TOPIC: PHOTOSYNTHESIS

Key Knowledge:

- General structure of the biochemical pathway in photosynthesis from initial reactant to final product
- Inputs, outputs and locations of the light dependent and light independent stages in C_3 plants
- Role of Rubisco, including adaptations of C_3, C_4 or CAM plants to maximise photosynthesis efficiency
- Factors affecting photosynthetic rate: light and water availability, temperature, CO_2 concentration

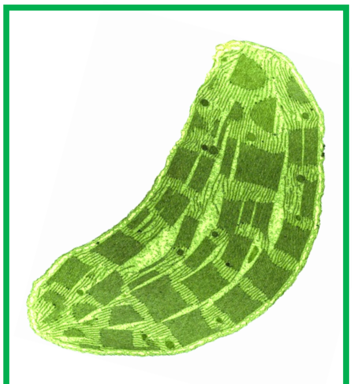
PHOTOSYNTHESIS

Photosynthesis is the process by which cells synthesise organic compounds from inorganic molecules in the presence of sunlight. This process requires a photosynthetic pigment (**chlorophyll**) and can only occur in certain organisms. In plants, photosynthesis occurs in a specialised organelle called the chloroplast and involves two main stages: the light dependent reactions and the light independent reactions (Calvin cycle).

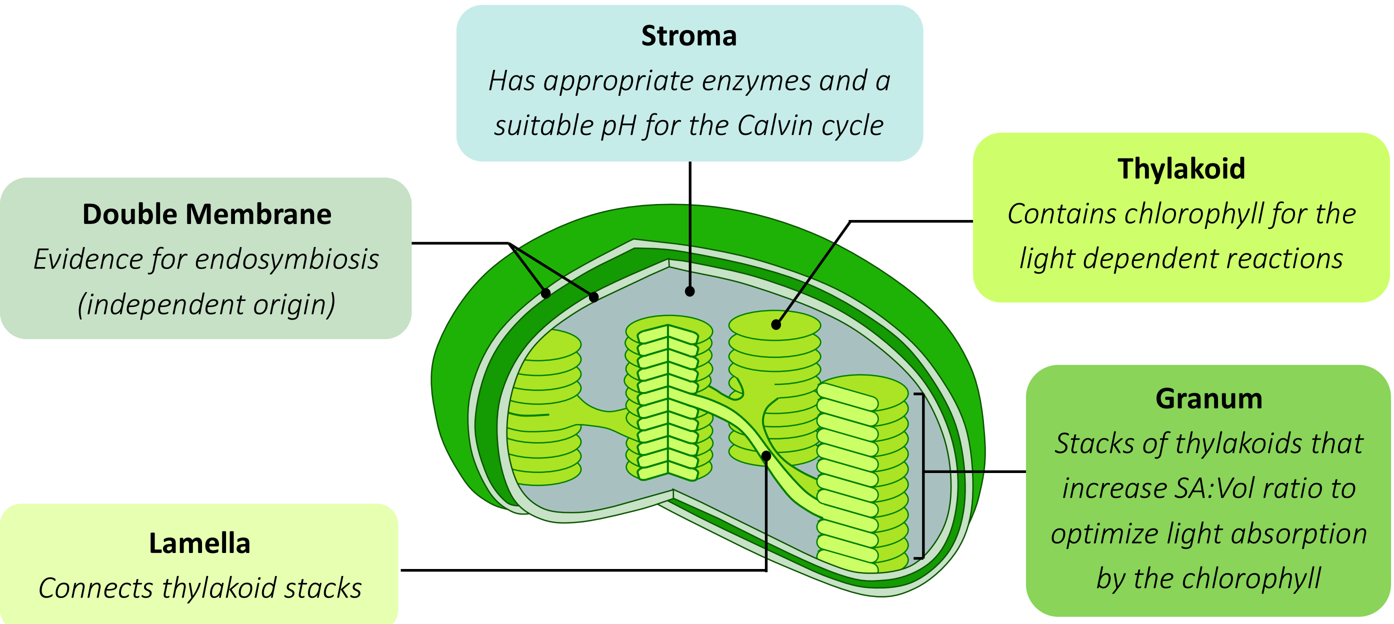
$$\underset{\textit{Carbon dioxide}}{6\ CO_2} + \underset{\textit{Water}}{12\ H_2O} \xrightarrow[\text{Chlorophyll}]{\text{Light}} \underset{\textit{Glucose}}{C_6H_{12}O_6} + \underset{\textit{Oxygen}}{6\ O_2} + \underset{\textit{Water}}{6\ H_2O}$$

CHLOROPLAST

The chloroplast is an organelle in the **leaf tissue** of plants that is responsible for photosynthesis. It is believed to have evolved via endosymbiosis, when a photosynthetic prokaryote (cyanobacterium) was engulfed by another cell. Evidence for this endosymbiotic origin includes the fact that the chloroplast has a double membrane, possesses circular DNA and has 70S ribosomes. In terms of structure, chloroplasts contain membranous discs called **thylakoids** that are arranged into stacks called **grana**. These thylakoids have chlorophyll and are the site of the light dependent reactions. The fluid of the chloroplast is called the **stroma** and is the location of the light independent reactions.

