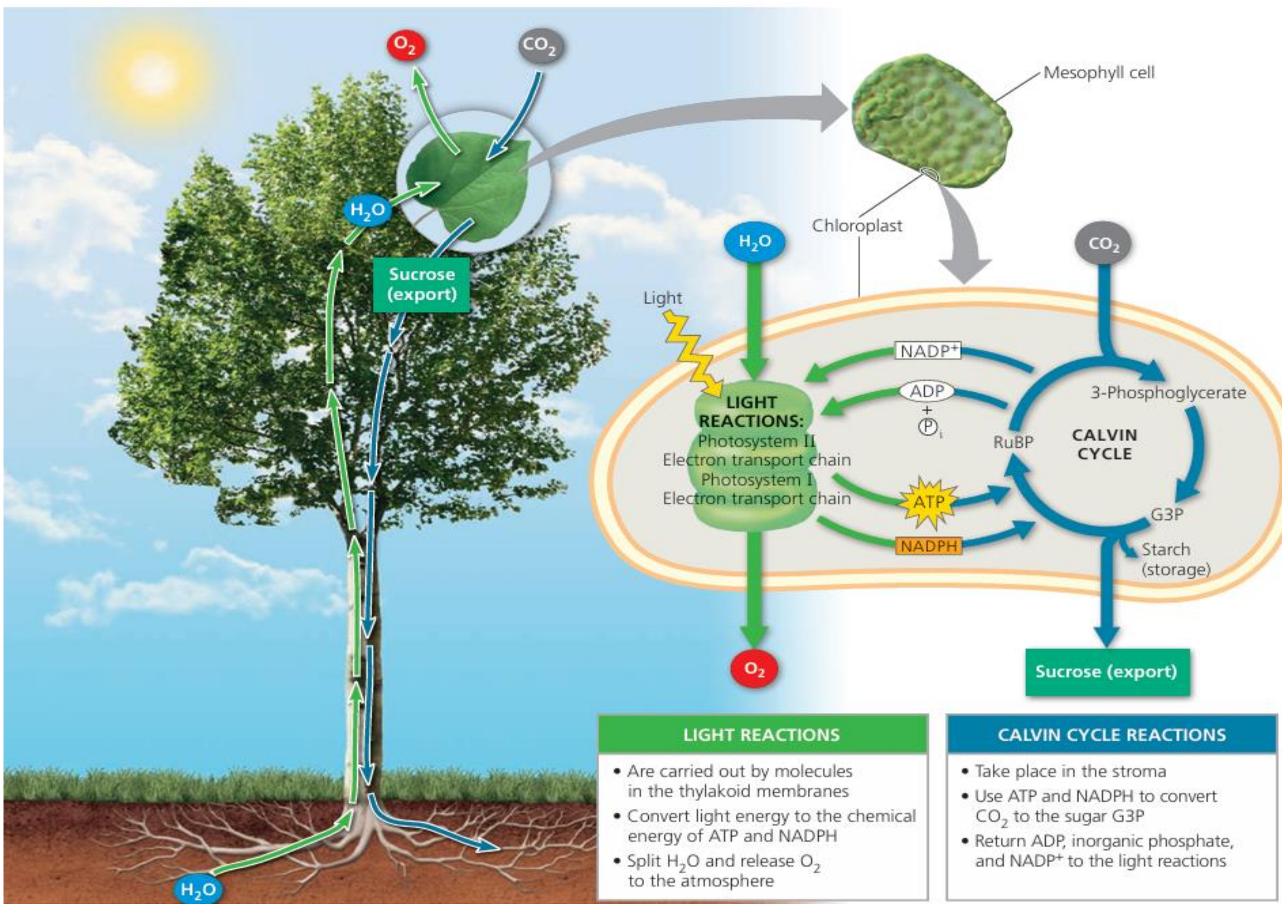
NUTRITION IN PLANTS

By the end of this topic learners are expected to:

- how the parts of the chloroplast suit their functions?
- the advantages of C4 over C3 plants.
- how plants form different products of photosynthesis
- ability to explain the effect of water stress on the rate of photosynthesis.
- the effect of light (intermittent and continuous) on the rate of photosynthesis
- ability to explain the relationship between varying sucrose concentration with stomatal opening/closing.
- understanding of the efficiency of PEP carboxylase versus Rubisco.
- the application of greenhouse technologies

Nutrition is the process by which organisms obtain energy to maintain life functions, and matter to create and maintain structure. Both energy and matter are obtained from nutrients.

Autotrophic nutrition (*autos*, self; *trophos*, nourishment): where organisms make their own organic nutrients from an external supply of relatively simple inorganic raw materials and energy. Such organisms have an inorganic source of carbon, namely carbon dioxide and are referred to as **autotrophs.**

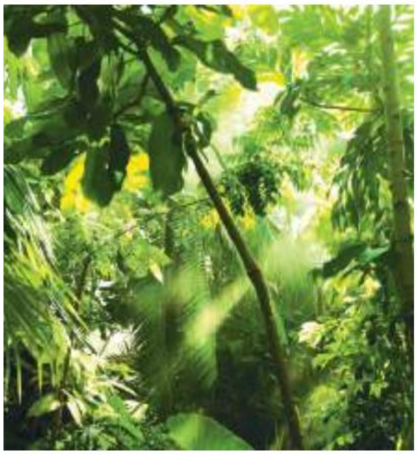


Types of autotrophic nutrition

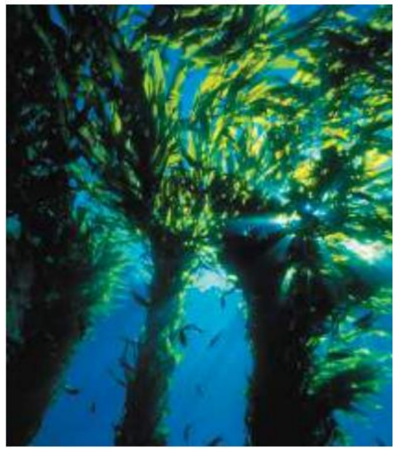
This is categorized into two groups basing on the source of energy

(i) **<u>Photosynthesis:</u>** This is the form of nutrition that occurs in all green plants, algae some protists and photosynthetic bacteria (cyanobacteria). It is the process by which organisms synthesize organic compounds sugars, protein and lipids from carbon dioxide and water using sunlight as source of energy and chlorophyll or some other closely related pigment for trapping the light energy.

Tropical rainforest



Large algae



Cyano-bacteria

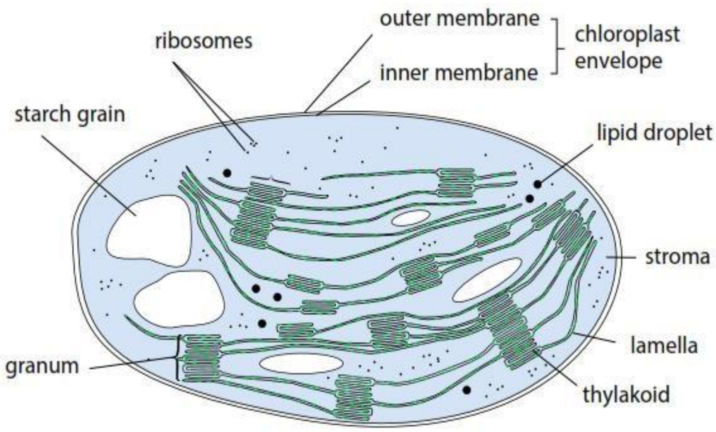
(ii) **<u>Chemosynthesis:</u>** this is form of nutrition that occurs in certain bacteria see table below. This is the synthesis of organic compounds from carbon dioxide and water using energy supplied by special methods of respiration involving the oxidation of various inorganic materials such as hydrogen sulphide, ammonia and iron (ii).

As a biology student explain this statement: No process is more important to the welfare of earth than the process of photosynthesis.

Structure of chloroplast

Is biconvex disc-shaped/ oval shaped, 3 – 10 µm long and 2 – 4 µm wide, enclosed by an envelope of two membranes; the smooth and continuous **outer membrane**, the **inner membrane** gives rise to strands of branching membranes called the **lamellae** extending throughout the organelle.

The interior is divided into grana which are surrounded by a, gelatinous semi-fluid called **stroma.** In the grana the lamellae are stacked in piles of flat, circular sacs called **thylakoids**, which contain photosynthetic pigments. In the stroma the thylakoids are crisscross loosely, suspended in an aqueous matrix containing circular DNA, ribosomes, ribosomes, enzymes used in photosynthesis.



Adaptations of chloroplast for photosynthesis

- Biconvex shape which increases surface area for exposure of photosynthetic pigments for maximum light absorption.
- Surrounded by a double membrane to prevent photosynthetic reactions from mixing with those in the cell cytoplasm.
- The surface membrane is permeable to allow exchange of materials like carbon dioxide which is a raw material for photosynthesis with the cell cytoplasm.
- The inner membrane is folded inwards to form a system of layers called lamellae to provide a large surface area for attachment of photosynthetic pigments.
- The internal membrane also contains electron transport systems for synthesis of ATP to drive cell metabolism.
- It has thylakoids that increase the surface area for holding chlorophyll molecules.
- The thylakoid granum is connected by inter-grana membranes thus maintaining the thylakoids and chlorophyll stationary in position.
- The stroma contains circular DNA and ribosomes for protein synthesis.
- The stroma contains a high concentration of the necessary enzymes for catalyzing metabolic reactions occurring within the chloroplast.
- Thylakoids are flattened discs to provide a small internal volume to maximize hydrogen gradient upon proton accumulation.
- Thylakoids stacked in piles forming grana to increase the surface area to volume ratio of the thylakoid membrane.
- Pigments organized into photosystems in thylakoid membranes to maximize light absorption.

MECHANISM OF PHOTOSYNTHESIS

The overall equation for photosynthesis is:

$$6CO_2 + 12\,H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 + 6H_2O + 6O_2$$

Photosynthesis is essentially a process of energy transduction. Light energy is first converted into electrical energy and then into chemical energy in three main phases i.e.

1. **Light harvesting.** Light energy is captured by the plant using a mixture of pigments including chlorophyll.
2. **Light dependent stage (photolysis**) in which a flow of electrons results from the effect of light on chlorophyll and so causes the splitting of water into hydrogen ions and oxygen
3. **The light independent stage** during which these hydrogen ions are used in the reduction of carbon dioxide and hence the manufacture of sugars.

