ESSENTIAL PLANT BIOLOGY

Plant Physiology

This session booklet provides an introduction to some of the processes that control plant growth and development.

LEARNING OUTCOMES

On completing this session learners will be able to:

- Describe the basic requirements for photosynthesis
- Explain the effects of environmental factors on the rate of photosynthesis
- Describe the basic requirements for respiration
- Describe the processes of water movement in a plant
- Explain the effect of day length on plant flowering
- Describe the processes of seed germination
- Describe the factors that affect the germination of seeds.

Introduction

This session booklet looks at the processes that **control** plant growth and development.

A plants **growth rate** is controlled by the amount of raw materials that it can take in and process. These raw materials are carbon dioxide, water, light and mineral nutrients such as nitrogen, phosphorous and potassium. This booklet is an introduction to **photosynthesis**, **respiration** and **water** (and nutrient) uptake, the most important processes that determine plant growth.

The various stages in a **plants development** are in part controlled by internal factors, and by the processes mentioned above, but may also occur in response to **environmental changes**. This booklet looks at one of these, day length, which allows a plant to control the timing of things like bud burst and flowering.

Photosynthesis

The sun is the main source of energy to all living things. Light energy from the sun is converted to the chemical energy of organic molecules by green plants by a complicated pathway of reactions called photosynthesis. This can be simplified

As:

$$\text{Carbon Dioxide} + \text{Water} \xrightarrow{\text{Light Energy}} \text{Glucose} + \text{Oxygen}$$

Or:

$$6CO_2 + 6H_2O \xrightarrow{\text{Light Energy} \quad 2880kj} C_6H_{12}O_6 + O_2$$

This means that the raw ingredients for photosynthesis are:

- **Carbon Dioxide**
- **Water**
- **Light Energy**

Also needed is: **Chlorophyll**

Photosynthesis consists of two main phases:

1) The Light Reaction or Light Dependent Reaction

Here **light energy** absorbed by **chlorophyll** splits water into oxygen and hydrogen. The oxygen is given off as a by product. The hydrogen is used to produce the energy carrying chemical **ATP**. The hydrogen then attaches to an NADP molecule forming **NADPH**. The light reaction can only take place in the presence of light and is thus light dependent.

2) The Dark Reaction or Light Independent Reaction

Here the energy in the ATP is used to convert the hydrogen plus carbon dioxide from the air into simple carbohydrates such as glucose. The Dark Reaction can take place in the absence of light if it has the necessary **ATP**, **NADPH** and **carbon dioxide**, but more often occurs in the light immediately after the Light Reaction. It is therefore more correctly termed the **Light Independent Reaction** and is sometimes referred to as the Calvin Cycle (after the scientist that who worked out the detail).

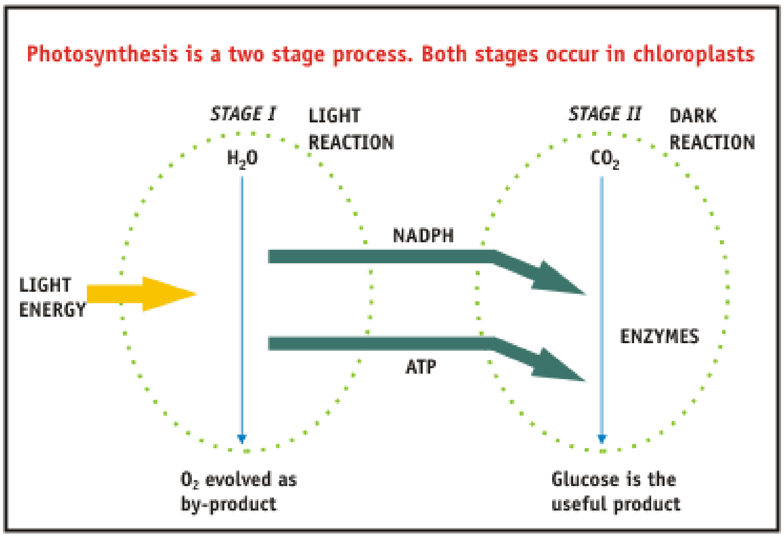


Figure 1: The Light and Dark Reactions of Photosynthesis

Where Do The Light and Dark Reactions Happen?

They happen in the **chloroplast**.

The Light reaction occurs on the **thylakoid membranes**, particularly in the **Grana**. The Dark reaction occurs in the **stroma**.

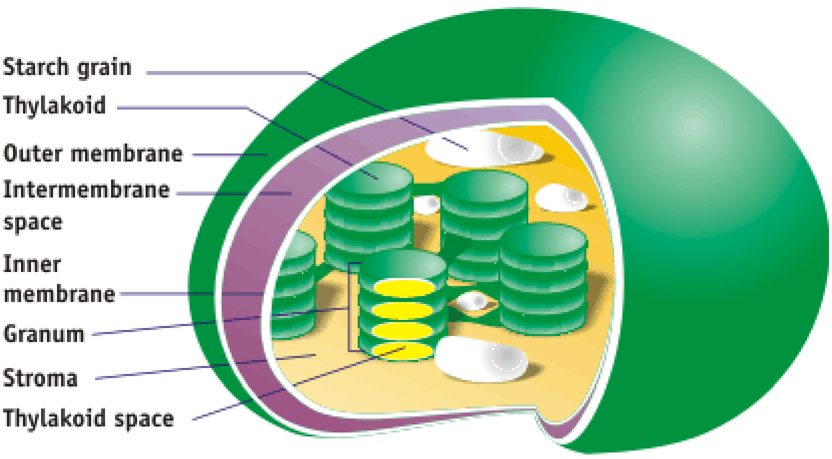


Figure 2: Structure of a Chloroplast

First Catch Your Light!

The first step in photosynthesis is to capture some light. So what is light and how do green plants catch it?

What Is Light?

Light is a form of energy known as electromagnetic radiation. Visible light is part of a wider electromagnetic spectrum. White Light is a mixture of light of different colours; the different colours have different wavelengths. The shorter the wavelength the more energy the light has.

Which has more energy Blue or Red light?

