

NUTRITION IN PLANTS

Learning Objectives

By the end of this topic, learners should be able to:

Describe the structure of chloroplasts in C3 and C4 plants.

Compare the distribution of chloroplasts in mesophyll and bundle sheath cells of C3 and C4 plants.

Explain how the chloroplast structure in C4 plants minimizes photorespiration and enhances photosynthetic efficiency.

Analyze the relationship between chloroplast specialization and environmental adaptation in C3 and C4 plants.

Evaluate how the chloroplast structure influences photosynthesis efficiency under different environmental conditions.

Identify key environmental factors (light intensity, CO₂ concentration, temperature, water availability) that affect photosynthesis.

Explain how variations in these factors influence the rate of photosynthesis in plants.

Investigate the role of greenhouse technologies in optimizing environmental conditions for maximum photosynthesis and crop yield.

Have you ever wondered how plants grow so tall and healthy without consuming food like humans and animals?

Where do they obtain their nutrients?

If plants don't eat, how do they acquire energy?

Why do some plants thrive better in certain soils than others?

What occurs when plants lack sufficient nutrients?

AUTOTROPHIC NUTRITION

Humans, along with almost every other living organism, owe their very existence to photosynthesis. The energy we use, whether from the food we respire or from the wood, coal, oil, or gas that we burn in our homes, has been captured from sunlight by photosynthesis. Photosynthesis also produces the oxygen we breathe by releasing it from water molecules.

Some common examples of the use of energy in living organisms are:

- synthesis of substances for growth and repair, for example, protein synthesis;

- active transport of substances into and out of cells against diffusion gradients, for example sodium-potassium pump, phagocytosis, and pinocytosis.
- Electrical transmission of nerve impulses;
- Mechanical contraction of muscles and beating of cilia and flagella;
- Heat energy released from respiration is used to maintain a constant body temperature in birds and mammals.
- bioluminescence, that is, the production of light by living organisms such as fireflies, glow-worms, and some deep-sea animals;
- electrical discharge, as in the electric eel

AUTOTROPHIC NUTRITION

Autotrophic nutrition entails the conversion of simple inorganic molecules, such as carbon dioxide and water, into complex organic compounds like lipids, carbohydrates, and proteins, using energy derived from light or chemical reactions. Plants, algae, and certain bacteria are classified as autotrophs.

The word autotroph means ‘self-feeding’ and refers to those organisms, such as plants, that have no obvious means of obtaining or digesting food; no mouth, teeth, alimentary canal, etc. Instead of obtaining their food by consuming complex organic molecules, they manufacture their own from simple inorganic substances using energy from two possible sources:

Photoautotrophs use light as their source of energy to drive the process of photosynthesis. Examples of photoautotrophs include green plants, algae and photosynthetic bacteria (e.g. cyanobacteria).

Chemoautotrophs use energy from certain chemical reactions. The process is far less common than photosynthesis, but takes place in the **nitrifying** and **denitrifying bacteria** that are important in the nitrogen cycle.

PHOTOSYNTHESIS

Photosynthesis is a process in which the light energy, by a series of steps, is converted into chemical energy.

Photosynthesis takes place largely in the leaf. Leaves are adapted to bring together the three raw materials of photosynthesis (water, carbon dioxide and light) and remove its products (oxygen and glucose). These adaptations include: a large surface area that collects as much sunlight as possible a thin lamina (leaf blade), to keep the diffusion distance short

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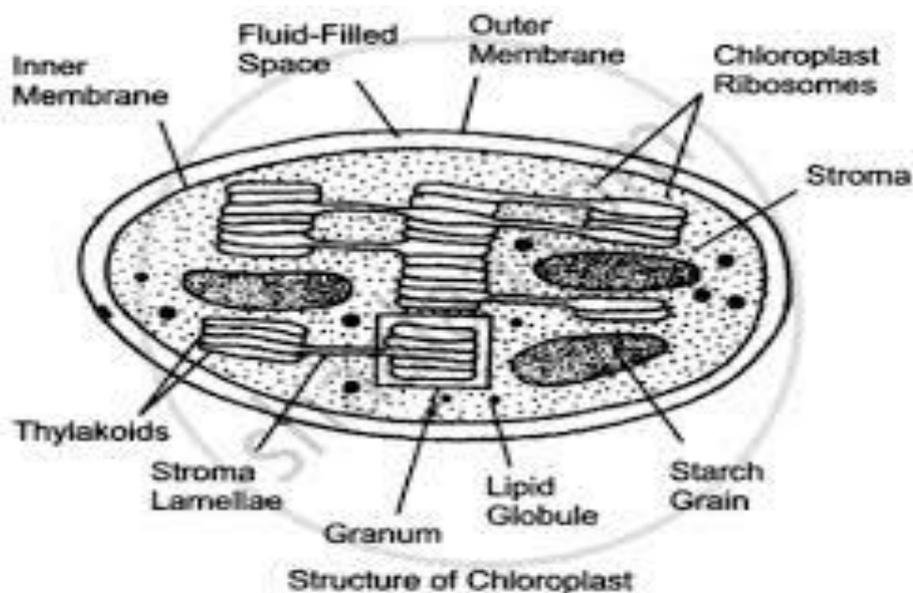
a transparent cuticle and epidermis that let light through to the photosynthetic palisade cells beneath
numerous stomata for gaseous exchange that open and close in response to changes in light intensity
many air spaces, especially in the spongy mesophyll, to allow diffusion of carbon dioxide and water vapour.

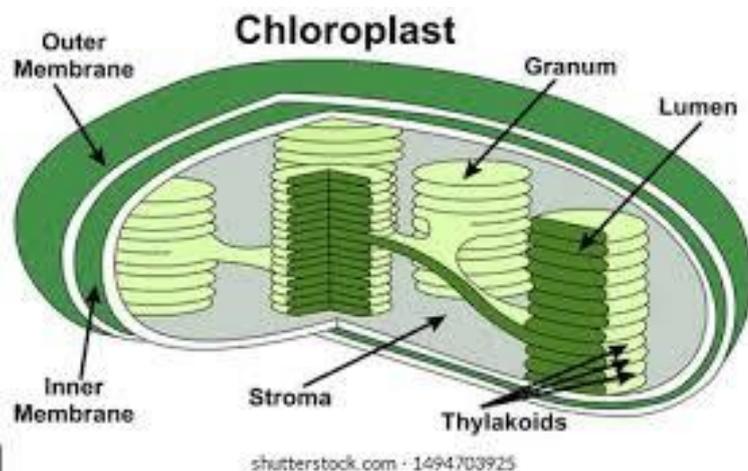
a network of vascular tissue made up of xylem that brings water to the leaf cells and phloem that carries away the sugars produced in photosynthesis.