LIGHT HARVESTING

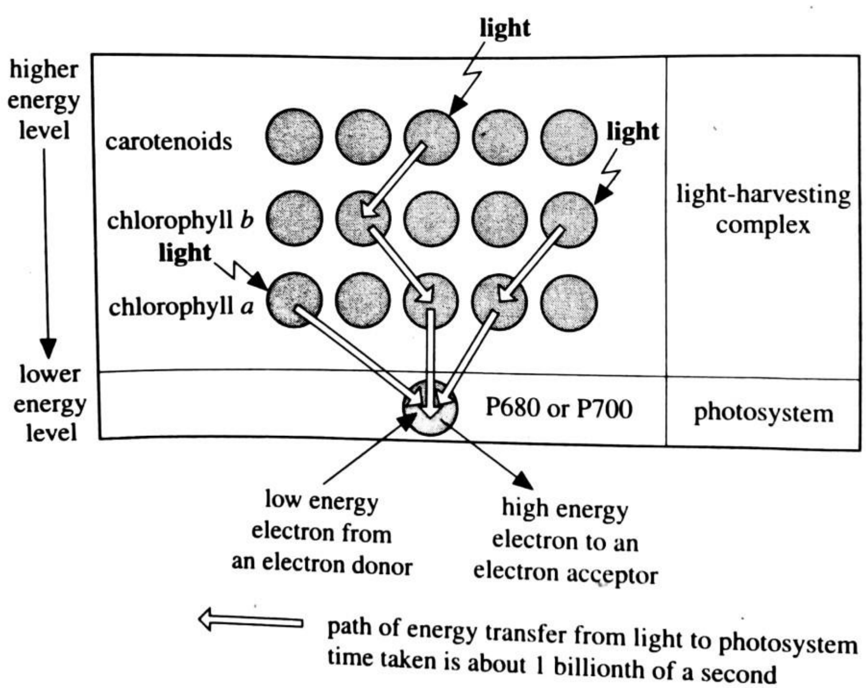
The photosynthetic pigment molecules are clustered in the thylakoid membranes. Each cluster is called an **antenna complex**

Special proteins associated with these pigments channel light energy entering the chloroplast on to special molecules of chlorophyll a, known as the reaction **center chlorophyll molecule**. The reaction Centre and all the other light-gathering molecules combine to form a **photosystem**. When light strikes this molecule, an electron in its orbit is raised to a higher energy level, thus initiating a flow of electrons.

There are two types of photosystems; **photosystem I** and **photosystem II**.

In photosystem I, the reaction Centre is called **P700** because its chlorophyll a has a maximum absorption at a wavelength of **700nm** (red light).

Photosystem II has a reaction Centre called **P680** because its chlorophyll a has a maximum absorption at **680nm** (orange-red).



A photosystem: a light-harvesting cluster of photosynthetic pigments in chloroplast thylakoid membrane

THE LIGHT-DEPENDENT STAGE

How light trapped by chlorophyll is used

1. Provides energy to convert ADP and an inorganic phosphate (Pi) to ATP a process called **photophosphorylation**
2. Necessary for the splitting of water molecules to release electrons and hydrogen ions a process known as **photolysis.**

Importance of light dependent stage of photosynthesis

1. produces Adenosine triphosphate (ATP) which is a source of energy for subsequent synthesis of carbohydrates.
2. Photolysis of water produces hydrogen atoms for the reduction of carbon dioxide during the dark stage.

The light dependent reactions of photosynthesis

The light-dependent reactions occur in the **thylakoid membranes** of a chloroplast's **grana**.

It involves the splitting of water by light **(photolysis of water)** to give hydrogen ions (protons) and the synthesis of ATP in **photophosphorylation**. The hydrogen ions combine with a carrier molecule NADP to make reduced NADP. ATP and reduced NADP are passed from the light dependent to the light independent reactions.

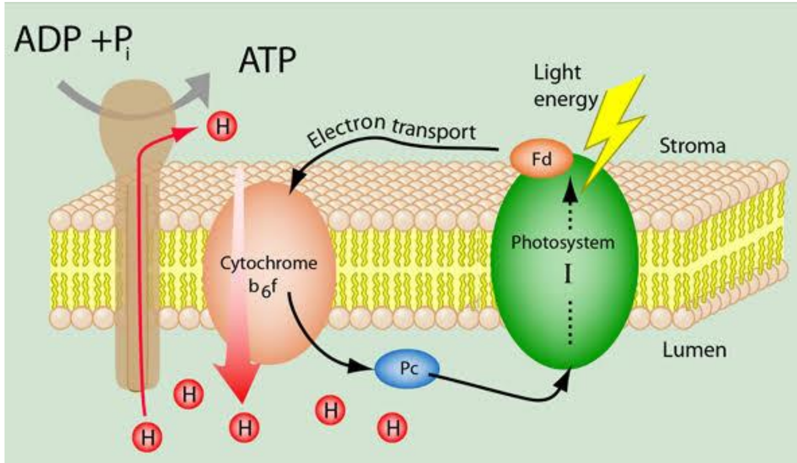
Photophosphorylation of ADP to ATP can be cyclic or non-cyclic, depending on the pattern of electron flow in one or both types of photosystem.

Cyclic photophosphorylation

Cyclic photophosphorylation involves only **photosystem I**. Light of wave length 700nm is absorbed by photosystem I (P700) and is passed to the primary pigment. An electron in the chlorophyll molecule is excited to a higher energy level and is emitted from the chlorophyll molecule. This is called **photo activation**. Instead of falling back into the photosystem and losing its energy as thermal energy or as fluorescence, the excited electron is captured by an electron acceptor and passed back to a chlorophyll molecule via a chain of electron carriers i.e. iron protein complex, to cytochromes b, to plastoquinone, to cytochrome-**f,** to plastocyanin and again back to P-700.

The flow of electrons through carriers in the thylakoid membrane releases energy for active pumping of hydrogen ions (H^+) from the stroma to the thylakoid space.

The highly concentrated H^+ inside the thylakoid space **diffuse** along the steep electrochemical gradient from the thylakoid space via the stalked particles into the stroma, thereby providing energy to form ATP in the presence of ATPase enzyme. this process is called chemiosmosis. The ATP then passes to the light independent reactions.



Non-cyclic photophosphorylation

Non-cyclic photophosphorylation involves both photosystems I and II in the so-called 'Z scheme' of electron flow (unidirectional electron flow).

Light strikes both photosystems I and II simultaneously, excited electrons are emitted from the primary pigments of both reaction centers. These electrons are absorbed by electron acceptors and pass along chains of electron carriers, leaving the photosystems positively charged. The electrons from photosystem II are passed from the electron acceptor along a series of electron carriers to photosystem I. The primary pigment at photosystem II receives replacement electrons from the splitting (photolysis) of water.

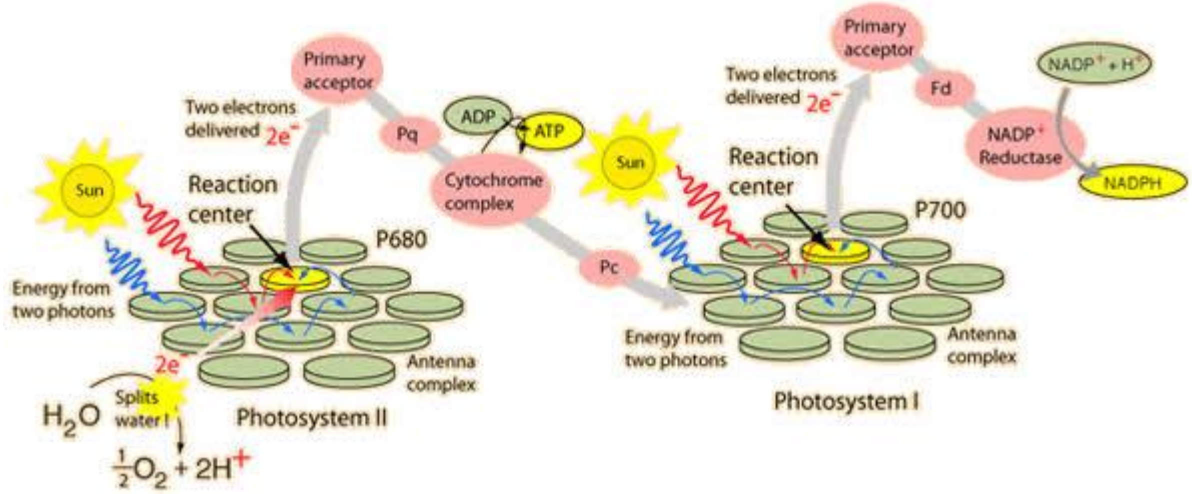
Photosystem II includes a water-splitting enzyme that catalyses' the breakdown of water:

$$H_2O \longrightarrow 2H^+ + 2e^- + {}^1/_2\, O_2$$

Oxygen is a waste product of this process. The hydrogen ions combine with electrons from photosystem I and the carrier molecule NADP to give reduced NADP.

$$2H^+ + 2e^- + NADP \longrightarrow \text{reduced NADP}$$

Reduced NADP passes to the light independent reactions and is used in the synthesis of carbohydrate. As in cyclic photophosphorylation, ATP is synthesized as the electrons lose energy while passing along the carrier chain.



The movement of electrons in the thylakoid membranes releases energy which enables active pumping of hydrogen ions (H^+) from the stroma to the thylakoid space. At the same time, photolysis of water