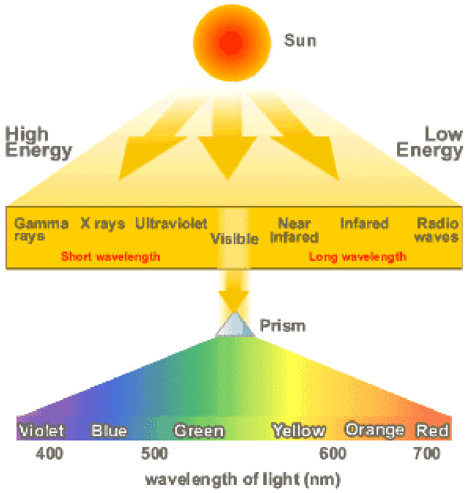


Figure 3: The Light Spectrum

Answer - Blue light has more energy as it has the shorter wavelength. UV light has an even shorter wavelength and so even higher energy, this is why it can cause damage to our skin!

Which Wavelengths Of Light Do Plants Need For Photosynthesis?

If we measure the rate of photosynthesis of a plant in different wavelengths of light we obtain what is known as an action spectra. This shows that blue and red light work best for photosynthesis, while green is the least effective.

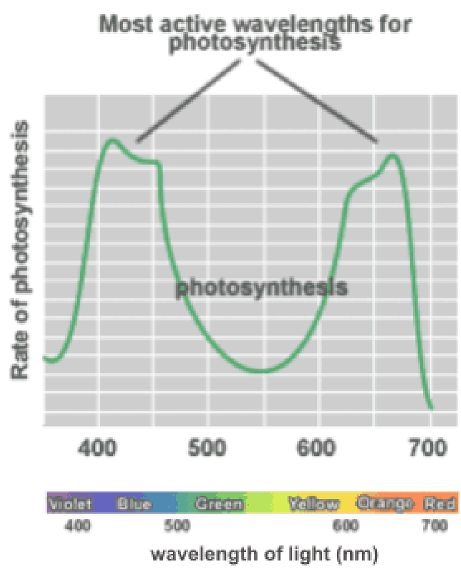


Figure 4: Photosynthetic Action Spectrum

Photosynthetic Pigments and Light Absorption

Plants use a number of pigments in the chloroplast to catch light. Different pigments catch or absorb different wavelengths of light.

1) The Chlorophylls

Chlorophylls are proteins. They have a complex ring structure with a magnesium atom (with loosely bonded electrons) in the centre and a long hydrocarbon tail. The ring is the part involved in capturing the light energy the hydrocarbon tail is used to attach the molecule to particular proteins within the thylakoid membrane. Chlorophylls absorb blue and red light energy best.

Chlorophyll a is found in all photosynthetic organisms. **Chlorophyll b** is found in green plants. **Chlorophyll c** is found in brown algae.

Chlorophyll a is blue-green in colour; where as chlorophyll b is yellow-green.

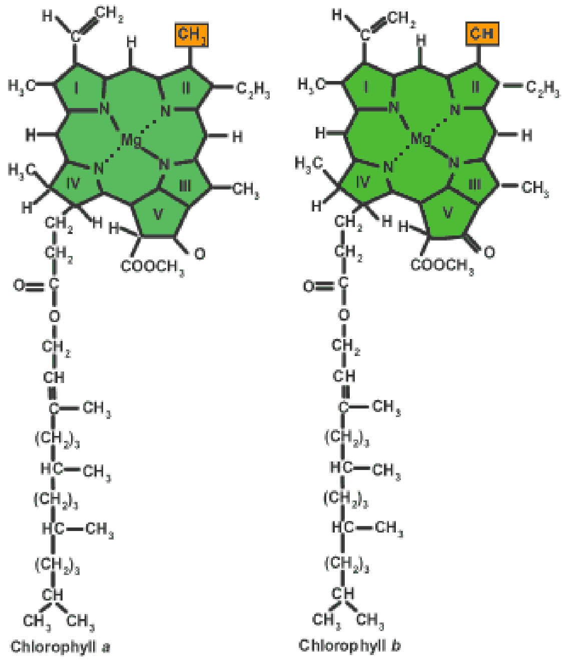


Figure 5: Structure of Chlorophyll

2) The Carotenoids

These are hydrocarbon compounds which absorb different wavelengths of light from those absorbed by chlorophyll. They transfer any light energy absorbed to the chlorophyll molecules. They can also act to protect the chlorophyll by taking energy away at excessive light intensities. They include **a carotene, b carotene** and **xanthophylls** and are various shades of yellow and orange.

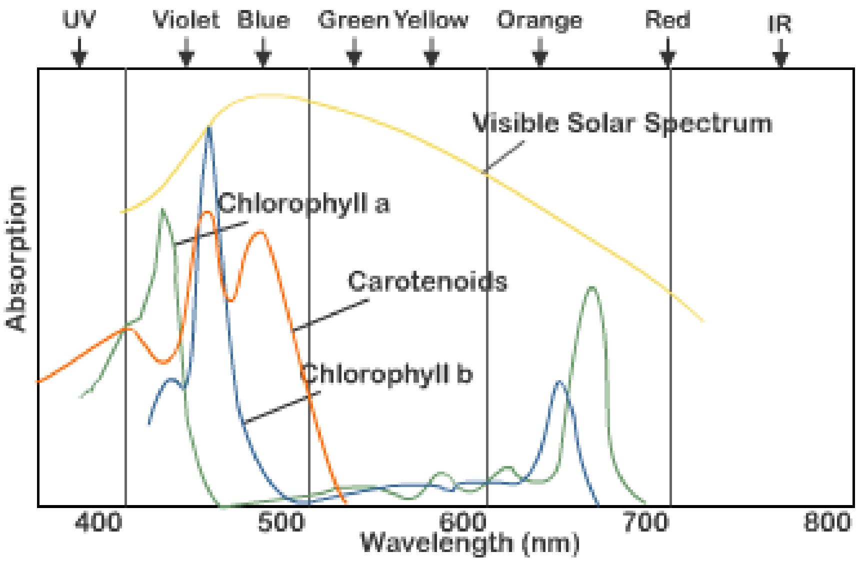


Figure 6: Absorption spectrum of photosynthetic pigments

Photosynthesis and the Environment

There is flexibility in the photosynthetic system to adapt to different conditions. The rate of photosynthesis is usually measured as either the rate of oxygen production or the rate of carbon fixation.

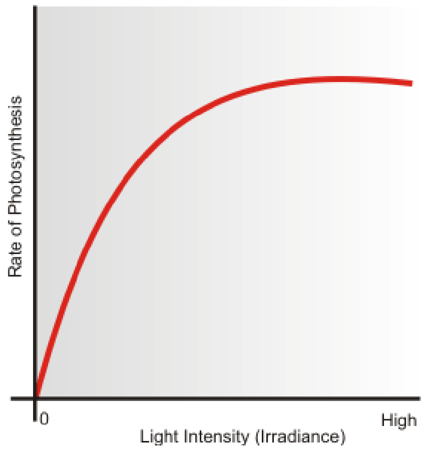
Which three of the following things particularly affect the rate of photosynthesis?

