S6 BIOLOGY NOTES

NUTRITION IN PLANTS AND ANIMALS

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.

Modes of nutrition

Organisms are categorized into two groups basing on their source of carbon i.e.

1. **Heterotrophic Nutrition** (*heteros*, other; *trophos*, nourishment): Where organisms depend on organic nutrients obtained from other organisms due to their inability to manufacture their own. Such organisms have an organic source of carbon and are referred to as **heterotrophs**. This is further categorized into saprophytism, mutualism, commensalism, parasitism and holozoic nutrition
2. **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.

   (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).

Table 1: ***Examples of chemosynthetic bacteria***

Bacteria	Inorganic material	Product	Habitat
1. *Nitrosomonas and Nitrococcus*	Ammonium (NH_4^+)	Nitrite (NO_2^-)	Soil
2. *Nitrobacter*	Nitrite (NO_2^-)	Nitrate ((NO_3^-)	Soil
3. *Ferrobacillus / Iron bacteria*	Ferrous (Fe^{2+})	Ferric (Fe^{3+})	Streams flowing over iron containing rocks
4. Hydrogen bacteria	Hydrogen (H_2)	Water (H_2O)	Soil
5. Colourless Sulphur bacteria	Hydrogen sulphide (H_2S)	Water and sulphur	Decaying organic matter

Importance of Photosynthesis

- It is the means by which the sun's energy is captured by plants for use by all organisms.
- It provides a source of complex organic molecules for heterotrophic organisms.
- It releases oxygen for use by aerobic organisms.

THE LEAF AS AN ORGAN OF PHOTOSYNTHESIS

Although stems, sepals and other parts of the plant photosynthesize, the leaf is the main organ for photosynthesis in plants.

Adaptations of plants for photosynthesis

(a) Adaptations for obtaining sunlight

- Phototropism causes shoots to grow towards the light in order to allow the attached leaves to receive maximum illumination.
- Etiolation causes rapid elongation of shoots which are in the dark, to bring leaves into light to capture light.
- Mosaic leaf arrangement minimizes leaf overlap and reduces shading of one leaf by another.
- Broad lamina to provide Larger leaf surface area enabling capturing maximum sunlight.
- Leaves held at an angle perpendicular to the sun during the day to expose the maximum area to light.
- Thinness of leaves enables easy penetration of light to lower layers.
- The cuticle and epidermis are transparent to allow light penetration into the photosynthetic mesophyll beneath.
- The palisade mesophyll cells are densely packed with chloroplasts and arranged with their long axes perpendicular to the surface to form a continuous layer which traps most of the incoming light.
- Chloroplasts within the mesophyll cells are capable of moving **(Cyclosis)** allowing them to arrange themselves into the best positions within the cells for efficient absorption of light.
- The chloroplasts hold chlorophyll in an ordered / structured 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.
- In leaves of sun plants the palisade layer, whose cells are densely packed with chloroplasts is more than one cell thick to increase on photosynthetic efficiency.
- In leaves of shade plants, the cells of palisade and spongy mesophylls are densely packed with chloroplasts to increase on light trapping hence photosynthetic efficiency.

(b) Adaptations for obtaining and removing gases

- Numerous stomata in the epidermis of leaves providing a larger surface area for diffusion of gases.
- Guard cells bordering stomata pores that open and close stomata to regulate the uptake of carbon dioxide and the loss of water.
- Numerous airspaces in spongy mesophyll for faster and uninterrupted diffusion of gases between the atmosphere and the palisade mesophyll.

(c) Adaptations for obtaining and removing liquids

- ❖ A large central midrib containing a large vascular bundle comprising xylem and phloem tissue in most dicotyledonous leaves, the xylem for the entry and transport of water and mineral salts, and the phloem for carrying away sugar solution, usually in the form of sucrose.
- ❖ 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.

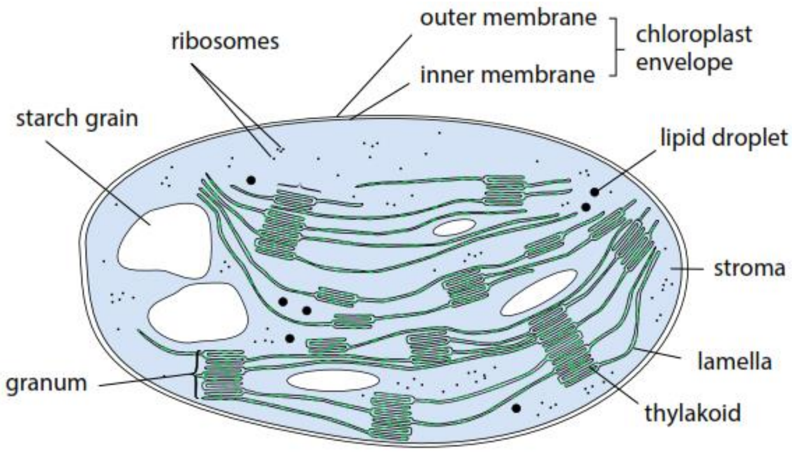
Assignment

a) *Outline ways in which the structure of a green leaf facilitates photosynthesis*

b) *What are the principle functions of leaf veins?*

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 criss-cross 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 intergrana 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.

THE REQUIREMENTS FOR THE PROCESS OF PHOTOSYNTHESIS

1. **Carbon dioxide:**

Carbon dioxide is a raw material for photosynthesis and is a source of carbon for the organic compounds produced in the process. Terrestrial plants obtain carbon dioxide: -

- from the atmosphere (where it's about 0.03%) via the stomata
- By absorbing carbonates from the soil through the roots, aquatic plants absorb dissolved bicarbonates through their general surface to carbon dioxide.

2. **Water**

Water is a raw material for photosynthesis. It is a source of hydrogen for reduction of carbon dioxide and also an essential donor of electrons to chlorophyll during non-cyclic phosphorylation which results in production of ATP and $NADPH_2$ both essential for carbon fixation in the light independent stage.

Water is also essential for the general metabolism of the plant and lack of it to the extent of causing wilting of leaves results in physiological stress on metabolism which in turn affects photosynthesis either directly or indirectly.

Qn . Why is it difficult to demonstrate the importance of water to photosynthesis?

3. **Temperature**

Photosynthesis proceeds by a series of chemical reactions controlled by enzymes. Suitable temperature is required for activation of enzymes that catalyse photosynthetic reactions.

4. **Light**

There are three features of light which make it biologically important

1. Spectral quality (color)
2. Intensity (brightness)
3. Duration (time)

To be of use as an energy source for organisms, light must first be converted to chemical energy. Radiant energy comes in discrete packets called quanta. A single quantum of light is called a photon. Light also has a wave nature and so forms a part of the electromagnetic spectrum. Visible light represents that part of this spectrum which has a wavelength between 400nm (violet) and 700 nm (red) see figure 2 below.