(i) causes accumulation of H^+ **inside the thylakoid space**

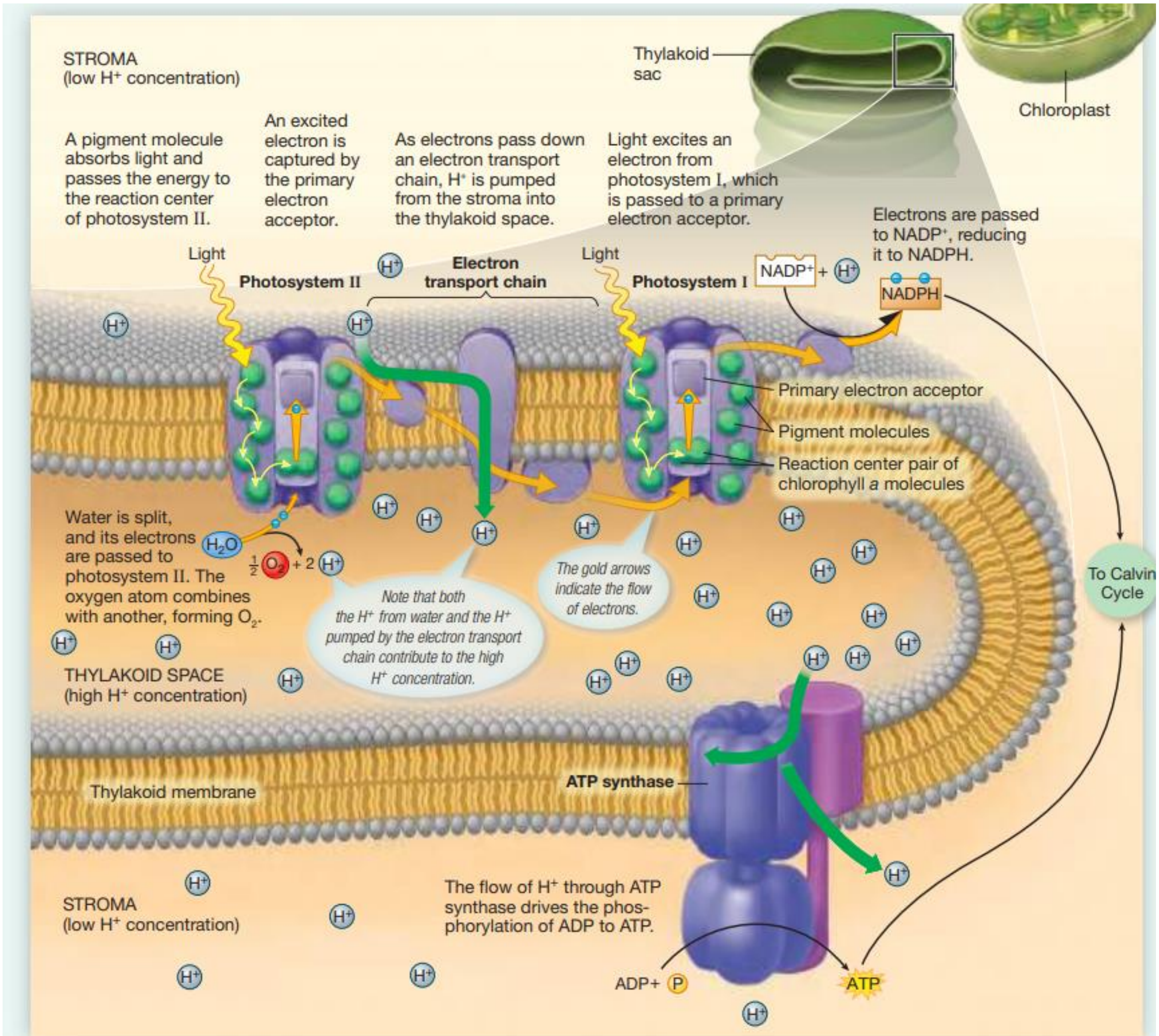
(ii) provides electrons to replace those lost from PSII.

The high accumulation of H^+ photolysis and active pumping of proton creates a steep electrochemical gradient between the thylakoid space and stroma, resulting in **diffusion** of H^+ via the stalked particles into the stroma this provides

(i) energy to form ATP in the presence of ATPase enzyme

(ii) H^+ for reducing NADP to form NADPH.

The NADPH and ATP formed then enter the dark stage.



COMPARISON BETWEEN CYCLIC AND NON-CYCLIC PHOTOPHORYLATION

Similarities

In both

- there is flow of electrons through electron carriers ▪ there are pigment systems which accept and lose electrons.
- ATP is formed.
- pigment system I is involved
- electron movement is located in the thylakoid membranes
- protons are moved outwards of the thylakoids.

- protons (**H^+**) are actively pumped from stroma into thylakoid space.
- there is photo-excitation of electrons in the pigment systems.

Differences

Non-cyclic photophosphorylation	**Cyclic photophosphorylation**
✦ Electrons flow unidirectional (noncyclically)	✦ Electrons flow in a cyclic pattern
✦ First electron donor is (source of electrons) water	✦ First electron donor is photosystem I
✦ Last electron acceptor is NADP	✦ Last electron acceptor is photosystem I
✦ The products are ATP, NADPH and Oxygen	✦ The product is only ATP.
✦ Involves both photosystems I and II	✦ Involves only photosystems I
✦ Photolysis of water occurs	✦ No photolysis of water
✦ Two electron acceptors involved	✦ Only one electron acceptor involved

Note

- During cyclic photophosphorylation no oxygen and NADPH produced as photolysis of water does occur,
- Relatively less energy is produced in cyclic photophosphorylation than in non-cyclic photophosphorylation since non-cyclic photophosphorylation involves two photosystems of which each takes up a quantum of light.
- When carbon dioxide concentration is limiting, both photosystems cannot operate at the same time hence only photosystem I operates and photophosphorylation is mainly cyclic.

THE LIGHT-INDEPENDENT STAGE

This also referred to as the dark stage because the reactions can take place in the dark if sufficient ATP and NADPH are available. It occurs in the stroma of the chloroplast and takes place whether or not light is present. The reactions are controlled by enzymes and their sequence was determined by Melvin Calvin, Benson and Bassham during a period of 1946-53. The process is often called the **Calvin cycle**.

The dark reactions involve main pathways which include

- Calvin-Benson cycle / C_3 pathway
- Hatch-Slack pathway / C_4 pathway

1. Calvin-Benson cycle / C_3 pathway

This is the series of reactions in plants involving formation of glycerate-3-phosphate which has 3 carbon atoms as first stable organic substance during photosynthesis.

MAIN STAGES OF C_3 PATHWAY

1. Carboxylation

Carbon dioxide diffuse into the stroma and then combines with a 5-carbon sugar, **Ribulose bisphosphate** (RUBP), in a reaction catalyzed by enzyme RuBP carboxylase (Rubisco), the resulting 6 carbon compound is unstable and immediately breaks down to form two molecules of 3-carbon compound known as 3-phosphoglyceric acid (PGA)/ glycerate-3-phosphate (GP), which is the **first stable organic compound in C_3 plants.**

2. ***Reduction phase***

3-phosphoglyceric acid (PGA) molecules are phosphorylated by ATP from the light stage ADP, and then reduced by NADPH (formed in light stage) to form a **triose phosphate (TP)** called 3phosphoglyceraldehyde (PGAL) or glyceraldehyde-3-phosphate(GALP), which is a 3-carbon sugar, **$NADP^+$**, ADP and an inorganic phosphate (Pi).

Note:

Triose phosphate is the first stable carbohydrate formed in the Calvin cycle.

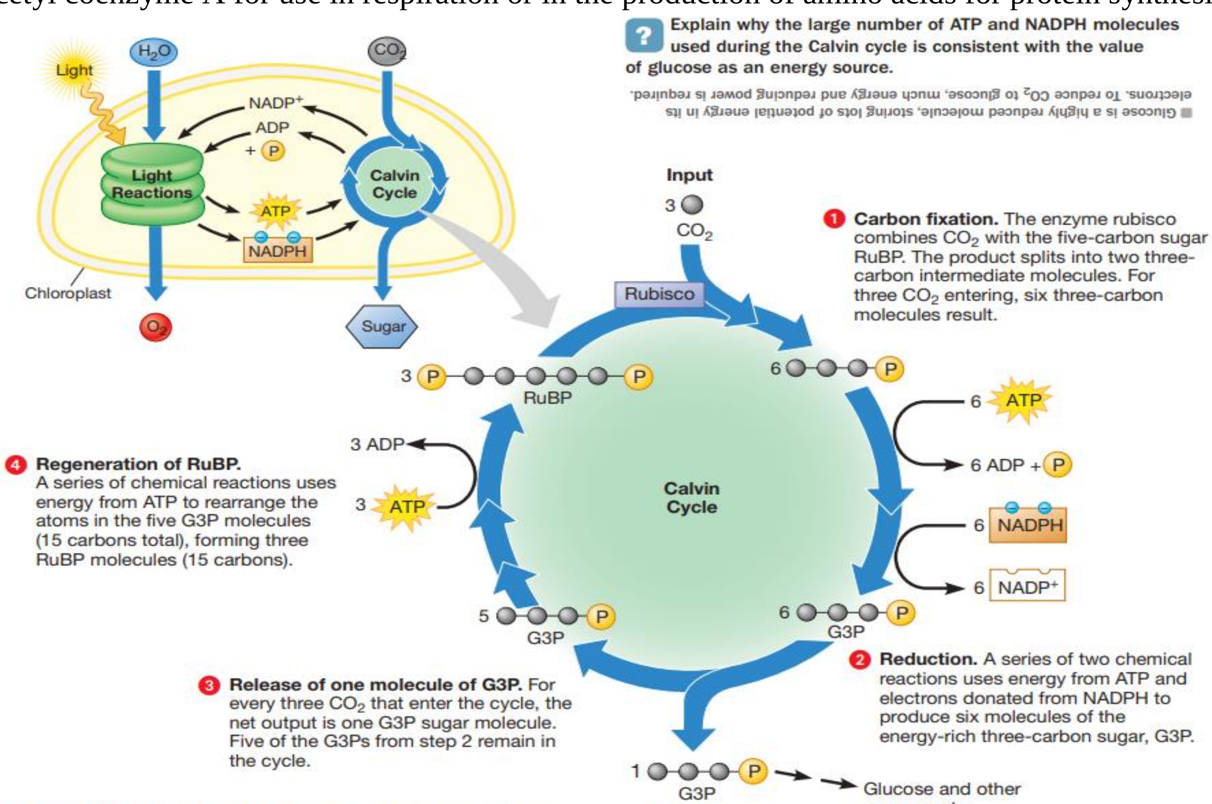
$NADP^+$ is regenerated and this returns to the light dependent stage to accept more hydrogen

3. **Regeneration phase**

Five-sixth of the triose phosphates are converted through a series of reactions into RUBP which then fixes more carbon dioxide. This reaction requires both ATP and NADPH from the light stage.

4. **Product synthesis phase**

One-sixth of the triose phosphate molecules are used to produce other molecules needed by the plant. Some of these triose phosphates condense to become hexose phosphates which, in turn, are used to produce starch for storage, sucrose for translocation around the plant, or cellulose for making cell walls. Others are converted to glycerol and fatty acids to produce lipids for cellular membranes or to acetyl coenzyme A for use in respiration or in the production of amino acids for protein synthesis.



▲ **Figure 7.10** Details of the Calvin cycle, which takes place in the stroma of a chloroplast

the Calvin cycle

Metabolism of Glycerate phosphate (GP) and Glyceraldehyde phosphate (TP/ PGAL)

(a) Synthesis of carbohydrates

Glyceraldehyde-phosphate molecules are converted to form monosaccharides e.g. glucose. Glucose may combine with fructose to form sucrose, transported in phloem sieve tubes or can be polymerized into starch for storage or cellulose; a component of plant cell walls.

