

# NUTRITION IN PLANTS

## Learning objectives;

### By the end of this topic learners are expected 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, CO<sub>2</sub> 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?

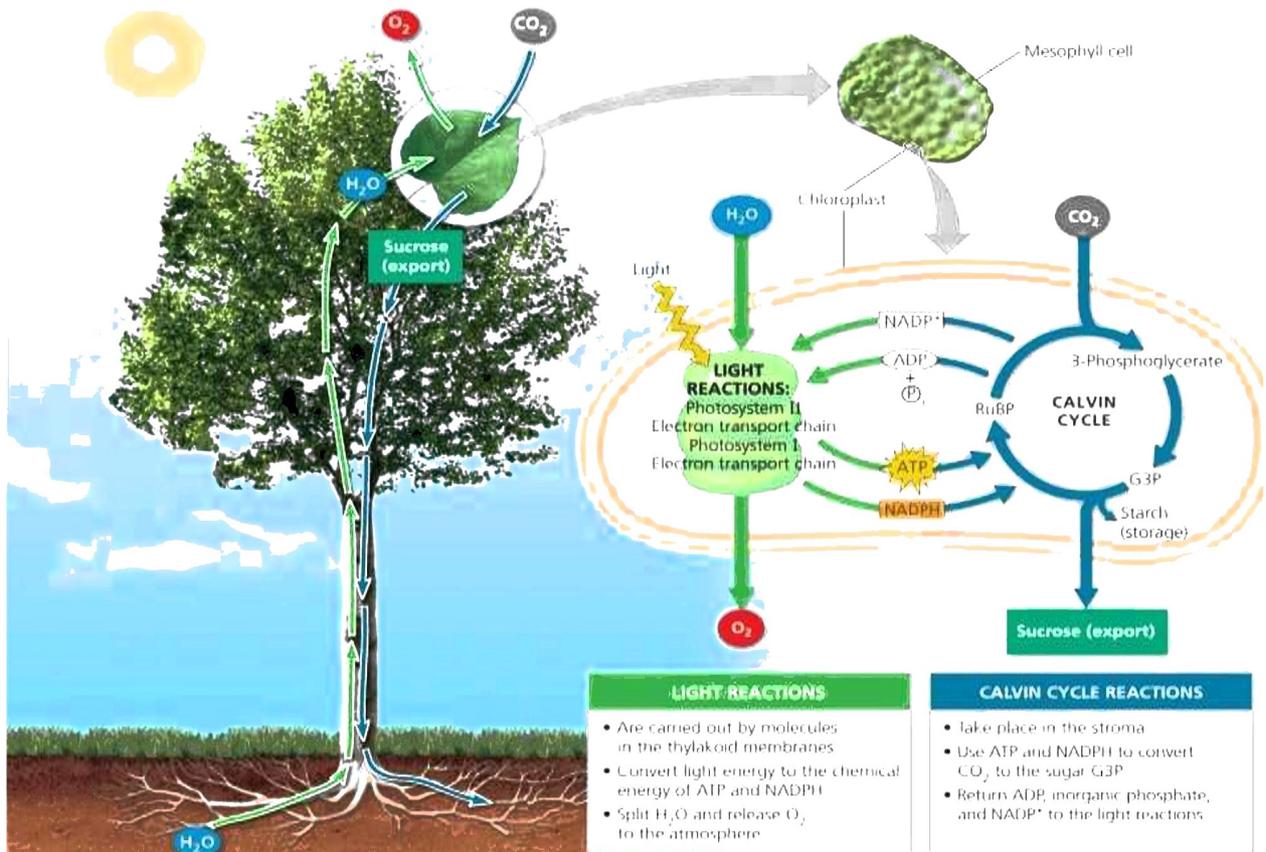
If plants don't eat, how do they acquire energy?

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

What occurs when plants lack sufficient nutrients?

**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

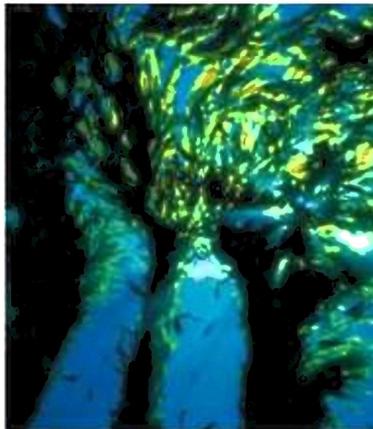
This is categorized into two groups basing on the source of energy

- (i) **Photosynthesis:** 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) **Chemosynthesis:** 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.**

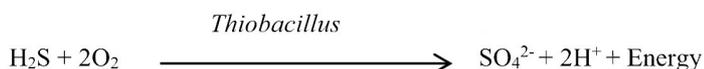
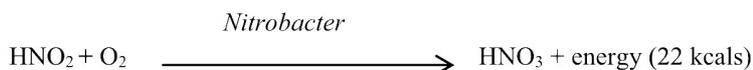
<i>Chemosynthetic bacteria</i>	<i>Substrate</i>	<i>Main product</i>	<i>Habitat</i>
<i>Nitrosomonas and Nitrococcus</i>	Ammonium (NH <sub>4</sub> <sup>+</sup> )	Nitrite (NO <sub>2</sub> <sup>-</sup> )	Soil
<i>Nitrobacter</i>	Nitrite (NO <sub>2</sub> <sup>-</sup> )	Nitrate ((NO <sub>3</sub> <sup>-</sup> )	Soil
<i>Thiobacillus</i>	Sulphur (H <sub>2</sub> S)	Sulphate (SO <sub>4</sub> <sup>2-</sup> )	Decaying organic matter
<i>Ferrobacillus / Iron bacteria</i>	Ferrous (Fe <sup>2+</sup> )	Ferric (Fe <sup>3+</sup> )	Streams flowing over iron rocks
<i>Hydrogenomonas</i>	Hydrogen (H <sub>2</sub> )	Water (H <sub>2</sub> O)	Soil

#### **Importance of chemosynthesis**

The chemical activities of the organisms involved bring about nutrient cycling; for example:

- *Nitrosomonas* and *Nitrobacter* bacteria are involved in nitrification in plants.
- *Thiobacillus* catalyse the conversion of Sulphur containing compounds to sulphates which are directly useful to plants.

#### **Mechanism of chemosynthesis in some bacteria**



The chemosynthetic bacteria utilize the energy from the chemical oxidation of inorganic chemicals to synthesize organic compounds, some of which are subsequently oxidized in respiration to yield energy for metabolism.



### **PHOTOSYNTHESIS**

It is the formation of complex organic substances inside the cell containing chlorophyll from carbon dioxide and water using sunlight energy.

#### **Importance of photosynthesis**

1. It is the means by which the sun's energy is captured by plants for use by all organisms.
2. It provides a source of complex organic molecules for heterotrophic organisms.
3. It releases oxygen for use by aerobic organisms.
4. It reduces on gaseous carbon dioxide, which would accumulate in the atmosphere to cause greenhouse effect.

### **GENERAL ADAPTATIONS OF LEAVES FOR PHOTOSYNTHESIS**

#### **Adaptations for obtaining sunlight**

1. **Phototropism** causes shoots to grow towards light in order to obtain energy.
2. **Etiolation** causes rapid elongation of shaded shoots to enable access to light.
3. The **mosaic** leaf arrangement minimizes leaf overlap and reduces leaves shading each other.
4. Leaf **large** surface area enables capturing maximum sunlight.
5. Thinness of leaves enables maximum light penetration.
6. The **transparence** of leaf cuticle and epidermis allow light penetration into the photosynthetic mesophyll.
7. The palisade mesophyll cells are densely packed with chloroplasts to trap much light.
8. **Cyclosis** (movement of chloroplasts within the mesophyll cells) allows repositioning in the direction of light.
9. The chloroplasts hold chlorophyll in an ordered way on the sides of the grana to present maximum chlorophyll to the light and also bring it close to other pigments / substances necessary for functioning.
10. Multiple cell layers in the palisade mesophyll of sun plants increases photosynthetic efficiency.

**Adaptations for gas entry and exit**

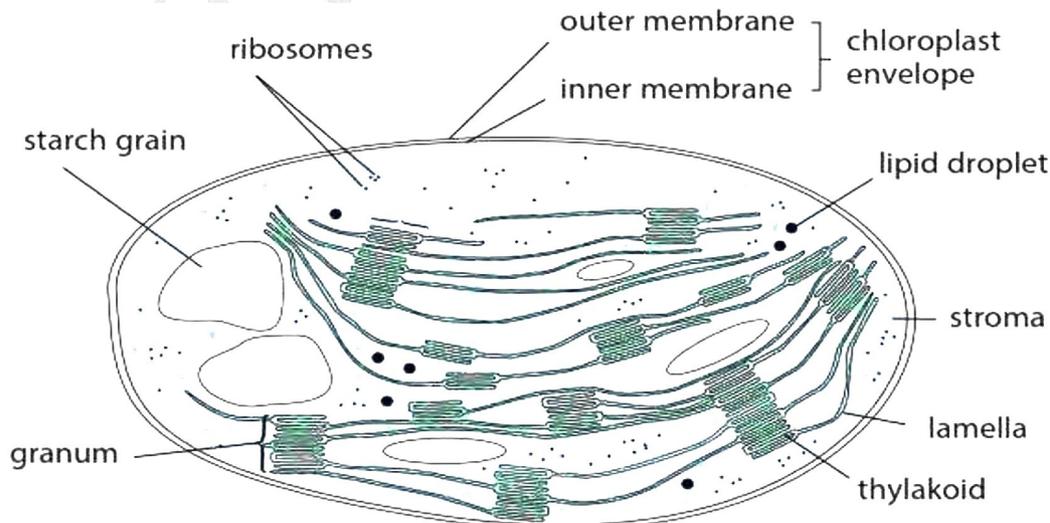
1. Numerous stomata are present in the epidermis of leaves to enable entry and exit of gases.
2. The guard cells bordering stomata pores can be opened and closed to regulate the uptake of carbon dioxide and the loss of water.
3. Spongy mesophyll possesses many airspaces to enable faster and uninterrupted diffusion of gases between the atmosphere and the palisade mesophyll which wouldn't happen if the gases were to diffuse through the cells themselves, a process which would be much slower.

