeable) making water to be absorbed directly into the root.

- Being slender and flexible to penetrate between the soil particles and absorb water from the soil spaces
- Having a lower water potential than the soil solution. This is because they have a cell sap in which are sugar and other metabolites. The resulting water potential gradient favours osmosis the main means of water absorption.

The absorption of water by the root hair cells in turn leads to an increase in their water potential relative to adjacent cells which results in the osmotic movement of water to neighbouring cells which have a lower water potential.

Movement of water and dissolved salts across the root:

This takes place via three different routes:-

i) **The Symplast:** i.e. from cytoplasm to cytoplasm through the plasmodesmata. The term symplast is used to refer to the continuous large fluid compartment consisting of the cytoplasm of adjacent cells and the plasmodesmata connecting them with no intervening cell surface membranes. Water enters the symplast by osmosis.

i i) **The Apoplast:** i.e. from cell wall to cell wall. The cellulose fibres which make up these cell walls leave many spaces between them which are filled with water just as are the iruerce llular spaces. Since these are freely permeable water moves across them by diffusion. It is this continuous fluid system in the cell walls that is known as the apoplast.

iii) **The vacuolar pathway**: i.e. from vacuole to vacuole. Since water is one of the components of the vacuole sap.

The most used route for water movement across the root is the apoplast because it offers relatively least resistance to water flow for it does not need to go through any impeding membranes. Compare this with the vacuolar in route where- to pass from cell to cell the water must move by osmosis through the tonoplast, and through the cell membranes and cell walls. This certainly offers great resistance and slows down its movement.

Diagram illustrating the routes taken by water across the root.
(FA page 184 fig 12.5 B&C)

Water moves along a water potential gradient by either of the above three routes from the piliferous layer to the epiblem, cortex, endodermis, pericycle and finally the xylem, At the endodermis due to the presence of the casparian strip water is forced to move only along the symplast.

The role of the endodermis and its casparian strip in water uptake and transport stems from the fact that:

(i) The endodermis secretes salts actively into the vascular tissues and the low water potential thus created there forces water to enter by osmosis.

(ii) The casprian strip prevents the outward leakage of salts from the vascular tissues hence maintaining this status quo of a low water potential.

Movement of water within the xylem (up the plant)

Three theories have been suggested to explain the movement of water through the xylem in the stem up the plant. These are:

1. The capillarity theory

Capillarity is the rise of liquids in narrow tubes and depends among other things on the adhension of water molecules to the walls of the tubes. As a result of this water tends to rise highest in the narrowest tubes because they present the largest relative surface area of wall in contact with adhering water molecules. Now since the xylem vessels are also tubes of very fine bore water adheres to the vessel walls and since they are stacked end to end they form long capillary tubes from roots to leaves.

Consequently water will rise up the xylem from the root by capillarity. However this process must be playing a minor role in the upward movement of water in a plant for even in the finest vessels it would only rise about 1metre which is not far enough to reach the leaves of even a small tree. Therefore other mechanisms must be involved.

2. **The Root pressure theory**

This has been suggested as a result of the common observation that water tends to exude from a cut stem indicating that some pressure in the root is actually pushing it up.

The origins of root pressure are in the endodermis where the active transfer of ions from the cortex into the xylem occurs which are subsequently prevented from leaking out by the casparian strip and result in a water potential gradient forcing water into the xylem via the symplast of the endodermal cells which results in a hydrostatic pressure which can only be relieved by water moving up the xylem.

Root pressure is an active process and is confirmed by the facts that:-

i) It occurs only in living plants

ii) It is affected by the same factors affecting respiration in cells like oxygen supply, temperature, carbohydrate supply and the presence of respiratory poisons like cyanide.

Like capillarity, root pressure is not sufficient on its own to push water to leaves at the top of tall trees.

3. The transpiration theory:

This theory suggests that water is not pushed up the stem but pulled up as a result of tensions (negative pressure) created in the leaves due to the loss of water in them by evaporation in the process of transpiration.

Thus the cells of the leaf mesophyll in order to replace the lost water exert a pull by which they draw water from the xylem vessels known as the **transpiration pull.** The resulting movement of water in the xylem in continuous column is called the **transpiration stream** and this is possible because water molecules being polar, i.e. have a property of attracting one another (cohesion) and other molecules as well like the walls of the vessels (adhesion). For this reason great tension can be maintained in the xylem without the columns of water breaking. By combination of the three forces transpiration, cohesion and tension the water column can be pulled to the top of the tallest trees.

