Transport in flowering plants

Transport systems in plants

Plants may not have blood vessels and a heart, but they nevertheless have transport systems of cells which form tubular vessels to transport molecules and ions in solution from one place to another. The xylem tissue carries water and dissolved ions from the roots to the aerial parts of the plant. In the tallest trees this can be over 100 metres. Phloem carries water and dissolved food molecules from the leaves to all parts of the plant.

For more about the solvent properties of water see *Soil water*.

Turgor and plasmolysis

The shape of plant cells is defined by their cell wall. This is normally slightly stretched and rigid, due to the uptake of water by osmosis. Water will move from a less concentrated solution into a more concentrated solution through a partially permeable membrane, as there will be a diffusion gradient from where there is more water to where there is less water.

The ability of water to move from one place to another is called water potential. Water will move from higher to lower water potential. The water potential of a cell, Ψ, is given by:

$$\Psi = \Psi s + \Psi p$$

Where Ψs is the solute potential, due to particles dissolved in the water in the cytoplasm (which lowers water potential), and Ψp is the pressure potential due to the stretching of the cell wall (which in increases water potential).

The water potential of pure water at one atmosphere pressure is zero, so adding solutes has a negative effect on water potential, tending to make water enter a system. Increasing the pressure has a positive effect, tending to make water leave.

In a solution of higher water potential, cells will take up water, the cell wall will stretch and the cell will become turgid. The pressure potential will increase until it cancels out the effect of having a more dilute solution outside the cell. At this point the solute potential and the pressure potential are equal and opposite, no more water enters and the cell is said to be fully turgid.

Turgid cells press against each other and provide support to the tissues in a plant.

In a solution of lower water potential, cells lose water by osmosis until the cell wall is no longer stretched and the pressure potential becomes zero. After this further water loss causes the cell vacuole to shrink and to pull the cell membrane away from the cell wall. Gaps appear between the cell wall and the cell wall, and the cell is said to be plasmolysed. Plasmolysed cells do not press against each other and tissues become soft. Leaves and stems will wilt.

It is therefore important that plants have adequate water to maintain turgidity of their cells, so they can support the leaves to present the maximum surface area to sunlight, to promote photosynthesis and maximum growth rates. Flowers must also be open for pollinating insects, to promote full fertilisation for maximum seed and fruit development.

The transpiration stream

Transpiration is the evaporation of water from the surface of the mesophyll cells (especially spongy mesophyll) in leaves. It diffuses out into the atmosphere through the stomata. The transpiration stream is the flow of water and dissolved inorganic ions from the roots up to the leaves. As water evaporates in the leaves, more water is pulled through the plant, in a continuous stream from the roots up through the xylem and into the leaves, due to the cohesion of the water molecules.

Cold, dull, damp or humid days, or soil water shortage slow down transpiration. Hot, dry, windy conditions favour transpiration, but also cause significant water loss from the plant. The guard cells therefore regulate the diffusion of water from leaves by opening and closing the stomata to different extents, depending on the water supply being taken from the soil and the rate of photosynthesis.

The waxy cuticle of the leaf greatly reduces water loss from the outside of the leaf, except through the stomata.

Figure 1 Guard cells in the epidermis of a leaf control the opening and closing of the stomata. This regulates loss of water by transpiration.

The thicker the waxy layer, the less water is lost through this surface.

The stomata must be open to allow carbon dioxide to diffuse in for photosynthesis to occur. ATP synthesised during the light reactions of photosynthesis in chloroplasts in the guard cells provides energy for the active uptake of potassium ions.

Water passes from the neighbouring epidermal cells (which have no chloroplasts) by osmosis into the guard cells, causing them to become turgid. The inner walls of the guard cells around the stomata are thickened and inelastic. The outer cell walls stretch as water enters, so the cells bend into a banana shape, opening the stomata. This can be modelled by putting sticky tape down one side of a sausage-shaped balloon. When the balloon inflates it will expand on the side away from the tape and bend.