The mesophyll cells contain numerous chloroplasts, which are the actual sites for photosynthesis.

Structure and role of chloroplasts in photosynthesis

Photosynthesis takes place within cell organelles called chloroplasts, the structure of which is shown below;





These vary in shape and size but are typically disc-shaped, 3-10 μ m long and 1 μ m in diameter. They are surrounded by a double membrane called the **chloroplast envelope**. The inner membrane is highly selective in what it allows to enter and leave the chloroplast. Inside the chloroplast envelope are two distinct regions: The leaf is the main photosynthetic organ of the plant. Within the leaf, photosynthesis occurs in the cells of the palisade and spongy mesophyll tissues. In these cells, the organelles where photosynthesis takes place are the chloroplasts.

The **stroma** is a fluid-filled matrix where the light independent stage of photosynthesis takes place. Within the stroma are a number of other structures such as starch grains and lipid droplets. A small, circular piece of DNA and 70S ribosomes are also present.

The **grana** are stacks of up to 100 disc-like structures called **thylakoids**, where the light dependent stage of photosynthesis takes place. Within the thylakoids are the chloroplast pigments, which are arranged in a structured way and form complexes called photosystems I and II. Some thylakoids have tubular extensions that join up with thylakoids in adjacent grana. These are called inter-granal lamellae. There are far fewer photosystem I complexes in the thylakoids than photosystem II. In the inter-granal lamellae most of the complexes are photosystem I.

ADAPTATIONS OF A CHLOROPLAST FOR ITS FUNCTION

Chloroplasts are adapted to their function of harvesting sunlight and carrying out the light-dependent and light-independent stages of photosynthesis in the following ways:

The granal membranes provide a large surface area for the attachment of the photosynthetic pigments, electron carriers, and enzymes that carry out the light-dependent reaction.

A network of proteins in the grana holds the photosynthetic pigments in a very precise manner that forms special units called photosystems, allowing maximum absorption of light.

The granal membranes have many ATP synthase complexes attached to them, which manufacture ATP by chemiosmosis.

The fluid of the stroma has all the enzymes needed to carry out the light-independent stage (Calvin cycle).

The stroma fluid surrounds the grana and so the products of the light-dependent stage in the grana can readily pass into the stroma.

Chloroplasts contain both circular DNA and 70S ribosomes so they can quickly and easily manufacture some of the proteins needed for photosynthesis.

The membranes are thin and this thinness minimizes the distance light has to travel, reducing light scattering and absorption by the membrane itself. This ensures that a maximum amount of light reaches the photosynthetic pigments embedded within the thylakoid membranes, optimizing light capture for the light-dependent reactions of photosynthesis.

PHOTOSYNTHETIC PIGMENTS

Inside the chloroplasts, light energy is absorbed by pigment molecules which are of two types;

1. Chlorophylls, designated chlorophyll *a* and chlorophyll *b*, absorb strongly in the blue and red regions of the visible spectrum. The presence of chlorophylls makes plants look green because they reflect green light, which they do not absorb. Chlorophyll is the main photosynthetic pigment.

2. Carotenoids absorb in the blue and green parts of the visible spectrum. Thus, carotenoids appear yellow, orange, or red. The most widespread and important carotene is β -carotene, which is familiar as the orange pigment of carrots. Vertebrates can break the molecule into two during digestion to form two molecules of vitamin A.

Carotenoids have three absorption peaks in the blue-violet range of the spectrum. The carotenoids found in plants belong to two classes, called

carotenes and xanthophylls. They are usually referred to as accessory pigments.

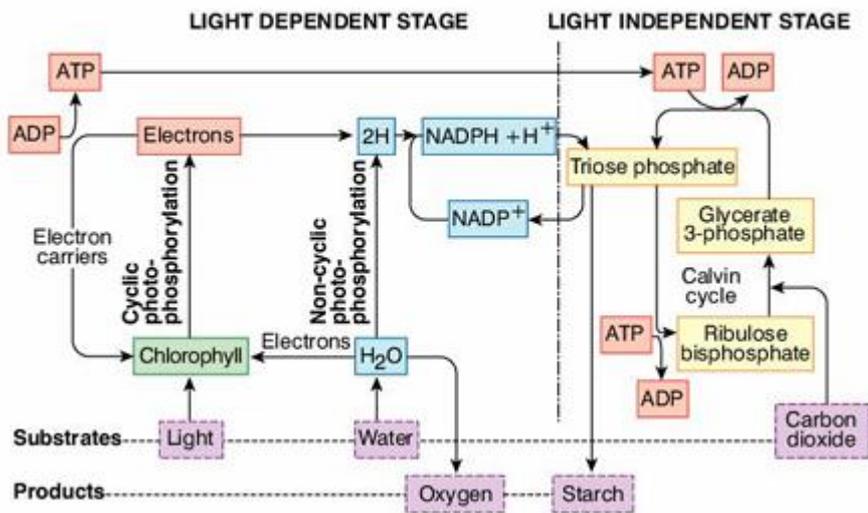
What Is the Role of Carotenoids and Other Accessory Pigments?

Carotenoids are called accessory pigments because they absorb light and pass the energy on to chlorophyll. Both xanthophylls and carotenes are found in chloroplasts. In late summer, the leaves of deciduous trees increase synthesis of carotenoids and other accessory pigments. In the autumn, when leaves start to die, their chlorophyll degrades first, leaving the carotenoids and other pigments that turn forests into spectacular displays of yellow, orange, and red. Carotenoids absorb some of the wavelengths of light that are not absorbed by chlorophyll. As a result, they extend the range of wavelengths that can drive photosynthesis.

Apart from acting as accessory pigments, they may also protect chlorophylls from excess light and from oxidation by oxygen produced in photosynthesis. They are usually masked by the green chlorophylls but can be seen in leaves before leaf-fall because chlorophylls break down first. They are also found in some flowers and fruits where the bright colors attract insects, birds and other animals for pollination or dispersal; for example, the red skin of the tomato is due to a carotene.