(b) Synthesis of lipids

- Glycerate-phosphate enters glycolysis pathway and is converted to pyruvate, which can be converted into acetyl group, which combines with coenzyme A to form acetyl coenzyme A. This can be used to form a variety of fatty acids in the cytoplasm and chloroplast.
- Glycerate-phosphate can also be converted to glycerol

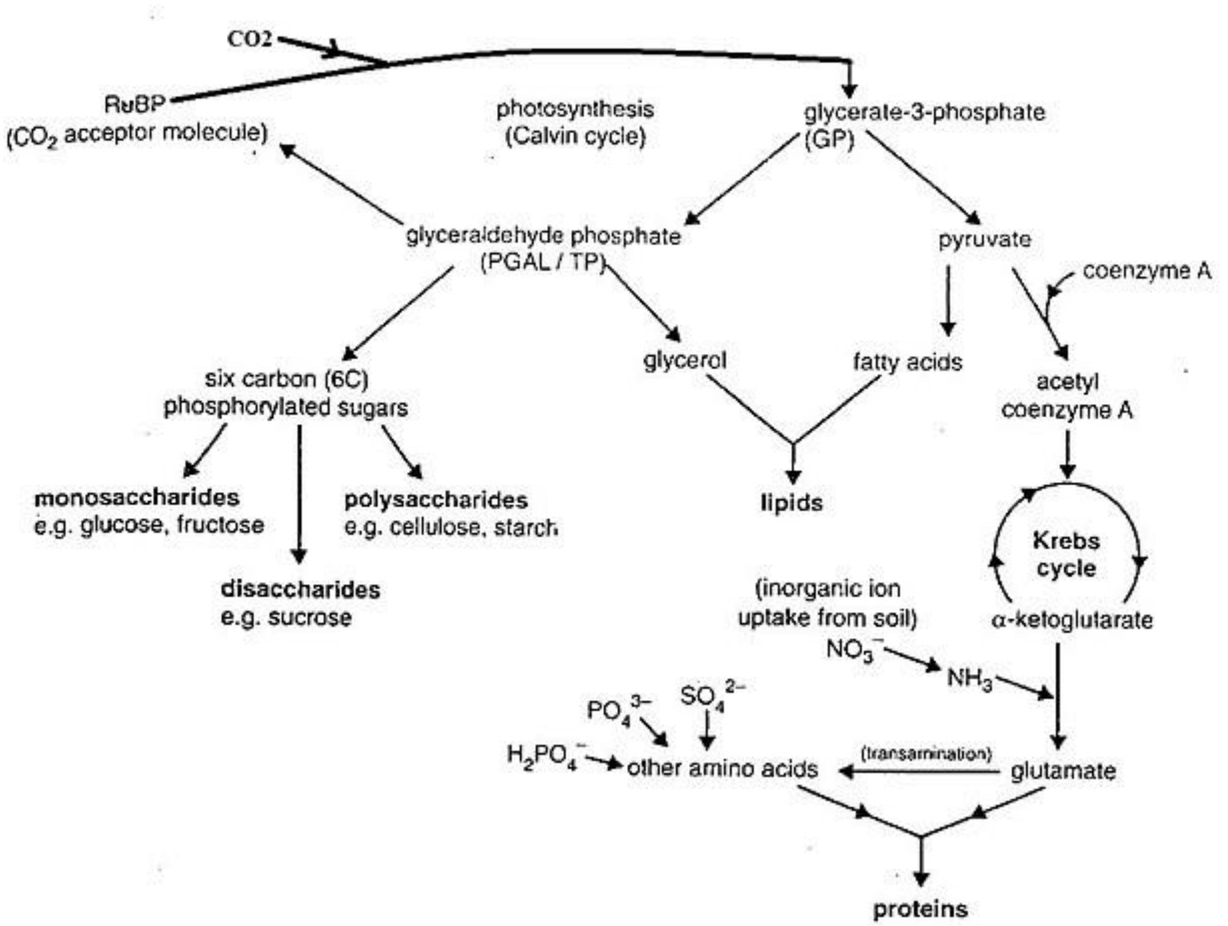
Lipids such as triglycerides are esters of fatty acids and glycerol, which are important components of cell membranes.

(c) Synthesis of proteins

Glycerate-phosphate is converted into acetyl coenzyme A and enters into the Krebs cycle. Some of its intermediates can produce different amino acids by transamination reactions. The amino acids are then polymerized into proteins which are required for growth and development, synthesis of enzymes and structural components of the cell.

NB:

The nitrogen, Sulphur and phosphorus required for protein synthesis are absorbed from the soil.
Nitrogen is taken up as nitrates or ammonia, Sulphur as sulphates and phosphorus as phosphates.



Summary of metabolism of intermediates of dark stage

Assignment 2: **Compare light dependent and light independent stages of photosynthesis**

NOTE

- The enzyme Ribulose bisphosphate carboxylase that catalyzes the reaction of carbon dioxide with RuBP unfortunately, it can also catalyze the reaction of oxygen with RuBP. When this happens, less photosynthesis takes place, because some of the RuBP is being 'wasted' and less is available to combine with carbon dioxide. This unwanted reaction is known as **photorespiration**. It happens most readily in high temperatures and high light intensity – that is, conditions that are found at low altitudes in tropical parts of the world.
- Photorespiration is a wasteful process in which carbon fixation in C_3 plants is prevented due to the light dependent uptake of oxygen by RuBP carboxylase (RUBISCO enzyme) and release of carbon dioxide
- Tropical grasses such as maize, sorghum and sugar cane which are C_4 plants have evolved a method of avoiding photorespiration. They keep RuBP and rubisco well away from high oxygen concentrations. The cells that contain RuBP and rubisco are arranged around the vascular bundles, and are called **bundle sheath cells** the arrangement known as the **Kranz anatomy.** They have no direct contact with the air inside the leaf.

2. HATCH-SLACK PATHWAY OR C4 METABOLISM

This is a type of photosynthesis in which CO_2 is first, fixed by phosphoenolpyruvate carboxylase (PEPCO) into Oxaloacetate (OAA) inside mesophyll cells, stored as organic acid (mainly malate) which is **later** decarboxylated, refixed and CO_2 is assimilated in the Calvin-cycle inside bundle sheath cells.
Examples of C_4 plants: maize, sorghum, *Amaranthus, Sugar cane*, paspalums *(Paspalum notatum)*, Bermuda grass, blue grama, Rhodes grass, troublesome weeds like nut grass, crabgrass and barnyard. They are found mainly in hot / arid / saline tropical habitats.

KRANZ LEAF ANATOMY

A condition in which bundle sheath cells and palisade cells of the mesophyll form two concentric layers (rings) around each vascular bundle of leaves.

This is a pathway for transporting carbon dioxide and hydrogen from mesophyll cells to bundle sheath cells. Once in the bundle sheath cells, the carbon dioxide is released again and normal C3 photosynthesis occurs. **Stages in C4 pathway**

1. acceptance of carbon dioxide (carbon dioxide fixation) in mesophyll cells

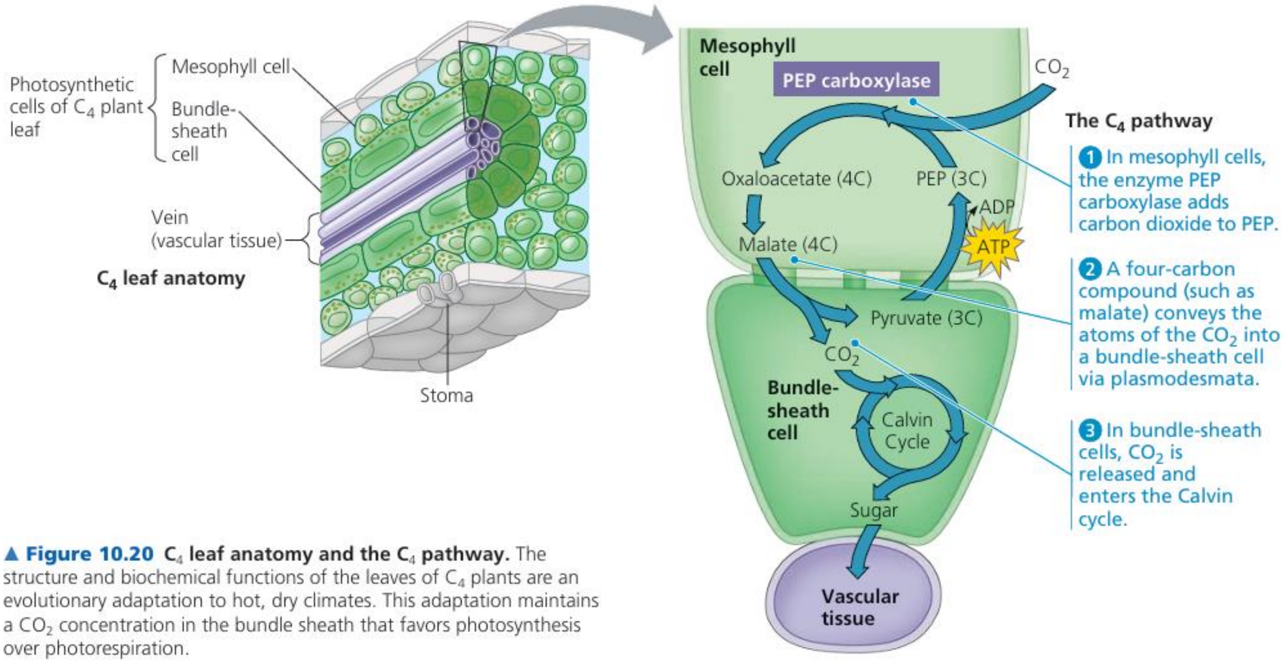
In the presence of phosphenol pyruvate carboxylase (PEPCO) enzyme, the carbon dioxide acceptor with 3 carbon atoms, phosphenol pyruvate (PEP) combines with carbon dioxide inside the chloroplasts of mesophyll cells to form oxaloacetate (OAA) a 4-carbon compound. This is the first stable compound formed in C4 plants. Oxaloacetate is reduced by NADPH from the light stage to malate a 4-carbon acid. This occurs in the presence of malate dehydrogenase enzyme.

2. Malate shunt

From chloroplasts of mesophyll cells, the malate is translocated (shunted) to the chloroplasts of bundle sheath cells where it is decarboxylated and dehydrogenated by NADP to form pyruvate a 3-carbon acid and carbon dioxide. The pyruvate produced returns to mesophyll cells for phosphorylation by ATP to regenerate **PEP;** the CO_2 acceptor.
Now the second carboxylation occurs in the chloroplasts of bundle sheath cells through Calvin cycle.

3. Regeneration of the carbon dioxide acceptor

Pyruvate is returned to the mesophyll cells and is used to regenerate PEP by the addition of phosphate from ATP. This requires the energy from two high energy phosphate bonds.



▲ **Figure 10.20** **C_4 leaf anatomy and the C_4 pathway.** The structure and biochemical functions of the leaves of C_4 plants are an evolutionary adaptation to hot, dry climates. This adaptation maintains a CO_2 concentration in the bundle sheath that favors photosynthesis over photorespiration.