**Adaptations for liquid entry and exit**

1. A large central midrib containing a large vascular bundle comprising xylem and phloem tissue is possessed by most dicotyledonous leaves for the entry and transport of water and mineral salts, and the phloem for carrying away sugar solution, usually in the form of sucrose.
2. A network of small veins is found throughout the leaf to ensure that every cell is close to xylem vessel or phloem sieve tube for constant supply of water for photosynthesis and a means of removing the sugars they produce.

**STRUCTURE OF CHLOROPLAST**

- Chloroplast shape and size vary from biconvex in higher plants with length of ~5 μm to filamentous in algae, spherical, ovoid, etc.
- It is enclosed by an envelope of double membranes; outer membrane is semi-permeable.
- Inner membrane surrounds the stroma, regulates entry and exit of materials to the chloroplast, and is a manufacturing centre for fatty acids, lipids and carotenoids.
- Intermembrane space is narrow, ~10 nm-20 nm in between the outer and inner membranes.
- Stroma is semi-gel-like fluid, alkaline, rich in protein (e.g. enzymes), with chloroplast DNA, 70S ribosomes, starch granules, lipid globules and thylakoid membrane system.
- Thylakoids are interconnected, membranous sacs, with chlorophyll in the membranes.
- At intervals, thylakoids form piles (~10-20) known as **grana**.



### 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.

### 4. PHOTOSYNTHETIC PIGMENTS

- Chlorophylls and carotenoids absorb light energy required in photosynthesis.
- Carotenoids also protect chlorophyll from photo damage.

<i>Photosynthetic Pigment</i>	<i>Distribution (occurrence)</i>	<i>Properties</i>
Chlorophyll <i>a</i>	All photosynthetic plants i.e. It is the most abundant	<ul style="list-style-type: none"> <li>●Bluish green in pure state</li> <li>●Very soluble in ether, and also soluble in lipid solvents e.g. chloroform, carbon tetrachloride, alcohols, etc</li> </ul>
Chlorophyll <i>b</i>	Higher plants	<ul style="list-style-type: none"> <li>●Olive green (yellow green) in pure state.</li> <li>●Very soluble in methyl alcohol and also soluble in lipid solvents e.g. chloroform, carbon tetrachloride, etc</li> </ul>
Bacteriochlorophyll	(1) Purple sulphur Bacteria,	<ul style="list-style-type: none"> <li>● Are related to chlorophylls</li> <li>●Conduct photosynthesis, but do not produce oxygen.</li> </ul>

	(3) Green sulfur bacteria	<ul style="list-style-type: none"> <li>●Absorbs wavelengths of light not absorbed by plants</li> </ul>
<b>CAROTENOIDS</b> (a) <i>xanthophylls</i> e.g. lutein (b) <i>carotenes</i> e.g. $\alpha$ -carotene, lycopene	Occur in chloroplasts of plants, algae, some bacteria, and some types of fungi	<ul style="list-style-type: none"> <li>●Xanthophylls are often yellow, Carotenes vary in colour: pale yellow, bright orange, deep red.</li> <li>● Are soluble in fat solvents e.g. ether, chloroform, acetone.</li> <li>●Carotenes are closely related to the vitamin A</li> </ul>

●Chlorophyll *b* and carotenoids are **accessory** pigments i.e. they hand over energy absorbed to chlorophyll *a*.

●Chlorophyll belongs to a class of organic compounds called **porphyrins** which have 4 **pyrrole** rings.

●Other **porphyrins** are **haem** and the **cytochromes**.

●However, Chlorophyll contains **magnesium atom** instead of **iron**.

### **SUN AND SHADE LEAVES**

●Sun leaves are those that grow on branches exposed to direct sunlight while shade leaves grow on branches exposed to light that has passed through leaves.

●In **low light**, plants need to maximise light absorption for photosynthesis to exceed respiration if they are to survive.

●In **high light** environment, plants maximise their capacity for utilising abundant light energy, while at the same time dealing with excess sunlight which can bleach chlorophyll.

### **ADAPTATIONS TO PHOTOSYNTHESIZE IN SUN AND SHADE**

**Adaptation:** a genetically determined capability to acclimate to environmental condition.

<b>Shade plant</b>	<b>Sun plants</b>
1. Abundant chlorophyll <i>b</i> (low chlorophyll <i>a</i> to chlorophyll <i>b</i> ratio) which gives leaves dark green colour to increase light absorption in the dark; 2. Palisade/ spongy mesophyll ratio low to allow maximum light penetration; 3. Mesophyll cell surface / leaf area ratio low to maximise light trapping; 4. Leaf orientation horizontal to maximise light trapping;	1. Abundant chlorophyll <i>a</i> (high chlorophyll <i>a</i> to chlorophyll <i>b</i> ratio) to increase light absorption; 2. Palisade/ spongy mesophyll ratio high to minimise light penetration; 3. Mesophyll cell surface / leaf area ratio high to minimise excessive light and transpiration; 4. Leaf orientation erect to minimise light trapping; 5. Stomatal density high to avoid over heating;

<p>5. Reddish leaf undersides to enhance reflectance back up through the photosynthetic tissue; giving the plant a second chance to utilize the light.</p> <p>6. Stomatal density low to avoid over cooling;</p> <p>7. Thin leaves to maximise light penetration;</p> <p>8. Stomatal size large to allow loss of excess water;</p> <p>9. Elongated internodes for increased access to light;</p> <p>10. Chloroplast size large to increase the surface area for storage of photosynthetic pigments.</p>	<p>6. Much carotenoids to prevent damage to chlorophyll from very bright light.</p> <p>7. Thick leaves to minimise light penetration;</p> <p>8. Stomatal size small to minimise water loss;</p> <p><b>Other features</b></p> <p>(i) RuBISCO and soluble protein content /mass higher</p> <p>(ii) Chlorophyll / soluble protein ratio high</p> <p>(iii) Chloroplast size small</p>
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### PHOTOSYNTHETIC PIGMENTS IN SUN LEAVES AND SHADE LEAVES OF BEECH TREE

Photosynthetic pigment	Mean mass of each pigment per m <sup>2</sup> of leaf area / µg	
	Sun leaves	Shade leaves
Chlorophyll <i>a</i>	299.3	288.9
Chlorophyll <i>b</i>	90.7	111.1
Carotenoids	0.10	0.07

Graphically, the data can be reflected by a **bar graph**.

### COMPARISON OF DISTRIBUTION OF PHOTOSYNTHETIC PIGMENTS

- The ratio of chlorophyll *a* : chlorophyll *b* is bigger in sun leaves than shade leaves (Sun leaves contain more chlorophyll *a* than shade leaves) because chlorophyll *a* is more effective at absorbing the light wavelengths available to sun leaves e.g. about 450 nm.
- Shade leaves contain more chlorophyll *b* than sun leaves because in shade plants chlorophyll *b* improves light-capturing capability of the chloroplast.
- Sun leaves contain more carotenoids than shade leaves because carotenoids are accessory pigments that shield chlorophylls from destruction by excessive sunlight.

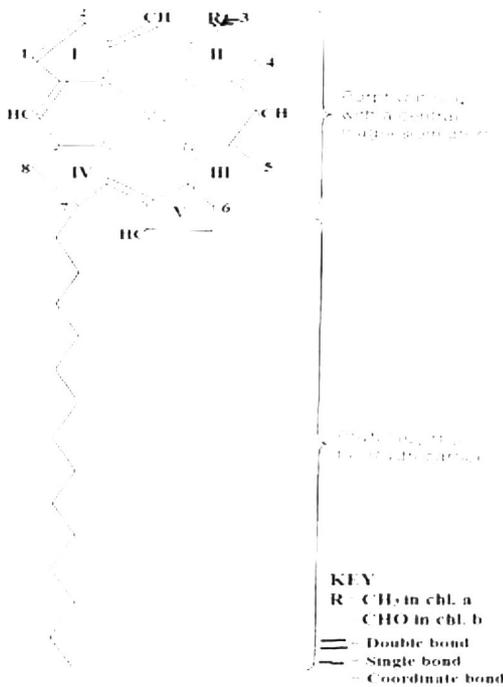
### Why few species of plant can survive under shady habitats.

- Less direct light reaches ground via gaps in the canopy hence minimum energy is available for effective photosynthesis.
- Of the light that passes through leaves, only a small range of wavelengths reaches the ground, which is not effective for photosynthesis.
- Therefore, under shady habitats little light energy is available for chlorophyll to absorb and hence photosynthesis is insufficient for growth.