PHOTOSYNTHESIS, A TWO-STAGE PROCESS

Photosynthesis, the remarkable process that sustains most life on Earth, is not a single event but rather a carefully orchestrated sequence of two distinct stages. The initial phase, known as the **light-dependent stage(light stage)**, centers around the capture of light energy by specialized pigment-protein complexes called **photosystems**, while the final stage, known as the **light-independent stage (dark stage)** centers around the reduction of carbon dioxide to form carbohydrates.



A summary of the two stages of photosynthesis

THE LIGHT STAGE

Light for photosynthesis, rather than being absorbed by independent pigment molecules, is captured by groups of chlorophyll molecules along with their accessory pigments. These groups are now known as **photosystems** and are located in the photosynthetic membranes (thylakoids and inter-granal lamellae).

They operate as follows:

Each photosystem is a collection of chlorophyll a molecules, accessory pigments and associated proteins all fixed within a protein matrix.

The remaining pigment molecules (accessory pigments) of the photosystem absorb light energy (photons). These molecules are called the **antenna complex**. The light-harvesting complex contains 200-300 pigment molecules. Different pigments collect light of different wavelengths, making the process more efficient. All the energy is transferred from molecule to molecule, and finally to a specialized form of chlorophyll a known as P700 in PSI and P680 in PSII. P stands for pigment; their absorption peaks are at wavelengths of 700nm and 680 nm respectively (both red light). The chlorophylls P700 and P680 become 'excited' by the energy they absorb and release high-energy electrons. These pigments are held tightly together by proteins that act as a framework holding the pigment molecules in the best positions to allow energy to be transferred between them. The photon absorbed by an accessory pigment creates an excitation energy that is passed along a chain of pigment molecules to the reaction Centre.

Energy from many pigment molecules in the antenna complex is funnelled in this way to the reaction centre. Energy from one photon excites an electron in each of the primary pigment molecules (special pair) of the reaction centre. These electrons play an important part in the light-dependent stage.

There are two different photosystems involved in photosynthesis:

Photosystem I (PSI) has a reaction centre with a light absorption peak of 700 nm and is therefore known as P700. Photosystem I occurs mostly on intergranal lamellae of the chloroplast.

Photosystem II (PSII) has a reaction centre with a light absorption peak of 680 nm and is therefore known as P680. Photosystem II occurs mostly on the granal lamellae of the chloroplast.

DIFFERENCES BETWEEN CYCLIC AND NON-CYCLIC PHOTOPHOSPHORYLATION

Feature	Non-cyclic Photophosphorylation	Cyclic Photophosphorylation
Pathway of electrons	Non-cyclic	cyclic
First electron donor	Water	P700
Last electron acceptor	NADP	P700
Products	useful: ATP, reduced NADP Waste: oxygen	Useful; only ATP
Photosystems involved	I and II	I only

Light-dependent reactions

Photosynthesis involves making sugar using carbon dioxide and hydrogen (from water). This requires energy. The energy and the hydrogen are supplied by the light-dependent reactions which make ATP (adenosine triphosphate), an energy carrier, and reduced NADP (Nicotinamide

Adenine Dinucleotide Phosphate) as a hydrogen carrier.

. ATP is made when energy is used to bond another phosphate to ADP, a process called phosphorylation. In photosynthesis, the energy is supplied by light and the process is therefore called **photo- phosphorylation**. this may be cyclic or non-cyclic photophosphorylation. Reduced NADP is made from NADP in a process called reduction. The hydrogen comes from water. This also requires energy which is provided by light. The role of ATP and reduced NADP is simply to carry the energy and hydrogen into the light-independent reactions which follow.

PHOTO-PHOSPHORYLATION

Cyclic photophosphorylation

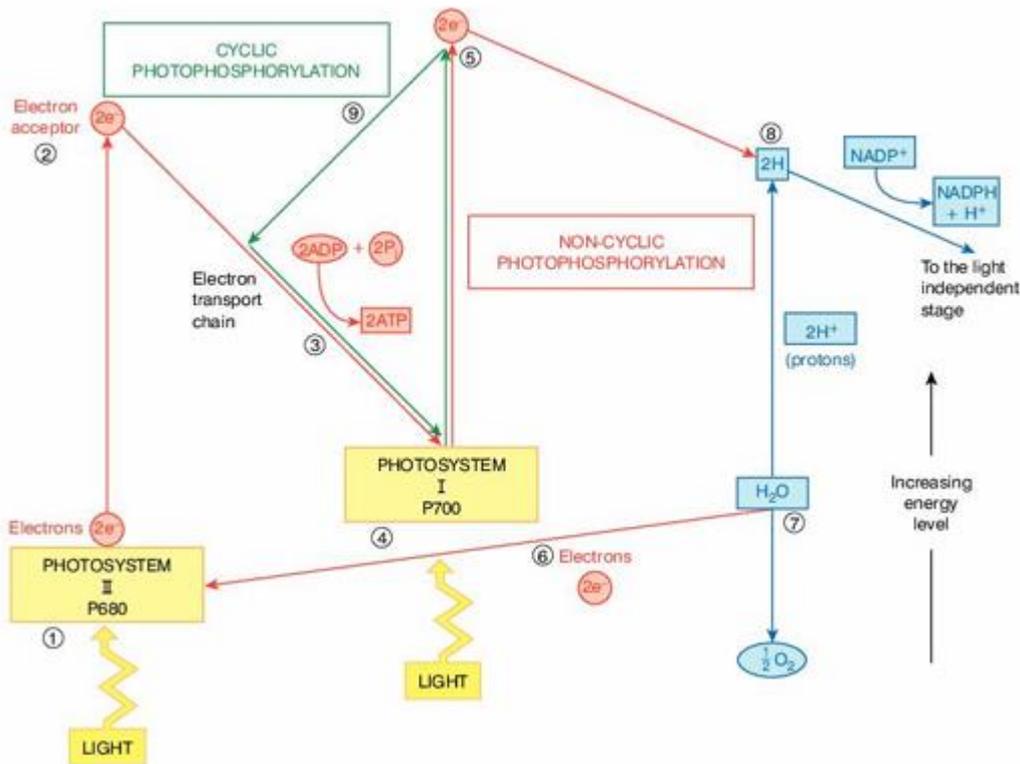
Cyclic photophosphorylation uses only photosystem I. When light raises an electron in a reaction centre chlorophyll molecule to an excited state, the electron is taken up by an electron acceptor, ferredoxin and simply passed back to the same chlorophyll molecule via a sequence of electron carriers, i.e. it is recycled. While this does not produce any reduced NADP, it does generate sufficient energy to combine inorganic phosphate with ADP. The ATP so produced is then used in the light-independent stage. The product of cyclic photophosphorylation is therefore only ATP.