(See next page for answer)

Soil pH	Carbon Dioxide Concentration	
Light Intensity	Oxygen concentration	Temperature

Effect of Light Intensity

At lower light intensities plants **increase their rate of photosynthesis** as the light intensity is increased. This can be represented by a photosynthetic response curve (see below). Beyond a certain light intensity the light capture system becomes **saturated**, and additional light energy cannot be used.



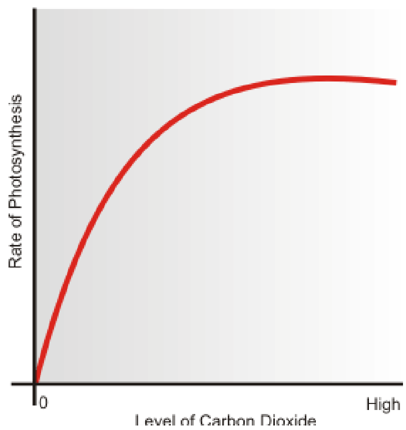
Full sunlight is about 400-500 Wm^{-2} (Watts per square metre); photosynthesis is typically saturated at around 200-300 Wm^{-2}. This is because the concentration of carbon dioxide is now limiting the overall reaction rather than the light level.

Figure 7: Effect of Light Intensity on rate of Photosynthesis

Effect of Carbon Dioxide Concentration

The rate of photosynthesis of most temperate (C_3) plants is **limited by CO_2** rather than by light. The CO_2 concentration will have an effect on the Calvin cycle, and this will in turn affect the light reactions.

Figure 8: Effect of Carbon Dioxide concentration on rate of Photosynthesis



CO_2 enrichment of glasshouses is a common practice; this can **increase crop yields** by relieving the inhibition described above, and allowing all the light energy to be utilised. Under these conditions an increase in light leads to higher rates of photosynthesis, until the process becomes limited by the capacity of the light harvesting system.

Effect of Temperature

The rate of photosynthesis varies with temperature because the reactions of photosynthesis require **enzymes** to work. At lower temperatures enzymes work slower, at higher temperatures they do not work at all.

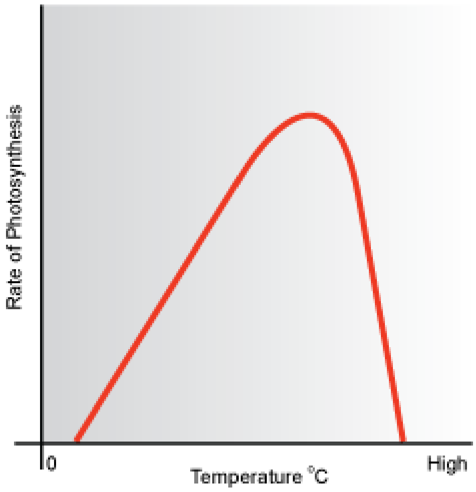


Figure 9: Effect of Temperature on Photosynthesis

Answers to question on previous page:

Carbon Dioxide Concentration

Temperature

Light Intensity

Respiration

Most living cells live by releasing the energy stored in organic compounds. Most use oxygen to oxidise the complex organic molecules, with some of the energy being used to do work, some dissipated as heat and the production of simpler chemical waste products. This is **aerobic respiration**.

Although very different in mechanism aerobic respiration is essentially similar to the combustion of fossil fuels in a car engine. The energy released in respiration is transferred to a carrier molecule ATP before being passed to other energy consuming processes.

Combustion:

Organic Compounds + Oxygen → Carbon Dioxide + Water + Energy

Aerobic Respiration:

Glucose + Oxygen → Carbon Dioxide + Water + Energy

Or:

C6H1206 + 602 → $6CO_2$ + $6H_20$ + Energy (2870KJ)

Plants and Oxygen

All living plant cells must respire in order to provide energy for all the chemical reactions that go on in the cell. For this reason even dormant seeds will require at least small amounts of **oxygen** to stay alive and will be using stored food, limiting survival time.

Under **anaerobic** conditions with no oxygen, such as occur in **waterlogged soils**, plants can carry out a modified version of respiration which produces smaller amounts of energy. This can only be done for a limited time because anaerobic respiration produces ethanol which is poisonous to plant cells once it reaches a certain concentration.

Photosynthesis v Respiration: Plants in the Shade

Photosynthesis varies with light intensity. Plants that live in shaded, **low light intensity** conditions may adapt by having **larger** but **thinner leaves**, and **higher concentrations of chlorophyll**, to catch more light. Respiration on the other hand continues in the dark and acts in the opposite direction in that sugars are used and carbon dioxide produced. An alternative adaptation is for shade plants to have **lower rates of respiration and growth** and so lower **compensation points.**

What is a compensation point?

Photosynthesis fixes carbon dioxide, respiration produces it. The rate of photosynthesis increases with light intensity whereas the rate of respiration is little affected by light (see Figure 10).

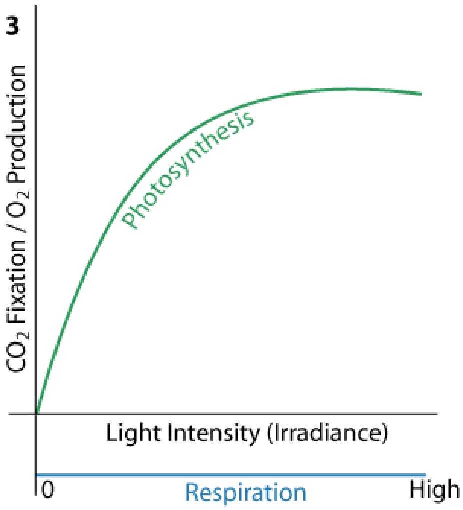


Figure 10: Effect of light intensity on Photosynthesis and Respiration

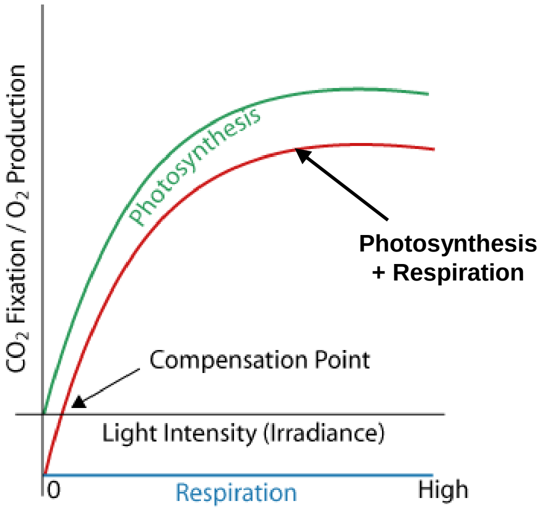


Figure 11: Compensation Point

The **net fixation** of carbon dioxide will be zero at a light intensity where the amount of photosynthesis is 'equal' to the amount of respiration. This light intensity is the **compensation point** (see Figure 11). The compensation point will be lower if the respiration rate is slower but lower respiration means lower growth rate!