Summary of Hatch-slack pathway

ADVANTAGES OF HATCH_SLACK PATHWAY

- C_4 plants ably photosynthesize at very low CO_2 concentration (e.g. in dense tropical vegetation) because PEP carboxylase enzyme has a very high affinity for carbon dioxide.
- Concentric arrangement of mesophyll cell produces a smaller area in relation to volume for better utilization of available water and reduce, the intensity of solar radiations.
- **Photorespiration,** which inhibits growth in C_3 plants is **avoided / reduced** in C_4 because
  - the CO_2 fixing enzyme PEP carboxylase has no affinity for oxygen
  - RUBISCO enzyme inside the bundle sheath cells is shielded from high oxygen concentration by the ring of palisade cells.
- The CO_2 fixing enzymes in C_4 plants are more active at hot temperature and high illumination, therefore photosynthesis occurs rapidly at low altitude, hot and brightly lit tropical conditions than in C_3 plants.
- The productivity of C_4 almost ***four times*** greater than in C_3 ***because:***

(i) of the increased rate of CO_2 uptake caused by
  - large internal leaf surface area
  - short CO_2 diffusion distance

(ii) CO_2 steep diffusion gradients in the bundle sheath cells in which dark reactions occur have
  - a large photosynthetic surface area enabled by un-usually large chloroplasts
  - lack of grana on which O_2 would be produced, so ***no photorespiration***.
  - the Palisade cells in which light reactions occur have large grana to increase the photosynthetic surface area.

Disadvantages of hatch-slack pathway

- The CO_2 fixing enzymes in C_4 plants are less active at cool temperature and low illumination, therefore photosynthesis occurs slowly at high altitude with cool temperature and in low light intensity of temperate conditions.
- Since every carbon dioxide molecule has had to be fixed twice, the energy requirements for C_4 photosynthesis is roughly double that for C_3 photosynthesis.

COMPARISON BETWEEN C_3 AND C_4 PLANTS

Similarities

Both:

- contain RUBISCO enzyme
- depend on light for their reactions
- show CO_2 fixation
- have RuBP
- form several same organic products e.g. PG, PGA, sucrose
- have the Calvin cycle

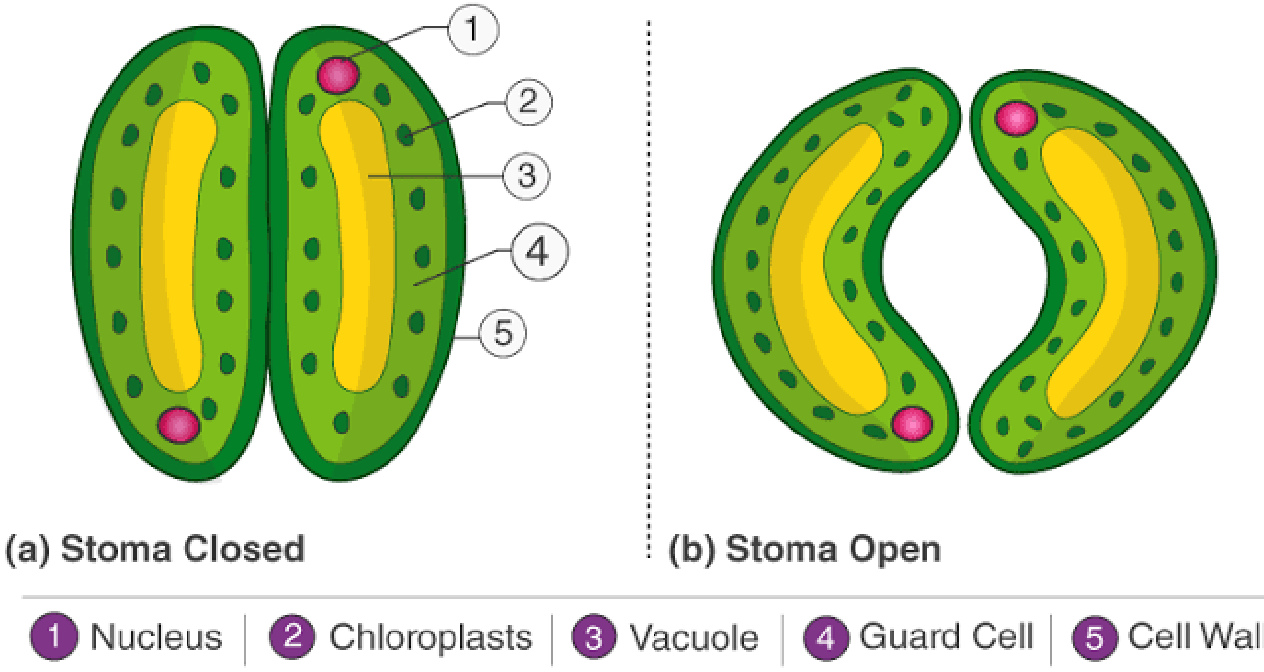
Differences

C_3 Plants	**C_4 plants**
Lack Kranz anatomy	Exhibit Kranz anatomy
All chloroplasts have identical structure	Chloroplasts are dimorphic (are in two forms) e.g. those of palisade cells have grana yet are lacking bundle sheath cells.
CO_2 acceptor is a 5-Carbon RuBP	CO_2 acceptor is a 3-Carbon PEP
CO_2 fixation occurs once	CO_2 fixation occurs twice
Photorespiration occurs	No photorespiration
Less photosynthetically efficient	More photosynthetically efficient
GP is the first organic product	OAA is the first organic product
Enzymes are more efficient at lower temperatures	Enzymes are more efficient at high temperatures
RUBISCO enzyme is used	PEP carboxylase enzyme is used
Compensation point is attained at higher CO_2 concentration	Compensation point is attained at lower CO_2 concentration

THE RELATIONSHIP BETWEEN VARYING SUCROSE CONCENTRATION WITH STOMATAL OPENING/CLOSING

Morphology of Stomata

Stomata vary considerably, in structure, distribution, size and frequency.



Occurrence of Stomata

The stomata usually occur in leaves and in most cases in both the upper and lower epidermis.

The stomata may also occur in:

+ Epidermis of young stems and petioles
+ Petals and sepals of flowers
+ Fruits such as bananas, beans, peas etc.
+ Awns of most graminaceous inflorescences
+ Tendrils.

In some of these structures, the stomata may be non-functional under ordinary conditions of illumination, [CO_2], water availability and humidity.

The number of stomata in the lower epidermis usually exceeds that in the upper epidermis which may be absent altogether.

- This is a morphological adaptation to avoid excessive water loss on hot days
- Leaves with stomata on both surfaces are called **AMPHISTOMATOUS** leaves.
- Leaves with stomata in the lower epidermis only are called **HYPOSTOMATOUS** leaves eg. *Hedera helix* (see table above)
- There are usually more cells per unit area in sun leaves than in shade plants. The reason being adaptation to reduce the rate of transpiration resulting from direct sun rays
- There are also more stomata per unit area in leaves of plants growing in dry soils and low humidity than those growing in moist soils and high humidity.

- This is due to physiological stress that results in reduced cell size and more cells per unit area in general
- Submerged leaves rarely bear stomata to avoid water logging.
- When stomata are present in submerged leaves, they may be on the upper epidermis only and are called **EPISTOMATOUS**

This enhances transpiration.

Structure of the stoma

Each stoma consists of a stomatal pore bordered by a pair of crescent or bean-shaped cells called guard cells. Unlike epidermal cells, guard cells contain chlorophyll. The inner cell wall of guard cells is thicker and less elastic than the outer wall. Microfibrils are radially orientated in the cell wall and the guard cells are joined at the ends. The epidermal cells surrounding the guard cells are subsidiary cells.

Ventilation (opening and closing of stomata)

The opening and closing of stomata occurs as a result of changes in the shape of the guard cells. When guard cells take in water by osmosis, they expand and become turgid. However, they do not expand uniformly in all directions. The thick inelastic inner wall makes the guard cells to curve away from each other, opening the stoma. When the guard cells lose water, they become flaccid and collapse, closing the stomata.

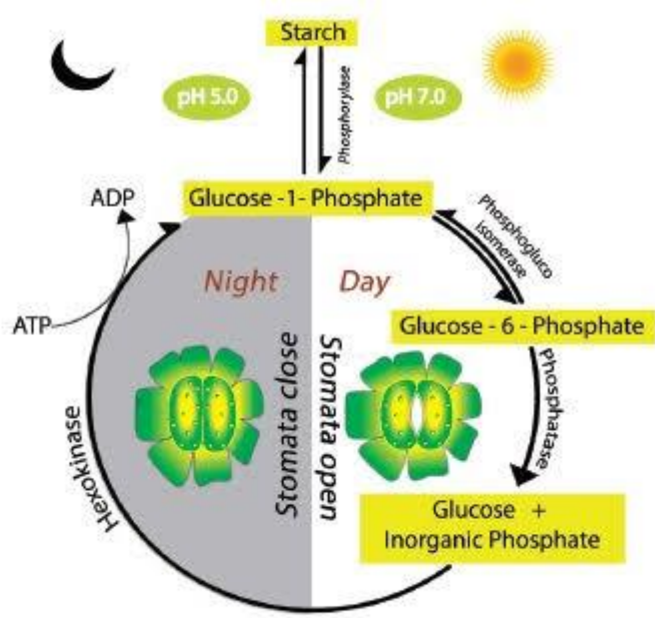
The closing and opening is controlled mainly by the intensity of light. They are normally open during daylight and closed during the night.

Photosynthetic product theory

Guard cells have chloroplast. During day light, they carry out photosynthesis producing sugar. The sugar increases the osmotic pressure of the cell sap. This causes water to move into the guard cells from nighbouring epidermal cells by osmosis. The result is an expansion and increase in turgidity of the guard cells containing the stomata to open.

In darkness, photosynthesis stops and the sugar in the guard cells is converted to starch. This lowers the osmotic pressure of guard cells causing them to lose water to neighboring cells by osmosis. The guard cells become flaccid and the stomata close.

Note; this theory does not explain how the low rate of glucose formation can account for the rapid opening of stomata



EFFECT OF CLIMATE CHANGE ON PLANT PRODUCTIVITY

In effect, the mesophyll cells of a C4 plant pump CO2 into the bundle sheath, keeping the CO2 concentration in the bundle-sheath cells high enough for rubisco to bind CO2 rather than O2.

The cyclic series of reactions involving PEP carboxylase and the regeneration of PEP can be thought of as a CO2-concentrating pump that is powered by ATP.

In this way, C4 photosynthesis spends ATP energy to minimize photorespiration and enhance sugar production. This adaptation is especially advantageous in hot regions with intense sunlight, where stomata partially close during the day, and it is in such environments that C4 plants evolved and thrive today.

The concentration of CO2 in the atmosphere has drastically increased since the Industrial Revolution began in the 1800s, and it continues to rise today due to human activities such as ***the burning of fossil fuels***. The resulting global climate change, including an increase in average temperatures around the planet, may have far-reaching effects on plant species.

Scientists are concerned that increasing CO2 concentration and temperature may affect C3 and C4 plants differently, thus changing the relative abundance of these species in a given plant community**.**

Which type of plant would stand to gain more from increasing CO2 levels?