### DESCRIPTION OF CHLOROPHYLL MOLECULE STRUCTURE

- Chlorophyll molecule has a *tadpole-like* structure, with a **hydrophilic head** called *porphyrin* and a **hydrophobic tail** made up of long chain alcohol called **phytol**.
- The **flattened** head is made up of **four nitrogen** containing **pyrrole** rings (labelled I-IV) which are linked by methine bridges (-CH=).
- The skeleton of each pyrrole ring is made up of 5 atoms - **four carbon** and **one nitrogen**. The nitrogen lies towards the centre.
- A magnesium atom is held in the centre of porphyrin head by **nitrogen**

### NUTRITION IN PLANTS TR.MUGA



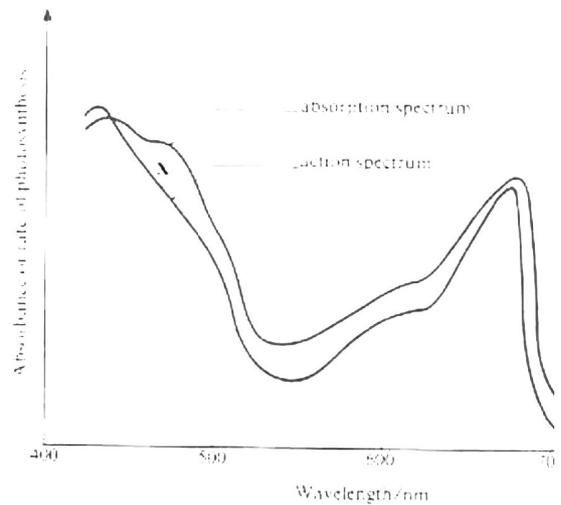
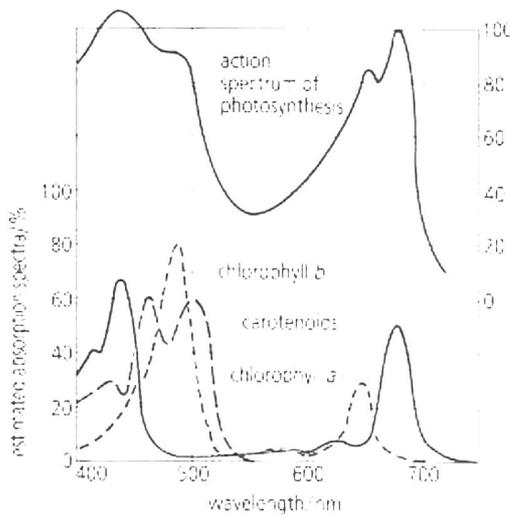
**ABSORPTION SPECTRUM OF PHOTOSYNTHETIC PIGMENTS**

It is a graph of the relative absorption of different wavelength of light by a pigments like chlorophyll. It is measured by a **spectrophotometer**

**ACTION SPECTRUM OF PHOTOSYNTHESIS**

A graph of the effectiveness of different wavelengths of light in stimulating the photosynthetic process. It represents the actual rate of photosynthesis in living cells.

*Absorption spectra of chlorophylls a & b, and carotenoids and the action spectrum of photosynthesis*



## P530/2 MUGABI GODFREY-0750363837

- The wave lengths of about 550 nm to 620 nm have the lowest absorption and action spectra for all the photosynthetic pigments.
- There are two absorption maxima of  $\lambda = 430$  nm and  $\lambda = 662$  nm for chlorophyll **a**, and 453 nm and 642 nm for chlorophyll **b**, but only one maximum for carotenoids at about 510 nm.
- The action spectrum peaks within the blue-violet and red regions of the light spectrum.
- The unabsorbed (reflected light) appears green, thus making chlorophyll, the chloroplasts and the leaves that contain it appear green to our eye.
- This shows that chlorophyll **a** as well as **b** are the main photosynthetic pigments, however, photosynthesis also occurs in the mid part of light spectrum where carotenoids are active.
- This shows that maximum photosynthesis occurs in red part and blue-violet part of visible light.

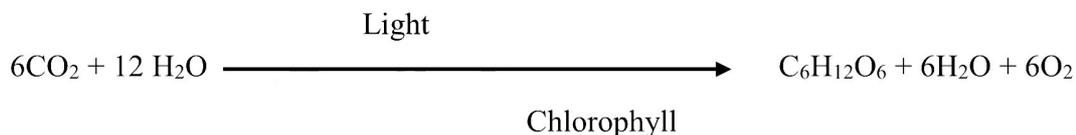
### OTHER OBSERVATIONS

- *Chlorophyll a* absorption in red light is about twice that of *chlorophyll b* and the absorption peak is at a slightly longer wavelength (lower energy)
- Absorption of chlorophyll **a** in the blue is lower and shifted to a slightly shorter wavelength (higher energy).

### MECHANISM OF PHOTOSYNTHESIS

● Photosynthesis is an oxidation-reduction process, in which water is oxidized to release oxygen and carbon dioxide is reduced to form carbohydrates.

The overall equation for photosynthesis is:



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.

**a. Light harvesting.** Light energy is captured by the plant using a mixture of pigments including chlorophyll.

**b. 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

**c. 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**

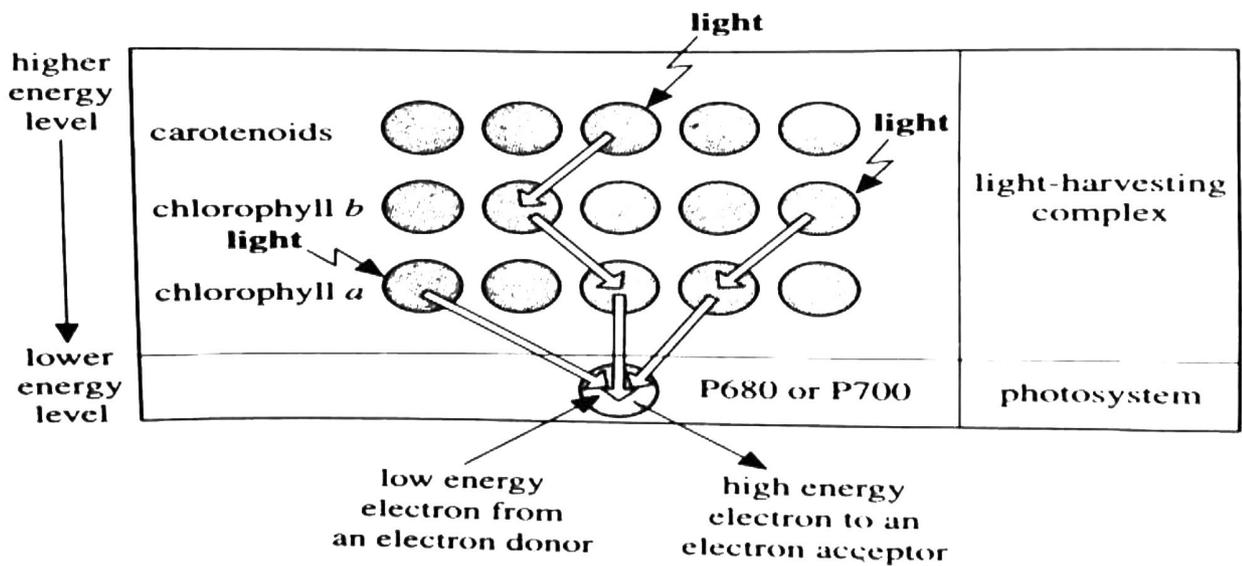
**NUTRITION IN PLANTS TR.MUGABI GODFREY MSS BIO DEPARTMENT 0750363837**

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).



← path of energy transfer from light to photosystem  
time taken is about 1 billionth of a second

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

### THE LIGHT-DEPENDENT STAGE

- It takes place in the thylakoid membranes of chloroplasts.

#### 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**.

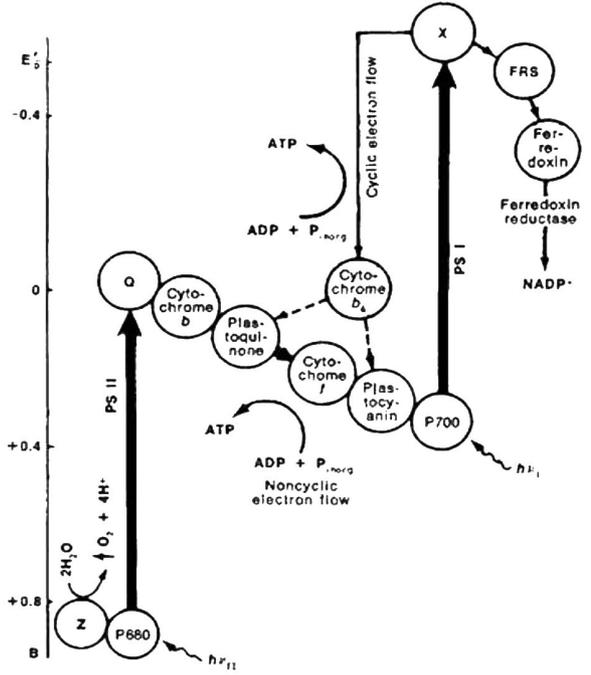
#### Importance of light dependent stage of photosynthesis

- Photolysis of water produces hydrogen atoms for the reduction of carbon dioxide during the dark stage.

- **Photophosphorylation** i.e. addition of an inorganic phosphate to Adenosine diphosphate (ADP) to form Adenosine triphosphate (ATP) using light energy.
- Formation of  $\text{NADPH}^+$  which is the reduced form of *Nicotinamide adenine dinucleotide phosphate*.

**DESCRIPTION OF LIGHT STAGE OF PHOTOSYNTHESIS**

Its reactions are triggered by light energy exciting photosystems **I** and **II** inside the **thylakoid membranes** at the same time, **not** one after the other.

