TRANSPORT IN PLANTS

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In a flowering plant the substances that would that need to be transported are water, mineral nutrients, organic nutrients and plant growth regulators. Over small distances substances move by diffusion and by cytoplasmic streaming supplemented by active transport.

Plants need to move molecules over very long distances, much more than animals do; they also do not have a circulatory system in place. Transport over longer distances proceeds through the vascular system (the xylem and the phloem) and is called translocation.

An important aspect that needs to be considered is the direction of transport. In rooted plants, transport in xylem (of water and minerals) is essentially unidirectional, from roots to the stems. Organic and mineral nutrients however, undergo multidirectional transport.

Organic compounds synthesized in the photosynthetic leaves are exported to all other parts of the plant including storage organs. From the storage organs they are later re-exported. The mineral nutrients are taken up by the roots and transported upwards into the stem, leaves and the growing regions.

- When any plant part undergoes senescence, nutrients may be withdrawn from such regions and moved to the growing parts.

Hormones or plant growth regulators and other chemical stimuli are also transported, though in very small amounts, sometimes in a strictly polarized or unidirectional manner from they are synthesized to other parts.

Hence, in a flowering plant there is a complex traffic of compounds (but probably very orderly) moving in different directions, each organ receiving some substances and giving out some others.

MEANS OF TRANSPORT

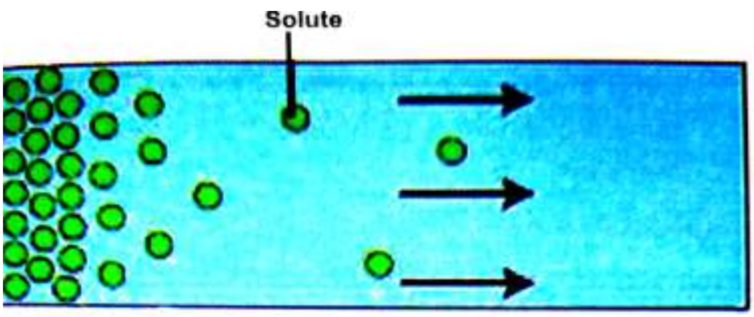
(Small distance transport)

Diffusion

1. **Simple Diffusion:** Movement of molecules from higher concentration to lower concentration.
   Movement by diffusion is passive, and may be from one part of the cell to other or from cell to cell, or over short distances (from the intercellular spaces of the leaf to the outside).
   No energy expenditure takes place. In diffusion, molecules move in a random fashion, the net result being substances moving from regions of higher concentration to regions of lower concentration.

- Diffusion is a slow process and is not dependent on a 'living system'

Diffusion is obvious in gases and liquids but diffusion in solids rather than of solids is more likely.



Diffusion Pressure

Pressure exerted, due to the tendency of the particles of a substances to diffuse is also called **diffusion pressure.**

Independent diffusion

Diffusion of particles of one substance is independent of the diffusion of particles of another substance, provided the two do not react. It is known as **independent diffusion.**

Partial pressure

eg- In photosynthesizing leaf, water vapours and oxygen diffuse out while carbon dioxide enters the leaf depending upon the difference in their pressures in the leaf interior and the outside. Diffusion is also responsible for uptake and distribution of water and solutes.

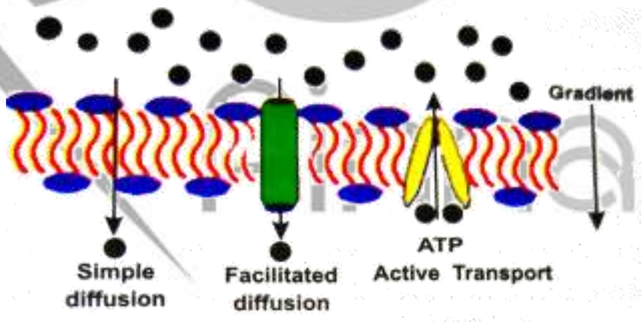
Factors influencing diffusion

- Diffusion rates are affected by gradient of concentration, the permeability of the membrane separating them, temperature and pressure.

1. **Density of substance:** Rate of diffusion of substance is inversely proportional to square root of its relative density.
2. **Density of medium:** Rate of diffusion decreases with density of the medium.
3. **Temperature:** A rise in temperature increases the rate of diffusion with $Q_{10} = 1.2 - 1.3$. Because of this, sugar crystals do not dissolve easily in ice cold water while they do so easily in warm water.
4. **Diffusion pressure gradient:** Rate of diffusion is directly proportional to the difference of difference of diffusion pressure at the two ends of a system and inversely proportional to the distance between the two.
5. **Size of substance:** smaller substances diffuse faster.

Importance

i. Diffusion is very important to plants since it is the only means for gaseous movement within plant body.
ii. Diffusion keeps the cell walls of internal plant tissues moist.
iii. Aroma of flowers is due to diffusion of volatile aromatic compounds to attract pollinating animals.

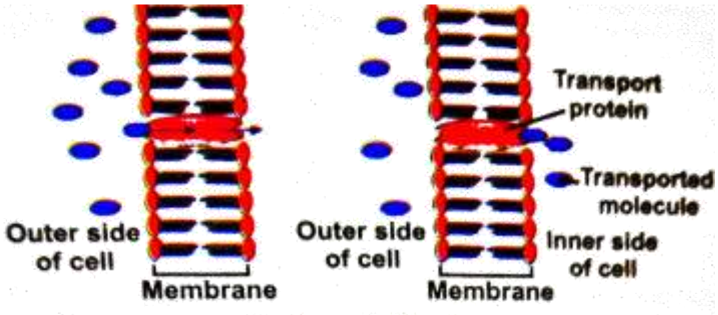


Mean of transport

2. **Facilitated diffusion:** The diffusion of any substance across a membrane also depends on its solubility in lipids, the major constituent of the membrane. Substances soluble in lipids diffuse through the membrane faster.

   Substances that have a hydrophilic moiety, find it difficult to pass through the membrane; their movement has to be facilitated. Membrane proteins provide sites at which such molecules cross the membrane. They do not set up a concentration gradient, a concentration gradient must already be present for molecules to diffuse even if facilitated by the proteins (facilitated diffusion).

- In facilitated diffusion special proteins help movement of substances across membranes without expenditure of ATP energy.



Facilitated diffusion

Facilitated diffusion cannot cause net transport of molecules from a low to a high concentration this would require input of energy.

Transport rate reaches a maximum when all of the protein transporters are being used (saturation).

Facilitated diffusion is very specific. It allows cell to select substances for uptake. It is sensitive to inhibitors which react with protein side chains.

The proteins form channels in the membrane for molecules to pass through. Some channels are always open. Other can be controlled. Some are large, allowing a variety of molecules to cross.

The **porins** are proteins that from huge pores in the outer membranes of the plastids, mitochondria and some bacteria allowing molecules up to the size of small proteins to pass through.

- Water channels – are made up of eight different types of aquaporin's.

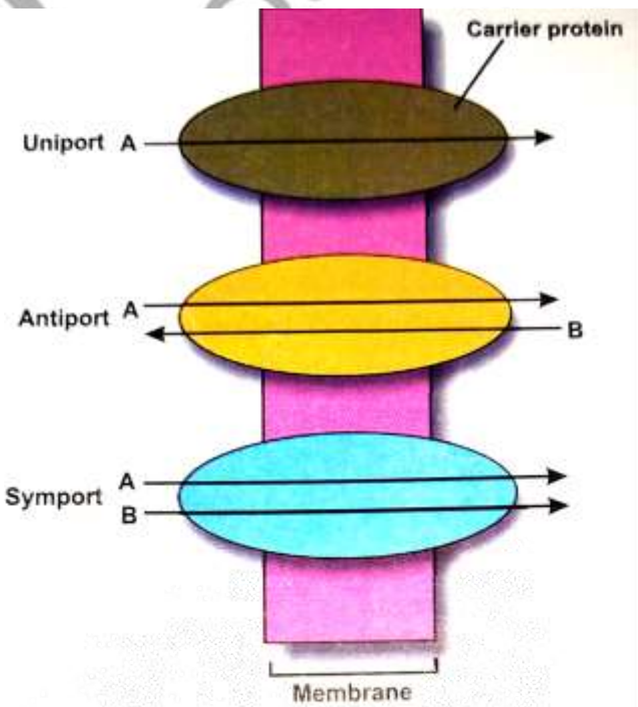
Passive symports and antiports:

Symport: Both molecules cross the membrane in the same direction.

Abtiport: Both molecules cross the membrane in the same direction.

Antiport: Both molecules move in opposite directions.

Uniport: Molecule moves across a membrane independent of other molecules.



3. **Active transport:** Active transport uses energy to pump molecules against a concentration gradient.

Active transport is carried out by membrane-proteins. Hence, different proteins in the membrane play a major role in both active as well as passive transport.

Pumps are proteins that use energy to carry substances across the cell membrane. These pumps can transport substances from a low concentration to high concentration (uphill transport).

Transport rate reaches a maximum when all the protein transporters are being used or are saturated. Like enzymes the carrier protein is very specific in what it carries across the membrane. These proteins are sensitive to inhibitors that react with protein side chains.