- In C3 plants, the binding of oxygen rather than CO_2 by Rubisco leads to **photorespiration**, lowering the efficiency of photosynthesis.
- C4 plants overcome this problem by concentrating CO_2 in the bundle sheath cells at the cost of ATP. Rising CO_2 levels should benefit C3 plants by lowering the amount of photorespiration that occurs.

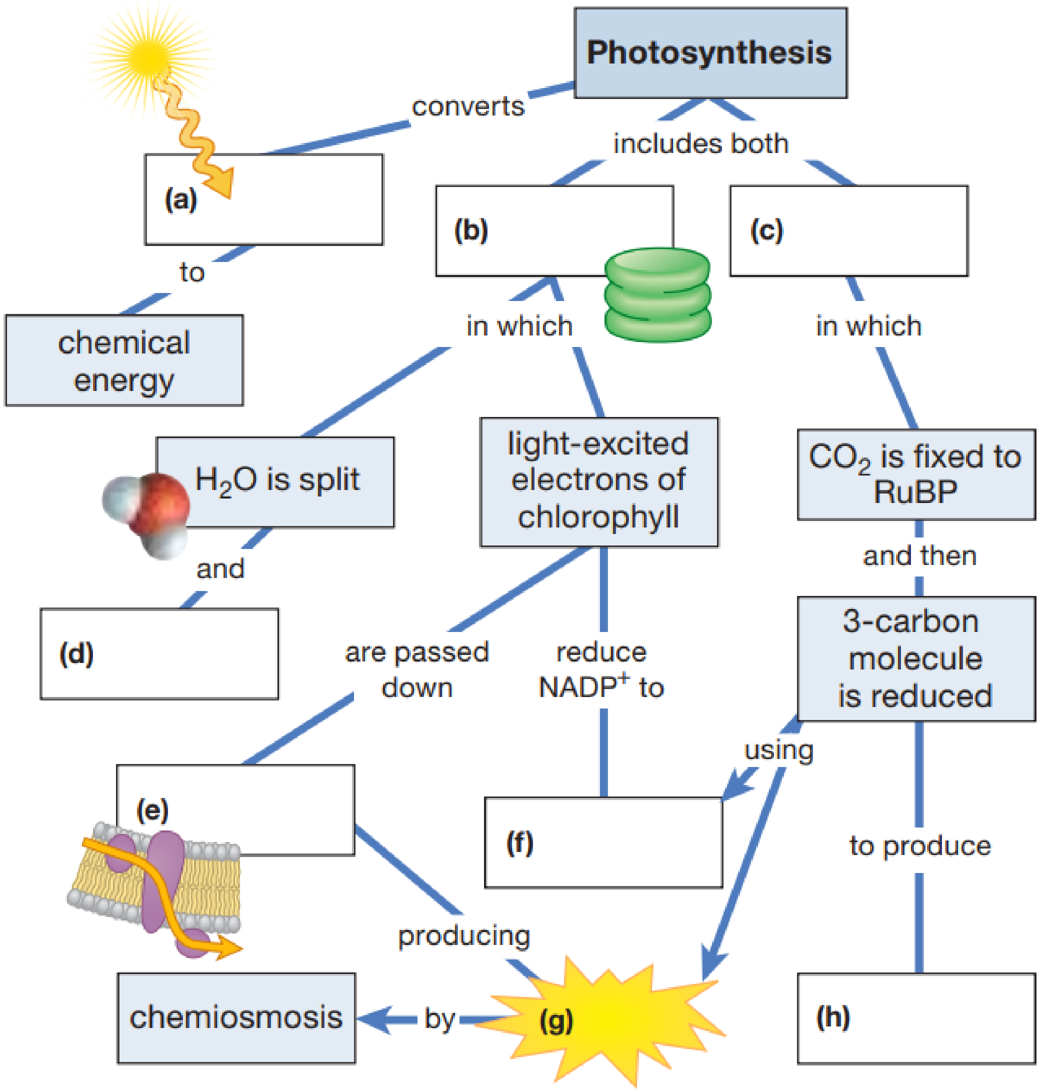
At the same time, rising temperatures have the opposite effect, increasing photorespiration. (Other factors such as water availability kept constant.) In contrast, many C4 plants could be largely unaffected by increasing CO_2 levels or temperature.

Researchers have investigated aspects of this question in several studies; you can work with data from one such experiment in the Scientific Skills exercise ***(CAMPBELL BIOLOGY 9TH EDITION Pg123).***

- In different regions, the particular combination of CO_2 concentration and temperature is likely to alter the balance of C3 and C4 plants in varying ways. The effects of such a widespread and variable change in community structure are unpredictable and thus a cause of legitimate concern.

CONNECTING THE CONCEPTS

1. Complete this summary map of photosynthesis.



FACTORS INFLUENCING THE RATE OF PHOTOSYNTHESIS

The rate of photosynthesis is affected by a number of factors which are both internal and external (environmental)

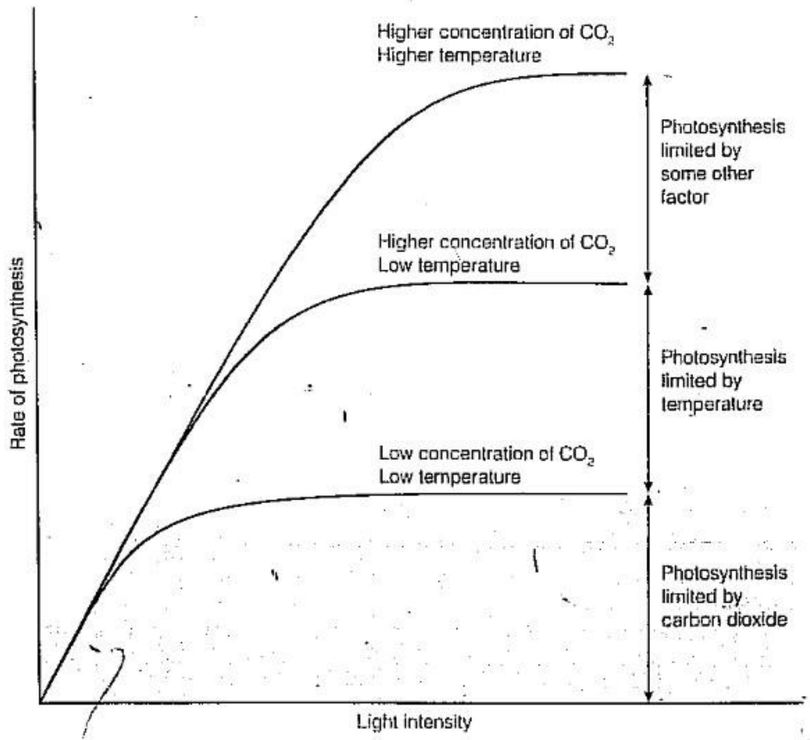
THE PRINCIPLE OF LIMITING FACTORS

It states that:

'At any given moment, the rate of a chemical process is limited by the one factor which is nearest its minimum value, and by that factor alone'

A limiting factor is a factor which is nearest to its minimum value in a chemical process that is affected by more than one factor.

<u>Graph illustrating the concept of limiting factors on the rate of photosynthesis</u>



From the graph above, the rate of photosynthesis increases with increase in light intensity and then rate remains constant as the process reaches its maximum rate due to;

(i) The photosynthesis process is going at the fastest possible pace, and no amount of additional light will make it go any faster.

(ii) There is insufficient carbon dioxide available to allow the process to speed up any further

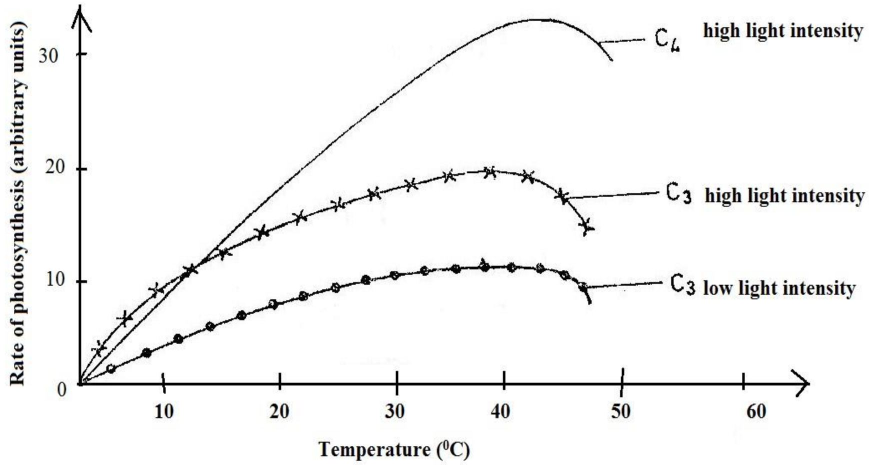
(iii) The temperature is too low for the chemical reactions to go any faster. Therefore, the rate of photosynthesis can be increased further by increasing either temperature of carbon dioxide concentration which are limiting factors.

(I) Temperature

Changes in temperature have little effect on the reactions of the light-dependent stage because these are driven by light, not heat. However, the reactions of the Calvin cycle are catalyzed by enzymes which, like all enzymes are sensitive to temperature.

Note:

- the effect of temperature on these reactions is similar to its effect on other enzymes
- The optimum temperature varies for each species, but many temperate plants have an optimum temperature ranging from 25°C to 35°C.

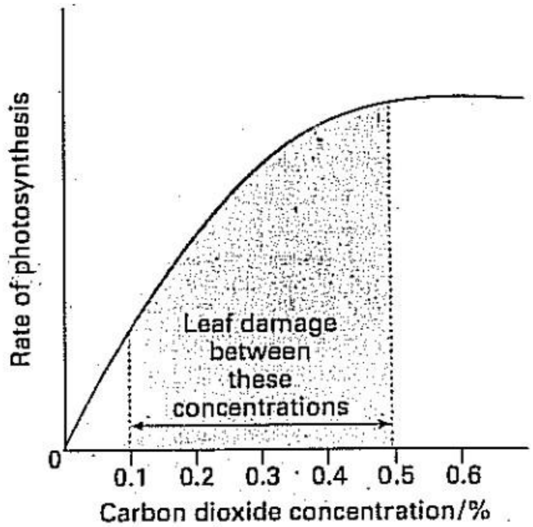


Observation / description	***Explanation***
✞ Below 10^0C, C_3 rate of photosynthesis is higher than in C_4 above 10^0C.	✞ C_4 photosynthetic enzymes are less active in the cold but become more active with increase in temperature.
✞ The maximum rate of photosynthesis attained in C_4 is much higher than in C_3	✞ The optimum temperature for enzymes involved in the C_4 cycle is higher than in the C_3 cycle
✞ At about 45^0C, the rate of photosynthesis decreases	✞ Enzymes controlling photosynthesis are denatured by very high temperatures
✞ There is an initial increase in photosynthetic rate to a maximum at about 40-42^0C, in spite of further increase in temperature	✞ Light intensity becomes a limiting factor in each of the three cases
✞ There is increase in the rate of photosynthesis with increase in temperature until up to at about 40^0C	✞ Increase in temperature activates enzymes to a level beyond which enzyme denaturation occurs.