THE Z-SCHEME SUMMARISING LIGHT STAGE	OPERATIONS OF PHOTOSYSTEMS I AND II
 <p>The diagram illustrates the Z-scheme of photosynthesis. The vertical axis represents the redox potential (E<sub>0</sub>) in Volts, ranging from +0.8 at the top to -0.4 at the bottom. The horizontal axis represents the sequence of electron carriers. The process starts at Photosystem II (PS II) where light energy (hν<sub>II</sub>) excites electrons from a low energy state (P680) to a high energy state (Z). This leads to the photolysis of water (2H<sub>2</sub>O → O<sub>2</sub> + 4H<sup>+</sup>). Electrons then flow through an unknown molecule Q, Cytochrome b, Plastoquinone, Cytochrome f, and Plastocyanin to Photosystem I (PS I). At PS I, light energy (hν<sub>I</sub>) further excites electrons to a higher energy state (X). From X, electrons can follow a cyclic path back to PS I, or a noncyclic path through Ferredoxin (FRS) and Ferredoxin reductase to reduce NADP<sup>+</sup> to NADPH. The flow of electrons through the carriers is coupled with the phosphorylation of ADP to ATP.</p>	<ul style="list-style-type: none"> <li>● Chlorophyll molecules of PSII and PSI are excited by light of wavelength 680 nm and 700 nm respectively; causing the loss of electrons to a chain of electron carriers in a series of reduction-oxidation reactions as follows:             <ol style="list-style-type: none"> <li>From PSI, some electrons may flow:                     <ol style="list-style-type: none"> <li><b>Cyclically</b> to iron-protein complex, cytochromes b<sub>6</sub>, plastoquinone, cytochrome-f, plastocyanin and back to P-700, during which electrons lose energy to form ATP from ADP and P<sub>i</sub>.</li> <li><b>Non-cyclically (Unidirectionally)</b> to unknown molecule A, iron-protein complex, Ferredoxin, Flavin-Adenine Dinucleotide (FAD) which becomes reduced (FADH), finally to NADP to form reduced NADP (NADPH).</li> </ol> </li> <li>From PSII to the unknown molecule Q, substance B, plastoquinone (PQ), cytochrome f, plastocyanin, (a copper enzyme), and finally to PSI, to replace the electrons earlier lost. During this flow, electrons lose energy to <b>phosphorylate</b> ADP to form ATP.</li> </ol> </li> <li>● The flow of electrons through carriers in the thylakoid membranes releases energy for active pumping of hydrogen ions (H<sup>+</sup>) from the stroma into the thylakoid space.             <ul style="list-style-type: none"> <li>● <b>At the same time, photolysis of water:</b> <ol style="list-style-type: none"> <li>Causes accumulation of H<sup>+</sup> <b>inside the thylakoid space</b>.</li> <li>Provides electrons to replace those lost from PSII, with evolution of oxygen molecule.</li> </ol> </li> <li>● <b>Chemiosmosis</b> occurs i.e. the highly concentrated H<sup>+</sup> inside the thylakoid space <b>diffuse</b> along the steep</li> </ul> </li> </ul>

electrochemical gradient from the thylakoid space via the stalked particles into the stroma, thereby providing:  
**(1)** energy to form ATP in the presence of ATPase enzyme  
**(2)** H<sup>+</sup> for reducing NADP to form NADPH, which together with the ATP formed enter the dark stage.

**NOTE**

The loss of 2 electrons by the chlorophylls in the photosystems **bleaches** the chlorophyll molecule. In this state, it can no longer absorb light energy effectively. Therefore, the electrons lost to the electron transfer chain must be replaced.

**WHAT IS MEANT BY?**

**Chemiosmosis:** It is the movement of ions across a selectively permeable membrane down an electrochemical gradient.

**Z-Scheme:** It is a diagrammatic representation of electron flow in cyclic phosphorylation and non-cyclic phosphorylation, showing the change in energy potential of the electrons.

**ROLE OF WATER IN PHOTOSYNTHESIS**

- Catalytic photolysis / splitting / breaking of water produces electrons (e<sup>-</sup>) and protons (H<sup>+</sup>).
- Water is a source of electrons to replace those lost by chlorophyll / photosystem II
- Water is a source of H<sup>+</sup> needed to produce NADPH + H
- Water is a source of H<sup>+</sup> which when flowing from thylakoid space into stroma via ATPase, ATP forms.
- Water is a substrate / reactant / raw material / for photosynthesis
- Water is transparent so photosynthesis can take place underwater / light can penetrate to chloroplasts

**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<sup>+</sup>) are actively pumped from stroma into thylakoid space.
- ✦ There is photo-excitation of electrons in the pigment systems.

**Differences**

Non-cyclic photophosphorylation	Cyclic photophosphorylation
<input type="checkbox"/> Electrons flow unidirectional (non-cyclically)	<input type="checkbox"/> Electrons flow in a cyclic pattern

<input type="checkbox"/> First electron donor is (source of electrons) water	<input type="checkbox"/> First electron donor is photosystem I
<input type="checkbox"/> Last electron acceptor is NADP	<input type="checkbox"/> Last electron acceptor is photosystem I
<input type="checkbox"/> The products are ATP, NADPH and Oxygen	<input type="checkbox"/> The product is only ATP.
<input type="checkbox"/> Involves both photosystems I and II	<input type="checkbox"/> Involves only photosystems I
<input type="checkbox"/> Photolysis of water occurs	<input type="checkbox"/> No photolysis of water
<input type="checkbox"/> Two electron acceptors involved	<input type="checkbox"/> 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**

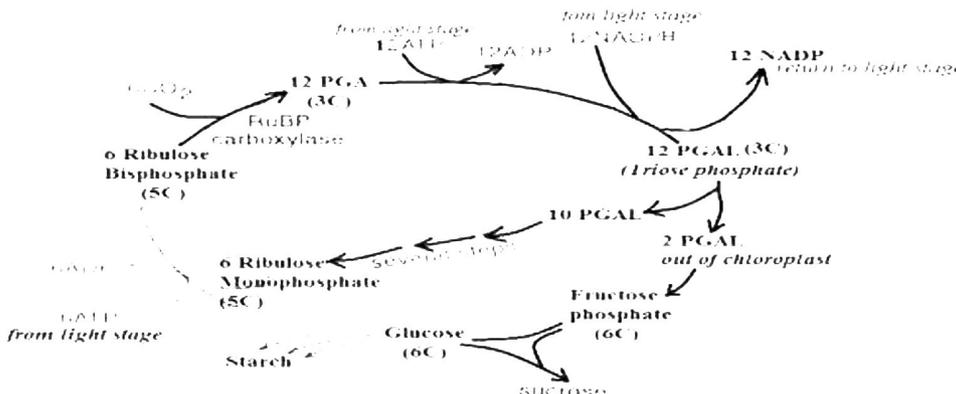
- ✚ Calvin-Benson cycle / C<sub>3</sub> pathway
- ✚ Hatch-Slack pathway / C<sub>4</sub> pathway

**1. Calvin-Benson cycle / C<sub>3</sub> pathway**

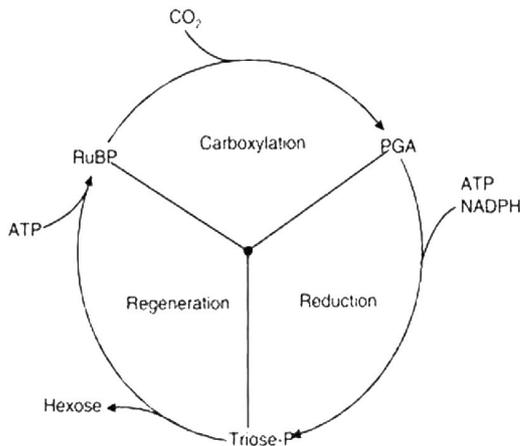
This is the series of reactions in plants involving formation of glycerate-3-phosphate which has 3 carbon atoms as first stable organic substance during photosynthesis.

**MAIN STAGES OF CALVIN-BENSON CYCLE (C<sub>3</sub> CYCLE)**

**C<sub>3</sub> Plants:** Plants whose first stable product of photosynthesis is a 3-carbon organic compound called **glycerate-3-phosphate**



0. Glycerate phosphate (glyceraldehydes 3-phosphate) is the **product** of the Calvin cycle / photosynthesis because subsequent reactions can also occur in non-synthetic organisms like animals and fungi. (Soper et al (1997). *Biological Science* p210:7.7)



### 1. CARBOXYLATION

● Catalysed by RuBP carboxylase, 6 molecules of RuBP react with 6 molecules of CO<sub>2</sub>, and 6 molecules of water forming 12 molecules of 3-phosphoglyceric acid (PGA), which is the **first carbohydrate made by C<sub>3</sub> plants**.

### 2. PHOSPHORYLATION AND REDUCTION

● 12 molecules of PGA react with 12 molecules of ATP forming 12 molecules of 1, 3-diphosphoglyceric acid and 12 molecules of ADP.

● 12 molecules of NADPH (formed in light stage) reduce 12 molecules of 1, 3-diphosphoglyceric acid to form 12 molecules each of 3-phosphoglyceraldehyde (PGAL) / triose phosphate (TP), NADP and phosphoric acid.

● Out of these 12 molecules of PGAL, only 2 molecules undergo **isomerization** and several reactions to form hexose sugar, sucrose or starch and 10 molecules are recycled to produce 6 molecules of ribulose monophosphate.

**3. REGENERATION:** ● The remaining 10 molecules of PGAL regenerate 6 molecules of ribulose-6-phosphate when 6 molecules of a 5-carbon sugar **ribulose monophosphate** react with 6 molecules of ATP (formed during light stage) to form 6 molecules of Ribulose-1,5-bisphosphate (RuBP) and 6 molecules of ADP.