Compensation Period

The time taken for a plant, which has been in darkness, to reach the compensation point, is the **compensation period**. The most important factor governing the length of the compensation period in natural conditions is light intensity; the higher the light intensity the **shorter the compensation period**. However, shade leaves, with lower rates of respiration, actually have shorter compensation periods than sun leaves which enables them to make more efficient use of light of low intensity.

Learning Activity

Now go and do the **'Photosynthesis and Respiration Quiz'** to be found in the Plant Physiology 'Interactive Learning Activities' folder.

Water Movement in a plant

Water is very important to a plant. 70-80% of a plant is water and water is the medium in which all the chemical reactions in a plant cell take place. Water is also used for transport, for structural support and for keeping the plant cool.

Movement of Water into a Plant

Water is taken into the roots of a plant from the soil by a process called **osmosis**. Osmosis can be thought of as a special form of **diffusion**.

Diffusion

Diffusion is movement of a substance from an **area where there is more** of it to an **area where there is less** through a gas or a liquid. Imagine the spread of a nasty smell from one end of a room to another!

The diagram below represents diffusion in a liquid, where random movement of water and ink molecules leads to an even spread of the ink throughout the beaker.

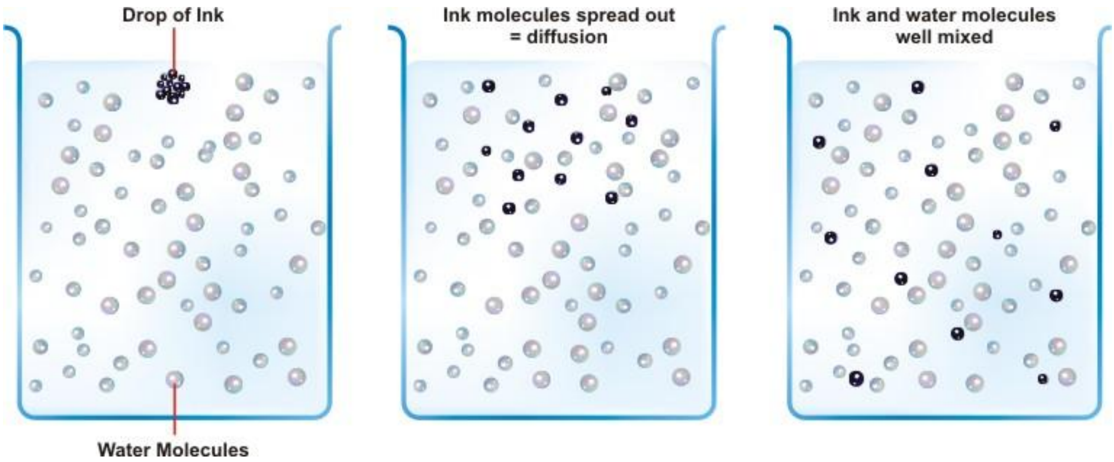


Figure 12: Diffusion

Diffusion is important for movement **of gases into and out of a leaf**. The stomata in the epidermis and air spaces in the spongy mesophyll allow gases to diffuse in and out. As carbon dioxide inside the leaf is used for photosynthesis during the day the concentration here is lowered and so more carbon dioxide moves in by diffusion. The reverse is true for oxygen levels. Diffusion of gases through the air is quicker than it would be through the watery cell contents. This explains the **benefit of air spaces**!

Osmosis

Osmosis is similar to diffusion, in that water is moving from an area where there is more of it, to an area where there is relatively less!

The molecules in the solutions on either side of the partially or **selectively permeable membrane** (the plant cell membrane) are moving around all the time and sometimes water molecules pass through small pores in the membrane. Water molecules can move either way through the membrane but, because there are more water molecules in the less concentrated solution, more will tend to go through from this side. This leads to a **net movement of water** from the less concentrated to the more concentrated solution through the membrane. The larger molecules, such as sugars, dissolved in the water, are effectively too big to go through these pores in the cell membrane.

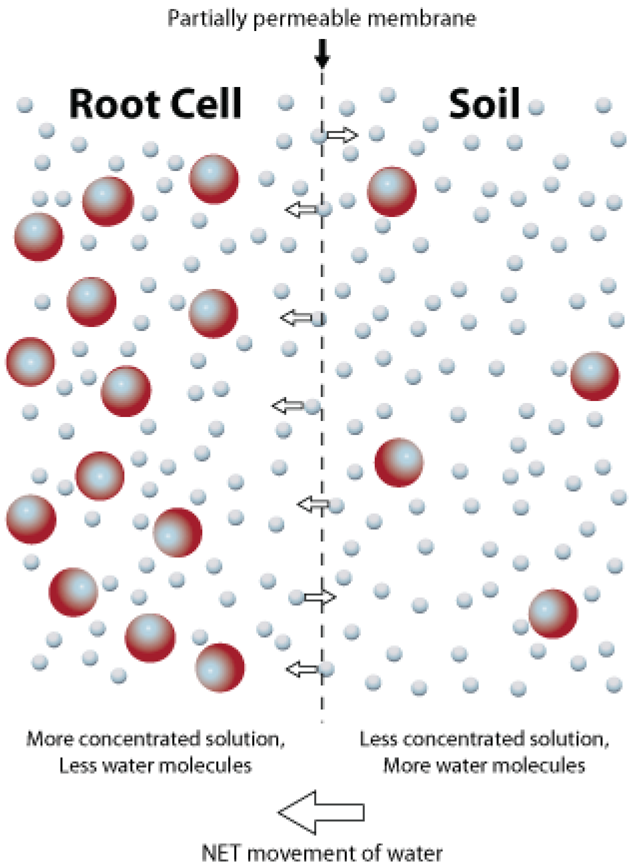


Figure 13: Osmosis

Osmosis can therefore be defined as the movement of **water** from a **weaker** solution to a **stronger** solution through a **selectively permeable membrane**.