(ii) Carbon dioxide concentration

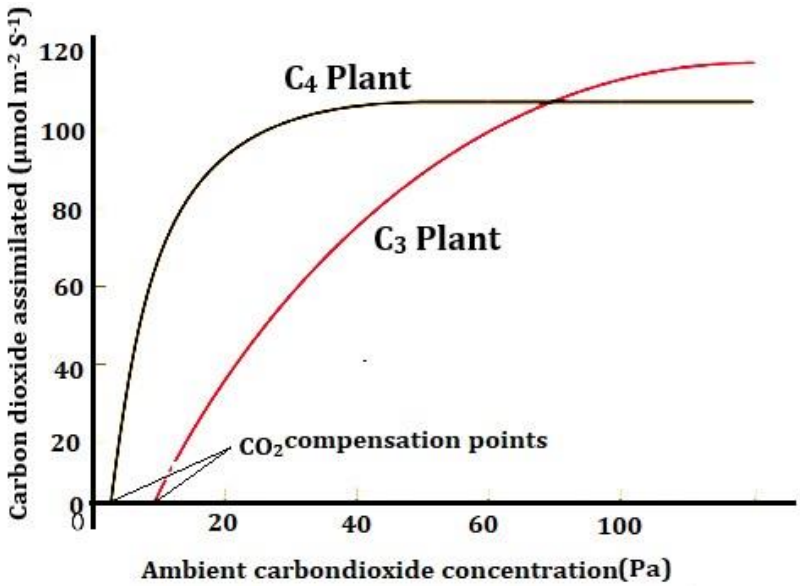
In the atmosphere, the concentration of carbon dioxide ranges from 0.03 to 0.04 %. However, it is found that 0.1% of carbon dioxide in the atmosphere increases the rate of photosynthesis significantly. As long as there is no other facto limiting photosynthesis, an increase in carbon dioxide concentration up to 0.5% usually results in an increase in the rate of photosynthesis.

However, concentrations above 0.1% can damage leaves see the graph below.



On a warm sunny day, the concentration of carbon dioxide in the air is probably the factor that limits photosynthesis more than any other.

Enriching air with carbon dioxide has a significant effect on crop plants, this is achieved in the greenhouses which are enclosed chambers where plants are grown under controlled conditions. Where the concentration of carbon dioxide is increased by installing gas burners which liberate carbon dioxide as the gas burns.



Observation / description	***Explanation***
✞ the rate of photosynthesis increases rapidly with increasing carbon dioxide concentration to a maximum at 30 Pa in C_4 plants and 90 Pa in C_3 plants.	✞ Rubisco fixes carbon dioxide instead of oxygen, because the carbon dioxide concentration is very high out competing oxygen for occupation of active site on RUBISCO.
✞ The rate of photosynthesis increases faster in C_4 than C_3.	✞ PEPCO of C_4 has a higher affinity for carbon dioxide than Rubisco of C_3.
✞ The overall photosynthetic products are greater in C_3 than in C_4	✞ C_4 needs more ATP than C_3 which generally reduces photosynthetic out put

✞ The C_4 plants are more efficient at lower CO_2 concentration while C_3 more efficient at higher CO_2	✞ **A**t lower **CO_2** concentration in C_3 photorespiration reduces the photosynthesis efficiency yet C4 plants are not affected by photorespiration as PEPCO has no affinity for oxygen even at very low carbon dioxide concentration.
✞ C_3 plant has a higher compensation point than C_4	✞ PEPC has a high affinity for carbon dioxide
✞ After attaining the maximum, the rate of photosynthesis remains constant in both	✞ It is because other factors limit the process e.g. temperature, light intensity etc.

(iii) Light intensity

Increase in light intensity results in an increased in the rate of photosynthesis.

With a continuing increase in light intensity a point is reached where carbon dioxide is neither evolved nor absorbed this point is the **Light compensation point**.

Light compensation point is the light intensity at which the photosynthetic intake of carbon dioxide is equal to the respiratory output of carbon dioxide.

The time taken for a plant which has been in darkness to reach the compensation point is called the **compensation period**.

The effect of light (intermittent and continuous) on the rate of photosynthesis.

Intermittent light is a form of lighting where the light source is turned on and off repeatedly, creating periods of light and darkness. Examples: Flashing lights, strobes, or even a light that is turned on and off at regular intervals can be considered intermittent.

Continuous light is a constant source of light that is always on, with no periods of darkness. Examples: Incandescent bulbs, fluorescent lights, LED panels, and other light sources that provide a steady stream of light are examples of continuous light.

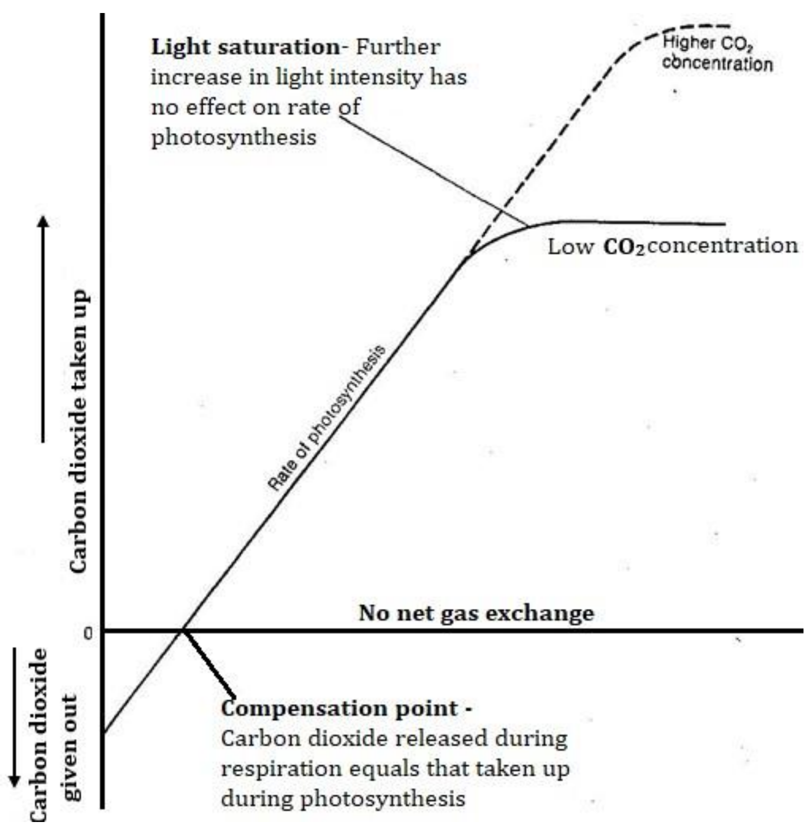
Intermittent light

Intermittent light can increase the rate of photosynthesis compared to continuous light, especially when the light pulses are short (micros to milliseconds). This occurs because the light reactions, which are faster, can occur during the light pulses, while the dark reactions, which are slower, can utilize the products of the light reactions during the dark periods.

When light is interrupted, the light reactions happen rapidly during the light pulses. The ATP and NADPH produced during these pulses are then used in the dark reactions during the dark periods. This allows the dark reactions to keep pace with the light reactions, potentially increasing overall photosynthetic efficiency while in continuous light, the light reactions may outpace the dark reactions, leading to an accumulation of ATP and NADPH and a subsequent decrease in the overall rate of photosynthesis.

Short pulses are key

The effectiveness of intermittent light is highly dependent on the duration of the light and dark periods. Very short pulses (e.g., microseconds) can be particularly beneficial, as they allow the plant to efficiently utilize the light energy.



However, after reaching a certain light intensity further increase in light intensity has no effect on the rate because photosynthetic pigments have become saturated with light, and some other factor either availability of carbon dioxide, amount of chlorophyll or temperature stops the reaction from going faster. Very high intensities may actually damage some plants in fact, it bleaches the chlorophyll reducing their ability to photosynthesize.

(iv) Salinity

Increase in salinity brings about osmotic stress, leading to drought stress or ‘water stress’. This results in stomata closure in an effort to avoid desiccation, which reduces photosynthesis because uptake of CO_2 reduces.

(v) Chlorophyll Concentration

The concentration of chlorophyll affects the rate of reaction as they absorb the light energy without which the reactions cannot proceed. Lack of chlorophyll or deficiency of chlorophyll results in ***chlorosis*** or ***yellowing*** of leaves. It can occur due to disease, mineral deficiency or the natural process of aging (senescence). Lack of iron, magnesium, nitrogen and light affect the formation of chlorophyll and thereby causes chlorosis.

(vi) Water

The effect of water can be understood by studying the yield of crops which is the direct result of photosynthetic activity. It is found that even slight deficiency of water results in significant reduction in the crop yield. The lack of water not only limits the amount of water but also the quantity of carbon dioxide. This is because in response to drying the leaves close their stomata in order to conserve water being lost as water vapor through them.

EFFECTS OF WATER STRESS ON PLANT PRODUCTIVITY

Water stress, or drought, significantly impacts photosynthesis by primarily reducing carbon dioxide (CO2) intake due to stomatal closure and potentially hindering photosynthetic capacity. This leads to decreased photosynthetic rates, affecting plant growth and yield.

Water stress triggers stomatal closure, small pores on leaves that regulate gas exchange. This closure minimizes water loss but also restricts CO2 uptake, which is essential for photosynthesis. The limited CO2 supply due to stomatal closure directly inhibits the rate of photosynthesis, impacting the conversion of light energy into chemical energy.

In addition to stomatal limitations, water stress can also directly affect the photosynthetic capacity of the mesophyll (leaf tissue) by inhibiting the Calvin cycle, which is part of the photosynthetic process.

Prolonged water stress can severely diminish plant growth and productivity due to the overall disruption of photosynthesis.

After water stress is relieved, plants may exhibit an "overcompensation" response, meaning they initially increase photosynthesis to make up for the previous deficit.

ADAPTATIONS OF PLANT TO WATER STRESS

Plants adapt to water stress by reducing photosynthesis through stomatal closure, limiting water loss. However, they also exhibit other adaptations to maintain photosynthetic capacity under stress conditions, including acclimation responses like changes in leaf morphology and enzyme activity.

- **Stomatal Closure**

The initial response to water stress is often stomatal closure, reducing water loss through transpiration. This also limits the intake of CO2 needed for photosynthesis.