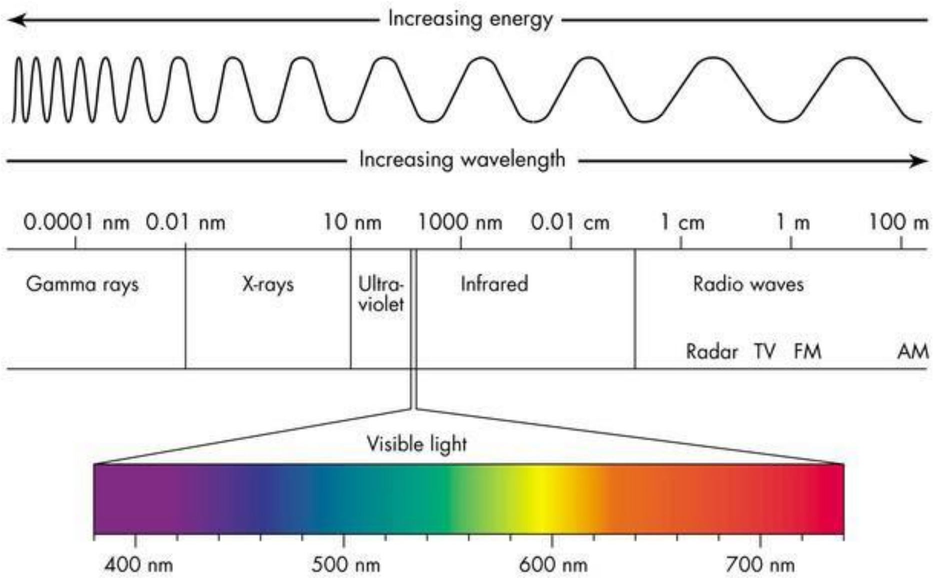


Figure2: The section of the electromagnetic spectrum

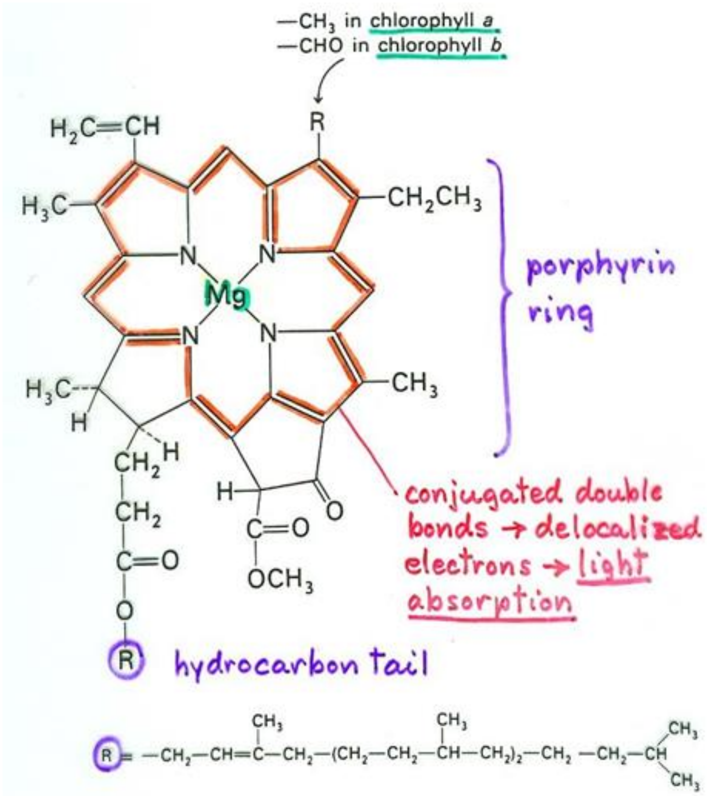
As sunlight falls on a plant, some wavelengths are absorbed, while others are reflected or transmitted. The absorbed light provides energy that excites electrons in the photosystems whose transition releases energy for synthesis of ATP, also light is necessary for photolysis of water to release electrons stabilizing photosystems and hydrogen atoms forming $NADPH_2$ for reduction of carbon dioxide.

5. Pigments

Photosynthetic pigments of higher plants are categorized into two groups i.e. chlorophylls and carotenoids. The algae in addition have phycobiliproteins like phycocyanin (blue) and phycoerythrin (red). The role of the pigments is to absorb light energy, thereby converting it into chemical energy. They are located on chloroplast membranes (thylakoids) and the chloroplasts are usually arranged within the cells so that the membranes are at right angles to the light source for maximum light absorption

(a) Chlorophylls

There are several types of chlorophyll, all containing a ring structure called porphyrin ring with magnesium at the center linked to a long hydrocarbon chain (figure 3)



The most common chlorophylls include chlorophyll a, chlorophyll b, some photosynthetic bacteria have another type of chlorophyll called bacteriochlorophyll, which contains manganese instead of magnesium. Chlorophylls absorb light in the blue-violet and the red region of the visible spectrum. The remaining light, in the green region of the spectrum, is reflected and gives chlorophyll its characteristic color.

Figure 3: Structure of chlorophyll molecule

(b) Carotenoids

Carotenoids are yellow, orange, red or brown pigments they absorb strongly in the blue-violet range of the spectrum.

Roles of carotenoids

- ❖ They are accessory pigments; they absorb light energy and pass the light they absorb on to chlorophyll.
- ❖ They protect chlorophylls from excess light and from oxidation by oxygen produced in photosynthesis.

Carotenoids are of two types, carotenes and xanthophylls, these are usually masked by the green chlorophylls but can be seen in leaves before leaf-fall because chlorophylls break down first. A common example of a carotene is β-carotene which gives carrots their familiar orange color. It is easily formed into two molecules of vitamin A.

Absorption and action spectra

If a pigment such as chlorophyll is subjected to different wavelength of light, it absorbs some more than others. If the degree of absorption at each wavelength is plotted, an absorption spectrum of that pigment is obtained **(figure 4).**

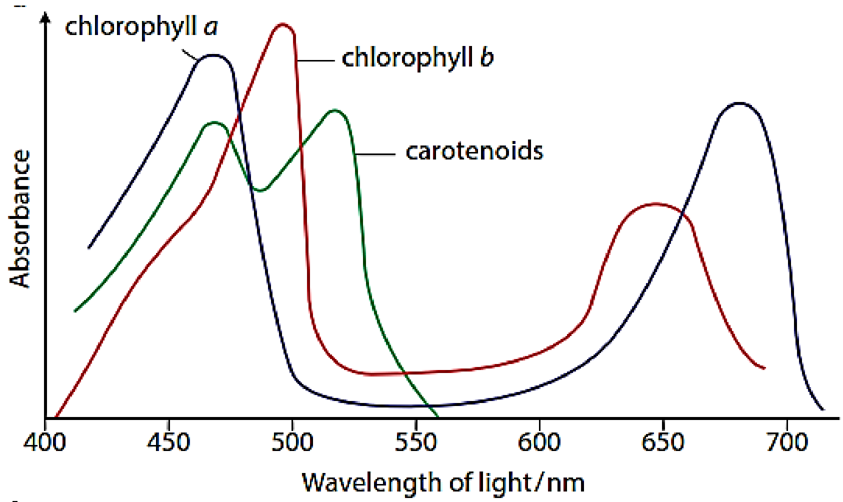


Figure 4: Absorption spectrum of chlorophylls and carotenoids

An **absorption spectrum** is a graph of the relative amounts of light absorbed at different wavelengths of light by a pigment.