Water generally **moves into a plant** because the root cells are more concentrated than the soil outside (because they have more chemicals such as sugars dissolved in the water). The selectively permeable membrane is the root cell membrane. However if too much fertiliser is added to a soil or compost it is possible to make the soil solution more concentrated than the solution inside a root cell. If this is the case then **water will move out** of the plant by osmosis instead of in! This is obviously not very good for the plant and may kill it!

Movement of Water up and out of a Plant

Water moves up a plant due to **three main processes**:

1. As water continues to move into the plant by osmosis it pushes the water up the stem; this is known as **Root Pressure**.

2. As water is lost from the top of the plant by evaporation, or transpiration, more water is drawn up to replace it, a bit like water being sucked up a straw; this is known as **Transpiration Pull**.

3. Water would not move up the plant in a continuous stream if water molecules were not inclined to stick together; this is known as **Cohesion**.

The fact that columns of water moving up the xylem are under tension due to the pull of transpiration has lead to the system of water movement up the plant being know as the **Cohesion Tension** theory

Transpiration

Water moves out of a plant by a combination of **evaporation** and **diffusion**. Most of the water evaporates from cell walls inside the leaf into the air spaces and then diffuses out of the leaf through the stomata. Little evaporates directly from the outside of the leaf due to the waxy, waterproof cuticle. The combined process is known as **transpiration**.

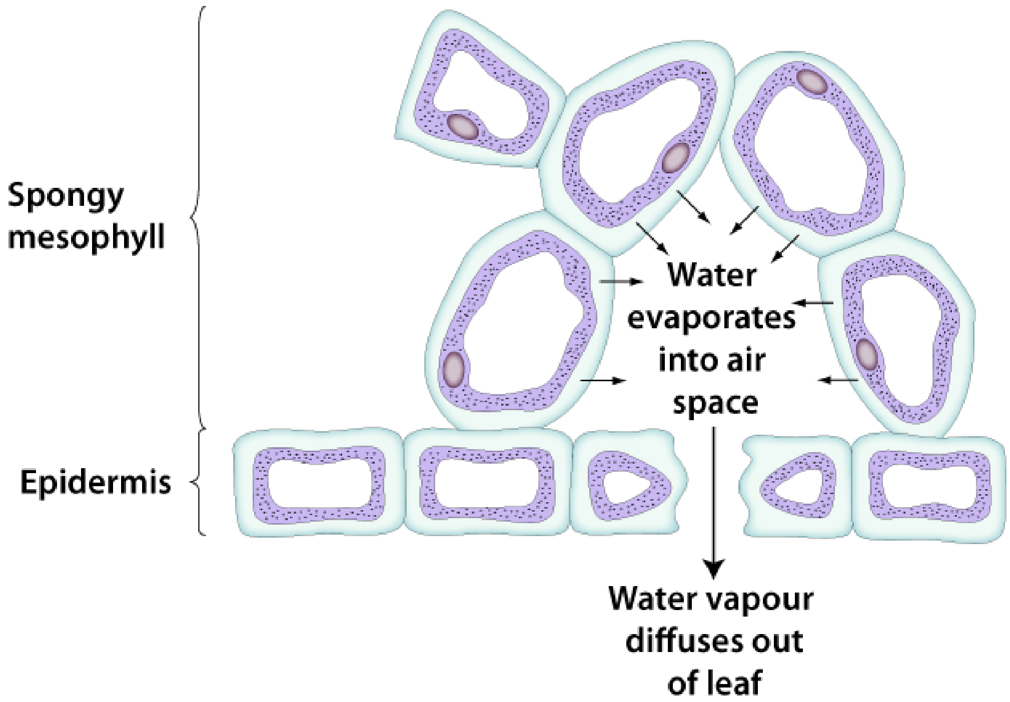


Figure 14: The Stages of Transpiration

Nutrients Uptake and Movement

Only small water molecules can move **passively** (without expenditure of energy by the cell) through the partially permeable cell membranes by osmosis. Nutrient molecules, such as nitrates and phosphates have to be taken up by the plant **against** a concentration gradient, as there is actually a higher concentration in the root cells than outside. This is an **active process** that requires **use of energy** from respiration and involves some of the protein molecules embedded in the phospholipid membrane. Undissolved solids will not pass through the cell membranes at all.

Movement of nutrients up the plant occurs in the xylem, by a process called **mass flow**, as nutrients are carried up with the flow of water.

Further Reading

Diffusion and Osmosis are covered well in a number of books on the book list and if you are not quite sure that you understand them it would be useful to do a bit of extra reading here. Campbell's book on Biology also has a CD with quite a good section on Osmosis. There are also some useful websites, try searching for 'osmosis explanation diagrams' on something like Google.

Photoperiodism

Many stages in a plants life cycle are seasonal or occur in response to environmental changes. For example:

- Flowering may be controlled by day length or temperature
- Leaf drop may be controlled by day length, temperature, drought, nutrient deficiency or disease

Control of Flowering by Day Length

The flowers of both wild and cultivated plants grown outdoors appear at a specific time of the year. Daffodils in early spring; grasses in summer; chrysanthemums in the autumn. This suggests that environmental stimuli control the time of flowering. The most common stimuli of flowering in temperate climates is the relative length of night and day.

Figure 15: Daffodils flower in spring

Some plants will flower only after several days when the number of light hours, the **photoperiod**, is of more than a critical length. Other species will flower only after exposure to a number of days with short photoperiods. A number of plants are unaffected by day length.

There are therefore three types of photoperiodic response shown by plants. We refer to the 3 types as: ***Short-day plants, Long-day plants and Day-neutral plants.***

Short-day plants

These require a light period shorter than a critical length to flower, as occurs in Britain during autumn and winter. This group of plants includes chrysanthemums, poinsettias and cotton.