## 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.

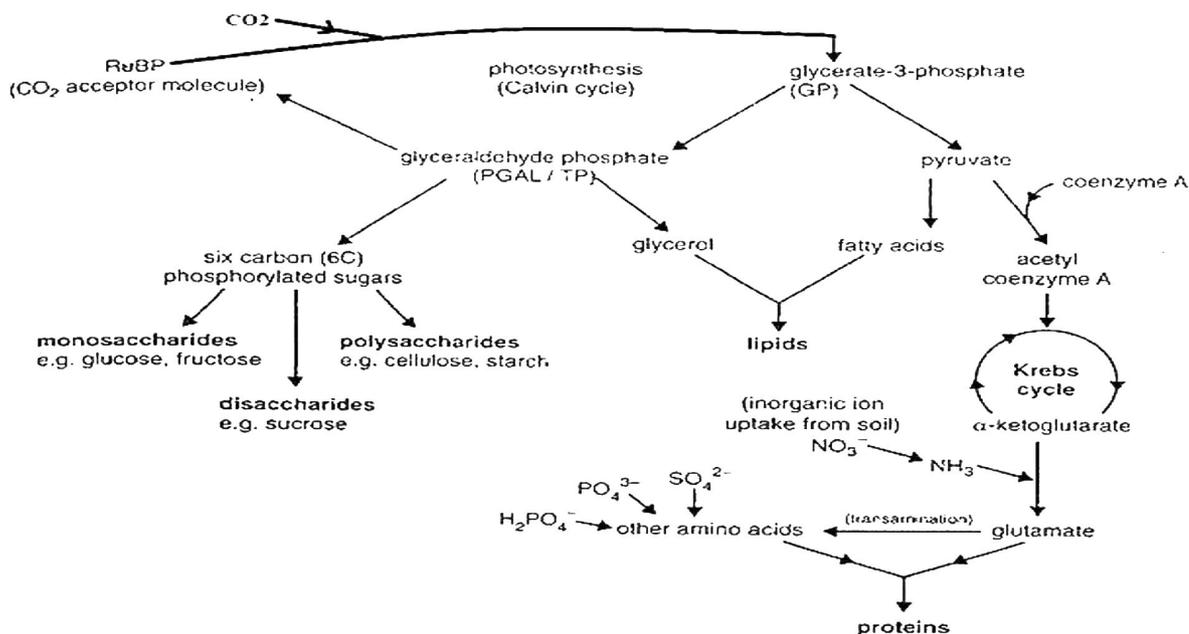
### (c) Synthesis of proteins

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*

**NOTE**

- ✦ The enzyme Ribulose biphosphate 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.

**WHAT IS PHOTORESPIRATION?**

Oxygenation of RuBP by RuBP oxygenase (RUBP carboxylase) at high temperature, low carbon dioxide and high oxygen concentration to form phosphoglycolate which undergoes oxidation in peroxisomes and metabolism in mitochondria to release CO<sub>2</sub>, thereby preventing carbon fixation in C<sub>3</sub> plants.

**HOW PHOTORESPIRATION AFFECTS PLANTS**

When C<sub>3</sub> plants are exposed to low carbon dioxide concentration (or high oxygen concentration) e.g. when stomata close to reduce water loss, RuBP carboxylase catalyses the reaction between RuBP and oxygen to form a 2-carbon compound; **phosphoglycerate**, which is oxidized to release carbon dioxide. Yet when the carbon dioxide concentration is high, RUBISCO enzyme catalyses the reaction between RuBP and carbon dioxide to form a 3-carbon compound; 3-**phosphoglyceric acid**, which undergoes several reactions to form sugar useful to the plant. It is estimated that Photorespiration **therefore reduces the potential yield of photosynthesis by 30-40%**.

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 $C_4$ 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.

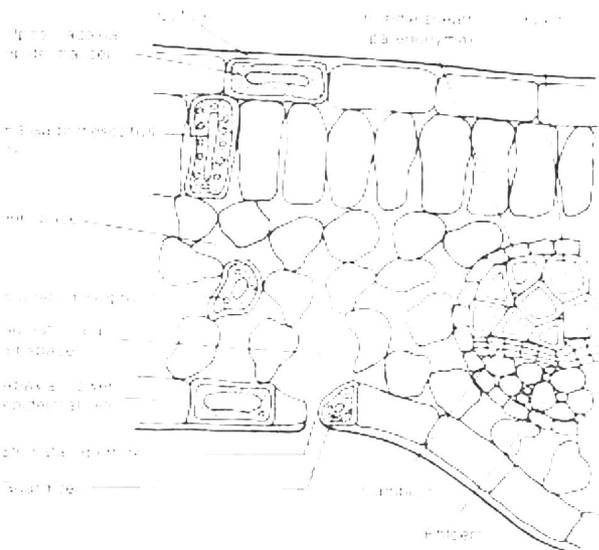
### KRANZ LEAF ANATOMY

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

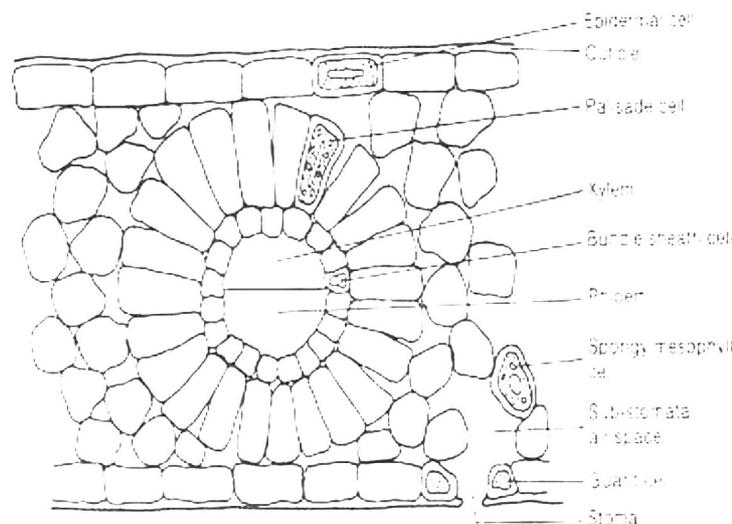
This is a pathway for transporting carbon dioxide and hydrogen from mesophyll cells to bundle sheath cells. Once in the bundle sheath cells, the carbon dioxide is released again and normal  $C_3$  photosynthesis occurs.

## COMPARISON OF LEAF ANATOMY IN $C_3$ AND KRANZ ANATOMY IN $C_4$ PLANTS

### *Leaf anatomy in $C_3$ plants*



### *Kranz anatomy in $C_4$ plants*



with 3 carbon atoms, phosphoenol pyruvate (PEP) chloroplasts of mesophyll cells to form oxaloacetate (OAA) a 4-carbon compound. This is the first stable compound formed in  $C_4$  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.

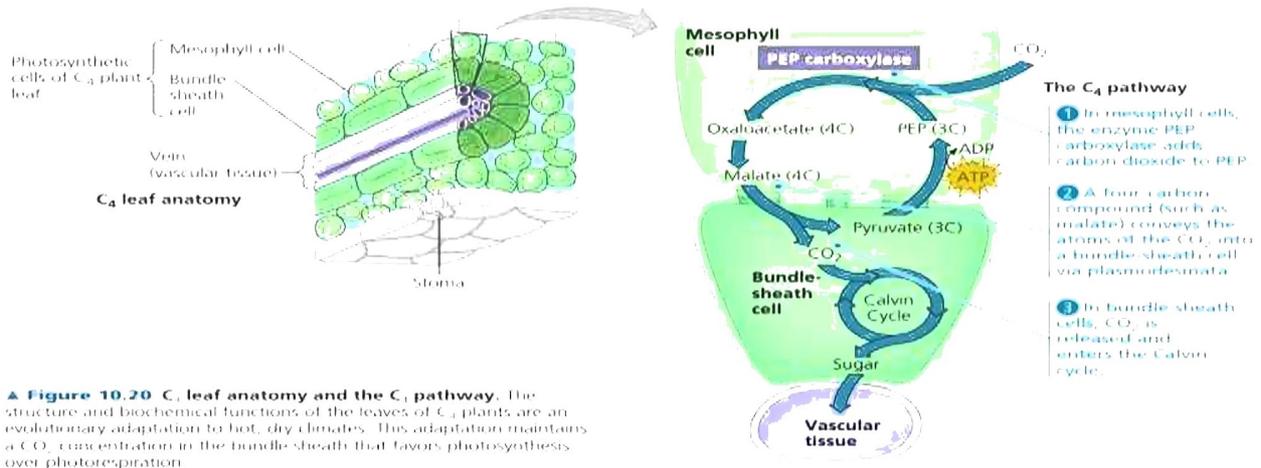
## 2. Malate shunt

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<sub>2</sub> acceptor.

Now the second carboxylation occurs in the chloroplasts of bundle sheath cells through Calvin cycle.

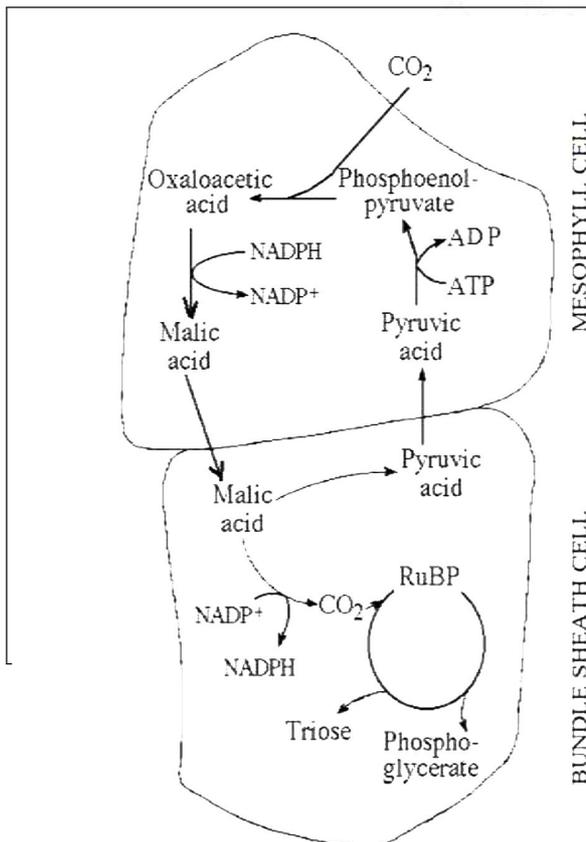
## 3. Regeneration of the carbon dioxide acceptor

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.



## Summary of Hatch-slack pathway

## DESCRIPTION OF C<sub>4</sub> CYCLE IN CO<sub>2</sub> FIXATION



1. In the presence of *phosphoenol pyruvic acid carboxylase* enzyme, *Phosphoenol pyruvic acid* is carboxylated inside the chloroplasts of mesophyll cells to form *oxaloacetic acid*.
2. *Oxaloacetic acid* is reduced by NADPH to *malic acid* in the presence of *malate dehydrogenase* enzyme.
3. From chloroplasts of mesophyll cells, malic acid is translocated (shunted) to chloroplasts of bundle sheath cells where it is decarboxylated by NADP to form *pyruvic acid* and *carbon dioxide*. The pyruvic acid produced returns to mesophyll cells for phosphorylation by ATP to regenerate **PEP**; the CO<sub>2</sub> acceptor.