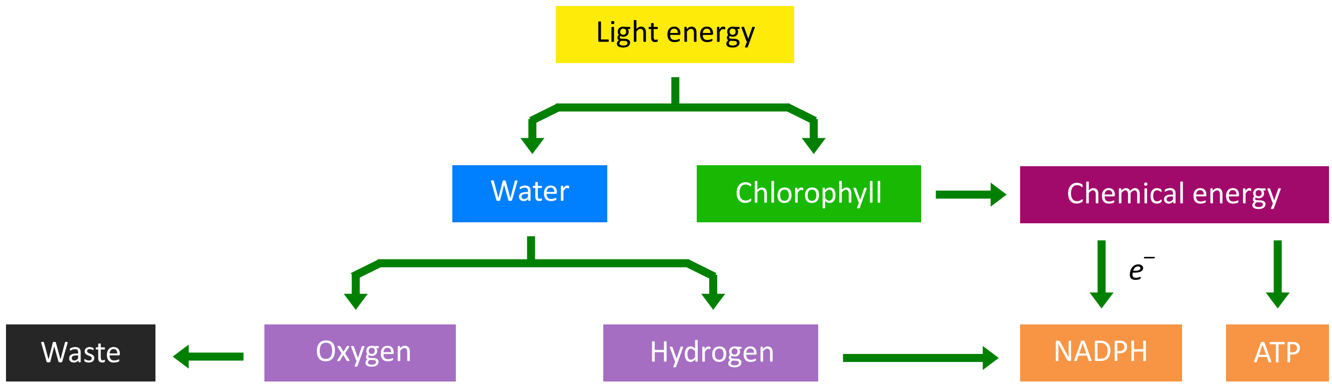


Micrograph: Chloroplast



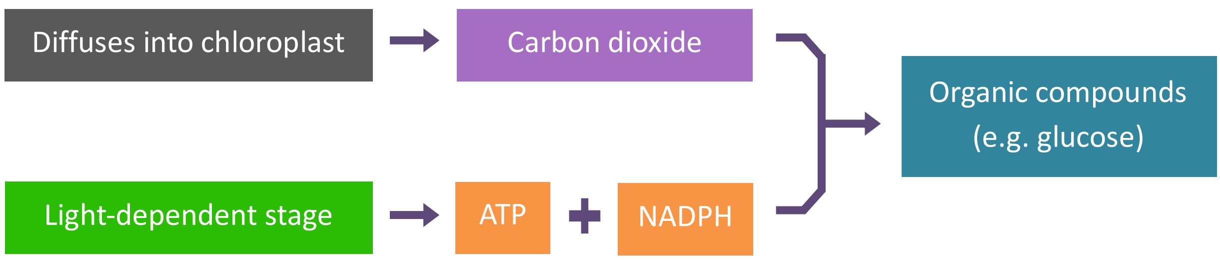
LIGHT-DEPENDENT REACTION

The first stage of photosynthesis is called the light dependent reaction and involves the conversion of light energy into chemical energy (ATP). A photosynthetic pigment called **chlorophyll** is exposed to sunlight and certain wavelengths are absorbed (red and blue light is absorbed; green light is reflected). The chlorophyll then transfers this light energy to an energy-carrying coenzyme, by synthesising ATP (a loaded coenzyme) from ADP (an unloaded coenzyme). This conversion of light energy into chemical energy (ATP) is called **photophosphorylation**. Simultaneously, light energy breaks water molecules (via **photolysis**) into oxygen and hydrogen. The hydrogen is transferred to a hydrogen carrier (NADPH), while the oxygen gas is released from the plant as a by-product. The inputs of the light dependent reactions are light and water, whereas the outputs (in the presence of chlorophyll) are the loaded coenzymes: ATP and NADPH.



LIGHT-INDEPENDENT REACTION

The second stage of photosynthesis is called the light independent reaction (or **Calvin cycle**) and uses the chemical energy produced in the light dependent stage to synthesise organic compounds (carbohydrates). Molecules of carbon dioxide are combined with hydrogen (transferred from the loaded NADPH) to form complex organic molecules (like glucose). This anabolic process is catalysed by the plant enzyme **Rubisco** and requires chemical energy (from ATP) to form the covalent bonds required for carbon fixation. The inputs of the light independent stage are carbon dioxide, ATP and NADPH, whereas the output is glucose.