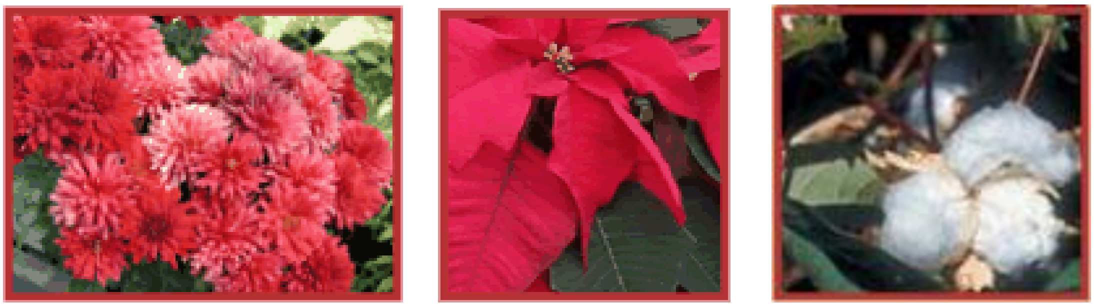


Figure 16: Short-day Plants – Chrysanthemums, Poinsettias and Cotton

Long-day Plants

These flower only after a sucession of long photoperiods over a critical length. Spinach for example, flowers when days are 14 hours or longer. This group of plants includes many important crop plants such as wheat, clover and lettuce.

Figure 17: Long-day Plants – Spinach, Wheat, Clover and Lettuce

Day-neutral plants

These flower when they reach a certain stage of maturity, regardless of the day length or photoperiod at that time. They include tomato, cucumber, rice and dandelions.

Figure 18: Day-neutral Plants – Tomato, Cucumber, Rice and Dandelions

Photoperiodism: Additional requirements

The **number of photoperiods** required to induce the formation of flowers varies from one species to another. Most plants need about ten consecutive photoperiods of a suitable length. For many plants the photoperiod treatment will only be effective in inducing flowering if it is received at an appropriate stage in the plant's development. In most species the plant needs the photoperiod treatment at the seedling stage whereas in others several mature leaves must be present.

For other plants flowering will only be induced if they have been exposed to **some other environmental stimulus** prior to the photoperiod treatment. Winter wheat for instance requires a period of cold temperatures. Even after an appropriate stimulus it may take several days or weeks for the vegetative apices of a plant to change to start producing flower initials.

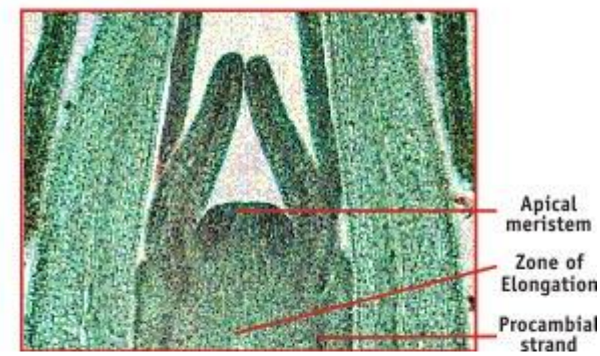


Figure 19: Shoot Apex

Light or Dark?

Research has shown that, for short day plants in particular, the length of the photoperiod is less critical than the length of the dark period. For **short-day plants** if the photoperiods (the light periods) are interrupted with short periods of darkness flowering still occurs. However, if the dark period is interrupted by as little as one or two minute's exposure to light, no flowering occurs.

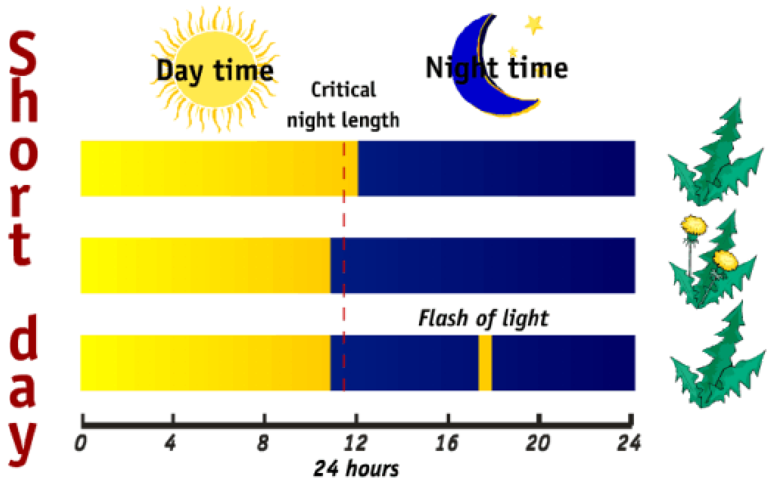


Figure 20: Typical response of Short-day plants to different light treatments

Learning Activity

Now go and do the **'Water Movement and Photoperiodism Quiz'** to be found in the Plant Physiology 'Interactive Learning Activities' folder.

Seed Germination and Dormancy

The Seed Germination Process

The process of germination involves **three** main stages:

- **Water uptake and cell expansion**
- **Mobilisation of stored food**
- **Cell Division and growth**

Water Uptake and Cell Expansion

The first step in the germination of many seeds is **imbibition**, the absorption of water by osmosis by the seed. Water initially enters the seed through the **micropyle** as the seed coat is relatively impermeable to water. Hydration of the cells causes cells, and seed to expand, rupturing the seed coat. It also triggers metabolic changes in the embryo, for instance the rate of respiration will increase. The water moving in through the micropyle may stop the entry of air and oxygen for a short while leading to a period of **anaerobic respiration** before the seed coat splits.

Mobilisation of Stored Food

Mobilisation of food reserves has been studied most extensively in the grains of barley and other **cereal** seeds.

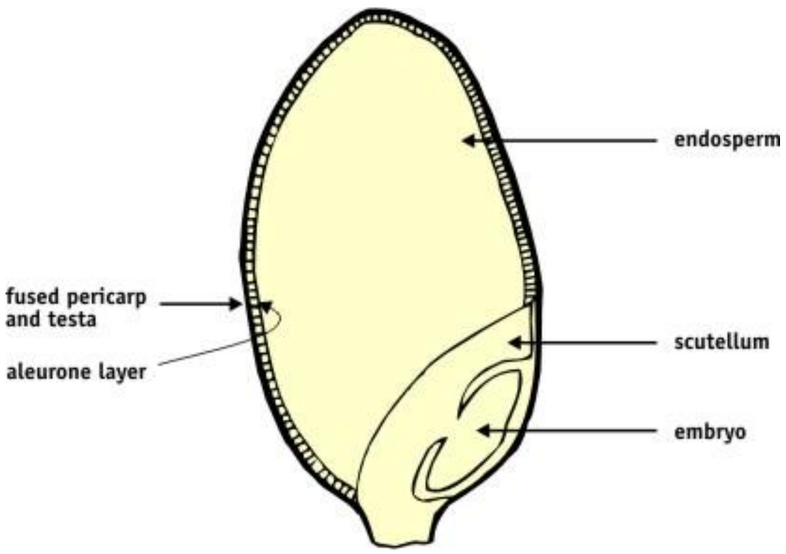


Figure 21: Structure of a Barley 'Seed'

There are three stages in the mobilisation of stored food in cereals:

STAGE A: When a dormant seed imbibes water the **embryo** produces **gibberellic acid**, GA, (a plant hormone which stimulates plant growth and cell division) which diffuses to the aleurone layer, the thin outer layer of the endosperm.