NON-CYCLIC PHOTOPHOSPHORYLATION (Z SCHEME)

Non-cyclic photophosphorylation uses both photosystem I and photosystem II. Electrons raised to an excited state in photosystem II are taken up by an electron acceptor, plastoquinone, and passed along a sequence of electron carriers to replace the electrons lost in photosystem I. The electrons raised to an excited state from photosystem I are taken up by an electron acceptor, ferredoxin, and are then taken up by NADP^+ (nicotinamide adenine dinucleotide phosphate), which becomes reduced and passed into the light-independent stage of photosynthesis. This leaves the reaction center chlorophyll molecules of photosystem II short of electrons and therefore positively charged. Before the photosystem can operate again, these electrons must be replaced. The replacement electrons are provided from water molecules that are split using light energy. This photolysis of water also yields hydrogen ions (protons) into the thylakoid lumen, where they contribute to the build-up of the proton gradient. Hydrogen ions in the stroma can be used for the reduction of NADP.

SUMMARY OF THE Z-SCHEME

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1. Light energy is trapped in photosystem II and boosts electrons to a higher energy level.
2. The electrons are received by an electron acceptor, plastoquinone.
3. The electrons are passed from the electron acceptor along a series of electron carriers to photosystem I. The energy lost by the electrons is captured by converting ADP to ATP. Light energy has thereby been converted to chemical energy.
4. Light energy absorbed by photosystem I boosts the electrons to an even higher energy level.
5. The electrons are received by another electron acceptor, ferredoxin.
6. The electrons which have been removed from the chlorophyll are replaced by pulling in other electrons from a water molecule.
7. The loss of electrons from the water molecule causes it to dissociate into protons and oxygen gas.

8. The protons from the water molecule combine with the electrons from the second electron acceptor and these reduce nicotinamide adenine dinucleotide phosphate. (NADP)
9. Some electrons from the second acceptor may pass back to the chlorophyll molecule by the electron carrier system, yielding ATP as they do so. This process is called cyclic photophosphorylation.

PHOTOLYSIS OF WATER

Photolysis is the splitting of water as a direct consequence of the photoactivation of chlorophyll. It occurs only in photosystem II, which is associated with an enzyme known as the oxygen-evolving complex. Having lost an electron, the chlorophyll molecule needs to replace it. In the case of non-cyclic photophosphorylation, it does this using electrons from water molecules that are split by the oxygen evolving complex into protons, electrons and oxygen according to the following equation:



The electrons replace those lost by the chlorophyll molecules. The protons reduce NADP to NADPH + H⁺, which then enters the light-independent stage where it reduces carbon dioxide.

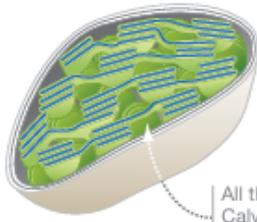
The oxygen by-product is either used in respiration or diffuses out of the leaf as a waste product of photosynthesis.

LIGHT INDEPENDENT STAGE

The light-independent (or dark) reactions, which take place in the stroma of the chloroplast, do not require light and use the energy (ATP) and reducing power (reduced NADP) produced by the light-dependent reactions to reduce carbon dioxide. The reactions are controlled by enzymes, and their sequence was determined by Melvin Calvin. The process is therefore often known as the Calvin cycle.

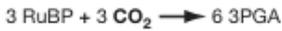
THE CALVIN CYCLE

(a) The Calvin cycle has three phases.



All three phases of the Calvin cycle take place in the stroma of chloroplasts

1. Fixation



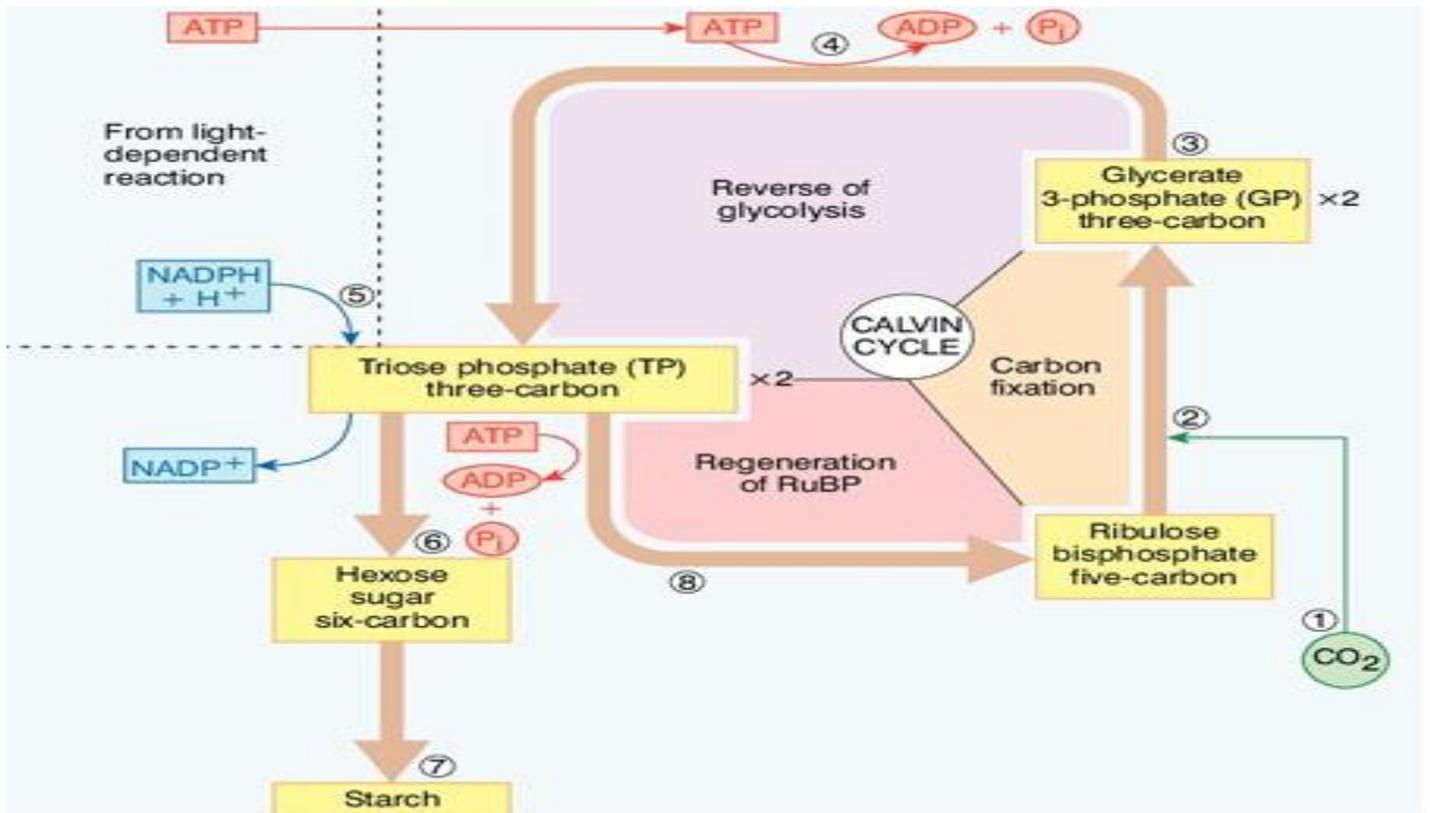
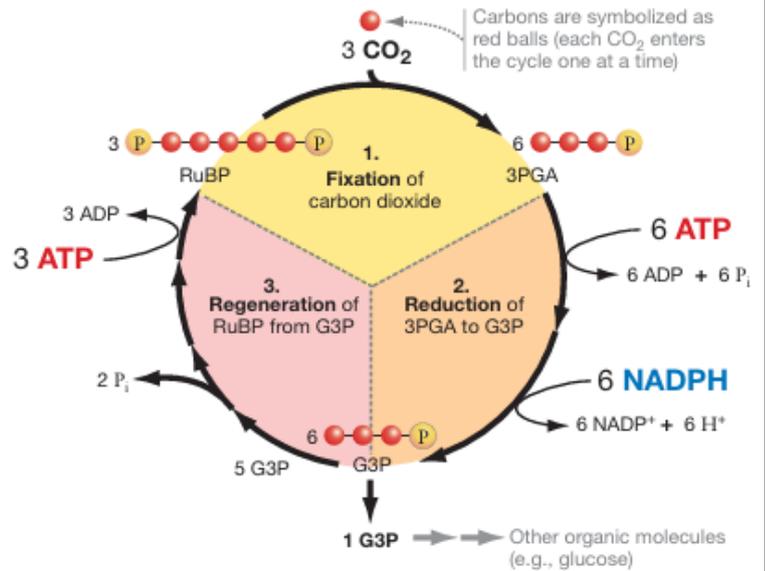
2. Reduction