	<p>4. Now the second carboxylation occurs in the chloroplasts of bundle sheath cells through Calvin cycle.</p> <ul style="list-style-type: none"> <li>● RuBP of Calvin cycle is called <i>final</i> or <i>secondary</i> CO<sub>2</sub> acceptor in C<sub>4</sub> plants.</li> <li>● Ribulose biphosphate accepts CO<sub>2</sub> produced in step 3 and to yield 3-phosphoglyceric acid as given in Calvin cycle.</li> <li>● Some of the 3-phosphoglyceric acid is utilized in the formation of glucose-6-phosphate and sucrose while rest regenerates ribulose-1, 5 biphosphate in the system.</li> <li>● In the Calvin cycle 3 ATP molecules are required for the C<sub>4</sub> plants, 5 ATP molecules are required for the fixation of CO<sub>2</sub>. For the formation of a glucose molecules, C<sub>4</sub> plants require 30 ATP while C<sub>3</sub> plants utilize only 18 ATP.</li> </ul>
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#### ADVANTAGES AND DISADVANTAGE OF C4 PATHWAY

<i>Advantages</i>	<i>Disadvantage</i>
<ul style="list-style-type: none"> <li>● C<sub>4</sub> plants ably photosynthesize at very low CO<sub>2</sub> concentration (e.g. in dense tropical vegetation) because PEP carboxylase enzyme has a very high affinity for carbon dioxide.</li> <li>● 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.</li> <li>● <b>Photorespiration</b>, which inhibits growth in C<sub>3</sub> plants is <b>avoided / reduced</b> in C<sub>4</sub> because <b>(1)</b> the CO<sub>2</sub> fixing enzyme PEP carboxylase does not accept oxygen <b>(2)</b> RUBISCO enzyme inside the bundle sheath cells is shielded from high oxygen concentration by the ring of palisade cells.</li> <li>● The CO<sub>2</sub> fixing enzymes in C<sub>4</sub> 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<sub>3</sub> plants.</li> <li>● The productivity of C<sub>4</sub> almost <i>four times</i> greater than in C<sub>3</sub> <i>because:</i> <b>(1)</b> of the increased rate of CO<sub>2</sub> uptake caused by <b>(i)</b> large internal leaf surface area <b>(ii)</b> short CO<sub>2</sub> diffusion distance <b>(iii)</b> CO<sub>2</sub> steep diffusion gradients</li> </ul>	<ul style="list-style-type: none"> <li>● The CO<sub>2</sub> fixing enzymes in C<sub>4</sub> plants are less active at cool, moist and low illumination conditions, therefore photosynthesis occurs slowly at high altitude with cool temperature and in low light intensity of temperate conditions.</li> </ul> <p><i>NB: C4 plants grow better under hot, dry conditions when plants must close their stomata to conserve</i></p>

<p>(2) the bundle sheath cells in which dark reactions occur have (i) a large photosynthetic surface area enabled by un-usually large chloroplasts (ii) lack of grana on which O<sub>2</sub> would be produced, so <b>no photorespiration</b>.</p> <p>(3) the Palisade cells in which light reactions occur have large grana to increase the photosynthetic surface area.</p>	<p><i>water – with stomata closed, CO<sub>2</sub> levels in the interior of the leaf fall, and O<sub>2</sub> levels rise</i></p>
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**QUESTION:**

*In spite of the higher productivity of C<sub>4</sub>, which is almost four times greater than in C<sub>3</sub>, majority of plants perform C<sub>3</sub> photosynthesis. Explain this statement fully.*

- CO<sub>2</sub> concentration is a major factor determining the pathway of carbon dioxide fixation.
- While C<sub>4</sub> plants are more productive at low CO<sub>2</sub> concentration, C<sub>3</sub> plants form the dominant plant life because they are effective at high CO<sub>2</sub>, whose concentration is high in most environments and steadily increases due to increasing combustion of fossil fuels.
- Also considering that C<sub>4</sub> photosynthesis is more complex i.e. it involves many reactions both in bundle sheath cells and in mesophyll cell, and requires a specialized Kranz anatomy, most plants have simpler structures.
- Therefore, unless water loss is a significant issue, C<sub>3</sub> dominate since C<sub>3</sub> photosynthesis is more effective.

**COMPARISON BETWEEN C<sub>3</sub> AND C<sub>4</sub> PLANTS**

**Similarities**

Both:

- ✦ contain RUBISCO enzyme
- ✦ depend on light for their reactions
- ✦ show CO<sub>2</sub> fixation
- ✦ have RuBP
- ✦ form several same organic products e.g. PG, PGA, sucrose
- ✦ have the Calvin cycle

**Differences**

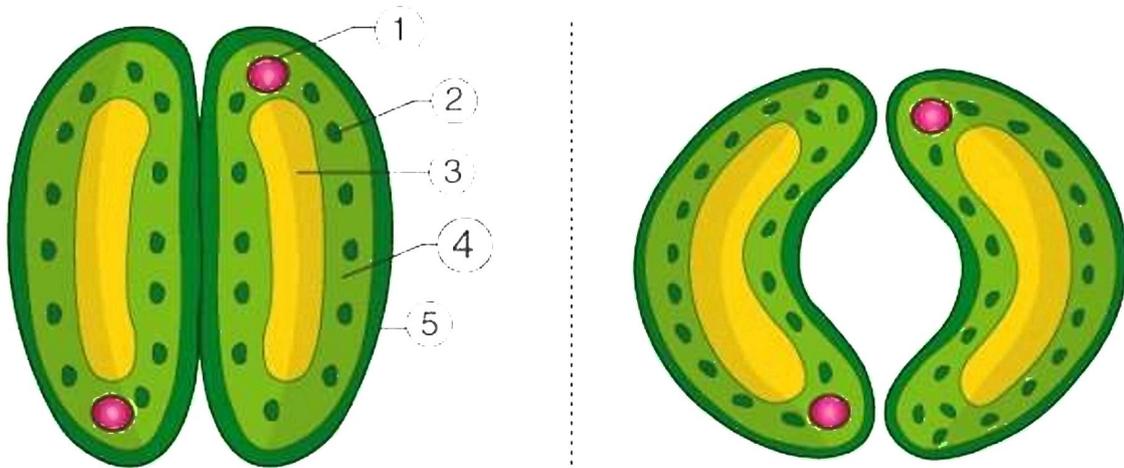
C <sub>3</sub> Plants	C <sub>4</sub> plants
<input type="checkbox"/> Lack Kranz anatomy	<input type="checkbox"/> Exhibit Kranz anatomy
<input type="checkbox"/> All chloroplasts have identical structure	<input type="checkbox"/> Chloroplasts are dimorphic (are in two forms) e.g. those of palisade cells have grana yet are lacking bundle sheath cells.
<input type="checkbox"/> CO <sub>2</sub> acceptor is a 5-Carbon RuBP	<input type="checkbox"/> CO <sub>2</sub> acceptor is a 3-Carbon PEP
<input type="checkbox"/> CO <sub>2</sub> fixation occurs once	<input type="checkbox"/> CO <sub>2</sub> fixation occurs twice
<input type="checkbox"/> Photorespiration occurs	<input type="checkbox"/> No photorespiration
<input type="checkbox"/> Less photosynthetically efficient	<input type="checkbox"/> More photosynthetically efficient
<input type="checkbox"/> GP is the first organic product	<input type="checkbox"/> OAA is the first organic product

<input type="checkbox"/> Enzymes are more efficient at lower temperatures	<input type="checkbox"/> Enzymes are more efficient at high temperatures
<input type="checkbox"/> RUBISCO enzyme is used	<input type="checkbox"/> PEP carboxylase enzyme is used
<input type="checkbox"/> Compensation point is attained at higher CO <sub>2</sub> concentration	<input type="checkbox"/> Compensation point is attained at lower CO <sub>2</sub> concentration

**THE RELATIONSHIP BETWEEN VARYING SUCROSE CONCENTRATION WITH STOMATAL OPENING/CLOSING**

**Morphology of Stomata**

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



(a) Stoma Closed

(b) Stoma Open

- ① Nucleus
- ② Chloroplasts
- ③ Vacuole
- ④ Guard Cell
- ⑤ Cell Wall

**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

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- + 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<sub>2</sub>], 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. Micro fibrils 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.

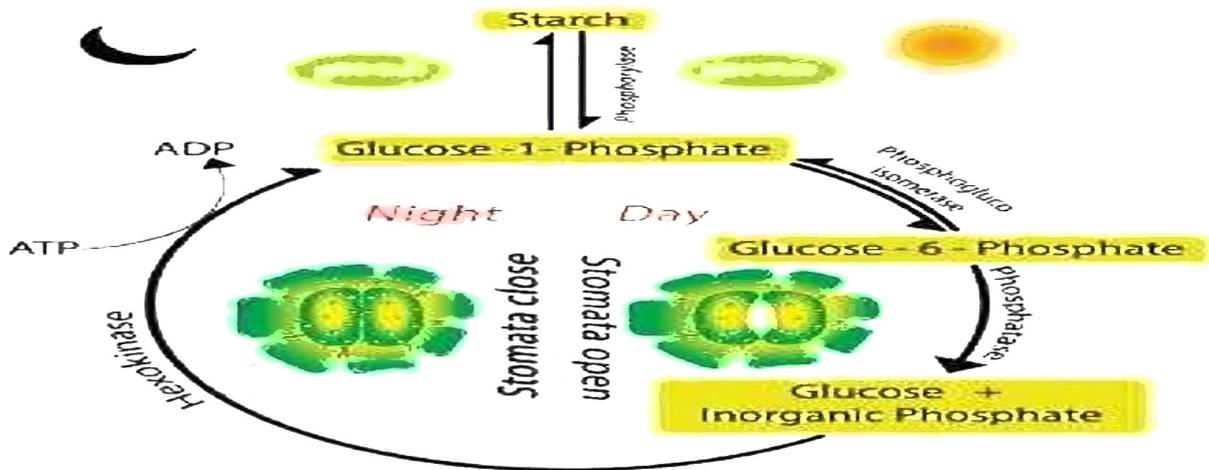
The closing and opening is controlled mainly by the intensity of light. They are normally open during daylight and closed during the night.