An **action spectrum** is a graph showing the effectiveness of different wavelengths of light in stimulating the process being investigated. **Figure 5** below shows an action spectrum for photosynthesis together with an absorption spectrum for combined photosynthetic pigments.

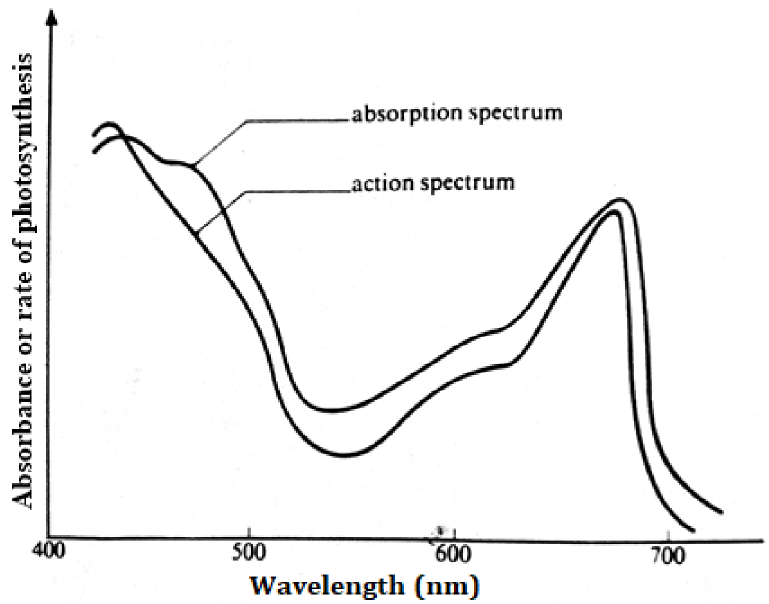


Figure 5: Action spectrum for photosynthesis compared with absorption spectrum of photosynthetic pigments.

From **figure 5 above: -**

- the red and blue ends are the most effective wavelengths in photosynthesis;
- green is only used to a slight extent.

- There is a close correlation between the absorption and action spectrum, indicating that the pigments, chlorophylls in particular, are responsible for the absorption of light used in photosynthesis.
- The non-correspondence in the two spectra between about 450nm and 470nm, is because this wavelength is absorbed by carotenes which are not used in photosynthesis.

Assignment: Explain the similarities and differences between the absorption and action spectra in figure 5 above.

Discovery of the role of red and blue light in photosynthesis

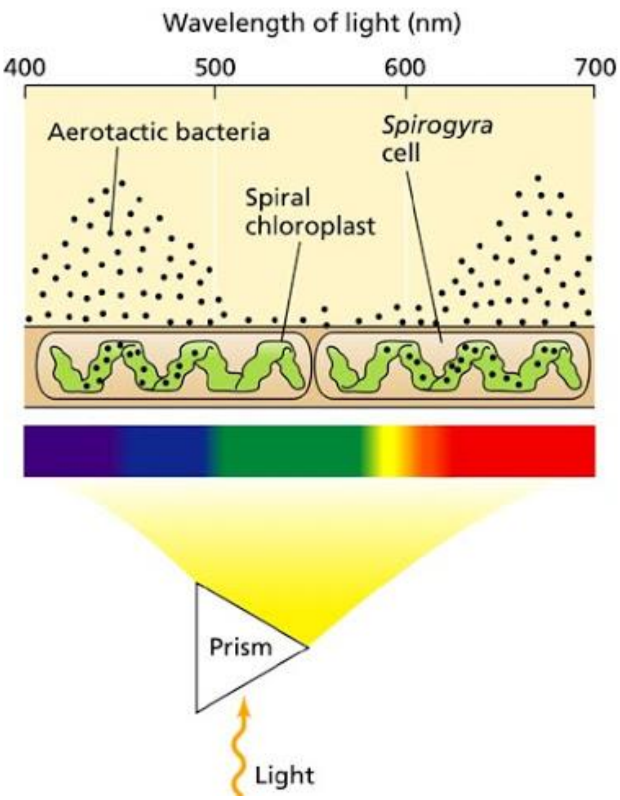


Figure 6: results of Engelmann's experiment

In an investigation Engelman, used a species of motile aquatic aerobic bacterium. Where these bacteria are found to accumulate, he knew that oxygen was also present.

Engelman split sunlight into its constituent colors by means of a prism, and projected them onto cells so that the different colors of light were received by different parts of the filament. The aerobic bacteria in the water collected around the filaments in areas where the chloroplast was receiving red and blue light.

Conclusion

Light in the violet-blue and red portions of the spectrum is most effective in driving photosynthesis.

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).

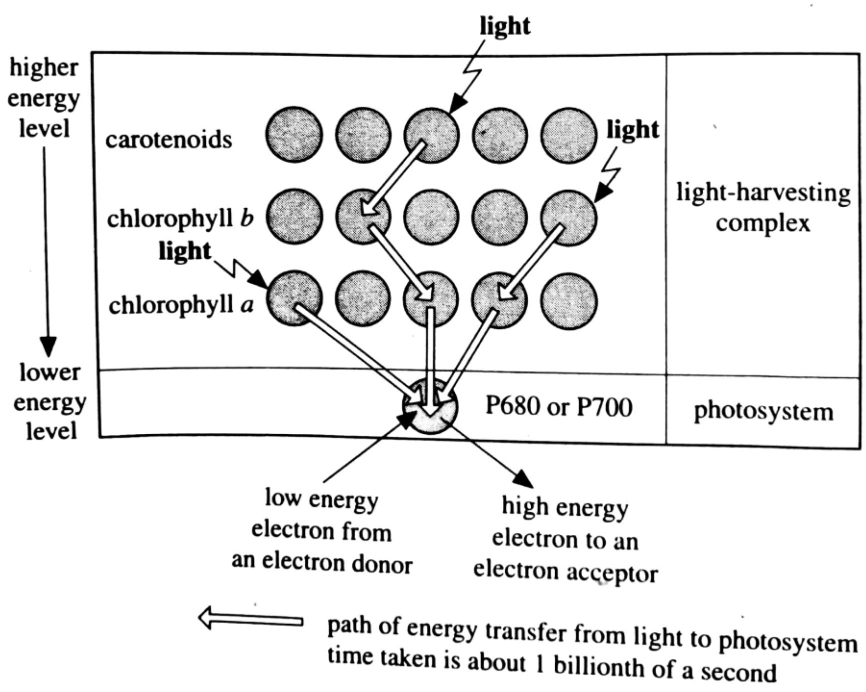


Figure 7: A photosystem: a light-harvesting cluster of photosynthetic pigments in chloroplast thylakoid membrane

Exercise 1

1. (a) Explain how a photosystem increases the light harvesting ability of a chloroplast? (b) Explain the relationship between the action spectrum and the absorption spectrum of photosynthetic pigments in green plants.