Comparison of different transport processes

Proteins in the membrane are responsible for facilitated diffusion and active transport and hence show common characteristics of being highly selective; they are liable to saturate, respond to inhibitors and are under hormonal regulation. But diffusion whether facilitated or not-take place only along a gradient and do not use energy.

Property	Simple diffusion	Facilitated Transport	Active Transport
Requires special membrane proteins	No	Yes	Yes
Highly selective	No	Yes	Yes
Transport saturates	No	Yes	Yes
Uphill transport	No	No	Yes
Requires ATP energy	No	No	Yes

PLANT WATER RELATIONS

Water is essential for all physiological activities of the plant and plays a very important role in all living organisms. It provides the medium in which most substances are dissolved. The protoplasm of the cells is nothing but water in which different molecules are dissolved and (several particles) suspended.

A watermelon has over 92 per cent water. Most herbaceous plants have only about 10 to 15 per cent of its fresh weight as dry matter.

Distribution of water within a plant varies. Woody parts have relatively very little water, while soft parts mostly contain water.

A seed may appear dry but it still has water –otherwise it would not be alive and respiring!

Terrestrial plants take up huge amount water daily but most of it is lost to the air through evaporation from the leaves, i.e., **transpiration. A** mature corn plant absorbs almost three litres of water in day. While a mustard plant absorbs water equal to its own weight in about 5 hours. Because of this high demand for water, it is not surprising that water is often the limiting factor for plant growth and productivity in both agricultural and natural environments.

To comprehend plant-water relations, an understanding of certain standard terms is necessary.

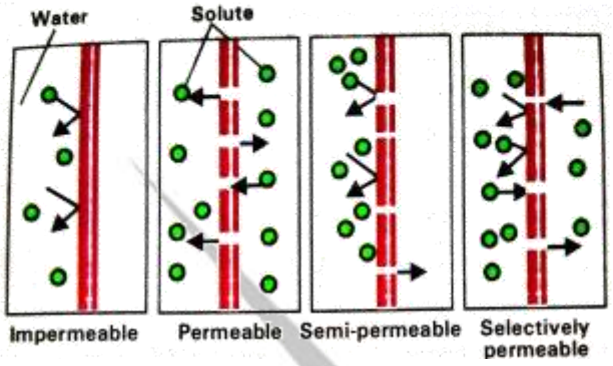
Membrane permeability

(i) **Permeable membrane:** membranes which primary cell wall allows the diffusion of both solvent and molecules through them are called as permeable membranes e.g.

(ii) **Impermeable membrane:** Membranes which will neither allow the diffusion of solutes nor of solvents through them e.g. heavily cutinised or suberised cell walls.

(iii) **Semipermeable membranes:** Such membranes allow the diffusion of solvents only but do not allow passage of solute molecules e.g. copper – ferrocyanide membranes, animal bladder, eggmemnrane + Parchment Paper + Cellophane Membrane

(iv) **Differentially** or selectively permeable membranes: Such membranes allow all the solvents to pass through them but allow selective passage of solutes through them e.g. plasma lemma, tonoplast.



Osmotic concentrations

Hypotonic solution: A solution having low osmotic concentration as compared to another solution is known as hypotonic solution.

Hypertonic solution: A solution having high osmotic concentration as compared to another solution is known as hypertonic solution.

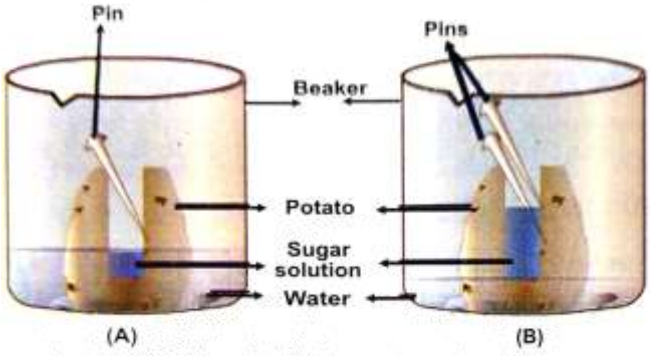
Isotonic solution: Two solutions having same osmotic concentration are named as isotonic solution.

Osmosis

Osmosis is the term used to refer specifically to the diffusion of water across a differentially-or semi-permeable membrane.

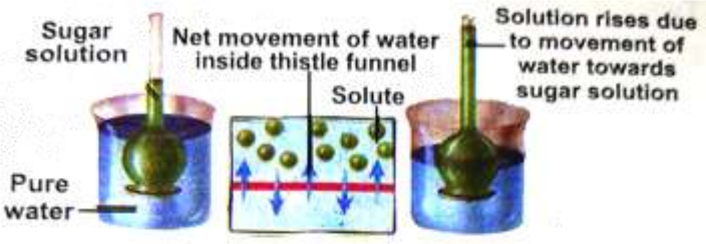
The plant cell is surrounded by a cell membrane and a cell wall. The cell wall is freely permeable to water and substances in hence is not a barrier to movement. In plants the cells usually contain a large central vacuole, whose contents, the vacuolar sap, contribute to the solute potential of the cell. In plant cells, the cell membrane and the membrane of the vacuole, the vacuole, the tonoplast together are important determinants of movement of molecules in or out of the cell.

Potato osmometer experiment: if the potato tuber is placed in water, the cavity in potato tuber containing a concentrated solution of sugar collects water due to osmosis.



(A) Before Osmosis, (B) After Osmosis

A thistle funnel experiment: A solution of sucrose in water taken in a funnel is separated from pure water in a beaker through a semi-permeable membrane. (This kind of a membrane is present in an egg, remove the yolk and albumin through a small hole at one end of the egg, and place the shell in dilute solution of hydrochloric acid for a few hours. The egg shell dissolves leaving the membrane intact). Water will move into the funnel, resulting in rise in the level of the solution in the funnel. This will continue till the equilibrium is reached.



Chemical potential is free energy of one mole of substance in a system under constant temperature and pressure.

Pure water has maximum chemical potential, because water molecules have maximum free energy. Whenever solutes are added to water chemical potential of water decreases. This is because of the interaction of solute –solvent molecules, which inhibits the random movement of the solvent molecules thus decreasing free energy of the molecules of solvent.

In an osmotic system, when a semi-permeable membrane separates pure water and solution, water molecules on both sides being in random motion, may strike semipermeable membrane & pass through it. Since water have more free –energy or chemical potential, more of it will strike the semipermeable membrane and pass through it to enter the solution, as compared to water molecules from solution to pure water. Therefore there is a **net** movement of water from its higher chemical potential to lower chemical potential.

A solution which can cause and osmotic entry of water into it is said to be **osmotically active solution.**

Sugar solution in the cavity in thistle funnel act as osmotically active solution

Electrolyte (ionic) or Non-electrolyte (non-ionic) solution:

When a small amount of sodium chloride is added to water, although a solution is formed, its formation is slightly different from that of the sugar and water.

Sugar is non ionic substance and therefore remains intact in water.

Sodium chloride is ionic substance, therefore dissociates to form sodium and chloride ions. That is why in equimolar solution of NaCl and sugar solution will have much lower chemical potential than sugar solution. Because in NaCl solution, twice as many water molecules will be involved in solution process as are required in sugar solution (which is non-dissociating).

Types of osmosis: Osmosis is of two types

Endosmosis: The osmotic entry of water into a cell, organ or system.

Exosmosis: The osmotic withdrawal of water from a cell, organ or system.

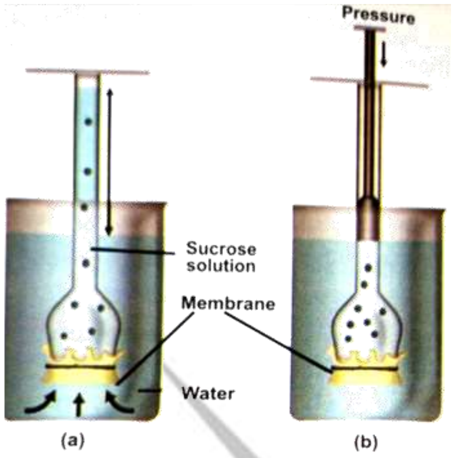
If a flowering plants is planted in an earthern pot and irrigated. Urea is added to make the plant grow faster, but after some time the plant dies. This may be due to Exosmosis.

Osmotic pressure (Pfeffer) (O.P)

It is defined as the maximum pressure that can be developed in a solution separated from pure water by a semipermeable membrane.

External pressure can be applied from the upper part of the funnel (in thistle funnel experiment) such that no water diffuses into funnel through the membrane. This pressure required to prevent water from diffusing is in fact, the osmotic pressure and this is the function of the solute concentration; more the solute concentration, greater will be the pressure required to prevent water from diffusing in.

- Osmotic pressure of a solution can be measured by osmometer.



Commonly used osmometers are

a. Pfeffer's osmometer.

b. Berkeley and Hartley 's Osmometer.

Maximum O.P. develops in a halophyte
Atriplex confertifolia (Halophyte) – O.P. = 202.4 atms.

Aquatic plants	-	O.P. = 1-3 atms
Mesophytic plants	-	O.P. = 5-13 atms
Xerophytic plants	-	O.P. = 10-30 atm.