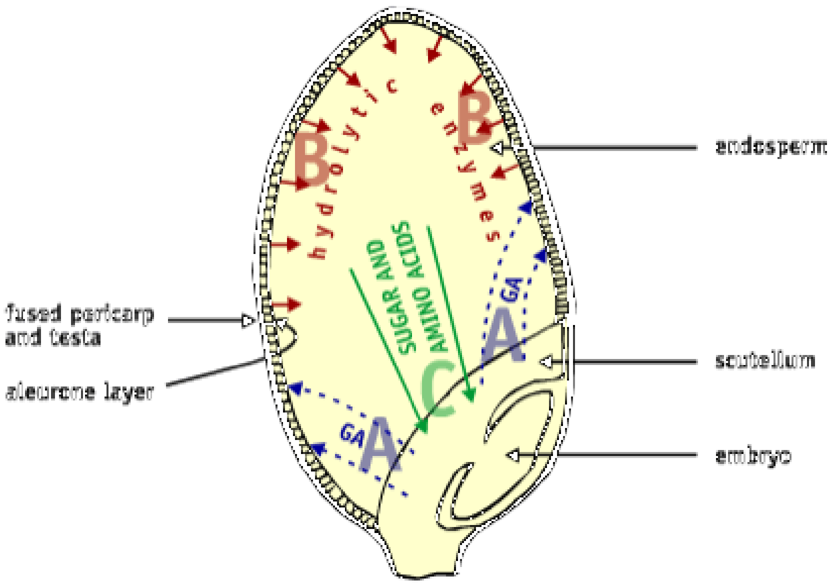


Figure 22: Stages in the Mobilisation of stored food in Cereals

STAGE B: The **aleurone layer** begins to make amylase and other **enzymes** that digest the starch and other foods in the endosperm. Starch is hydrolysed to maltose, glucose and sucrose; proteins are hydrolysed to amino acids, fats and oils to glycerol and fatty acids.

STAGE C: The soluble sugars and other nutrients are absorbed into the scutellum (cotyledon) and used for the growth of the embryo.

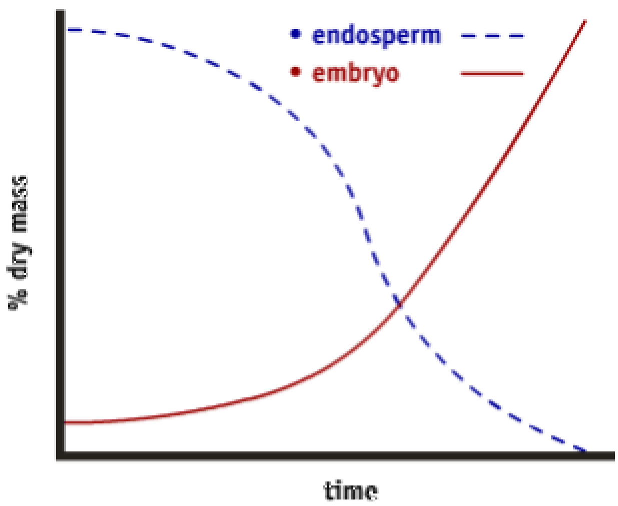


Figure 23: Changes in a cereal grain as germination progresses

Types of Germination

There are two different types of germination

- **Epigeal**
- **Hypogeal.**

Epigeal germination involves fastest growth of the hypocotyl, the part of the stem between the cotyledon stalks and the radicle, with the cotyledons appearing above the soil surface. Sunflowers, Acers, sycamore and French beans all show epigeal germination.

Hypogeal germination involves rapid elongation of the epicotyl, the region of stem just below the pumule, with the cotyledons remaining below the surface (Hypo = below). Broad bean, horse chestnut and oak all show hypogeal germination.