### 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 neighbouring 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 CO<sub>2</sub> into the bundle sheath, keeping the CO<sub>2</sub> concentration in the bundle-sheath cells high enough for rubisco to bind CO<sub>2</sub> rather than O<sub>2</sub>. The cyclic series of reactions involving PEP carboxylase and the regeneration of PEP can be thought of as a CO<sub>2</sub>-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 CO<sub>2</sub> 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 CO<sub>2</sub> concentration and temperature may affect C<sub>3</sub> and C<sub>4</sub> 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 CO<sub>2</sub> levels?**

- In C<sub>3</sub> plants, the binding of oxygen rather than CO<sub>2</sub> by Rubisco leads to **photorespiration**, lowering the efficiency of photosynthesis.
- C<sub>4</sub> plants overcome this problem by concentrating CO<sub>2</sub> in the bundle sheath cells at the cost of ATP. Rising CO<sub>2</sub> levels should benefit C<sub>3</sub> 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<sub>2</sub> levels or temperature.

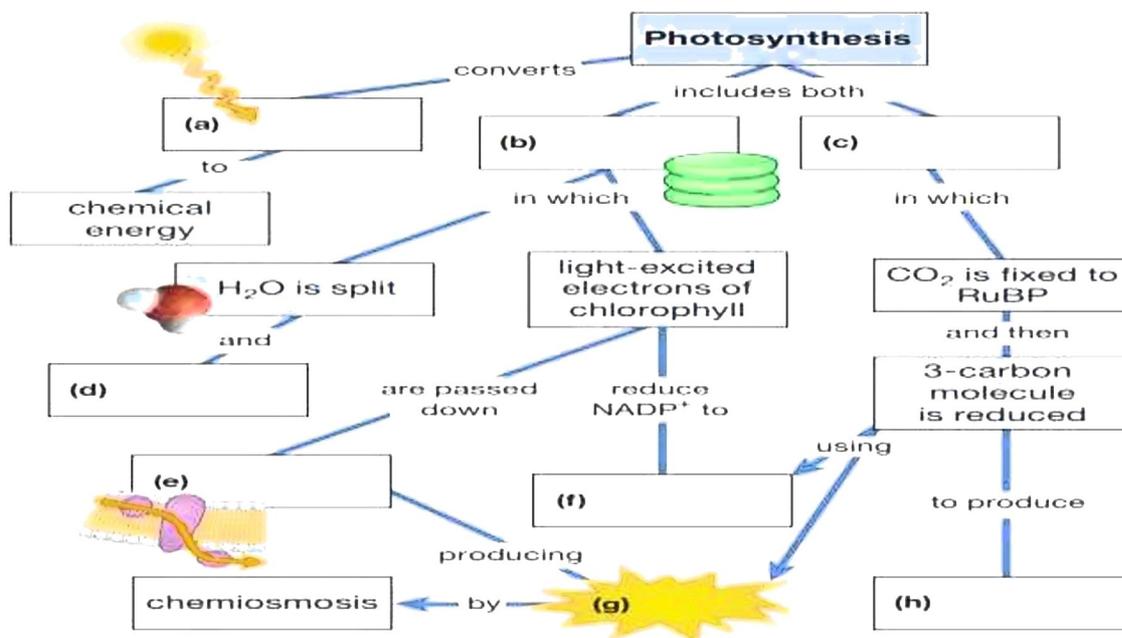
Researchers have investigated aspects of this question in several studies; you can work with data from one such experiment in the Scientific Skills exercise

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□ In different regions, the particular combination of CO<sub>2</sub> concentration and temperature is likely to alter the balance of C<sub>3</sub> and C<sub>4</sub> 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)

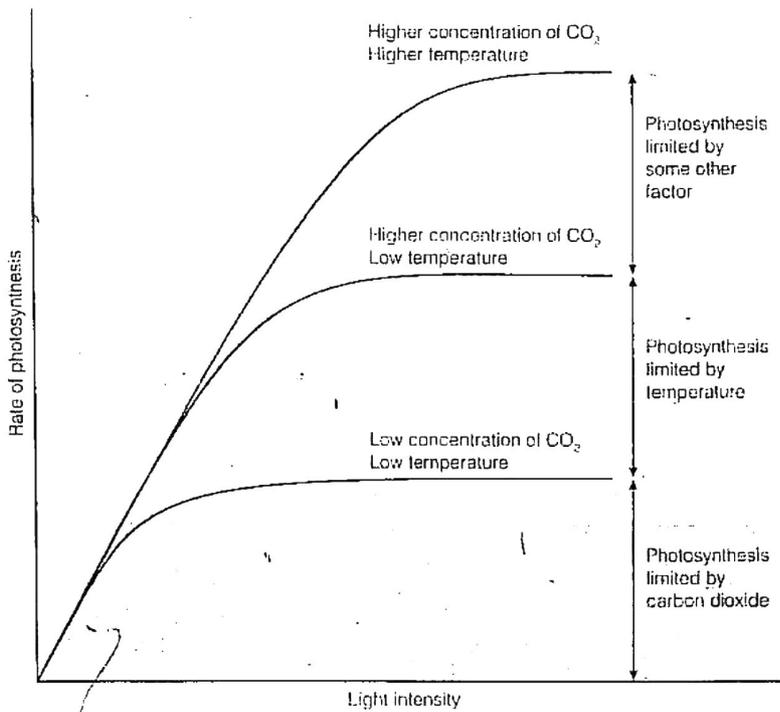
**THE PRINCIPLE OF LIMITING FACTORS**

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.

**Graph illustrating the concept of limiting factors on the rate of photosynthesis**



temperature of carbon dioxide concentration which are limiting factors.

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

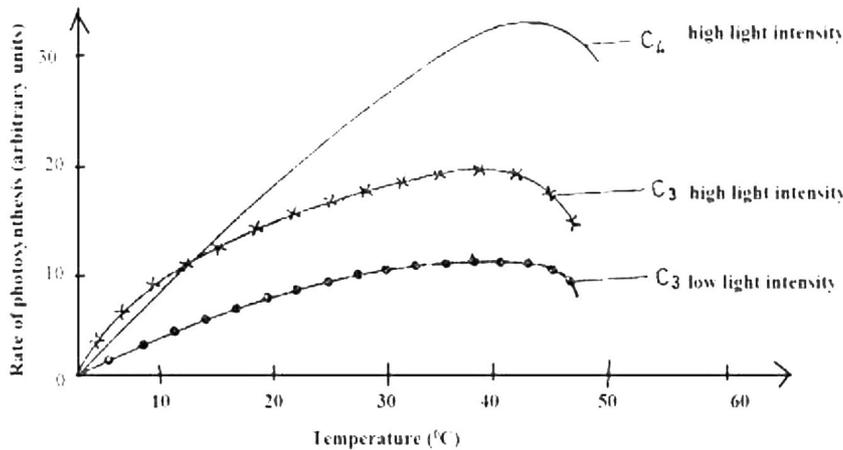
(iii) The temperature is too low for the chemical reactions to go any faster. Therefore, the rate of photosynthesis can be increased further by increasing either

**(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**

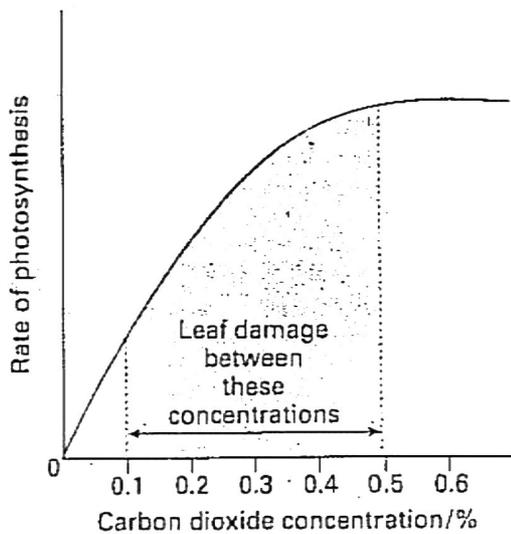
**Explanation**

- |  |  |
|--|--|
| <ul style="list-style-type: none"> <li><input type="checkbox"/> Below 10<sup>0</sup>C, C<sub>3</sub> rate of photosynthesis is higher than in C<sub>4</sub> above 10<sup>0</sup>C.</li> <li><input type="checkbox"/> The maximum rate of photosynthesis attained in C<sub>4</sub> is much higher than in C<sub>3</sub></li> <li><input type="checkbox"/> At about 45<sup>0</sup>C, the rate of photosynthesis decreases</li> <li><input type="checkbox"/> There is an initial increase in photosynthetic rate to a maximum at about 40-42<sup>0</sup>C, in spite of further increase in temperature</li> <li><input type="checkbox"/> There is increase in the rate of photosynthesis with increase in temperature until up to at about 40<sup>0</sup>C</li> </ul> | <ul style="list-style-type: none"> <li><input type="checkbox"/> C<sub>4</sub> photosynthetic enzymes are less active in the cold but become more active with increase in temperature.</li> <li><input type="checkbox"/> The optimum temperature for enzymes involved in the C<sub>4</sub> cycle is higher than in the C<sub>3</sub> cycle</li> <li><input type="checkbox"/> Enzymes controlling photosynthesis are denatured by very high temperatures</li> <li><input type="checkbox"/> Light intensity becomes a limiting factor in each of the three cases</li> <li><input type="checkbox"/> Increase in temperature activates enzymes to a level beyond which enzyme denaturation occurs.</li> </ul> |
|--|--|