Under drought conditions O.P. may be upto 60 atm.
Seeds may develop O.P. 100 atm.

Reverse osmosis

It is the expulsion of pure water from solution through a semipermeable membrane under the influence of pressure higher than O.P. it is used in removing salts from saline water as well as for extra purification of water.

- Reverse osmosis is an active process.

Turgor pressure (T.P)

Turgor pressure is defined as the pressure which develops in the confined part of an osmotic system due to the osmotic entry into it. Whenever, a plant cell is placed in pure water, water will move into the cell and will cause plasma membrane to be pressed against cell wall. The pressure responsible for pushing membrane against cell wall is termed as **turgor pressure.**

The cell wall being rigid or elastic to some extent, exerts an equal and opposite pressure which is known as **wall pressure.**

Diffusion pressure deficit (Meyer) or DPD

Pure water has the maximum diffusion pressure (because of high chemical potential). When solutes are added to pure water, its diffusion pressure is lowered. (because solutes lower the chemical potential of solvent).

The reduction in the diffusion pressure of water in solution over its pure state is called **diffusion pressure deficit**, so is also defined as the amount of pressure with which water will be drawn in, it is also known as **suction force or suction pressure (S.P)** or absorption potential.

DPD = OP – TP (=WP)

DPD is the force which determines whether a cell shall absorb or lose water.

OP of the cell is related to the osmotic concentration of the cell sap. In osmotic relations of the cell, where each cell functions as an osmotic apparatus, it is the DPD which will determine the direction of the flow of water.

Water will always move from low DPD (low suction pressure or high chemical potential) to high DPD (high suction pressure or low chemical potential).

As water enters the cell its turgor pressure increases which will decreases the DPD of the cell. The turgor pressure of the cell which has lost water will decrease which will increase DPD. Water will keep on moving into the cell, till DPD of both the cells is at equilibrium.

- In a fully turgid cell DPD = O because at this point OP= TP.
- For a plasmolysed cell DPD =OP

Water potential (Slatyer and Taylor)

Osmotic relations are studied now-days in terms of energy changes, therefore, the term DPD has been replaced by water potential.

Water potential is a concept fundamental to understanding water movement.

Water potential is denoted by the Greek symbol Psi or and is expressed in pressure units such as pascals (Pa).

Solute potential Ψ_s and pressure potential Ψ_p are the two main components that determine water potential.

Water molecules possess kinetic energy. In liquid and gaseous from they are in random motion that is both rapid and constant. The greater the concentration of water in a system, the greater is its kinetic energy or 'water potential'. Hence, it is obvious that pure water will have the greatest water potential. If two system containing waster are in contact, random movement of water molecules will result in net movement of water molecules from the system with higher energy to the one with lower energy . Thus water will move from the system containing water at higher water potential to the one having low water potential. This process of movement of substances down a gradient of free energy is called diffusion.

- By convention, the water potential of pure water at standard temperatures, which is not under any pressure, is taken to be zero.
- Since chemical potential of pure water at normal temperature and atmospheric pressure is taken as zero, the value of water potential in a system or solution is always negative or loss than zero.

Osmotic potential or Solute potential Ψ_s

Osmotic pressure value of a solution does not refer to actual pressure, because it only refers to the potential pressure, because it only refers to the potential pressure which can be developed in a solution due to osmotic entry of water into it. This term now is replaced by osmotic potential or solute potential.

If some solute is dissolved in pure water, the solution has fewer free water and the concentration of water decreases, reducing its water potential. Hence, all solutions have a lower water potential than pure water; the magnitude of this lowering due to dissolution of a solute is called **solute potential** or Ψ_s. Ψ_s is always negative. The more the solute molecules, the lower (more negative) is the Ψ_s

For a solution at atmospheric pressure (water potential) Ψ_w = (solute potential) Ψ_s. If a pressure greater than atmospheric pressure is applied to pure water or a solution, its water potential increases. It is equivalent to pumping water from one place to another.

- Magnitude of osmotic pressure and osmotic or solute potential is same but former is always positive while latter is negative.

Pressure potential (Ψ_p)

Pressure can build up in a plant system when water enters a plant cell due to diffusion causing a pressure built up against the cell wall, it makes the cell **turgid.** Pressure potential is usually positive, though in plants negative potential or tension in the water column in the xylem plays a major role in water transport up a stem. Pressure potential is denoted as Ψ_p. It is the hydrostatic pressure which develops in plant cell or any enclosed system due to osmotic entry or exit of water. Due to positive hydrostatic pressure protoplast presses the cell wall to outside. Wall being elastic presses protoplast with equal and opposite force i.e. wall pressure (W.P.).

Loss of water produces negative hydrostatic pressure or pressure potential (tension).

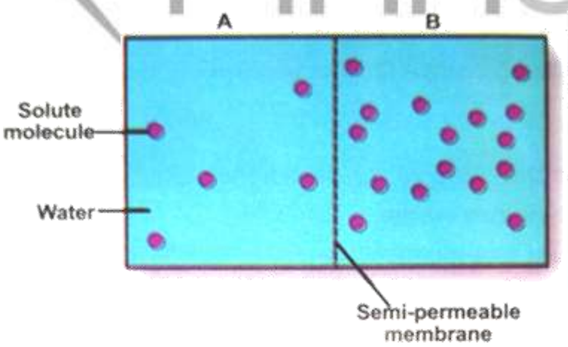
The net direction and rate of osmosis depends on both the **pressure gradient** and **concentration gradient**

Movement of water between two adjacent cells

Suppose A and B are two adjacent plant cells where osmotic movement of water can occur. Cell A has osmotic potential (Ψ_s) of – 16 bars and pressure potential of 8 bars. The cell B has osmotic potential of – 12 bars and pressure potential of 2 bars. The movement of water will be as follows

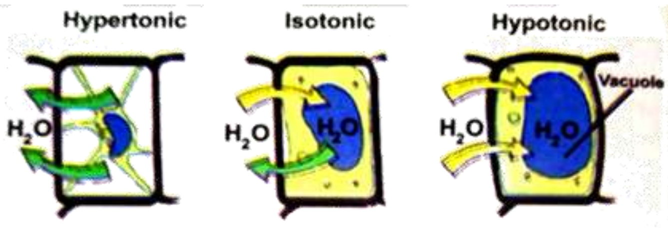
Cell A	Cell B
$\Psi_s = -16$	$\Psi_s = -12$
$\Psi_p = 8$	$\Psi_p = 2$
$\Psi = \Psi_s + \Psi_p$ = - 16 + 8 = - 8	$\Psi = \Psi_s + \Psi_p$ = - 12 + 2 = - 10

- Water will move from its region of higher chemical potential (or concentration) to its region of lower chemical potential until equilibrium is reached. At equilibrium the two chambers should have the same water potential. Two chambers, A and B, containing solution are separated by a semi-permeable membrane in the following diagram.



(i) Solution of B chamber has a lower water potential
(ii) Solution of B chamber has a lower solute potential.
(iii) Osmosis will occur from A to B.
(iv) Chamber A has a higher solute potential.
(v) At equilibrium, water potential becomes lowered in chamber A.
(vi) If one chamber has a Ψ of – 2000 kPa and the other chamber has – 1000 kPa, other chamber has the higher Ψ.

Plasmolysis



The behaviour of the plant cells (or tissues) with regard to water movement depends on the surrounding solution. If the external solution balances the osmotic pressure of the cytoplasm, it is said to be **isotonic.**

If the external solution is more dilute than the cytoplasm, it is **hypotonic** and if the external solution is more concentrated, it is **hypertonic.** Cells swell in hypotonic solutions and shrink in hypertonic ones. **Plasmolysis** occurs when water moves out of the cell and the cell membrane of a plant cell shrinks away from its cell wall. This occurs when the cell (or tissue) is placed in a solution that is hypertonic (has more solutes) to the protoplasm. Water moves out; it is first lost from the cytoplasm and then from the vacuole. The water when drawn out of the cell through diffusion into the extracellular (outside cell) fluid causes the protoplast to shrink away from the walls. The cells is said to be plasmolysed. The movement of water occurred across the membrane moving from an area of high water potential (i.e., the cell) to an area of lower water potential outside the cell.

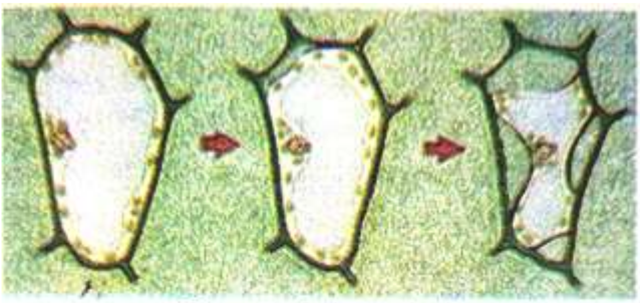
- Hypertonic solution occupies the space between the cell wall and the shrunken protoplast in the plasmolysed cell.