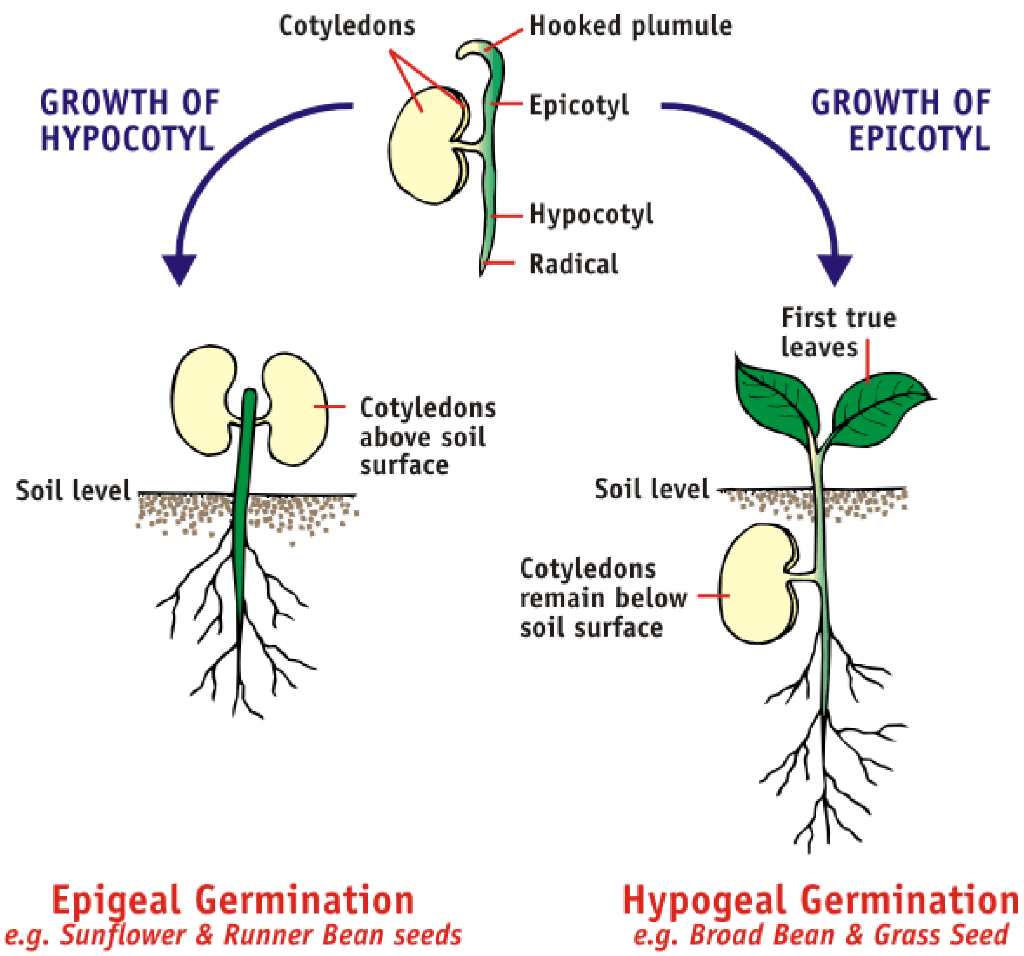


Figure 24: Types of germination

Environmental Factors affecting Seed Germination

A number of environmental factors can influence seed germination. The grower usually controls these by choice of sowing time and by appropriate seedbed preparation. They include temperature, oxygen, water and light.

Temperature

Many of the metabolic changes which take place in germination are catalysed by enzymes. Enzyme activity is effected by temperature. Seeds of each species have an optimum temperature for germination. Some may require a chilling period (0-5°C) after water absorption e.g. red fescue grass.

Figure 25: Grass Seeds

Oxygen

Synthesis of new cellular components in germination requires energy from respiration and this requires oxygen to be absorbed through the seed coat. The testa in some seeds is relatively impermeable to O_2 so they respire anaerobically at the start of germination. Large bulky seeds, as produced by many trees, have a small surface area to volume ratio which may also result in an inadequate oxygen supply and some anaerobic respiration.

Water

The water content of most seeds in storage is about 5-10%. More water is needed for metabolic activity, vacuolation of cells and transport. In nature, when dispersed in the soil, seeds may contain more water than this but other factors may prevent germination. High levels of water in waterlogged soils may not allow a plant to take in enough oxygen.

Light

Some seeds require light before they germinate but light treatment is only effective if the seeds have absorbed water. Generally only low levels of light intensity are required. Some plants, particularly woodland margin plants, will only germinate in direct sunlight and not in shade others require dark. Light requiring plants include lettuce, many grasses and birch. Light dependent seeds may be small and need to germinate on or near to the surface of the soil or maybe woodland herbs that need to germinate in spring before the leaf canopy appears.

Figure 26: Lettuce

Seed Dormancy

True dormancy is a state in which the seed will not germinate even if the conditions are suitable. Most wild plants use some sort of dormancy mechanism to spread the time of germination and aid survival. Cultivated plants have often been selected for their lack of complex dormancy mechanisms (although many tree species do still exhibit some interesting examples!).

Dormancy mechanisms may involve the embryo, the seed coat, or both. They may involve **physical restriction** by a hard seed coat (or the pericarp) or the presence of **chemical inhibitors** in the seed coat. Conditions that break dormancy are usually designed to ensure that seeds germinate in good conditions for seedling growth.

Chemical inhibitors may be broken down or removed by:

- Extensive **washing**, which removes inhibitors, and particularly in desert species, ensures that seedlings grow when there is sufficient water.
- Exposure to a prolonged period of **low temperature**, stratification, (especially tree species) ensuring that seedlings germinate after, rather than before, a cold winter, for example **primroses**.
- Exposure to a prolonged period of **high temperature**, ensuring that seedlings germinate after, rather than before, a hot, dry summer.

Figure 27: Primroses

Physical restrictions may be broken down by:

- **Fire,** ensuring that germination occurs after a fire, in high light conditions, with nutrient rich soils and little competition.
- **Bacterial action** in the soil, so that seed with a variety of coat thicknesses can be used to spread germination time.
- **Freeze–thaw action,** ensuring that seedlings germinate after a cold winter.
- Breakdown of seed coat as it passes through the **gut of animals**, enabling the plant to make use of animals to spread seed.

Learning Activity

Now try the **'Seed Germination and Dormancy Quiz'** in the 'Interactive Learning Activities' folder.

Senescence

Senescence is aging that leads to death. It can occur on a small scale as organs such as petals or leaves are shed, or during development of fleshy fruit, or it may mark the end of the plant life cycle or the growing season. When an organ is to be shed, an **abscission zone** develops.

Senescence is generally an **organized dismantling of the cellular contents** which results in the release of nitrogen, phosphorus, carbon and other nutrients for redistribution to the rest of the plant. Sometimes senescence is pre programmed (and controlled by the nucleus), other times it may be induced by an external stimuli such as nutrient stress or pathogen attack.

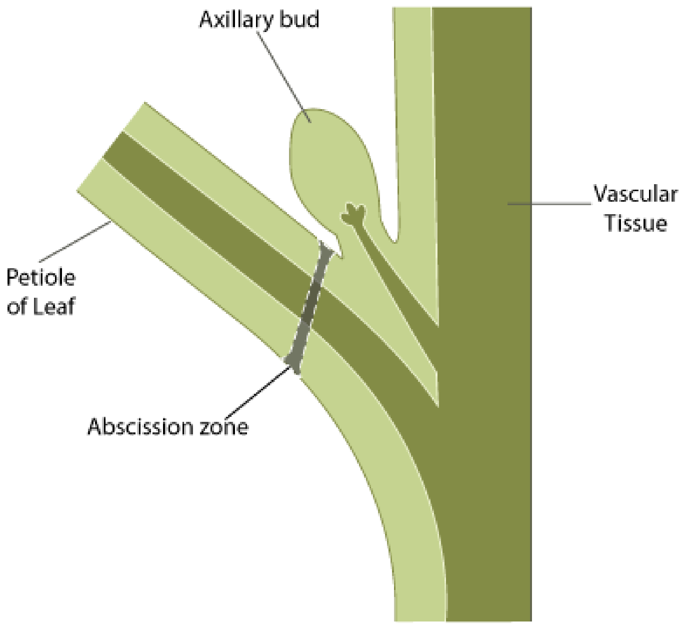


Figure 28: Diagram of an abscission zone