Evidence that photosynthesis is a two-stage process

(i) The overall process is influenced by increase in temperature which would not be the case if it was dependent on light alone.

(ii) The amount of carbohydrate produced in a given quantity of light is greater if the light is supplied intermittently/in flashes rather than continuously suggesting that some part of photosynthesis is independent of light.

(iii) By use of radioactive tracers like C^{14} in $C^{14}O_2$ which have subsequently been detected in the organic compounds produced. It has been shown that the reduction of carbon dioxide can occur in the absence of light.

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.

(i) 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 **photoactivation**. 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.

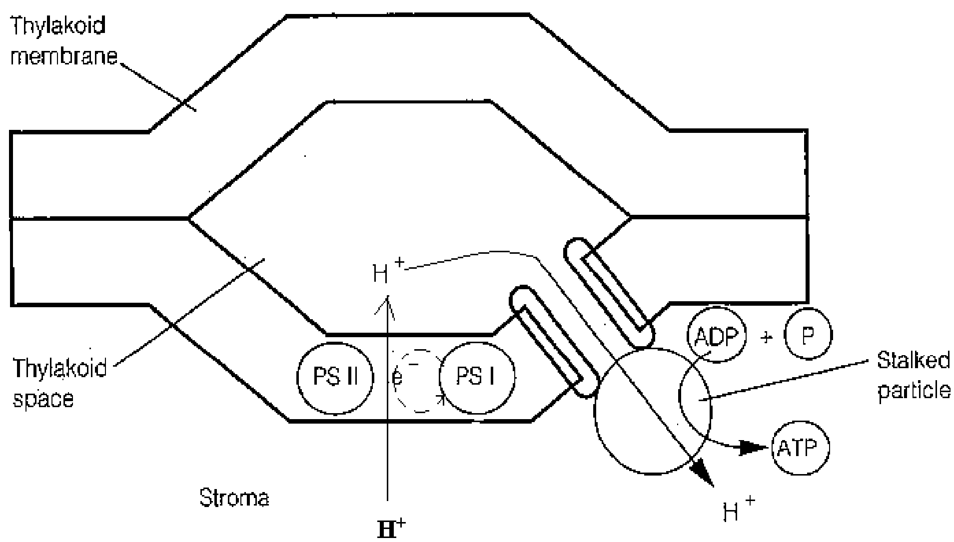


Figure 8: Summary of events that occur during cyclic photophosphorylation

(ii) Non-cyclic photophosphorylation

Non-cyclic photophosphorylation involves both photosystems I and II in the so-called 'Z scheme' of electron flow (unidirectional electron flow) (Figure 9).

Light strikes both photosystems I and II simultaneously, excited electrons are emitted from the primary pigments of both reaction centres. 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:

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

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.

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

Reduced NADP passes to the light independent reactions and is used in the synthesis of carbohydrate.

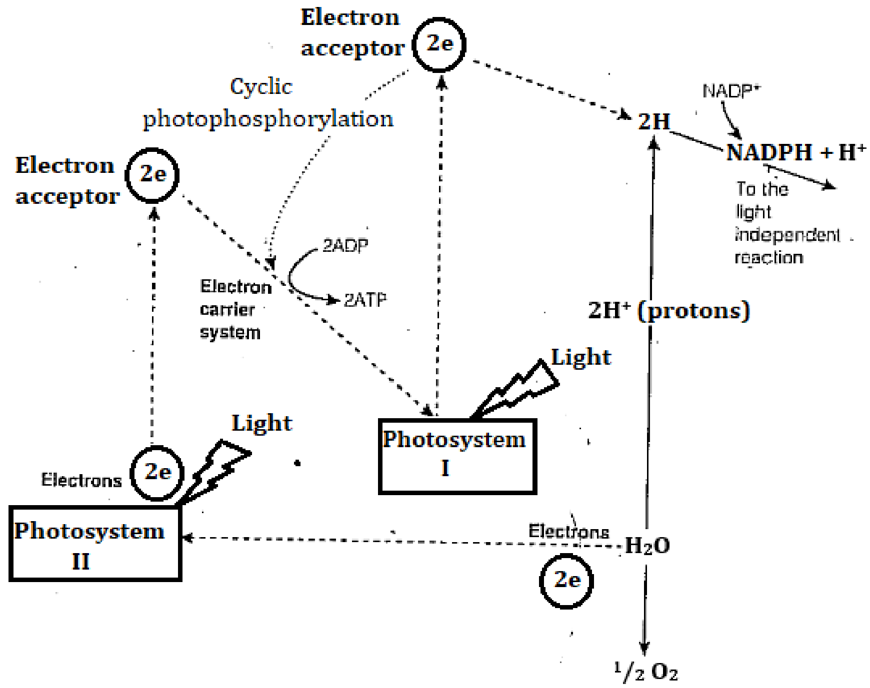


Figure 9: The Z-Scheme

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.