When the cell (or tissue) is placed in an **isotonic** solution, there is no net flow of water towards the inside or outside. If the external solution balances the osmotic pressure of the cytoplasm it is said to be isotonic. When water flows into the cell and out of the cell and are in equilibrium, the cells are said to be **flaccid.**

The process of plamolysis is usually reversible. When the cells are placed in a **hypotonic** solution (higher water potential or dilute solution as compared the cytoplasm it is said to be isotonic. When water flows into the cell and out of the cell and are in equilibrium, the cells are said to be **flaccid.**

He process of plamolysis usually reversible. When the cells are placed in a **hypotonic** solution (higher water potential or dilute solution as compared to the cytoplasm), water diffuses into the cell causing the cytoplasm to build up a pressure against the wall that is called **turgor pressure.** The pressure exerted by the protoplasts due to entry of water against the rigid walls is called pressure potential Ψ_p. Because of the rigidity of the cell wall, the cell does not rupture. This turgor pressure is ultimately responsible for enlargement and extension growth of cells.

- Ψ_p of flaccid cell is nearly zero.
- Organisms other than plants which possess cell wall: Bacteria, fungi and some members of protista.



Stages of plasmolysis

Importance of plasmolysis

i. By salting tennis lawns, the weeds can be killed due to permanent plasmolysis and consequent death of their cells.

ii. Plants are not allowed to grow in the cracks of the walls by the method of salting.
iii. Salting of pickles, meat and fish and sweetening of the jams and jellies with sugar kill the spores of fungi and bacteria.
iv. Excessive concentration of chemical fertilizers at one place in the soil should be avoided, otherwise the plants **will die down.**

Cut pieces of beet root do not leave color in cold water but do so in hot water because in hot water cell membrane get killed and the cell membrane becomes permeable. Therefore colour leaks out the cut pieces of beet roots.

Deplasmolysis: Swelling of a plasmolysed protoplast under influence of hypotonic solution or water is called **Deplasmolysis.** It is due to endosmosis.

An onion peel is taken and placed in salt solution for five minutes, it results in shrinkage of cytoplasm from the cell wall due to Exosmosis. After sometime onion peel is placed in distilled water, it results indeplasmolysis and swelling of cells due to endosmosis.

Imbibition

Imbibition is a special type of diffusion when water is absorbed by solids- colloids – causing them to enormously increase in volume.

The absorption of liquid by the solid particles of a substance without forming a solution is called imbibition. Solid substances which take part in imbibition are called **imbibants,** the liquid which is imbibed is known as **imbibate.** The force which hold the molecules of imbibate, of imbibate, between the particles of solid substances or over these particles are capillarity and adsorption.

- Classical examples of imbibition are absorption of water by seeds and dry wood.

In plants imbibate is water. Imbibition increase the volume of the imbibant but this increase is less than the volume of water absorbed. It is caused by the compression of water which releases energy in the form of heat (**heat of wetting).** Pressure developed by the swelling imbibant is known as imbibition pressure **(Matric potential).** A very high imbibition pressure can be produced by an imbibant if it is confined and then allowed to imbibe water.

Two conditions are essential for imbibition to occur:

i. A water potential gradient must exist between the surface of the adsorbent and the liquid imbibed.
ii. Affinity must exist between component of the adsorbent and the imbibed substance is pre-requisite.

Dry plant and materials have very high negative water potential, therefore when such materials are placed in pure water, a steep water potential gradient is established and water moves rapidly to the surface of adsorbent.

Imbibition

An adsorbent cannot imbibe all kinds of liquids. Dry plant material cannot imbibe ether, but can imbibe. However, rubber cannot imbibe water.

Plant imbibants are made up of hydrophilic colloids (they have a strong attraction for water). The most important of them are proteins, pectic compounds, starch and cellulose.

Agar-agar is known to imbibe 99 times its weight of water. Lignin is hydrophobic. It therefore does not show imbibition of water.

Importance of imbibition

i. The pressure that is produced by the swelling of wood had been used by prehistoric man to split rocks and boulders.
ii. If it were not for the pressure due to imbibition, seeding would not have been to emerge out of the soil into open; they probably would not have been able to establish! Breaking of the seed coats in germination seeds is due to greater swelling of seed kernel which is made up of proteins, lipids and starch than seed coat which is made up of cellulose.
iii. Jamming of wooden frames during rains is caused by swelling of wood due to imbibition.

How do Plants Absorb Water

The roots absorb most of the water that goes into plants; obviously that is why we apply water to the soil and not on the leaves. The responsibility of absorption of water and minerals is more specifically the function of the root hairs that are present in millions at the tips of the roots.

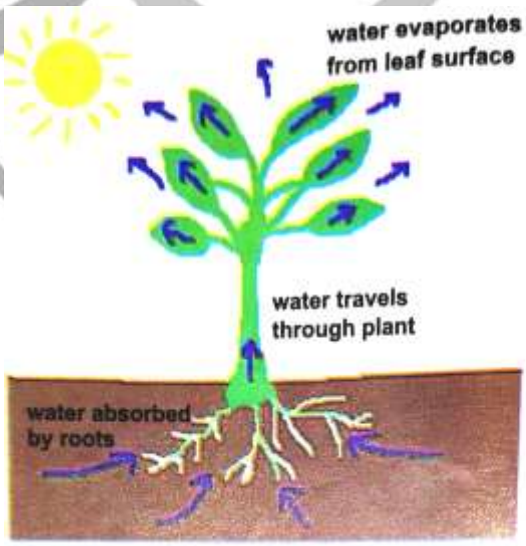
Root hairs are thin-walled slender extensions of root epidermal cells that greatly increase the surface area for absorption.

Water is absorbed along with mineral solutes, by the root hairs, purely by diffusion.

Mechanism of water absorption: Absorption of water by roots is of two types

1. Passive water absorption (Renner)

The force for this water absorption is generated in the aerial parts of the plants through transpiration.



Transpiration creates a tension in the tracheid and vessels due to the development of low water potential or high DPD. This low water potential or negative water potential i. e. tension is passed on to root hairs through xylem channels because of which root hairs develop water potential of – 3 to – 8 bars. As a result, soil water which has Ψ_w = – 0.1 to – 0.3 bars, passes into the root hair cell through the process of osmosis. This raises the water potential of root hairs. Root hairs cells will loose water to cortical cells because they have lower or more negative water potential.

From cortical cells water will move to inner cells, endodermis, pericycle and xylem vessels along a gradient of water potential. It is the most common method of water absorption (96% of the total).

Active water absorption

Forces for this type of water absorption are generated in the roots itself and energy is required for this type of absorption. This energy is used for the accumulation of salts in xylem vessels which will cause withdrawal of water from surrounding cells as well as from root hair (osmotically active water absorption).

Pathway of movement of water: Once water is absorbed by the root hairs it can move deeper into root layers by two distinct pathways.

i. **Apoplast pathway:** The **Apoplast** is the system of adjacent cell walls that is continuous throughout the plant, except at the **Casparian** strips of the endodermis in the roots.

The Apoplastic movement of water occurs exclusively through the intercellular spaces and the walls of the cells. Movement through the Apoplast does not involve crossing the cell membrane. This movement is dependent on the gradient.

Apoplast does not provide any barrier to water movement & water movement is through mass flow.

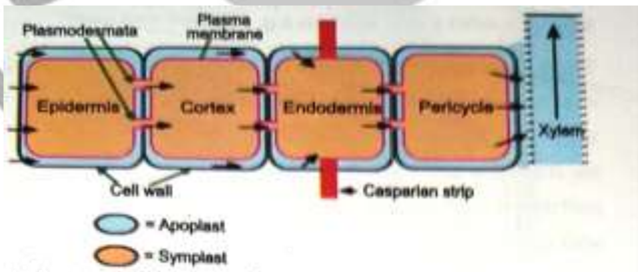
As water evaporates into the intercellular spaces or the atmosphere, tension develop in the continuous stream of water in the Apoplast, hence mass flow of water occurs due to the adhesive and cohesive properties of water.

ii. **Symplastic pathway**: It is the system of interconnected protoplasts. Neighbouring cells are connected through cytoplasmic strands that extend through **Plasmodesmata.**

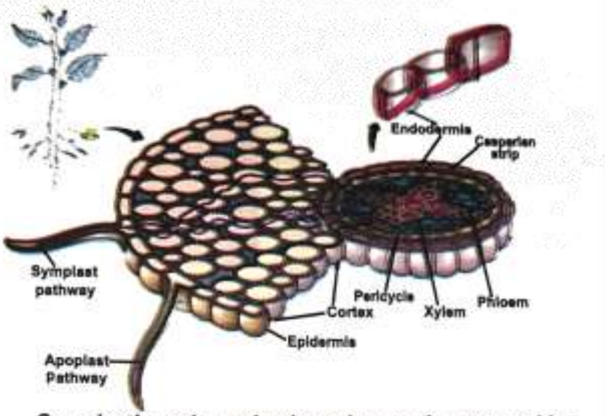
During Symplastic movement, the water travels through the cells-their cytoplasm; intercellular movement is through the Plasmodesmata.

Water has to enter the cells through the cell membrane, hence the movement is relatively slower. Movement is again down a potential gradient.

- Symplastic movement may be aided by cytoplasmic streaming i. e. cells of *Hydrilla* leaf: the movement of chloroplast due to streaming is easily visible.