MEASURING PHOTOSYNTHESIS

Metabolic processes can be measured by the rate of input consumption or the rate of output production. In the case of photosynthesis, the process can therefore be measured by a variety of factors, including:

- **Oxygen production:** Oxygen gas is a by-product of photosynthesis and can be measured either via the rate of bubble formation (for plants in solution) or via a **pressure change** in an enclosed container
- **Carbon dioxide uptake:** Carbon dioxide interacts with water to form an acidic solution (carbonic acid) that lowers pH. Hence, the amount of CO_2 production can be measured in solution via a **pH indicator**.
- **Biomass:** Organic compounds contribute to the total dry weight of an organism. Hence, the production of glucose can be indirectly measured according to the change in **plant mass** (grams per dry weight).

PHOTORESPIRATION

The light independent reactions use the enzyme Rubisco to fix carbon (from CO_2) in order to synthesise carbohydrates (such as glucose). However, Rubisco can alternatively use oxygen as a substrate to undergo a different series of reactions known as **photorespiration**. These alternative reactions create a product that <u>cannot</u> be used to make sugar and hence the efficiency of photosynthesis is reduced. The oxygen gas functions as a competitive inhibitor, preventing Rubisco from undergoing the light independent reactions. Additionally, ATP is required to convert the products of photorespiration back into usable substrates for the light independent reactions, resulting in a further reduction in the energy yield from photosynthesis.

C3 PLANTS

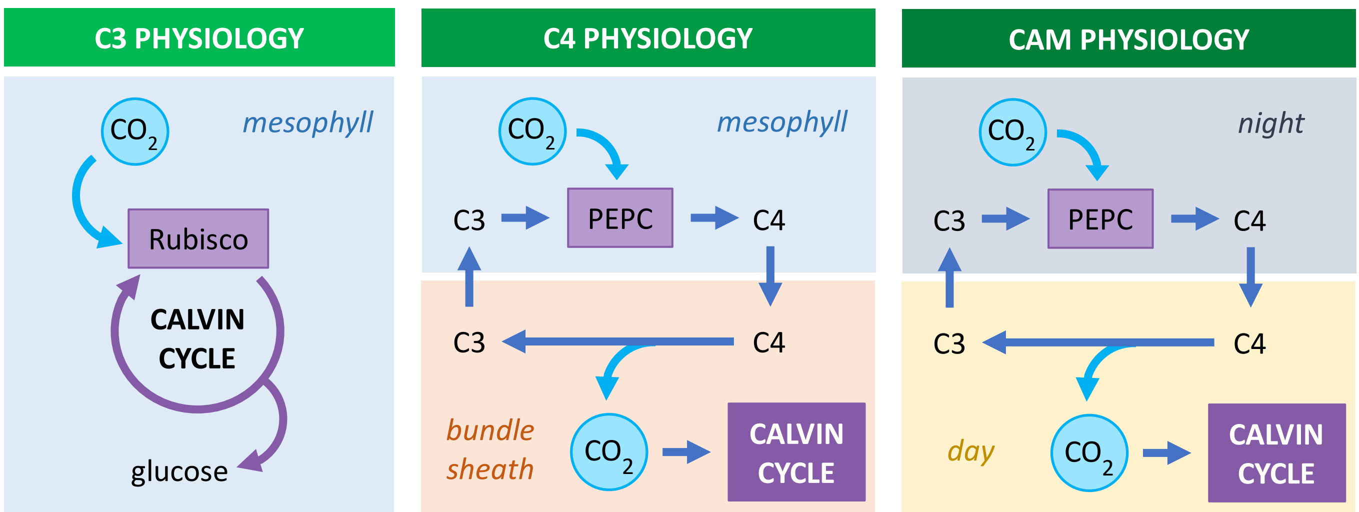
When Rubisco fixes carbon dioxide, it normally produces a 3C intermediate called glycerate-3-phosphate (**GP**), which can be combined to form glucose. Plants that exclusively fix carbon dioxide this way are called C_3 plants. Photorespiration will reduce the levels of photosynthesis by ~25% in C_3 plants, and these plants will be less efficient in hot or dry regions as the stomata must remain closed, in order to prevent excessive water loss (when stomata are closed, oxygen cannot diffuse out of the leaf, increasing levels in the tissues).

C4 PLANTS

C_4 plants possess adaptations to reduce the effects of photorespiration and improve photosynthetic efficiencies (particularly in hot and dry regions). These plants possess an oxygen-insensitive enzyme called PEP carboxylase (**PEPC**) within the mesophyll, which functions fix the carbon dioxide into a 4C compound (**malate**). The malate is then transferred to a deeper region of tissue known as the **bundle sheath**, where less oxygen is present. Here, the carbon is released from the 4C compound and Rubisco can undergo the light independent reactions without competition from oxygen. In order to improve efficiency via spatial separation, Rubisco is concentrated heavily within the bundle sheath of C_4 plants (it is equally distributed across all tissues in C_3 plants), and the bundle sheath cells are also larger than those found in C_3 plants.