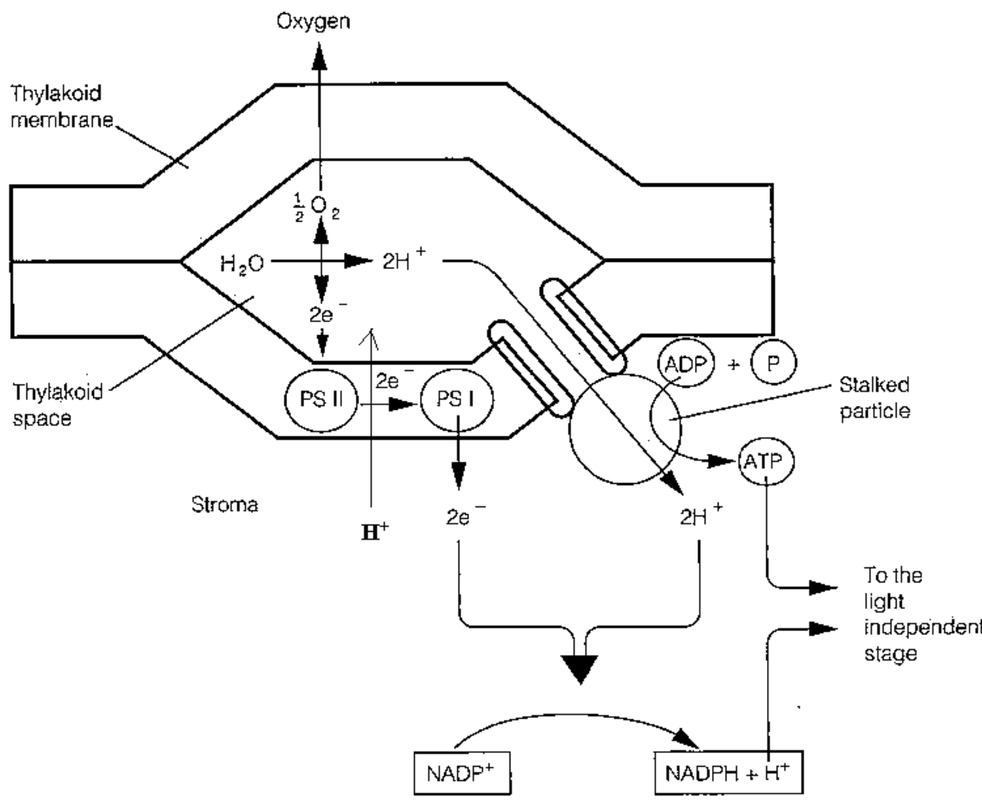


Figure 10: Summary of events that occur during non-cyclic photophosphorylation

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 unidirectionally (non-cyclically)	▪ 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 biphosphate** (RUBP), in a reaction catalysed 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 3-phosphoglyceraldehyde (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.

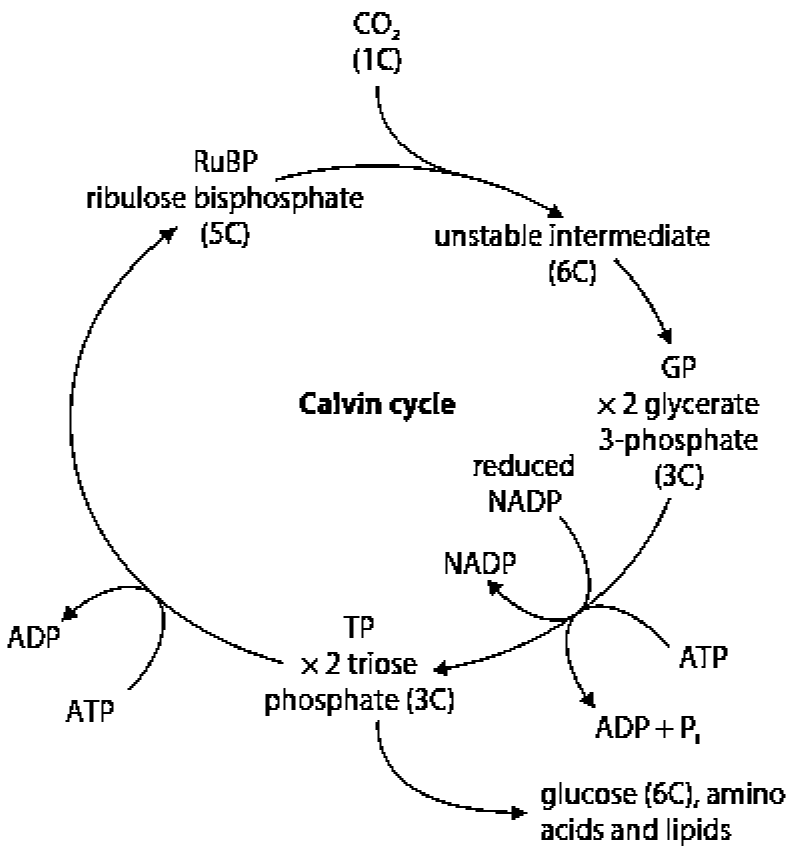


Figure 11: the Calvin cycle

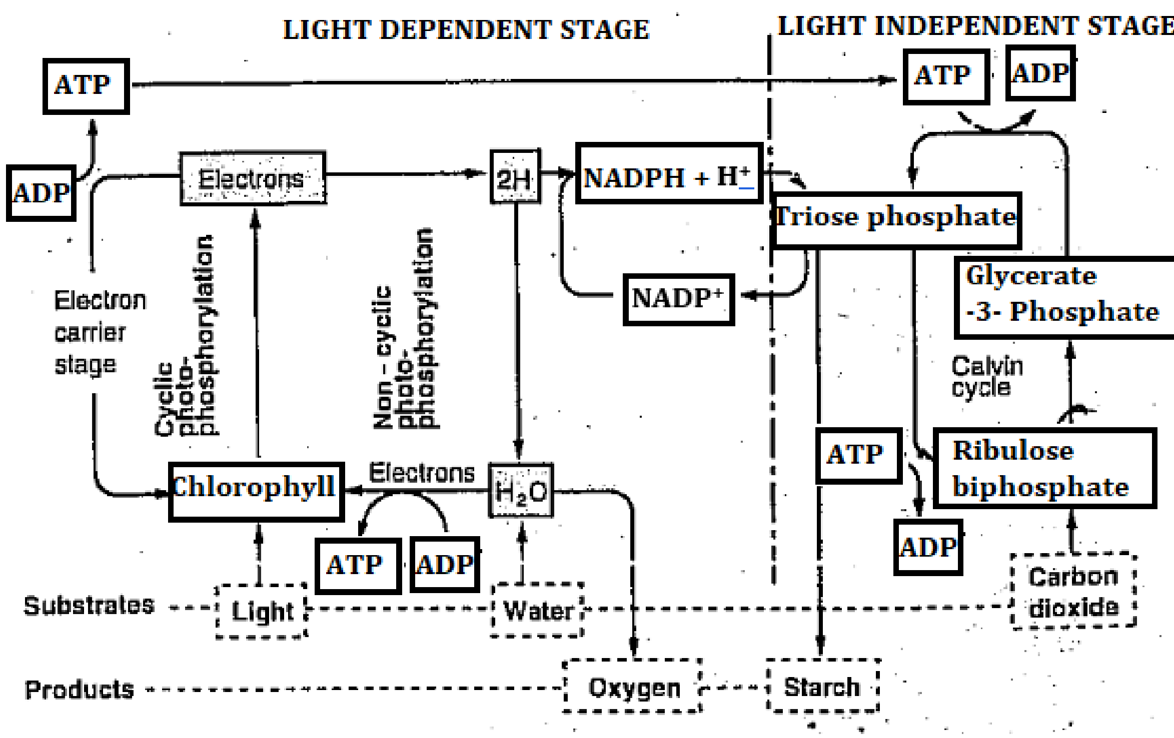


Figure 12: Summary of process of photosynthesis

Exercise 2

1. (a) Outline the light-independent reactions of photosynthesis.
   (b) Explain:
   (i) why the light-independent reactions of photosynthesis can only continue for a short time in darkness.
   (ii) how the light-independent reactions of photosynthesis rely on light-dependent reactions.
2. (a) Outline the formation of carbohydrate molecules in photosynthesis starting from the absorption of light energy
   (b) Compare the structure of a chloroplast and a mitochondrion in relation to function.
3. (a) Explain photophosphorylation in terms of chemiosmosis in chloroplast.
   (b) Explain the reactions involving the use of light energy that occur in the thylakoids of the chloroplast.