3. Regeneration



(b) The reaction occurs in a cycle.



Each step in the Calvin cycle is enzyme controlled.

Carbon dioxide from the atmosphere diffuses into the leaf through stomata and dissolves in water around the walls of the palisade cells. It then diffuses through the cell surface membrane, cytoplasm, and chloroplast envelope into the stroma of the chloroplast.

In the stroma, the carbon dioxide combines with the five-carbon compound ribulose biphosphate (RuBP) using the enzyme ribulose biphosphate carboxylase (rubisco), to form an unstable six-carbon compound.

The unstable six-carbon compound immediately breaks down into two molecules of the three-carbon glycerate 3-phosphate (GP)

Using one of the ATP molecules from the light-dependent reaction, the GP (glycerate 3-phosphate) is converted into a 3-carbon triose phosphate (TP).

Reduced NADP from the light-dependent stage provides hydrogen for the reduction of GP to TP (glycerate-3-phosphate to triose phosphate).

Triose phosphate molecules combine in pairs to form six-carbon (hexose) sugars.

The six-carbon sugars can be polymerized into starch.

Five out of every six triose phosphate molecules produced are used to regenerate ribulose biphosphate, using the remainder of the ATP from the light-dependent stage as the source of energy.

Formation of other substances for use by the plant

Plants, like other organisms, are made up of a range of complex organic molecules. The bulk of these includes carbohydrates, lipids, and proteins. They must synthesize them from the various compounds of the Calvin cycle.

- Carbohydrates, e.g., sucrose (the carbohydrate which is transported in the phloem) are made by combining the two hexose sugars, glucose and fructose. Glucose is used as a respiratory substrate.
- Starch (the storage carbohydrate) and cellulose (the essential component of cell walls) are made by polymerizing glucose in different ways.
- Lipids are made up of glycerol and fatty acids. Plants make glycerol from triose phosphate and fatty acids from glycerate 3-phosphate (GP). Lipids are used in plant cells for storage and to form phospholipids in their cell membranes.
- Proteins are made up of amino acids that, in turn, can be produced from glycerate 3-phosphate (GP) via acetyl coenzyme A and the intermediates of the Krebs cycle. Proteins are important components of cell membranes, and all enzymes are proteins.

RELATIONSHIP BETWEEN VARYING SUCROSE CONCENTRATION AND STOMATAL OPENING/CLOSURE.