The diameter of most tall trees has been found to decrease during periods of maximum transpiration e.g. around mid day. This is explained by the fact that columns of water molecules now draw this by the tension exerted by the transpiration pull still continue to adhere to the xylem vessel walls and pull them inwards. However the theory does not explain why it is not possible to block the xylem vessels with air bubbles e.g. when branches on a tree breaks off.

TRANSPORT OF ORGANIC SOLUTES IN THE PHLOEM

Soluble products of photosynthesis formed by photosynthetic tissue enter the sieve tubes by active transport. Once in the sieve tubes the speed at which they move along the concentration gradient is too fast to be explained by diffusion alone.

Theories explaining the mechanism of translocation.

1. The mass flow hypothesis:
2. Electro osmosis theory
3. The cytoplasmic streaming hypothesis

a) The mass flow hypothesis:

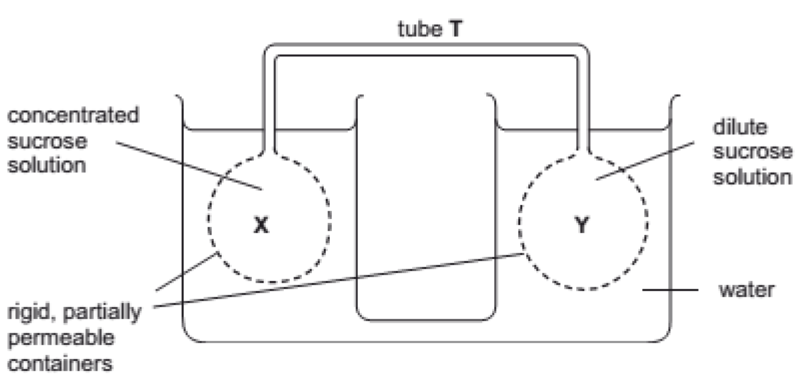
Mass flow also known as **Pressure Flow** *refers to the bulk transport of materials from one point to another as a result of turgor pressure difference between the two points..*

Mass flow hypothesis explains translocation as a result of photosynthetic products moving through the phloem tissue from the leaves to the roots due to the turgor pressure gradient.
In the leaves, turgor pressure is high due to manufacture of food substances and materials produced e.g. sucrose increases the osmotic pressure of mesophyll cells which when absorbed would result into increase in turgor pressure.
In the roots, turgor pressure is very low because food substances respired to release energy.
The difference in turgor pressure enables food substances to flow from the source to the sinks.
Any area of a plant from which sucrose is loaded into the phloem is called a **source**. An area that takes sucrose out of the phloem is called a **sink**.
There are several evidences to show that mass flow occurs in plants. These include;

1. There is flow of food substances/solution; there is flow of sap from a cut stem.
2. There is flow of sap from aphid stylets.
3. There is a difference in the concentration of sucrose between the leaves and roots. Concentration of sucrose is higher in leaves than the roots therefore turgor pressure gradient occurs.
4. Some viruses and growth substances applied to the leaves move through the phloem to the roots.

Munch demonstrated mass flow as a physical process as illustrated below;

Copy the **Illustration (Functional Approach) page 195 fig 12.17**



The model above illustrates mass flow i.e. bulk movement of food substances from higher turgor pressure to a lower turgor pressure.
Flask X contains a concentrated solution which in plants may stand for leaves. Flask Y contains a dilute solution which in plants may be roots. Fluid flows from flask X to flask Y through the delivery tube T. The delivery tube may represent phloem tissue which connects the source to the sink.

Shortcomings of the mass flow hypothesis

Although the mass flow hypothesis is widely accepted, there are some observation that regard translocation that it can't explain.

1. Different solutes have been observed to move at different speeds since the sieve tubes are not equally permeable to all solutes. The ratios of concentrations of various solutes changes as the solutes move along the sieve tube resulting in a change in their rate of flow.
2. Materials have been observed to move up and down at the same time in the phloem tissue, mass flow can't account for bi-directional flow.
3. In some plants, gradients of turgor pressure are insufficient to overcome the resistance caused by the sieve pores and plates to move the food substances.

b) Electro osmosis

This is the movement of ions in an electrical field through a fixed porous electrically charged surface. It follows observations that:-

(i) Ions move in an electrical field to the pole with a charge opposite to their own i.e. + to – and vise versa
(ii) Ions with a like charge repel each other.
(iii) Ions in aqueous solution are surrounded by a shell of water i.e. they are hydrated.
(iv) Water and its dissolved solutes e.g. sucrose which surrounds the hydrated ions is bound to the hydration shell by hydrogen bonds.
(v) When hydrated ions move in an electric field water and dissolved solutes will follow such ions.
(vi) The sieve plates and phloem proteins are normally negatively charged thus forming the required fixed and charged porous surface.