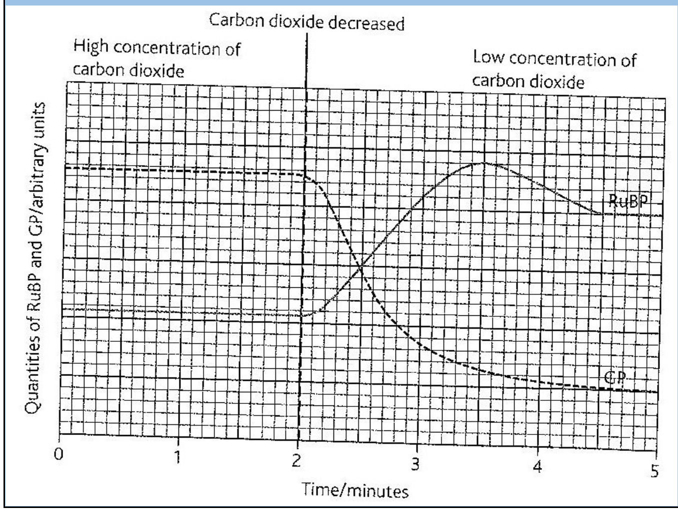
4. Experiments on cultures of a unicellular protist to investigate the effect of light and carbon dioxide on certain metabolites. In the first experiment, the levels of PGA, RuBP and sucrose in the protest were determined at different time intervals in the presence of light. At the 35th minute, light was switched off, suddenly putting the protists in darkness; the results are shown in the table below

Time (minutes)		0	20	35	40	50	60	70
Amount of metabolite	RuBP	35	35	35	30	15	10	10
	PGA	45	45	45	50	65	70	70
	Sucrose	10	54	72	66	52	35	20

(a) Represent the data provided graphically

(b) Using the graph obtained in (a) above, explain the variation in the levels of the metabolites with time

5. In an experiment, samples of algae were collected at 1-minute intervals over a period of 5 minutes. The quantities of glycerate-3-phosphate (GP) and ribulose bisphosphate (RuBP) were measured. At the beginning of the experiment, the concentration of carbon dioxide supplied was high. After 2 minutes, the concentration of carbon dioxide was reduced. The graph in the figure below shows the results of this experiment.



(a) Describe the effects of the decrease in carbon dioxide after 2 minutes on:

(i) Glycerate 3-phosphate (GP)

6. (ii) Ribulose bisphosphate (RuBP)

(b) Suggest explanation for these changes to the levels of glycerate 3phosphate (GP) and RuBP.

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.

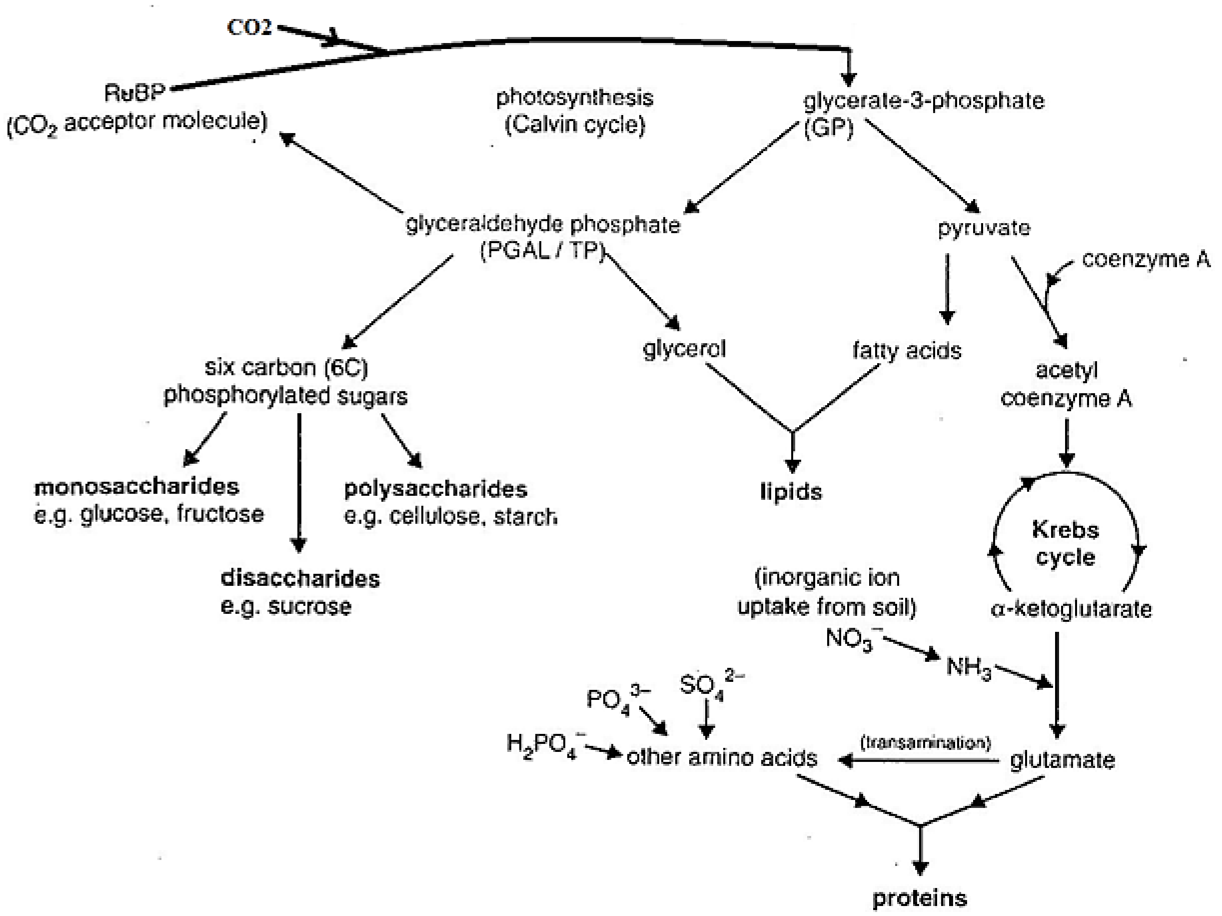


Figure 13: Summary of metabolism of intermediates of dark stage

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

NOTE

- The enzyme Ribulose biphosphate carboxylase that catalyses the reaction of carbon dioxide with RuBP unfortunately, it can also catalyse 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