Pathway of movement of water



Symplastic and apoplastic pathway of water and ion absorption and movement in roots

As the cortical cells are loosely packed & have large intercellular spaces, so most of water flow occurs through Apoplast.

The inner boundary of the cortex, the **endodermis,** is impervious to water because of a band of suberized matrix called the **Casparian strip.** Water molecules are unable to penetrate the layer, so they are directed to wall regions that are not suberized, into the cells proper through the Symplast and again cross a membrane to reach the cells of the xylem. The movement of water through the root layers is ultimately Symplastic in the endodermis. This is the only way water and other solutes can enter the vascular cylinder.

Once inside the xylem, water is again free to move between c ells as well as through them. In young roots, water enters directly into the xylem vessels and/or tracheids. These are non-living conduits and so are parts of the Apoplast.

Mycorrhizal water absorption

Some plants have additional structures which help in absorption of water. Mycorrhiza is symbiotic association of fa fungus with a root system e.g. *pinus.*

The fungal filaments form a network around the young root or they penetrate the root cells. The hyphae have a very large surface area that absorb mineral ions and water from the soil from a much larger volume of soil that perhaps a root cannot do. The fungus provides minerals and water to the roots, in turn the roots provide sugars and N- containing compounds to the mycorrhizae. Some plants have an obligate association with the mycorrhizae.

Long Distance Transport in Plants:

In large and complex organisms, often substances have to be moved across very large distances. Sometimes the sites of production or absorption and sites of storage are too far from other; diffusion or active transport would not suffice.

Long distance transport of substances within a plant cannot be by diffusion alone.

Diffusion is a slow process e.g. the movement of a molecule across a typical plant cell (about 50 µm) takes approximately 2.5 second. At this rate, it will take many years for the movement of molecules over a distance of 1 metre within a plant by diffusion alone.

Special long distance transport system become necessary so as to move substances across long distances and at a much faster rate.

Water and minerals, and food are generally moved by a mass or **bulk flow** system. **Mass** flow is the movement of substances in bulk or *en masse* from one point to another as a result of pressure differences between the two points.

In mass flow, substances, whether in solution or in suspension, are swept along at the same pace, as in a flowing river. This is unlike where different substances move independently depending on their concentration gradients.

- Bulk flow can be achieved either through a positive hydrostatic pressure gradient (e.g., a garden hose) or a negative hydrostatic pressure gradient (e.g., suction through a straw).

The higher plants have highly specialized vascular tissues – xylem and phloem. Xylem is associated with translocation of mainly water, mineral salts, some organic nitrogen and hormones, from roots to the aerial parts of the plants. The phloem translocates a variety of organic and inorganic solutes, mainly from the leaves to other parts of the plants.

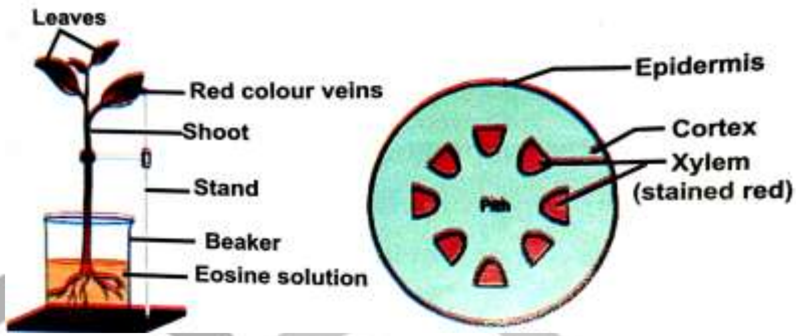
Every plant species has its own adaptation to enhance water absorption and reduce transpiration.

ASCENT OF SAP (Water movement up a plant)

It is the long distance upward movement of water and minerals in mass flow roots to the tips of the stem branches and their leaves against the forces of gravity. Pathway for the ascent of sap is the treachery elements of the xylem. Tracheids and vessels are dead and empty channels for this purpose.

Experiment for a ascent of sap:

Placed a twig bearing white flowers in coloured water and had watched it turn colour. On examining the cut end of the twig after a few hours, noted the region through which the coloured water moved. This experiment very easily demonstrates that the path of water movement is through the vascular bundles, more specifically, xylem.



Theories of Ascent of sap: Water column is lifted from roots to great heights sometimes more than 100 metres with translocation rate of 15 m/hr. Three types of theories have been put forward to explain the force responsible for ascent of sap.

1. **Root pressure theory:** It was given by Priestly.
   As various ions from the soil are actively transported into the vascular tissues of the roots, water follows (its potential gradient) and increases the **pressure** inside the xylem. This positive pressure is called **root pressure,** and can be responsible for pushing up water to small heights in the stem. Take a small soft-stemmed plant and on a day, when there is plenty of atmospheric moisture, cut the stem horizontally near the base with a sharp blade, early in the morning. We will soon drops of solution ooze out of the cut stem; this comes out due to the positive root pressure. This pressure pushes the sap upwards towards the top of the plant. A root pressure of 1-2 atm has been reported in a number of plants. Root pressure is result of active absorption so is retarded at low temperature, reduced availability of oxygen and under starvation.

- Root pressure provides only a modest push in water transport. They do not play a major role in water movement up tall trees.
  The greatest contribution of root pressure may be tp re-establish the continuous chains of water molecules in the xylem which often break under the enormous tensions created by transpiration.
  Root pressure does not account for the majority of water transport due to following reasons.
  i. It is not developed by all plants. Root pressure is not found in gymnosperms which have some of the tallest tree of the world.
  ii. Water continues to rise even in the absence of roots.
  iii. Rapidly transpiring plants do not develop any root-pressure. In summers when water requirements are high, the root pressure is absent.
  iv. Normally observed root pressure is generally low which is unable to raise the water to the top of the trees.
- Active water absorption is manifestated in the form of **root pressure.**

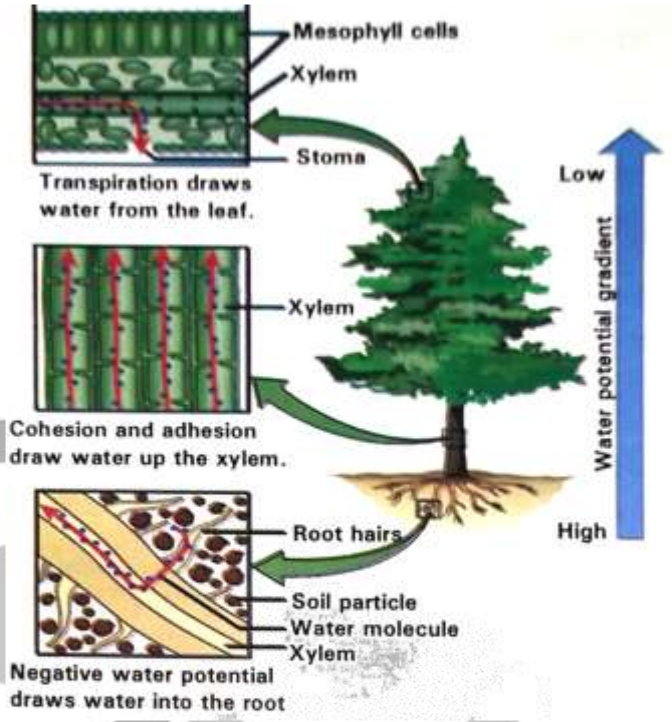
1. **Cohesion tension transpiration pull theory:** A comprehensive theory of ascent of sap was proposed by Dixon and Jolly. It is also known as Dixon's theory of ascent of sap or Transpiration pull theory.

The transpiration driven ascent of xylem sap depends mainly of the following physical properties of water:

Cohesion - mutual attraction between water molecules.

Adhesion – attraction of water molecules to polar surfaces (such as the surface of Tracheary elements).

Surface Tension – water molecules are attracted to each other in liquid phase more than to water the gas phase.



These properties given water high **tensile strength,** i. e, an ability to resist a pulling force, and high capillarity, i.e., the ability to rise in thin tubes. In plants capillarity is aided by the small diameter of the Tracheary elements – the tracheids and vessel elements.

Force due to surface tension is directly proportional to surface area. Rise of water in a narrow tube is inversely proportional to the radius of the tube.