Thus it is argued that when mass flow occurs downwards through the phloem the anions being repulsed accumulate above the sieve plate so that the cell above the sieve plate becomes negative with respect to that below. A potential difference builds up on the sieve plate and when it reaches a critical value (the threshold) protons (H^+) surge from the wall of the upper cell into its cytoplasm lowering its pH and making the cytoplasm above the sieve plate positively charged. This pushes other positive ions (cations) mainly K^+ by electrical repulsion through the sieve plate from the upper to the lower cell (i.e electro-osmosis occurs). This surge of hydrated potassium ions carries water molecules and dissolved solutes like sucrose across the sieve plate. Later on using ATP from the mitochondria in the companion cell, proton pumps in the surface membrane of the sieve tube cell quickly pump protons out of its cytoplasm and back into its cell wall. The cell therefore reverts to its original state and the process begins all over again.

(vii) This theory does not object Munch's mass flow hypothesis but modifies it to explain among other things:- The great velocity of translocation in the phloem, the great energy demands and the fact that presence of sieve pores does not necessarily increase resistance to flow. It therefore accounts for the need for companion cells and sieve plates in the phloem and this is compatible with Munch's hypothesis by suggesting that solutes move in the phloem by mass flow but the flow is boosted at intervals (at the sieve plates) by electro-osmosis.

Evidence that transport occurs through the xylem and phloem

i) Use of ringing experiments

The active phloem of a woody stem is located on the inside of the bark while the xylem is located in the interior woody region. Hence the removal of a complete strip of bark in a ring around a woody stem known as ringing removes phloem but leaves xylem intact. The results show that the sugar concentration increases immediately above the ring and decreases below it indicating that the downward movement of the sugar is blocked.

ii) Use of ^{14}C labelled sucrose:

A plant is exposed to CO_2 labeled with radioactive 14C which becomes incorporated into the products of photosynthesis like sucrose which are subsequently detected in the part of the stem that contains the phloem. By use of autoradiographs of sections through plant tissues it has been shown that radioactive sucrose is carried in the sieve tube cells of the phloem but not in the xylem.

Such experiments have to assume that plants transport sucrose molecules containing radioactive carbon atoms (^{14}C) in the same way as those containing only non-radioactive carbon atoms (^{12}C). This technique could be combined with ringing experiments to ascertain the effect of removing phloem on the transport of labeled sucrose.

iii) Use of radioactively labeled ions:

If plant roots are treated with solutions containing such radio-active inorganic isotopes of organic ions and later autoradiographs prepared they show radioactivity in both the xylem and phloem. If however the xylem and phloem are separated e.g. by use of paraffined paper radioactivity is detected only in the xylem.

If plant leaves are treated with solutions containing such radio-active inorganic ions detection of radioactivity in the stem is in the phloem and not in the xylem.

These experiments suggest that ions from the roots tend to travel in the xylem while those from the leaves travel through the phloem though some communication seems to occur between the phloem and xylem.

iv) Experiments using aphid stylets:

It has been observed that when aphids feed, their stylets penetrate into the hosts phloem and sometimes into a single sieve tube from which sugar and other phloem contents are forced up the stylet by the hydrostatic pressure which exists in the sieve tubes into their alimentary canals.

Thus the use of feeding aphids enables an analysis of the contents of phloem sieve tube cells by cutting through the stylet of anaethesised aphids and collecting the exuded sap by micropipetes. Chemical analysis of this sap can then be carried out. Such analysis here shown that phloem sap is an alkaline solution containing a mixture of organic compounds and inorganic ions. Up to 90% of the organic solutes being sugar (mainly sucrose) and up to about 12% being amino acids. Other substances present in the phloem include ATP, preteins (including enzymes), hormones, alkaloids, vitamins and of course water.

c) **Cytoplasmic streaming**

Within the phloem tissue, there are cytoplasmic strands or filaments which are proteins in nature and they are continuous from one sieve element to another via the pores. Food substances are able to move along these strands due to wave-like contractions generated by the filaments. The sieve elements use energy provided by the companion cells to carry out such contractions. Cytoplasmic streaming enables some food substances to move upwards while others downwards. It therefore accounts for the bi-directional flow of substances observed in the phloem tissue.

Shortcomings/criticisms:

Plants would require a lot of energy to transport the observed food units of food substances.