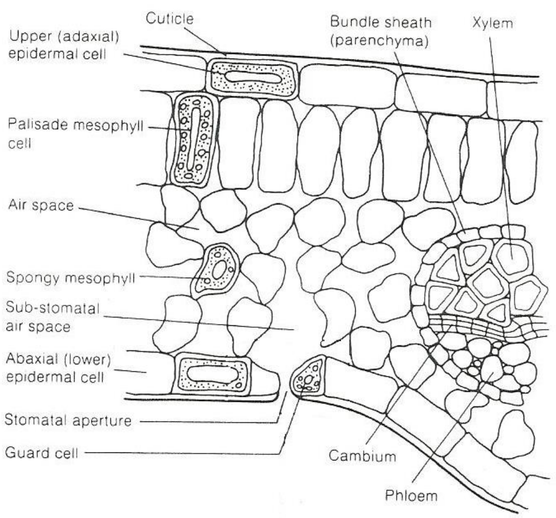
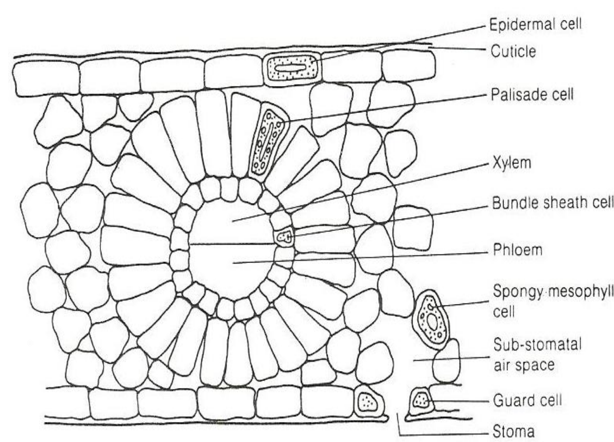
This is a type of photosynthesis in which CO_2 is first, fixed by phosphoenolpyruvate carboxylase (PEPCO) into Oxaloacetate (OAA) inside mesophyll cells, stored as organic acid (mainly malate) which is **later** decarboxylated, refixed and CO_2 is assimilated in the Calvin-cycle inside bundle sheath 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.

WHAT IS 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.

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
	

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.

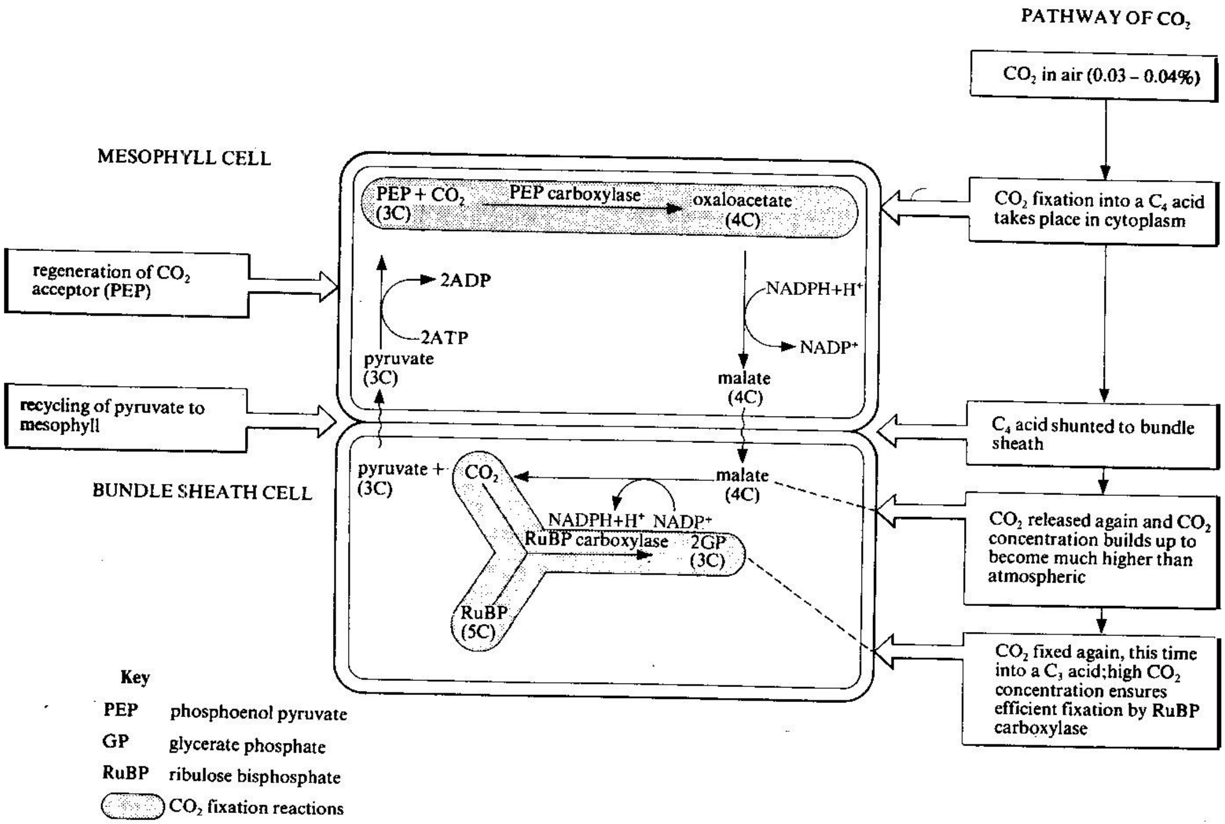


Figure 14: Summary of Hatch-slack pathway

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

CRASSULACEAN ACID METABOLISM (CAM) PHOTOSYNTHESIS

This is a type of photosynthesis in which CO_2 is taken in at night via open stomata, fixed by phosphoenolpyruvate carboxylase (PEPC) into OAA, stored as organic acid (mainly malate) which is **later** decarboxylated during daytime, refixed and CO_2 is assimilated in the Calvin-cycle when stomata are closed.

Examples of CAM plants

Cacti, agaves (sisal), opuntia, *Kalanchoe* (Bryophyllum), Vanilla (family: Orchidaceae), *pineapples (Family*: ***Bromeliaceae)***, Mesembryanthemum crystallinum (Common ice plant), and *Euphorbia milii* **(**Crown of Thorns plant). These are mainly succulent plants that live in hot arid climates.

When the stomata open at night, carbon dioxide enters the leaves and combines with PEP to form OAA in the presence of an enzyme PEPCO found in their cytoplasm. The OAA is then reduced to malate a reaction catalysed by an enzyme malic dehydrogenase which accumulates in the leaf vacuoles.

During the day when the stomata are closed the malate is transported to the cytoplasm where it is decarboxylated to pyruvate and carbon dioxide, the carbon dioxide released enters the chloroplast where it is fixed to sugars in the Calvin cycle.