There is a daily cycle. As daylight increases in the morning, photosynthesis also increases and the stomata open to allow carbon dioxide to enter, but also transpiration to occur. In the evening light fades, photosynthesis ceases, the potassium ions migrate out of the guard cells so that they lose water and turgor, and the stomata close to prevent transpiration and conserve water.

Water travels from the xylem through the leaves by three routes:

- Apoplast route. Water is able to pass out of the xylem and move freely through the spaces in the highly porous cellulose cell walls in the leaves.

- Symplast route. As water evaporates it also causes a concentration gradient between neighbouring cells. Evaporation of water causes the cytoplasm and vacuoles of cells to become slightly more concentrated. Water can diffuse freely from cell to cell as the cytoplasm of neighbouring cells is connected by plasmodesmata.

- Vacuolar route. Water can also pass through cell membranes and through the tonoplasts -the surrounding membranes of cell vacuoles. Water therefore passes from cell to cell by osmosis down the concentration gradient from the xylem (higher water concentration, higher water potential) to the surfaces of the mesophyll cells (lower water concentration, lower water potential), where water is evaporating.

The xylem

The xylem of flowering plants (angiosperms) contains two types of cells that carry water. The cells die, leaving only a woody cell wall (thickened with lignin). These cells have great mechanical strength and are able to withstand the forces that develop inside them and they also give support to the plant.

Tracheids are elongated cells with tapered ends that overlap. Pits in the cell walls allow movement of water and dissolved inorganic ions from cell to cell. Xylem vessels grow end to end and lose their end walls to form continuous tubes, so that there is no resistance to water flow in these vessels.
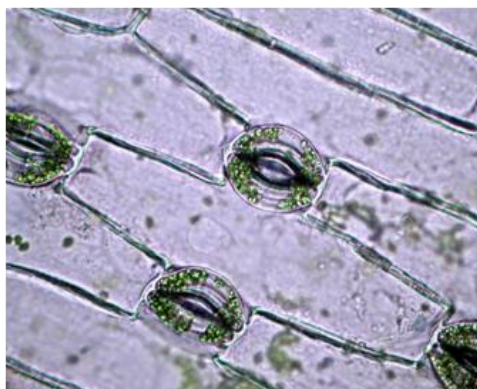
Roots

The xylem is found in a vascular bundle in the centre of roots. Here it provides resistance to stretching forces, thereby helping to anchor the plant in the ground. A sheath of specialised cells called the endodermis surrounds the vascular bundle. Each cell is bound to its neighbours by a strip of corky material (suberin) forming the Casparian strip. This forces all the water that passes into the xylem in the root to pass through selective cell membranes that control which inorganic ions reach the xylem. Important ions that are transported include nitrates, phosphates, potassium and magnesium.
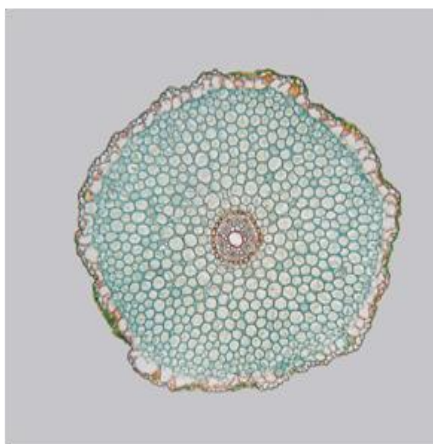

Figure 2 Cross section of a dicot root. Xylem vessels can be seen inside the ring of cells that form the endodermis in the centre of the root.

Protein carrier molecules in the cell membranes use energy from ATP to actively transport inorganic ions through the endodermis. This lowers the water potential of the cells inside the endodermis, so water follows by osmosis.

This creates root pressure; water is forced into the xylem even if there is no transpiration. Water is also taken up into the xylem by capillarity - adhesion of water molecules to xylem cell walls and surface tension effects cause water to rise up the narrow tubes, especially when they are very narrow like xylem vessels, with a diameter of the order of 0.02 mm.

As water is being removed into the xylem, a water potential gradient is set up and water will pass into the root and through to the endodermis by the same three roots found in the leaves: apoplast, symplast and vacuolar.