Main features of this theory are:

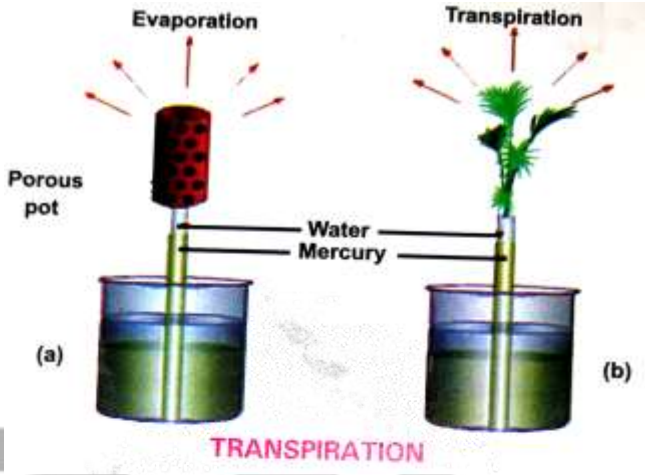
i. **Continuous water column:** There is a continuous column of water from the root through stem and the leaves. It is also named as hydrostatic system.

ii. **Cohesion or tensile strength:** Transpiration pull produced due to transpiration is unable to break the continuity of hydrostatic system because water molecules have a strong cohesive force. **Cohesion force** is the force with which water molecules cling together because of hydrogen bonding. Cohesion force is therefore also called **tensile strength.** Because of this force water column can bear a pull up to 100 atmospheres. There is another force of adhesion which holds water to walls of xylem channels.

iii. **Transpiration pull:** As a result of transpiration, water evaporates from the mesophyll cells of the leaves. Reduction in the water content decreases their water potential. As a result they withdraw water from the deeper cells which in turn obtain water from the Tracheary elements. Due to continuous withdrawal of water from the xylem by the transpiring leaf cells, whole water column of the plant comes under tension or strain. This is known as transpiration pull. On account of the tension created by transpiration the water column of the plant is pulled up passively from below to the top of the plant like a rope.

EXPERIMENT OF TRANSPIRATION PULL

Atmometer – apparatus consisting of a porous pot connected to a narrow glass tube. The apparatus is filled with water. The free end of glass tube is dipped in beaker containing mercury. As water evaporates from porous pot, mercury begins to rise upward in the glass tube showing a pull to evaporation (similar to pull by transpiration).

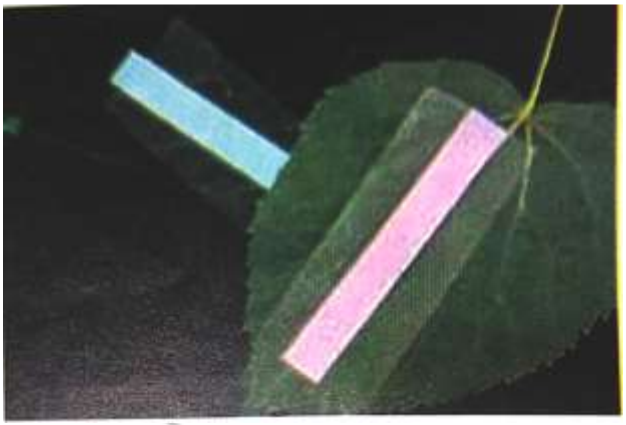


Water is transient in plants. Less than 1 per cent of the water reaching the leaves is used in photosynthesis and plant growth. Most of it is lost through the **stomata** in the leaves. The loss of water in vapour form from the exposed parts of the plant is called **transpiration.**

Experiment on transpiration

i. Enclosing a healthy plant in polythene bag and observing the droplets of water formed inside the bag.

ii. $CoCl_2$ test



Dry $CoCl_2$ paper –blue; Moist $CoCl_2$ paper – pink

Take a potted plant, select a healthy strong leaf. Clean its surface with dry cotton without rubbing. Place a small cobalt chloride blue – coloured paper on leaf surface.

Immediately cover them with cellotape. Alternatively the dry cobalt chloride papers can be covered with two glass slides having veselined boundaries. After sometime cobalt chloride paper becomes pink in colour. This proves that transpiration occurs from **leaf surface.**

Types of transpiration

Transpiration can take place from any exposed part of the plant. Most of the transpiration takes place through leaves –it is known as **foliar transpiration.** A little transpiration can take place from stem, it is called as **cauline transpiration.**

Aerial parts show four types of transpiration

Stomatal transpiration: It constitutes 50-97% of the total transpiration. In this type of transpiration water is lost in vapour form, from stomata. It stops only when the stomata get closed completely.

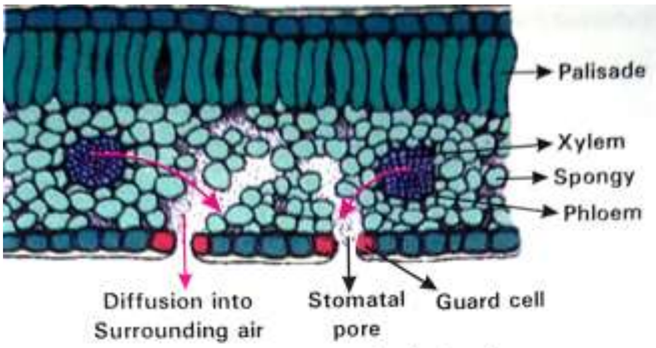
Cuticular transpiration: it occurs through the cuticle or epidermal cells. In most of the land plants it accounts for 3 -10% of the total transpiration. But in herbaceous plants it may be upto 50%. It occurs at all times.

Lenticular transpiration: This is the transpiration through lenticels or aerating pores present in the bark. It is only 0.1% of the total transpiration.

Bark transpiration: This takes place through the corky covering of the stem.

MECHANISM OF TRANSPIRATION

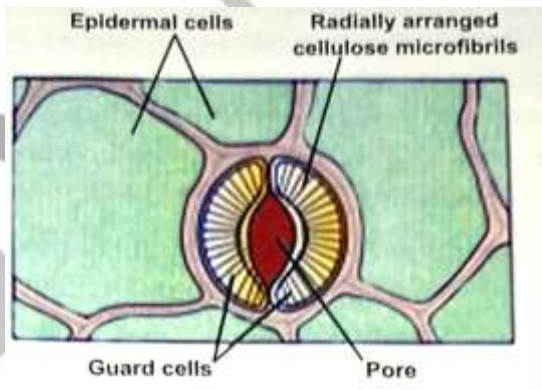
The process of photosynthesis requires water. The system of xylem vessels from the root to the leaf vein can supply the needed water. But what force does a plant use to move water molecules into the leaf parenchyma cells where they are needed? As water evaporates through the stomata, since the thin film of water over the cells is continuous, it results in pulling of water, molecule by molecule, into the leaf from the xylem. Also, because of lower concentration of water vapour in the atmosphere as compared to the substomatal cavity and intercellular spaces, water diffuses into the surrounding air. Measurements reveal that the forces generated by transpiration can create pressures sufficient to lift a xylem sized column of water over 130 metres high.



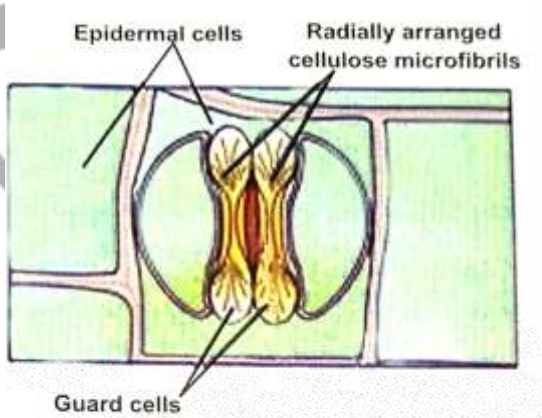
Water movement in the leaf

Structure of stomata

Stomata are tiny pores found in the epidermis of leaves and other soft aerial parts.



Stomata of dicot plants

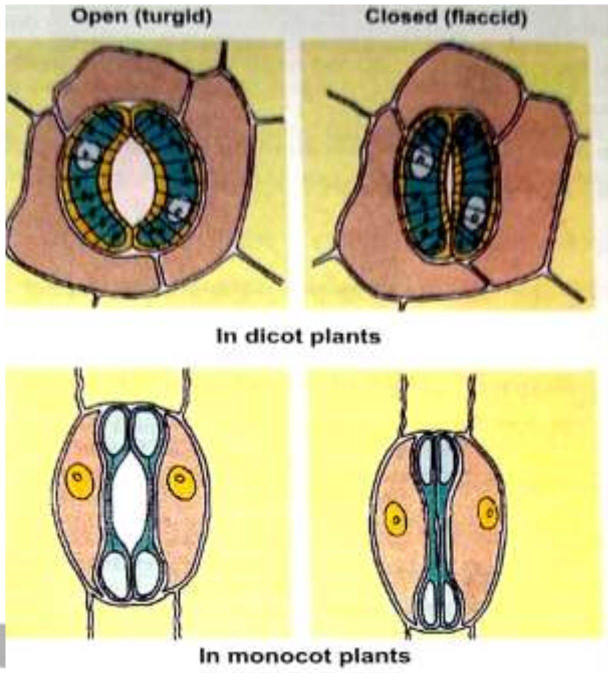


Stomata of dicot plants

Stomata not only results in transpiration but also are meant for exchange of gases. Stomata are microscopic and are guarded by two specialized epidermal cells called as **guard cells.** Because of their small size, they are rapidly influenced by turgor changes. The guard cells are connected with the adjacent epidermal cells through Plasmodesmata.

In most of the dicot plants guard cells are kidney/bean shaped in outline. The walls of the guard cells are thick-ened on the concave or inner side and thin on the convex or outerside. Inner walls of the guard cells have cellulosic Microfibrils which are oriented radially (radial micellations) rather than longitudinally.

In the family Poaceae (monocot), guard cells are dumbbell shaped. Their expanded ends are thin walled while middle portions are highly thick-walled.