- **Acclimation**

Over time, plants can acclimate to water stress through various mechanisms. This may involve changes in leaf morphology (like thicker cuticles or sunken stomata), osmotic adjustments, and modifications in enzyme activity related to photosynthesis.

- **Photosynthetic capacity**

Even with stomatal closure, plants can still maintain some level of photosynthesis. This is often achieved through adjustments in the photosynthetic machinery, like the Calvin cycle, to better utilize available CO2.

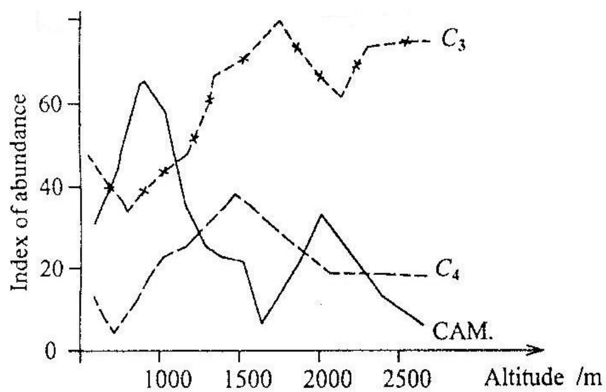
Some plants develop long-term adaptations, such as deeper root systems to access water at lower depths, or succulent tissues for water storage.

- Recent studies suggest that even already developed leaves can acclimate to water stress within a few days, with changes in gene expression and protein activity associated with metabolism.
- Plants also exhibit adaptations to improve their water use efficiency, which refers to the amount of biomass produced per unit of water transpired. This can involve reducing transpiration while maintaining photosynthetic capacity.
- Hormones like abscisic acid (ABA) play a crucial role in mediating the plant's response to water stress, influencing stomatal closure and other physiological processes.

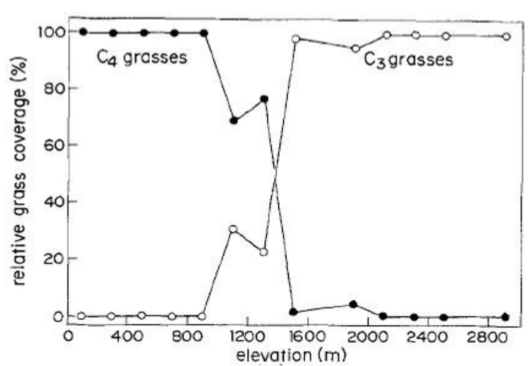
(vii) Pollution

Pollution of the atmosphere with industrial gases has been found to result in as much as 15% loss. Soot can block stomata and reduce the transparency of the leaves. Some of the other pollutants are ozone and Sulphur dioxide. In fact, lichens are very sensitive to Sulphur dioxide in the atmosphere. Pollution of water affects the hydrophytes. The capacity of water to dissolve gases like carbon dioxide and oxygen is greatly affected.

(viii) altitude and oxygen



Relative grass species composition and coverage along an elevational gradient in Hawaii Volcanoes National Park. Data adapted from Newell (1968)



Observation / description

✞ C3 plants are more abundant at high altitude/elevation

Explanation

✞ The decrease in atmospheric pressure at higher altitude decreases the partial pressure of oxygen enables more productivity since photorespiration reduces

✞ CAM plants are more abundant at low altitude	✞ Even when temperature is high, nocturnal stomatal opening and closure in day light enables them to reduce transpiration. ✞ CAM plants that store a lot of malate and due to its high osmotic value conserve a lot of water, are usually less frost resistant than C_3 plants.
✞ C4 plants are widely distributed at low altitude and slight elevation	✞ The enzymes are tolerant to these high temperatures and the Kranz mesophyll anatomy shields Rubisco in bundle sheath cells from much oxygen to avoid photorespiration.

PRODUCTIVITY OF PLANTS AND PLANT COMMUNITIES

The entire plant is potential food for consumer organisms. Plants normally grow with others of the same species or of different species in plant communities e.g. a field of wheat, natural forest and a woodland. The efficiency with which whole plants and plant communities produce dry matter determines how much food is available for the higher trophic levels in an ecosystem.

Factors of fundamental importance to crop yield

- Leaf area index
- Unit leaf rate

1. Leaf area index

Plants with a large surface area of leaves and other parts which can photosynthesise may be expected to produce more dry matter than plants having shoot systems with small surface area. The area of leaves available for photosynthesis can be expressed as the leaf area index (LAI)

$$LAI = \frac{Total\ leaf\ area\ of\ plant}{area\ of\ ground\ covered\ by\ plant}$$

It determines the amount of light intercepted by the shoot system of a plant.

During the early stages of growth, crop plants have small LAI values because each plant has only a few small leaves and is surrounded by a patch of bare ground, as growth proceeds and the shoot system enlarges, the LAI increases

Note

The shape of the shoot system is particularly important in determining the leaf area index of a plant where plants which can be grown close to each other and which have leaves held vertically have higher LAI than those with horizontally held or drooping leaves.

2. Unit leaf rate

Whatever the LAI value**,** increases in organic matter occur efficiently only if most of the photosynthetic products are converted to plant tissue or storage materials. If most of the products of photosynthesis are respired dry matter accumulates slowly.

Unit leaf rate expresses the efficiency of dry matter accumulation by green plants.

ULR of a plant can be calculated from measurements of the leaf area and dry mass of a representative sample of plants at different stages of growth.

Note

- Some species have higher ULR values than others because they do not photo respire and have very short compensation periods. E.g. C4 plants such as sugar cane and maize have a much greater unit leaf rate than most C3 plants.

Synthesis of dry matter by green plants is called primary production, the total amount of dry matter produced per unit area of ground per year is called gross primary productivity. Some dry matter is used by green plants in respiration. What is left is called net primary productivity (NPP) and it is which is available for consumer organisms including man **NPP = LAI x ULR**

Therefore, plants which quickly achieve high LAI values and which sustain an efficient ULR over a long growing period are highly productive.

GREEN HOUSE FARMING

Greenhouse technology implies production of plants for economic use in a covered structure that allows rapid harvesting of solar radiation and modification of agro-climatic conditions conducive for plant growth and development.

A greenhouse is a framed or an inflated structure covered with a transparent or translucent material which permits at least partial control of plant environment and which are large enough to permit a person to carry out cultural operations.

The purpose of growing crops under greenhouse conditions is to extend their cropping season and to protect them from adverse environmental conditions, such as extreme temperatures and precipitation, and from diseases and pests.

Greenhouse structures are essentially light scaffolding covered by sheet glass, fiberglass, or plastic. Such materials have a range of energy-capturing characteristics, all designed to maximize light transmission and heat retention.

Crops may be grown in ground bed soil, usually amended with peat or farmyard manure, in benches, in pots containing soil or soil mixtures or soil substitutes, and in hydroponic systems, such as sand or rock wool cultures and flowing nutrient systems, without a matrix for the roots.

Growing of vegetable and floriculture crops under protected cultivation is receiving utmost attention and gaining popularity among farming community.

Objectives of greenhouse technology

- Extend growing seasons.
- Increase crop yield and quality.
- Protect crops from adverse weather and pests.
- Enable cultivation of high-value crops.

FACTORS THAT NEED TO BE CATERED FOR IN A GREEN HOUSE

Agro-climate

There are several climatic factors that need care in the management of a greenhouse. The following factors are important for greenhouse cultivation:

- **Sunlight**

The direction of the greenhouse should be such that it receives sunlight for maximum hours. In hilly regions, greenhouse should face the southeast direction and its location should not be under shade. However, under the tropical condition, temperature retention can be reduced by choosing a less sunny site.

Sunlight is essential for augmentation of the process of photosynthesis and minimum sun requirement of crop should be kept in mind. In addition, sunlight also provides requisite thermal environment for various other physiological processes including photosynthesis. Hilly regions receive clear sunny days in winter so sunlight as such may not be a limiting factor, but its tapping and conservation could be a major concern for further investigation.

- **Temperature**

Sunlight is the major rather than the sole source of temperature. Examples of providing external heat source other than sunlight are rare in hilly regions. Temperature during night hours may drop down to below 0 °C and heat obtained from trapped solar radiation is not properly conserved.

The following steps are advantageous to maintain a thermal environment of the greenhouse:

- Blackening of internal surface of brick wall and soil bed surface
- Providing insulation by doubling the brick wall
- Covering polyethylene or glass external surface with multilayer covering during night hours
- Mud plastering in the case of stone walls
- Placing of black-colored stones in the greenhouses
- Keeping containers filled with water.

- **Relative Humidity**

The minimum limit of relative humidity for normal physiological functioning of the plants is 50 %. Extreme xeric conditions hardly allow relative humidity to rise to this level in the outer environment, but inside the greenhouse, sufficient water application and restricted air circulation gear up and maintain relative humidity at higher level. It may be increased by keeping pan evaporation. A mechanical device automatically controls relative humidity by periodical sprinkling of water. Cooling pads are usually installed in low- humidity and tropical areas.

- **Carbon Dioxide Enrichment**

Carbon dioxide (CO_2) is the basic ingredient required for manufacturing of organic matter by process of photosynthesis. In cold arid regions, CO_2 concentration is below normal and in the closed structures like greenhouses, it may drop down further because of its consumption by the plants. At relatively high sunlight intensities and temperature, photosynthetic rate is directly proportional to CO_2 concentration up to 2400 ppm. Hence supplementary application of CO_2 will boost plant productivity inside the greenhouse. Under the hilly region situation, appropriate air circulation is a better and economic means to prevent undesirable lowering of CO_2, while for conservation of CO_2 produced at night, a tightly closed greenhouse is a prerequisite.

- **Soil**

Soil serves as growth medium for plants. Sandy loam soil is the best choice. It should be supplemented with well-rotten FYM, compost, or bio-fertilizers. Inorganic fertilizers need to be used as per recommendations. Continuous cultivation inside the greenhouse may give rise to buildup of pathogens. To destroy pathogens, pasteurization of soil is recommended (steam aeration) before every crop and soil replacement is recommenced after every 3 years. Steam aeration temperature of 60 °C for 30 min is good enough to accomplish the task. Chemical fumigation can also be used but steam is the best as it is not selective thus attacking all sort of pathogens.

Components of a Greenhouse

- **Structural frame:** Supports the covering material.
- **Covering material:** Determines light transmission and insulation.
- **Ventilation systems:** Maintains temperature and humidity.
- **Heating/cooling systems:** Provides temperature control.
- **Irrigation systems:** Drip or mist systems for efficient water use.
- **Shading devices:** Protects from excessive sunlight.
- **Environmental control systems:** Automated systems to manage internal climate.

Benefits of Greenhouse farming

- Year-round production.
- Improved quality and quantity of produce.
- Efficient use of water and fertilizers.
- Pest and disease control.

Challenges

- High initial cost.
- Technical know-how required.
- Maintenance demands.
- Energy consumption.

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