UPTAKE OF IONS

Ions are absorbed into the root hairs, transported across the root, and then into the xylem. They then travel in solution in water to all parts of the plant.

The mechanism by which ions are taken up by root hairs depends on their concentration in the soil solution. If a particular type of ion is in a higher concentration in the soil than inside the root hair cell, then it will be absorbed by ***facilitated diffusion.*** This does not require any energy input by the plant. If, however, the concentration of the ion in the soil is lower than that inside the root hair cell, then it must be absorbed by ***active transport***. Specific transporter proteins use energy derived from the hydrolysis of ATP to move ions through the cell membrane into the cytoplasm.

TRANSPIRATION

This is the loss of water inform of water vapour from the aerial parts of the plant to the atmosphere. Transpiration is as a result of evaporation of water from the mesophyll cells into the air spaces then out of the leaf through the stoma. It normally occurs over the leaves that have numerous pores (stoma). It can also occur at the bark where there are lenticels and some water can be lost through the cuticle.

Importance of transpiration in plants

Transpiration has been described as a *necessary evil* because it is an inevitable but potentially harmful consequence of the existence of moist cell walls from which evaporation occurs. Water vapour escapes along the routes used for gaseous exchange between the plant and its environment which is essential for the process of photosynthesis and respiration.

Loss of water can lead to wilting, cause desiccation and kill the plant if conditions of drought are experienced. Evidence shows that even mild water stress results in reduced growth rate. However, despite its inevitability, it is worth to note that there are some advantages associated with transpiration.

i) It cools down the plant.

ii) It helps in the movement of water and mineral salts through transpiration pull.

iii) It leads to remove of excess water.

iv) Keeping mesophyll cells moist ensures that gaseous exchange occurs especially in leaves.

Factors affecting transpiration

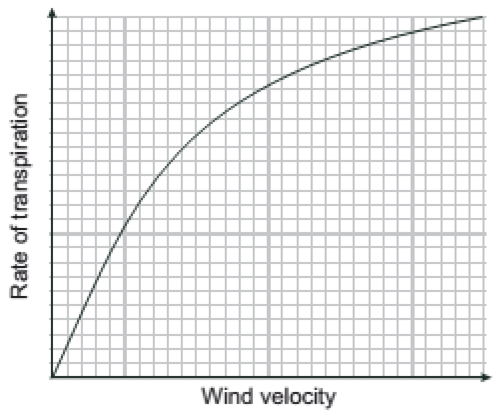
Anything that increases the water potential gradient between the air spaces in the leaf and air outside, or that speeds up the movement of the water molecules, will increase the rate of transpiration.

i) **Humidity:** humidity is a measure of how much water vapour is held in the air. In conditions of low humidity – that is, when the air is dry – there is a steep water potential gradient between the leaf and the air. Transpiration rates are therefore greater in low humidity than in high humidity.

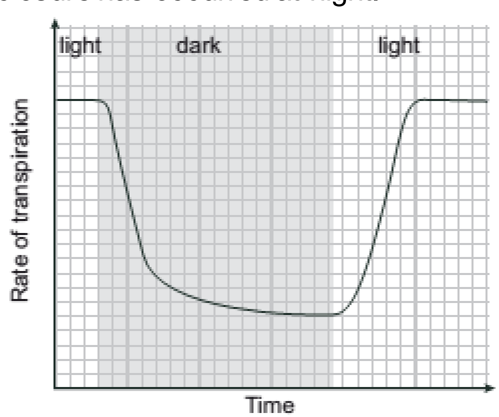
ii) **Temperature:** an increase in temperature causes an increase in the kinetic energy of water molecules. This increases the rate of evaporation of water from the cell walls into the air spaces, and also the rate of diffusion of the water vapour out of the leaf. An increase in temperature therefore increases the rate of transpiration.

iii) **Light intensity:** light does not normally have any direct effect on the rate of transpiration during the daytime. However, many plants close their stomata at night, when it is dark and they are unable to photosynthesis and so do not need to use carbon dioxide from the air.

iv) **Air movements:** the more the air around the plant's leaves is moving, the faster the humid air surrounding them is carried away. This helps to prevent the leaf becoming surrounded by air that is saturated with water vapour, and maintains a water potential gradient from the air spaces inside the leaf to the air outside. Transpiration therefore happens faster on a windy day than on a still day. ***Fig. below***



v) **Stomatal aperture:** in many plants, stomata close at night. In the graph below stomatal closure has occurred at night.