When turgidity increases within the two guard cells flanking each stomatal aperture or pore, the thin outer walls bulge out and force the inner walls into a crescent shape. The opening of the stoma is also aided due to the orientation of the microfibrils in the cell walls of the guard cells. Cellulose microfibrils are oriented radially rather than longitudinally making it easier for the stoma to open. When the guard cells lose turgor, due to water loss (or water stress) the elastic inner walls regain their original shape, the guard cells become flaccid and the stoma closes.

Internally guard cells contain small chloroplasts. In certain cases, guard cells are surrounded by number of slightly modified epidermal cells called **subsidiary or accessory** cells.

Stomatal frequency: Number of stomata per unit area of leaf.

Usually the lower surface of a Dorsiventral (often dicotyledonous) leaf has a greater number of stomata while in and isobilateral (often monocotyledonous) leaf they are about equal on both surfaces.

Photometer: this is the instrument for measuring the rate of transpiration by shoot, through measuring the rate of their water absorption. e.g., Ganong's Potometer.

Porometer: This is the instrument for measuring degree of stomatal opening (Pore size).

Most of the plants open their stomata during day time and close it during night time (**photoactive)** e.g. Opuntia.

The main theory to explain stomatal movement is malate or K^+ ion pump hypothesis:

Main features of the theory were given by **Levitt.**

During stomatal opening, ph of the guard cells can rise due to:

i. Active H^+ uptake by chloroplast and mitochondria of guard cells.
ii. CO_2 assimilation by guard cells.

Rise in pH will stimulate enzyme phosphorylase which causes hydrolysis of starch to form organic acids instead of sugars. Starch $\xrightarrow{Phosphorylase}$ Hexosephosphate $\longrightarrow$ Phosphoglyceric acid - Phosphoenol pyruvate $\frac{+CO_2}{PEPCO}$ malic acid $\xrightarrow{\text{disoicates}}$ Malate & H^+

Efflux of H^+ and influx of K+ with the help of ATP, cyto - kinin and

The uptake of K^+ with ions is balanced by uptake of Cl^- and negative charge on malate ions. Higher concentration of organic salts (potassium malate) in guard cells result in endosmosis from adjoining cells. Guard cells become turgid and stomatal pore opens.

During stomatal closure pH decreases because of diffusion of H^+ out of chloroplasts of guard cells. At low pH free malate ions combine with H^+ to form malic acid. High CO_2 concentration can also decrease pH. K^+ ions dissociate from malate and pass out of guard cell.

Formation of abscissic acid also promotes reversal of $H^+ \rightleftharpoons K^+$ pump. Loos of K^+ ions decrease osmotic concentration of guard cells as compared to adjacent cells. This causes exosmosis and hence guard cells become flaccid and stomatal pore closes.

Factors affecting transpiration

External Factors

Light: In most of the plants, stomata open during the day and close during night. Blue light is more effective in causing stomatal opening.

Temperature: Relative humidity is the percentage of water vapour present in the air relative to the amount required to be present to make the air saturated at the temperature. The rate of transpiration is inversely proportional to relative humidity.

Relative humidity: relative humidity is the percentage of water vapour present in the air relative to the amount required to be present to make the air saturated at that temperature. The rate of transpiration is inversely proportional to relative humidity.

Wind: If wind velocity is high (20-30 km/hr), the rate of transpiration is high, because wind removes humid air around the leaf which decreases water potential. A wind velocity of 40-45 km/hr decreases transpiration by closing the stomata due to mechanical effect.

Atmospheric pressure: Low atmospheric pressure produces air currents and increases rate of transpiration.

Availability of water: The rate of transpiration depends upon the rate of absorption of soil water by roots. A decrease in the water uptake by the root causes partial dehydration of the leaf cells resulting in wilting that is condition of loss of leaf turgidity resulting in drooping and folding.

Internal Factors

Plant factors that affect transpiration include number and distribution of stomata, percent of open stomata, water status of the plant, canopy structure etc.

Leaf area: A plant with large leaf area show more transpiration (more water lost) than the plant with less leaf area.

However a prunned plant, show higher rate of transpiration, because of more air movement and less shading effect.

Leaf structure : The anatomical features of leaves like sunken or vestigial stomata; presence of hair, cuticle or waxy layer on the epidermis; presence of hydrophilic substances such as gums, mucilage etc. in the cells; compactly arranged mesophyll cells etc. help in reducing the rate of transpiration.

Root shoot ratio: The rate of transpiration is directly proportional to the root-shoot ratio.

Age of plants: Germinating seeds show a slow rate of transpiration. It becomes maximum at maturity. However, it decreases at senescence stage.

Antitranspirants: Factors or agents that reduce the rate of transpiration are called as Antitranspirants. Antitranspirants are of two types:-

Metabolic inhibitors are those inhibitors which reduce stomatal opening for a period of two or more weeks. Important inhibitors are Phenyl mercuric acetate (**PMA**) and abscisic acid (**AMA**).

Surface films: Films check transpiration but allow the exchange of gases. Film forming chemicals are silicon emulsions, colourless plastic resins and low viscosity waxes.

Transpiration and photosynthesis: a compromise, Transpiration has more than on purpose it

i. Creates transpiration pull for absorption and transport of plants.
ii. Supplies water for photosynthesis.
iii. Transports minerals form the soil to all parts of the plant.
iv. Cools leaf surfaces, sometimes 10 to 15 degrees, by evaporative cooling.
v. Maintains the shape and structure of the plants by keeping cells turgid.

- Most of the physiologist holds the view that transpiration is a price, which the part pays for photosynthesis because transpiration occurs along with photosynthesis.
  An actively photosynthesizing plant has an insatiable need for water. Photosynthesis is limited by available water which can be swiftly depleted by transpiration. The humidity of rainforests is largely due to this vast cycling of water from root to leaf to atmosphere and back to the soil.
- Curtis (1926) truly called 'transpiration as a necessary evil'.
- Transpiration is unavoidable evil (Steward).

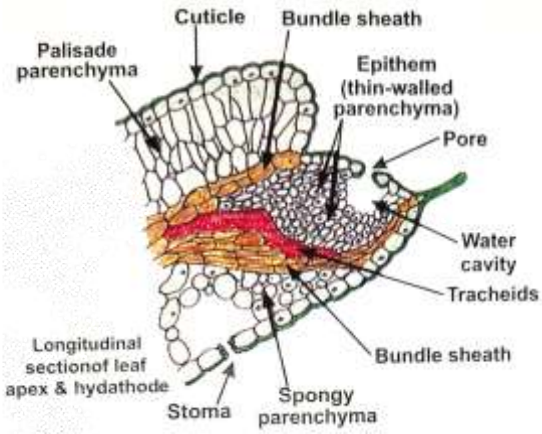
Guttation

The loss or excretion of water in the form of liquid droplets from the leaves is called **Guttation** (Bergerstein). All plants do not show guttation. Gymnosperms also do not show guttation.

Water lost has both organic (Carbohydrates, amino acids) and inorganic salts (Ca, Mg, K, Na).

It usually occurs during the night or early morning hours when there is high atmospheric humidity and rate of absorption of water is more than rate of transpiration and excess water collection in the form of droplets around special opening of veins near the tip of grass blades and leaves of many herbaceous pants.

Guttation takes place through special pores called **hydathodes.** Each hydathode consists of group of loosely arranged, colorless, parenchymatous cells called **Epithem.** It lies over the tip of a vascular strand and communicates with the outside through a permanent pore (guard cells are immobile) called water pore. Exudation of liquid through water pore takes place due to the development of positive pressure in the xylem which is root pressure.



Bleeding

It is exudation of sap or watery solution from the cut or injured parts of plant, e.g., *Agave, Acer, Vitis,* Today palm. It occurs due to root pressure, phloem pressure, local pressure in xylem (stem pressure) latex or resin canals.

UPTAKE AND TRANSPORT OF MIERAL NUTRIENTS

Plants obtain their carbon and most of their oxygen from CO_2 in the atmosphere. However, their remaining Type equation here.nutritional requirements are obtained from minerals and water for hydrogen in the soil.

Uptake of Mineral lons:

Unlike water, all minerals cannot be passively absorbed by the roots. Two factors account for this:

i. Minerals are present in the soil as charged particles (ions) which cannot move across cell membranes.
ii. The concentration of minerals in the soil is usually lower than the concentration of minerals in the root.

Therefore, most minerals must enter the root by **active absorption** into the cytoplasm of epidermal cells. This needs energy in the form of **ATP**.

- The active uptake of ions is partly responsible for the water potential gradient in roots, and therefore for the uptake of water by osmosis. Some ions also move into the epidermal cells passively.

Ions are absorbed from the soil by both passive and active transport. Specific proteins in the membranes of root hair cells actively pump ions from the soil into the cytoplasm of the epidermal cells.

Like all cells, the endodermal cells have many transport proteins embedded in their plasma membrane; they let some solutes cross the membrane, but not others.

Transport proteins of endodermal cells are control points, where a plant adjusts the quantity and types of solutes that reach the xylem.

Translocation of Mineral Ions:

After the ions have reached xylem through active or passive uptake, or a combination of the two, their further transport up the stem to all parts of the plant is through the transpiration steam.

Xylem sap consists of water, trace of all minerals, some may be even in organic form.