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During the Day

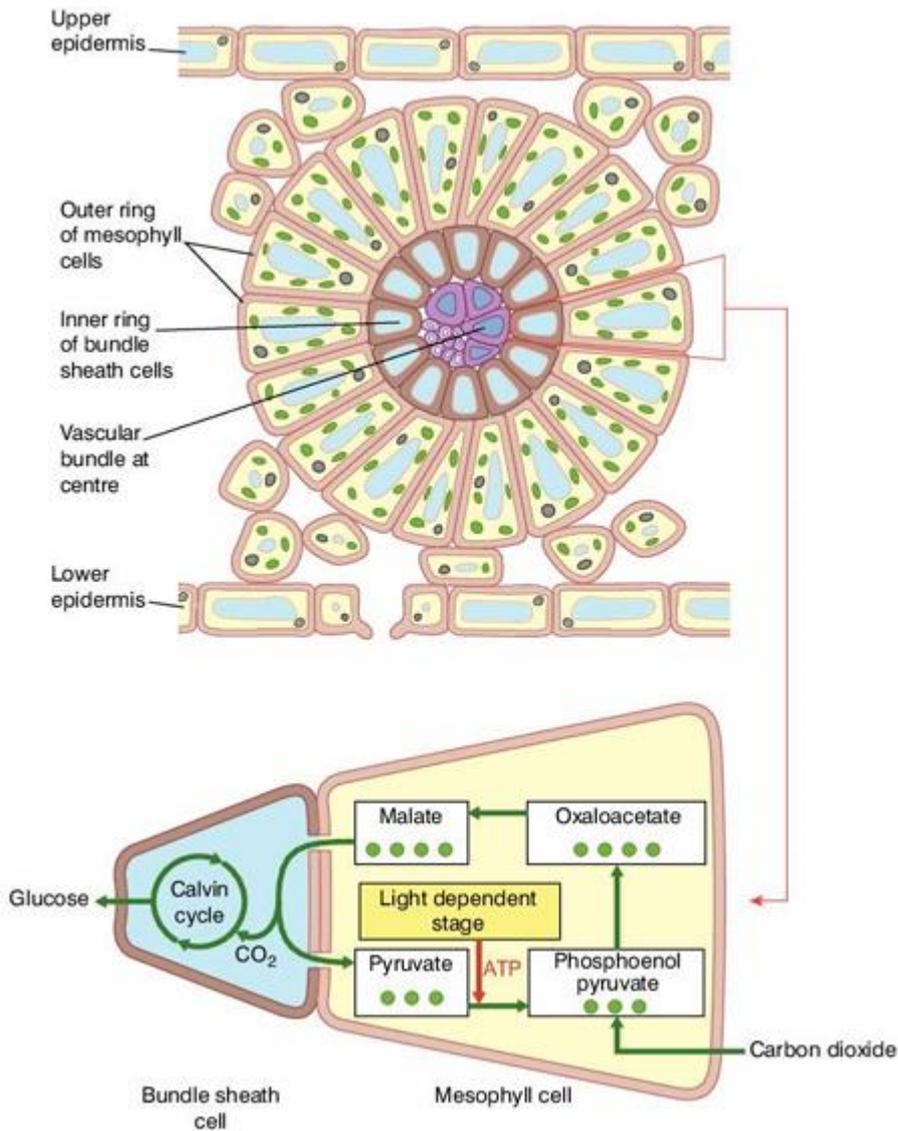
- As **photosynthesis** occurs in the leaf, **sucrose is produced** in large amounts.
- Some of this sucrose **accumulates in guard cells**.
- This **increases the solute concentration** inside guard cells.
- As a result, the **water potential (Ψ) of guard cells becomes lower (more negative)** than that of the surrounding epidermal cells.
- **Water moves osmotically** from the epidermal cells (higher water potential) into the guard cells (lower water potential).
- This influx of water **increases turgor pressure** in the guard cells, causing stretching of their walls and **stomata to open**.

During the Night

- **Photosynthesis stops**, so sucrose production and accumulation decrease.
- Sucrose inside guard cells is either **metabolized or transported away**.
- This leads to a **decrease in solute concentration** in guard cells.
- The **water potential of guard cells becomes higher (less negative)** than that of epidermal cells.
- Water **moves out of the guard cells** into the surrounding cells due to the gradient.
- This **reduces turgor pressure** in the guard cells, causing them to collapse and **stomata to close**.

During the Calvin cycle, this important enzyme combines carbon dioxide with a five-carbon ribulose biphosphate molecule to form a six-carbon compound. This compound is unstable and immediately splits into two three-carbon compounds. Plants that photosynthesize in this way are therefore called C₃(carbon-3) plants since the first stable product of their photosynthesis has three carbon atoms.

Rubisco also catalyzes a second reaction in which ribulose biphosphate combines with oxygen rather than carbon dioxide. This process is called photorespiration, and it releases carbon dioxide. This works against the Calvin cycle in which carbon dioxide is incorporated into molecules rather than released from them.



CO₂ fixation in mesophyll cells:

- Carbon dioxide (CO₂) in the mesophyll cell cytoplasm combines with phosphoenolpyruvate (PEP) (a 3-carbon molecule).
- This reaction is catalyzed by the enzyme pep carboxylase.
- The product is a 4-carbon acid called oxaloacetate (oxaloacetic acid)
- Oxaloacetate is then reduced by hydrogen accepted by NADP to another 4-carbon acid, malate.

Malate shunt

- Malate (the 4-carbon acid) is actively transported from the mesophyll cells to the chloroplasts of the bundle sheath cells via plasmodesmata.

CO₂ release and NADPH generation in bundle sheath cells:

- Inside the bundle sheath chloroplasts, malate undergoes decarboxylation (loss of a carbon atom as CO₂) and dehydrogenation (removal of hydrogen atoms).
- Carbon dioxide (CO₂) is released within the bundle sheath chloroplast. This CO₂ then enters the Calvin cycle for sugar synthesis.

- The hydrogen atoms (and electrons) removed from malate are used to reduce NADP^+ to NADPH (reduced NADP). This NADPH will also be used in the Calvin cycle within the bundle sheath cells.
- The remaining 3-carbon molecule from malate is pyruvate.

Pyruvate transport and PEP regeneration in mesophyll cells:

- Pyruvate (the 3-carbon molecule) is transported back from the bundle sheath cell chloroplasts to the mesophyll cells.
- In the mesophyll cells, pyruvate undergoes a series of enzymatic reactions that require ATP (produced during the light-dependent reactions in the mesophyll cells). This process regenerates the initial 3-carbon CO_2 acceptor, phosphoenolpyruvate (PEP), allowing the hatch-slack cycle to continue.

DIFFERENCES BETWEEN MESOPHYLL AND BUNDLE SHEATH CHLOROPLAST.

Mesophyll cell chloroplast	Bundle sheath cell chloroplast
Large grana; Therefore light – light-dependent reactions favoured, so plenty of ATP, reduced NADP, and oxygen are generated.	No grana (or very few and rudimentary). Therefore, light-dependent reactions occur at a very low rate, so little reduced NADP, ATP, or O_2 is generated
Virtually no RuBP carboxylase, so no CO_2 fixation (CO_2 fixation occurs in the cytoplasm by PEP carboxylase)	High concentration of RuBP carboxylase so CO_2 fixation occurs as in C_3 plants, but more efficiently
Little starch	Abundant starch grains

ADAPTATION OF THE LEAF IN C_4 PLANTS

Specialized leaf anatomy: C_4 plants exhibit a distinct arrangement of cells in their leaves, characterized by:

A tight ring of bundle sheath cells surrounding the vascular bundle.

A ring of tightly fitting mesophyll cells surrounding the bundle sheath cells.

Isolation of bundle sheath cells: this specific cellular arrangement ensures that the bundle sheath cells are isolated from the air spaces inside the leaf.

Prevention of photorespiration: the isolation of bundle sheath cells prevents high concentrations of oxygen from reaching them, thereby minimizing the occurrence of photorespiration.