**(ii) Carbon dioxide concentration**

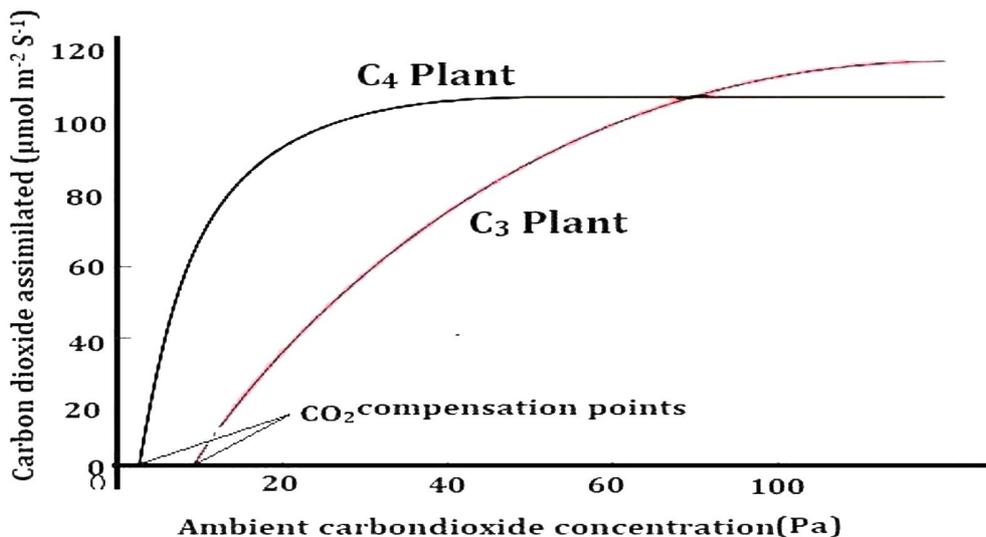
In the atmosphere, the concentration of carbon dioxide ranges from 0.03 to 0.04 %. However, it is found that 0.1% of carbon dioxide in the atmosphere increases the rate of photosynthesis significantly. As long as there is no other facto limiting photosynthesis, an increase in carbon dioxide concentration 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 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 30 Pa in C<sub>4</sub> plants and 90 Pa plants
- ☞ The rate of photosynthesis increases faster in C<sub>4</sub> than C<sub>3</sub>.
- ☞ The overall photosynthetic products are greater in C<sub>3</sub> than in C<sub>4</sub>
- ☞ The C<sub>4</sub> plants are more efficient at lower concentration while C<sub>3</sub> more efficient at higher CO<sub>2</sub>

- ☐ Rubisco fixes carbon dioxide instead of oxygen, because the carbon dioxide concentration is very high out competing oxygen for occupation of at in C<sub>3</sub> active site on RUBISCO.
- ☐ PEPCO of C<sub>4</sub> has a higher affinity for carbon dioxide than Rubisco of C<sub>3</sub>.
- ☐ C<sub>4</sub> needs more ATP than C<sub>3</sub> which generally reduces photosynthetic out put
- ☐ At lower CO<sub>2</sub> concentration in C<sub>3</sub> photorespiration reduces the photosynthesis efficiency yet C<sub>4</sub> plants are not affected by photorespiration as PEPCO has no affinity for Oxygen even at very low carbon dioxide concentration.

- ☞ C<sub>3</sub> plant has a higher compensation point than C<sub>4</sub>      □ 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.

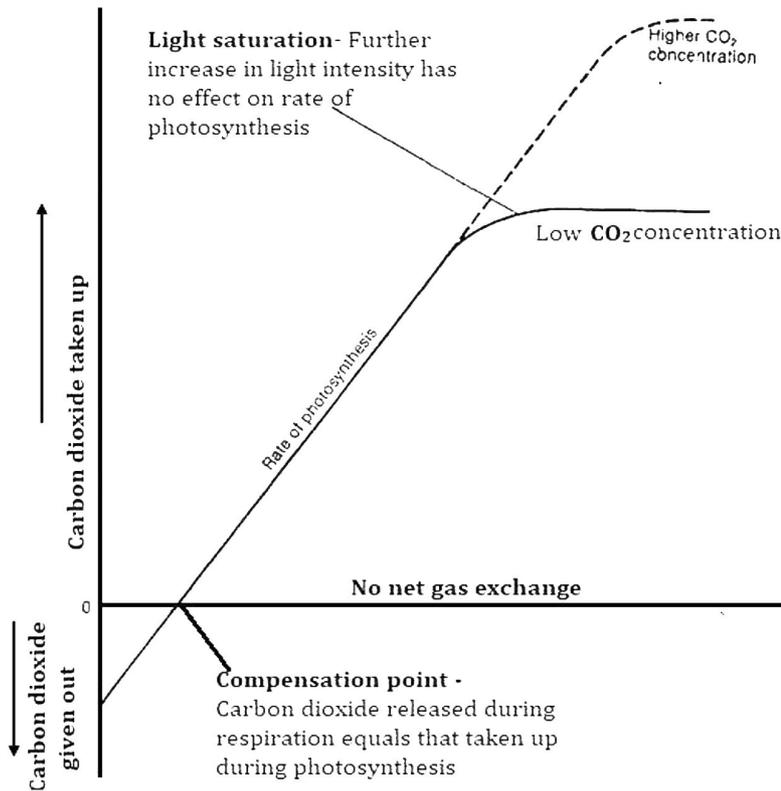
**Intermittent light**

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<sub>2</sub> 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 (CO<sub>2</sub>) 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 CO<sub>2</sub> uptake, which is essential for photosynthesis. The limited CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>.

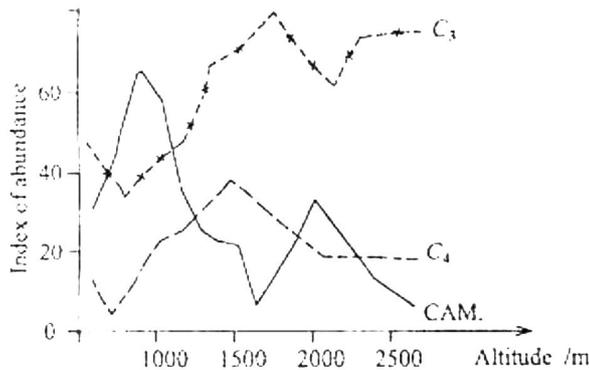
Some plants develop long-term adaptations, such as deeper root systems to access water at lower depths, or succulent tissues for water storage.

- 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.

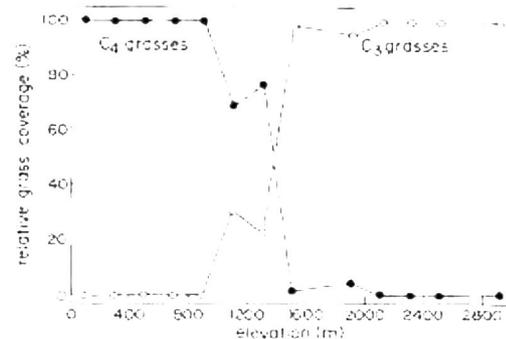
**(vii) Pollution**

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)



**Effect of altitude explained**

Observation / description	Explanation
●C <sub>3</sub> plants are more abundant at high altitude/elevation	●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 the thus high osmotic value also a lot of water, are usually less frost resistant than C <sub>3</sub> plants.
●C <sub>4</sub> plants are widely distributed at low altitude and slight elevation	●Enzymes are tolerant to high temperatures and the Kranz mesophyll anatomy shields RuBISCO in bundle sheath cells from much O <sub>2</sub> to avoid photorespiration.

**RESPONSE OF LEAF DISCS FROM SUN AND SHADE PLANTS TO GREEN LIGHT**

- Several leaf discs from a sun plant and a shade plant are put in two separate 10 cm<sup>3</sup> capacity syringes containing sodium hydrogen carbonate solution (**source of carbon dioxide**).
- The air is sucked out of them so that they sink, then they are illuminated with white light.
- As they photosynthesise, the oxygen produced makes them re-float, while the time taken to rise is noted. Calculate the average time for the leaf discs to float
- The experiment is repeated, this time covering the syringes with a green filter, so that the discs are illuminated with green light and the time taken for leaf discs to rise is noted again.

● Calculate the average time for the leaf discs to float as before.

**OBSERVATION:**

- (1) Leaf discs from **shade plants** eventually float, an indicator that they are able to use green light for photosynthesis.
- (2) Leaf discs from sun plants sink at bottom of the container which indicates that they cannot use green light to photosynthesise.

**NOTE**

- 1. Time taken for leaf discs to float can thus be used as an indirect measure of the rate of photosynthesis i.e. the more quickly flotation occurs, the faster the rate of photosynthesis.
- 2. The experimental results mimic the conditions in the plant's **natural habitat** i.e. the sun plant in the canopy receives white light and absorb the blue and red light from it in order to photosynthesise while the shade plant receives light that has already passed through the canopy, . In order to photosynthesise it absorbs many other wavelengths of light, including **green**.

**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)

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

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  **$NPP = LAI \times ULR$**

**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:

**o 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.

**o 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.

**o 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.

**o Carbon Dioxide Enrichment**

Carbon dioxide (CO<sub>2</sub>) is the basic ingredient required for manufacturing of organic matter by process of photosynthesis. In cold arid regions, CO<sub>2</sub> 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<sub>2</sub> concentration up to 2400 ppm. Hence supplementary application of CO<sub>2</sub> 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<sub>2</sub>, while for conservation of CO<sub>2</sub> produced at night, a tightly closed greenhouse is a prerequisite.

**o 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.

END