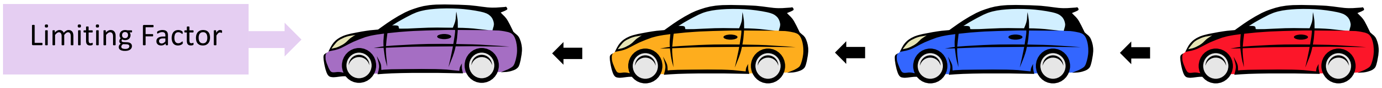
CAM PLANTS

CAM plants are found in hot and dry habitats that require stomata to be closed during the day to prevent excessive water loss. These plants use PEP carboxylase to sequester carbon dioxide into malate at night, when stomata are open and gases can diffuse into the leaf. The carbon reserve is then released during the day, when the closed stomata would otherwise prevent the light independent reactions from occurring. Whereas C_4 plants *spatially* separate the carbon dioxide from oxygen, CAM plants *temporally* separate the periods of carbon dioxide collection (night) and carbon dioxide use (day).



LIMITING FACTORS

Photosynthesis is a complex metabolic process that involves several distinct reactions with specific inputs. The law of limiting factors states that when a chemical process depends on **multiple** essential conditions being favourable, the rate of reaction will be limited by the factor that is nearest to its minimum value.



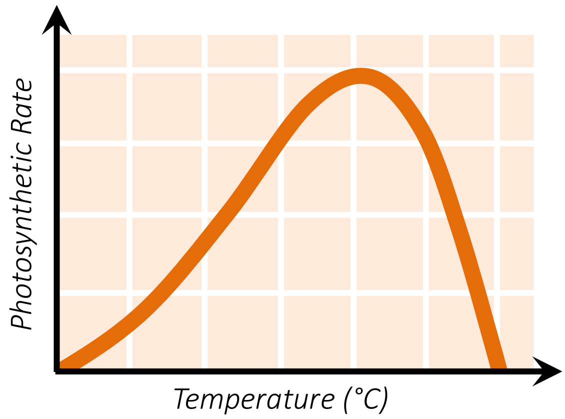
In a convoy, the slowest car (limiting factor) sets the speed at which the cars will travel (reaction rate)

Photosynthetic rate is influenced by numerous conditions; including temperature, light and carbon dioxide.

- Limiting factors change as environmental conditions change (e.g. light is limiting at night but not day)
- While water is required for photosynthesis, it can also be produced via cell respiration or condensation

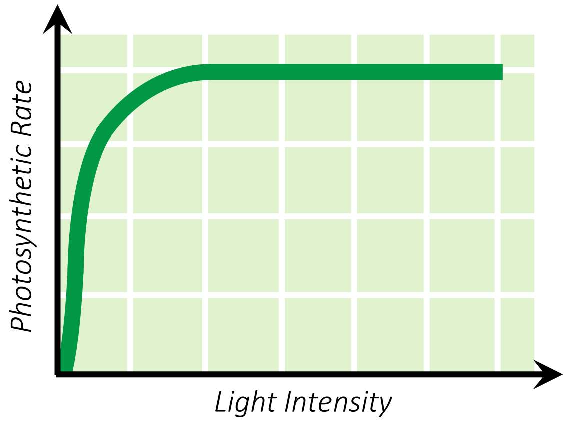
TEMPERATURE

Photosynthesis is catalysed by a variety of **enzymes** and is therefore impacted by ambient temperatures. If the temperature is too low, the activation energy threshold cannot be reached. As temperatures increase, reaction rate will also increase as more kinetic energy results in more frequent enzyme-substrate collisions. At optimal temperatures, activity will peak, as higher temperatures result in the denaturation of photosynthetic enzymes.



LIGHT INTENSITY

Light is required for the photoactivation of **chlorophyll**. Higher levels of light intensity will increase the rate of photosynthesis as more photoactivation can occur (i.e. increased levels of light dependent reactions). Above a certain light intensity, the rate of photosynthesis will plateau, as all chlorophyll has become photoactivated and saturated with light. At this point, light is no longer the limiting factor in the process of photosynthesis.



CO_2 CONCENTRATION

Carbon dioxide is a substrate for the enzyme **Rubisco**, which is responsible for carbon fixation in the Calvin cycle. Hence, increasing the CO_2 concentrations will result in a higher rate of photosynthesis as there are more frequent collisions between the enzyme and the substrate (CO_2). At higher concentrations, the activity will plateau, as the Rubisco is saturated (active sites are all occupied). At this point, carbon dioxide levels are no longer the limiting factor in photosynthesis.