Accumulation of carbon dioxide: the arrangement also prevents carbon dioxide from being lost from the bundle sheath cells, leading to its accumulation within them.

Carbon dioxide storage: the accumulated carbon dioxide in the bundle sheath cells serves as a reserve that can be used when the external supply of CO_2 is limited

DIFFERENCES BETWEEN C₃ AND C₄ PLANT

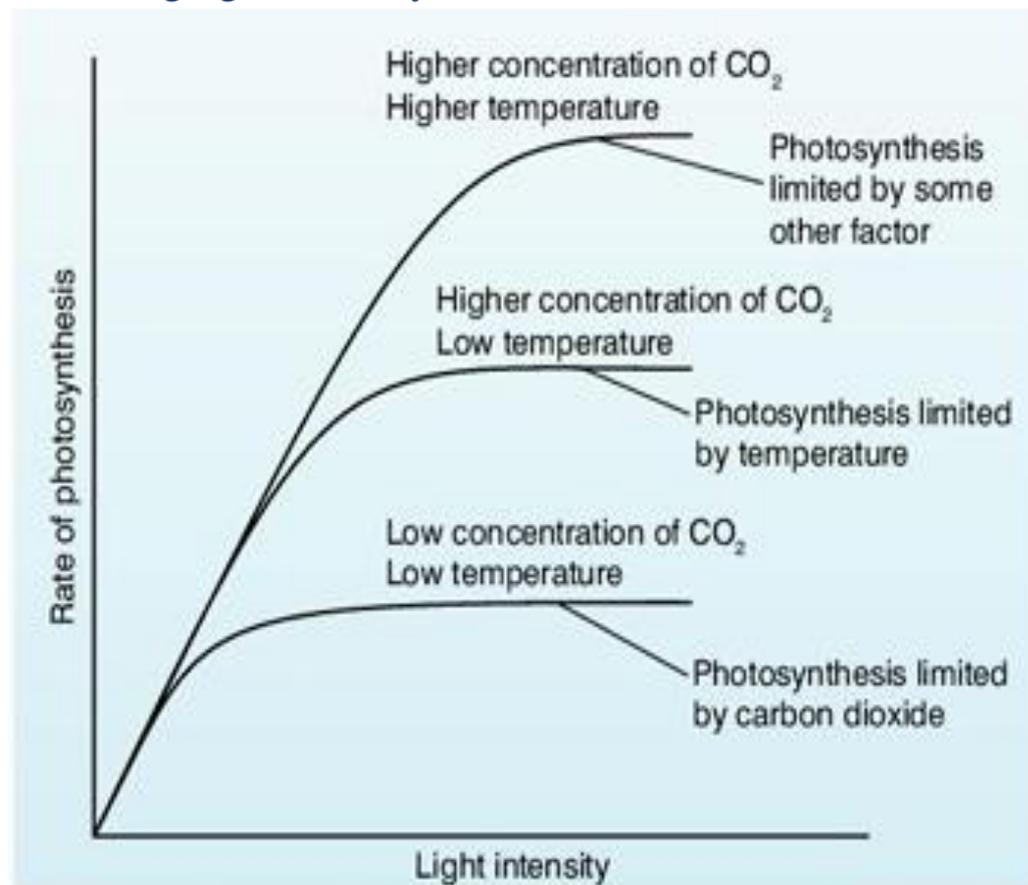
Feature	C ₃ plants	C ₄ plants
Representative species	Most crop plants, e.g., Cereals, tobacco, beans	Maize, sugarcane
Effect of temperature rise from 25 °c. To: 35°C	No change in rate or lower rate	50% greater at 35°C
Point at which no more CO ₂ can be taken up	40-60 ppm CO ₂	Around zero ppm CO ₂ > 250-350
First product of photosynthesis	A 3c acid, GP	A c ₄ acid, e.g. Oxaloacetate
Carbon dioxide acceptor	RuBP, a 5c compound	Pep, a 3c compound
Carbon dioxide fixation	Occurs once	Occurs twice, first in mesophyll cells, then in bundle sheath cells
Leaf anatomy and efficiency	Only one type of chloroplast has less efficient photosynthesis than C ₄ plants. Yields are usually much lower	'Kranz' anatomy, i.e., two types of cells, each with its type of chloroplast. More efficient photosynthesis than C ₃ plants, but they use more energy. Yields usually yield a much higher.
Carbon dioxide fixing enzyme	RuBP carboxylase, which is inefficient	Bundle sheath cells: RUBP carboxylase, working efficiently because the carbon dioxide concentration is high Mesophyll cells: PEP carboxylase, which is very efficient

FACTORS AFFECTING PHOTOSYNTHESIS

Photosynthesis, the process by which plants convert light energy into chemical energy, is influenced by several key environmental factors: light intensity, carbon dioxide concentration, temperature, and water availability. Light provides the energy, carbon dioxide is a reactant, temperature affects enzyme activity, and water is essential for the process. The rate of photosynthesis is often limited by the factor that is in shortest supply, meaning that increasing other factors won't increase the rate unless the limiting factor is also increased. Understanding these interactions is crucial for optimizing plant growth and productivity. In any complex process, such as photosynthesis, the factors that affect its rate all operate simultaneously. However, the rate of the process at any given moment is not affected by a combination of all the factors, but rather by just one - the one whose level is at the least favourable value. This factor is called the **limiting factor** because it alone limits the rate at which the process can take place. However much the levels of the other factors change, they do not alter the rate of the process.

To take the example of light intensity limiting the rate of photosynthesis:

The graph below shows the variation of the rate of photosynthesis with increasing light intensity.



- In complete darkness, it is the absence of light alone that prevents photosynthesis from occurring.

- No matter how much we raise or lower the temperature or change the concentration of carbon dioxide, there will be no photosynthesis. Light, or rather the absence of it, is the factor determining the rate of photosynthesis at that moment.
- If we provide light, however, the rate of photosynthesis will increase.
- As we add more light, the more the rate increases. This does not continue indefinitely, however, because there comes a point at which further increases in light intensity do not affect the rate of photosynthesis.
- At this point, some other factor, such as the concentration of carbon dioxide, is in short supply and so limits the process.
- Carbon dioxide is now the limiting factor and only an increase in its level will increase the rate of photosynthesis.
- In the same way as happened with light, adding more carbon dioxide will lead to more photosynthesis.
- Further increases in carbon dioxide levels will fail to have any effect.