In especially dry conditions, the plant may close its stomata even when light levels are ideal for photosynthesis, to avoid losing too much water from its leaves. There is often a compromise to

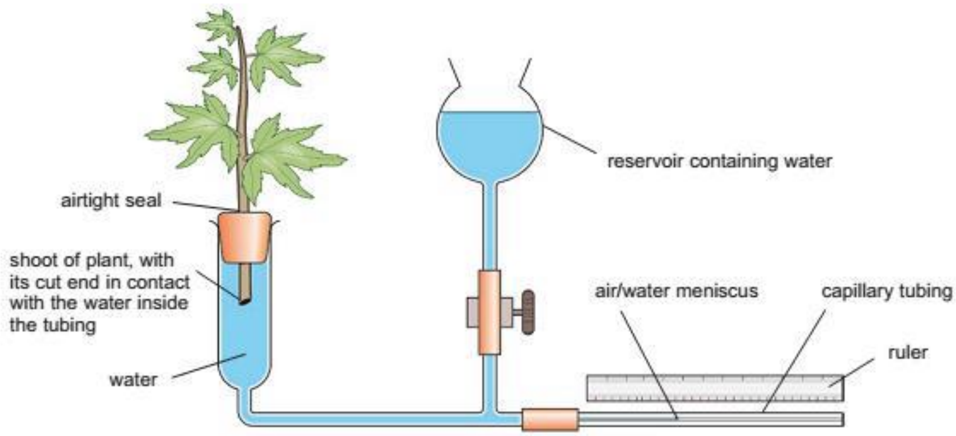
be reached between allowing in enough carbon dioxide for photosynthesis, and not letting out too much water vapour. The rate of transpiration is higher at larger aperture.
However, in still air, the increase in the rate of transpiration is very little at larger apertures, whereas in windy conditions, the rate continues to increase even with larger apertures.
vi) **Plant structure:** transpiration occurs from the surface of leaves and green stems. For plants that need to conserve water, reducing the area of these surfaces will limit the rate of transpiration. This can be done by dropping leaves in dry seasons, having small leaves or having no leaves (relying on green stems for photosynthesis).

vii) **Leaf anatomy:** a number of structural features can reduce the rate of transpiration, even when stomata are open. All of these features act by trapping still air outside the stoma. This increases the distance water has to diffuse before it can be carried away in the mass flow of air in the wind. The further the distance water has to diffuse, the slower the rate of transpiration.

This is achieved by one of the following; having stomata set in pits, having stomata on a leaf surface that is on the inside of a rolled leaf, having dense hairs on the leaf surface or having a thick layer of wax on the leaf.

Measuring/comparing the rate of transpiration

It is not easy to measure the rate at which water vapour is leaving a plant's leaves. This makes it very difficult to investigate directly how different factors, such as light or air movement, affect the rate of transpiration. However, it is relatively easy to measure the rate at which a plant stem takes up water. A very high proportion of the water taken up by a stem is lost in transpiration. As the rate at which transpiration is happening directly affects the rate of water uptake, this measurement can give a very good approximation of the rate of transpiration. The apparatus used for this is called a ***potometer.***



It is essential that everything in the potometer is completely watertight and airtight, so that no leakage of water occurs and so that no air bubbles break the continuous water column.

To achieve this, it helps if you can insert the plant stem into the apparatus with everything submerged in water, so that air bubbles cannot enter the xylem when you cut the stem. It also helps to cut the end of the stem with a slanting cut, as air bubbles are less likely to get trapped against it.

As water evaporates from the leaves, more water is drawn into the xylem vessels that are exposed at the cut end of the stem. Water is drawn along the capillary tubing. If you record the position of the meniscus at set time intervals, you can plot a graph of distance moved against time. If you expose the plant to different conditions, you can compare the rate of water uptake.

Adaptations of plants to prevent water loss

1. Reduction of leaves to fine spines
2. Small leaves to reduce on the number of stomata
3. Stem with hard thick epidermis covered with waxy cuticle.
4. Ability to fix CO_2 at night so that the stomata can be closed during the day.
5. Possession of thick succulent leaves that can store water.
6. They have organ pipe-like stem that point vertically upwards to minimize the surface area exposed to the midday sun.
7. They have sunken stomata reduced in number and confined to the surface of the leaf.
8. Have a layer of stiff interlocking hairs in the inter-epidermis that reduces transparency by trapping air within the leaf.
9. Have shallow but extensive root system so they allow efficient absorption of water.

Qn: How are xerophytes adapted to their habitats (20 marks)