The chief sinks for mineral elements are the growing regions of the plant, such as the apical and lateral meristems, young leaves, developing flowers, fruits and seeds, and the storage organs. Unloading of mineral ions occurs at the fine vein endings through diffusion and active uptake by these cells.

Mineral ions are frequently remobilized particularly from older, senescing parts to younger ones. Similarly before leaf fall in deciduous plants, minerals are removed other parts. e.g. N, P, K. Some elements that are structure components like Ca are not remobilised.

An analysis of the xylem exudates shows that though some of the nitrogen travels as inorganic ions, much of it is carried in the organic form as amino acids and related compounds. Similarly, small amounts, small amount of exchange of materials does take place between xylem and phloem.

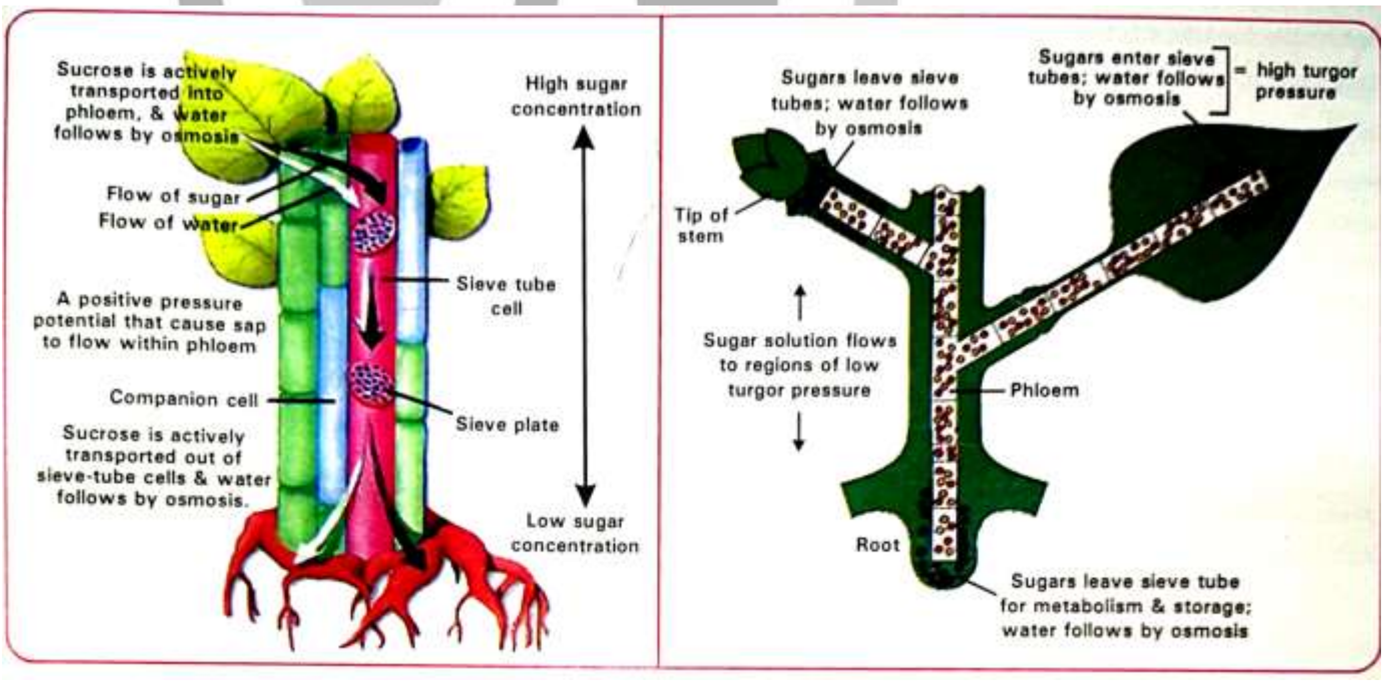
Hence, it is not that we can clearly make a distinction and say categorically that xylem transports only inorganic nutrients while phloem transports only organic materials as was traditionally believed.

PHLOEM TRNSPORT

Food, primarily sucrose, is transported by the vascular tissue phloem from a source to a sink.

Usually the source is the part of the plant which synthesises the food, i.e., the leaf and sink, the part that needs or stores the food. But, the source and sink may be reversed depending on the season, or the plant's needs. Sugar stored in roots may be mobilized to become a source of food in the early spring when the buds of trees, act as sink; they need energy for growth and development of the photosynthetic apparatus. The xylem where the movement is always **unidirectional,** i. e., upwards. Hence, unlike one-way flow of water in transpiration, food in phloem sap can be transported in any required direction so long as there is a source of sugar and a sink able to use, store or remove the sugar.

Since the source-sink relationship is variable, the direction of movement in the phloem can be upwards or downwards, i.e., **bi-directional.**



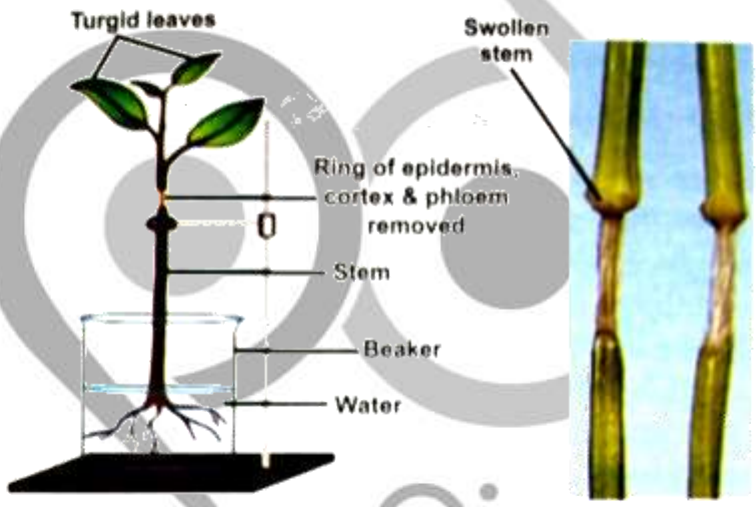
Phloem sap is mainly water and sucrose, but other sugars, hormones and amino acids are also transported or **translocated** through phloem.

THE PRESSURE FLOW OR MASS FLOW HYPOTHESIS

The accepted mechanism used for the translocation of sugars from source to sink is called the pressure flow hypothesis. As glucose is prepared at the source (by photosynthesis) it is converted to sucrose (a disaccharide). The sugar is then moved in the form of sucrose into the companion cells and then into the living phloem sieve tube cells by active transport. This process of loading at the source produces a hypertonic condition in the phloem. Water in the adjacent xylem moves into the phloem by osmosis. As osmotic pressure builds up the phloem sap will move to areas of lower pressure. At the sink osmotic pressure must be reduced. Again active transport is necessary to move sucrose out of the phloem sap and into the cells which will use the sugar –converting it into energy, starch, or cellulose. As sugars are removed, the osmotic pressure decreases and water moves out of the phloem.

The movement of sugars in the phloem begins at the source, where sugars are loaded (actively transported) into a sieve tube, loading of the phloem sets up a water potential gradient that facilitates the mass movement in the phloem.

Phloem tissue is composed of sieve tube cells. Which form long columns with holes in their end walls called sieve plates. Cytoplasmic strands pass through the holes in the sieve plates, so forming continuous filaments. As hydrostatic pressure in the phloem sieve tube increases, pressure flow begins, and the sap moves through the phloem. Meanwhile, at the sink, incoming sugars are actively transported out of the phloem and removed as complex carbohydrates. The loss of solute produces a high water potential in the phloem, and water passes out, returning eventually to xylem.



Girdling Experiment

Girdling/ringing experiment can be used to identify the tissue through which food is transported. On the trunk of a tree a ring of bark up to a depth of the phloem player, can be carefully removed. In the absence of downward movement of food the portion of the bark above the ring on the stem becomes swollen after a few weeks. This simple experiment shows the phloem is the tissue responsible for translocation of food; and that transport takes place in one direction, i.e., towards the roots.

Important points:

i. If a gardener forgot to water a potted plant for a day during summer, plant develops water deficit condition. Tis leaves undergoes wilting or loss of turgidity. As the pot is watered next day, more water enters the plant than is lost through transpiration. Therefore, the cell reg

ii. ain turgidity and wilting disappear.

iii. By adding cytokinin into water of the vase-we can increase the life of cut plants.

iv. When a freshly collected *spirogyra* filament is kept in a 10% potassium nitrate solution, the protoplast shrinks due to exosmosis.

v. Sugar crystals do not dissolve in ice cold water because in ice cold water, more water molecules are held together by hydrogen bonds, so that fewer molecules are available for random movement.

vi. **Temporary wilting -** it usually occurs during noon and is corrected in the evening. It does not kill the plant. Temporary wilting is caused by high rate of transpiration and reduced water absorption due to its temporary depletion around rootlets.

vii. **Permanent wilting -** it can occur at any time and is not corrected unless until the soil is watered immediately. It kills the plant. Permanent wilting is caused by reduction in water content of soil. Permanent wilting indicates the water status of soil. In this stage the water availability of the soil decreases to such an extent that plants are unable to absorb water.