NOTE: In a process dependent on multiple factors, the limiting factor is the single factor that, at any given moment, is at its least favorable level, thereby determining the overall rate of the process. Changes in other factors will not affect the rate unless the limiting factor itself changes.

EFFECT OF LIGHT INTENSITY ON THE RATE OF PHOTOSYNTHESIS

When light is the limiting factor, the rate of photosynthesis is directly proportional to light intensity. The rate of photosynthesis is usually measured in two ways:

- The volume of oxygen produced by a plant
- The volume of carbon dioxide taken up by a plant.

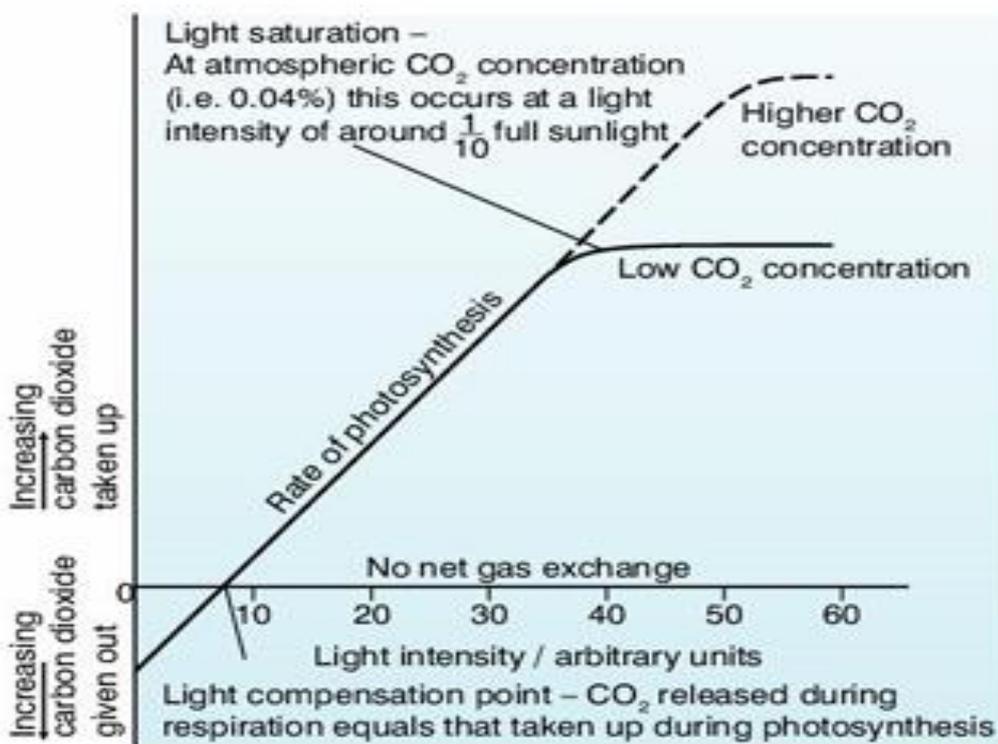
These measurements do not, however, provide an absolute measure of photosynthesis because:

some of the oxygen produced in photosynthesis is used in cellular respiration and so never leaves the plant and therefore cannot be measured.

some carbon dioxide from cellular respiration is used up in photosynthesis, and therefore, the volume taken up from the atmosphere is less than that used in photosynthesis.

As light intensity is increased, the volume of oxygen produced and carbon dioxide absorbed due to photosynthesis will increase to a point at which it is exactly balanced by the oxygen absorbed and carbon dioxide produced by respiration. At this point, there will be no net exchange of gases into or out of the plant. This is known as the light *compensation point*.

Graph showing the effect of light intensity on the rate of photosynthesis as measured by the amount of CO₂ exchange



Further increases in light intensity will cause a proportional increase in the rate of photosynthesis, and increasing volumes of oxygen will be given off and carbon dioxide taken up. A point will be reached at which further increases in light intensity will have no effect on photosynthesis. At this point, some other factor, such as carbon dioxide concentration or temperature, is limiting the reaction.

Effect of carbon dioxide concentration on the rate of photosynthesis.

Carbon dioxide is present in the atmosphere at a concentration of around 0.04%. This level continues to increase as a result of human activities such as burning fossil fuels and the clearing of rainforests. It is often the factor that limits the rate of photosynthesis under normal conditions. The optimum concentration of carbon dioxide for a consistently high rate of photosynthesis is 0.1%, and growers of some glasshouse crops like tomatoes enrich the air in the glasshouses with more carbon dioxide to provide higher yields.

Effect of temperature on the rate of photosynthesis

Provided that other factors are not limiting, the rate of photosynthesis increases in direct proportion to the temperature. Between the temperatures of 0°C and 25°C, the rate of photosynthesis is approximately doubled for each 10°C rise in temperature. Above the optimum temperature of 25°C the rate levels off and then declines, largely as a result of enzyme denaturation.

EFFECT OF WATER ON RATE OF PHOTOSYNTHESIS

Water is a raw material in photosynthesis, but so many cell processes are affected by lack of water that it is impossible to measure the direct effect of water on photosynthesis. However, by studying the yields of water-deficient plants, it can be shown that periods of temporary wilting can lead to drastic reduction in photosynthetic yields. Even slight water deficiency, with no visible effects, might significantly reduce crop yields. One obvious factor is that plants usually close their stomata in response to wilting and this would prevent access of carbon dioxide for photosynthesis. Abscisic acid, a growth inhibitor, has also been shown to accumulate in water-deficient leaves of some species.

CONTROLLING THE FACTORS AFFECTING PHOTOSYNTHESIS

Photosynthesis is the cornerstone of food production. Since the rate of photosynthesis is dictated by the most limited resource (the limiting factor), identifying and addressing this constraint is crucial for maximizing yields. By optimizing the limiting factor, we can enhance photosynthesis and, consequently, increase food output.

Unlike open-field cultivation, greenhouses offer precise environmental control. Growers can manipulate temperature, humidity, light, and carbon dioxide levels. Scientists can predict how altering these conditions impacts photosynthesis, allowing them to advise farmers on achieving optimal growth.

While it might seem advantageous to maximize all factors for peak photosynthesis, different plants have unique needs, and excessive levels can be detrimental. For instance, while some species thrive in high temperatures, others suffer from enzyme denaturation. Moreover, indiscriminate resource use is wasteful and inefficient. Therefore, precise environmental management is essential, ranging from manual adjustments to sophisticated automated systems. This control on environmental factors affecting photosynthesis cannot be done in a natural environment, but usually in greenhouses.