Water can only be taken up in parts of the root near the growing tips called the piliferous region. Here the epidermis is freely permeable to water. The rate of water and inorganic ion uptake is enhanced by greatly increasing the surface area of the root cells in contact with soil water, through the use of the long thin extensions found in root hair cells in the piliferous regions.

Mycorrhizae

The roots of most plants are colonised by symbiotic fungi which greatly increase the surface area available for water and mineral uptake by the plant. Phosphate uptake in particular is boosted. In return, the fungi are able to obtain carbohydrates from the plant. These fungi are most beneficial in nutrient poor soils. Companies such as The Royal Horticultural Society and Myccorrhizal Applications Inc. offer products like RHS Rootgrow which boost the myccorhizae in soil and claim significant improvements in plant growth rates and FDSAC crop yields.

Water-logging

The ability of the plant to actively uptake inorganic ions depends on having a supply of ATP for the protein carrier molecules. Energy must be supplied by aerobic respiration in the mitochondria. Waterlogging excludes air and oxygen from the soil, without which plant roots are unable to take in the minerals that the plant needs. Prolonged water logging will lead to the death of roots.

Water potential gradient

Through the active uptake of ions in the endodermis and the transpiration stream the plant is able to maintain a water potential gradient from the soil to the atmosphere.

This provides a supply of water for photosynthesis and to maintain cell turgidity.

Photosynthesis uses carbon dioxide and water to synthesise sugars, starch and fats.

Inorganic ions taken from the soil are used for the manufacture of other organic molecules, including proteins, chlorophyll, ATP, DNA and other molecules needed to sustain life.
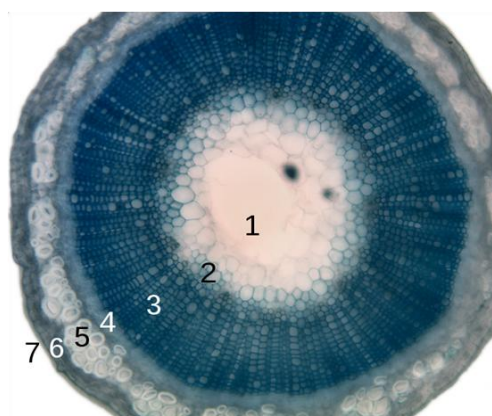
Figure 3 Cross section through a flax stem. Key:

1 Pith (parenchyma)

2 Protoxylem

3 Xylem

4 Phloem

5 Sclerenchyma (fibres)

6 Cortex

7 Epidermis

Translocation

Food molecules that have been synthesised in the leaves have to be moved to all the other parts of the plant in a process called translocation. Nutrients like sugars (glucose and starch are converted to sucrose for translocation) and amino acids are moved up and down in the plant in the phloem. Meristems (growing regions), fruits and seeds, and root storage systems in particular need good supplies of nutrients. When necessary, molecules must be retrieved from storage and redistributed. The place of origin of a nutrient is called its source and its destination is called the sink.

The phloem

Phloem is found in vascular bundles, closely associated with the xylem. It is a living tissue. Translocation requires energy. If phloem cells are killed, translocation will cease. Phloem tissue contains sieve tube cells which lie end to end to form continuous tubes. The cellulose cells walls at the ends of the cells are perforated to form sieve plates that allow cytoplasm to run from one cell into the next. These cells translocate nutrients, but lose their nuclei and most of their organelles when they mature.

Companion cells run alongside the sieve tube cells. These are connected to them by plasmodesmata. They do not translocate nutrients, but control the activity of the sieve tube cells. They have cytoplasm with many cell organelles.

Finding out

The mechanism of movement of nutrients is not well understood. The mass flow (or pressure flow) hypothesis suggests that phloem is loaded with sugars by active transport, using energy from respiration in mitochondria in companion cells. Water follows by osmosis, the subsequent pressure driving fluid through the phloem. This hypothesis does not account for movement of nutrients both up and down the plant in phloem. More recent suggestions include the electroosmosis (postulating an electrical imbalance) and cytoplasmic streaming offer hypotheses, but neither provides a complete explanation of observations.

What is electroosmosis?

What is cytoplasmic streaming?