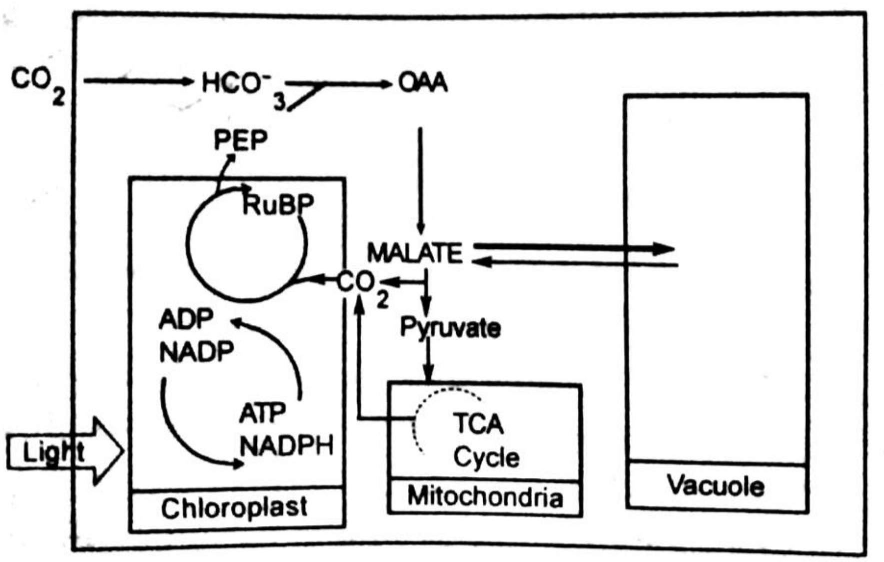


Figure 15: A representation of the CAM cycle

Assignment: State the differences between metabolism in C4 plants and CAM plants

Exercise 3

1. (a) Distinguish between light compensation point and compensation period (02 marks)

   (b) (i) Explain why C_3 plants have a higher carbon dioxide compensation point compared to the C_4 plants. (02 marks)

   (ii) Suggest the physiological advantages of C4 having low carbon dioxide compensation point compared to C_3 plants. (03 marks)

   (c) State any three differences between the mesophyll and bundle sheath chloroplasts in C_4 plants. (03 marks)

2. (a) What is meant by the term C_4 plant? (02 marks)
(b) (i) explain the significance of C_4 plants for being more efficient at carbon dioxide fixation than C_3 plants. (06 marks)
(ii) Explain how carbon dioxide is fixed by C_4 plants. (06 marks)
(c) How are leaves of C_4 plants modified to suit it for carbon dioxide fixation? (06 marks)

Significance of CAM photosynthesis

For terrestrial CAM plants, there is increased water use efficiency in which nocturnal stomatal opening greatly reduces stomatal loss of water as it would in day light.

Note

- CAM is an adaptation for hot and dry conditions. It enables the plant to conserve water by keeping stomata closed in the heat of the day when transpiration would be most rapid
- CAM plants are extremely efficient at conserving water but unfortunately their rate of net photosynthesis per unit area of plant or ground is very low and correspondingly their growth rates are also very low.

MEASUREMENT OF THE RATE OF PHOTOSYNTHESIS

Rate of photosynthesis can be measured by measuring the rate of:-

- uptake of CO_2
- production of O_2
- production of carbohydrates
- increase in dry mass

(a) ***Measuring the rate of Uptake of CO_2***

Uptake of CO_2 can be measured with the means of an IRGA (Infra-Red Gas Analyser) which can compare the CO_2 concentration in gas passing into a chamber surrounding a leaf / plant and the CO_2 leaving the chamber. **The soil and roots must NOT be in the bag to avoid CO_2 production from respiration**

NOTE: CO_2 uptake can also be measured by following the uptake of carbon dioxide labelled with 14C

(b) Rate of ***Production of carbohydrates***

This is a **crude** method where a disc is cut out of one side of a leaf (using a cork borer against a rubber bung) and weighed after drying. Some weeks later, a disk is cut out of the other half of the leaf, dried and weighed. Increase in mass of the disc is an indication of the extra mass that has been stored in the leaf.

Explain why this method is inaccurate.

(c) ***Measuring the increase in dry mass-***

Dry mass is often monitored by the technique of '*serial harvests'* where several plants are harvested, dried to constant weight and weighed - this is repeated over the duration of the experiment so as to have an accurate measure of the surplus photosynthesis over and above the respiration that has taken place. As with most methods, several plants are needed to have replicate measurements which are used to calculate the average and a standard deviation if necessary.

(d) ***Measuring the rate of production of O_2***

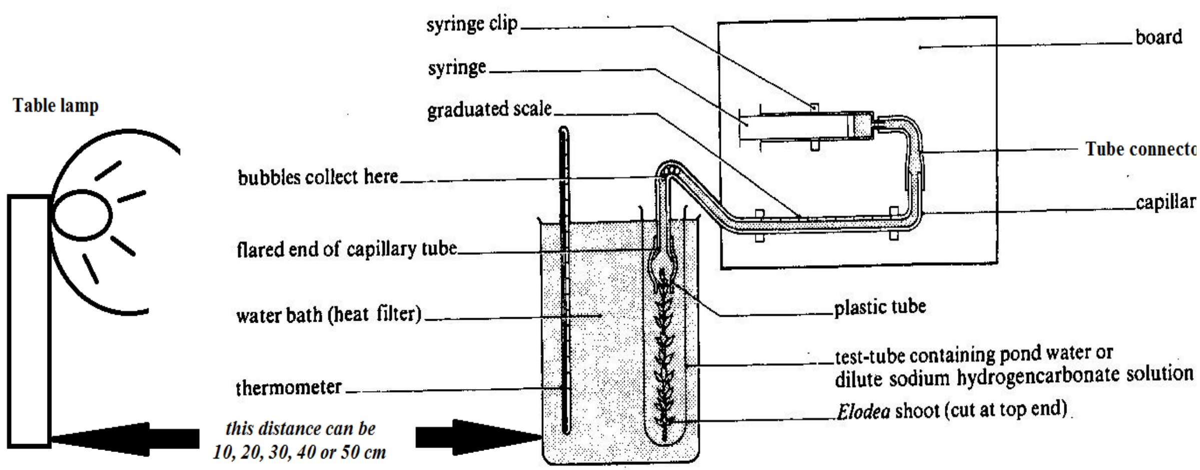
Oxygen can be measured by (a) counting bubbles evolved from pond weed with the Audus apparatus

Requirements

- ✓ Test tube
- ✓ Watch
- ✓ Water at room temperature
- ✓ bench lamp to provide light
- ✓ Knife
- ✓ 500 cm^3 glass beaker
- ✓ plastic tube connector
- ✓ graduated scale
- ✓ retort stand
- ✓ soft board
- ✓ thermometer
- ✓ capillary tube
- ✓ Ruler
- ✓ Previously well illuminated aquatic plant e.g. *Elodea* or *Cabomba*
- ✓ 0.2 % sodium bicarbonate solution
- ✓ plastic Syringe

Procedure:

- ❖ Set up the apparatus as below in **TOTAL DARKNESS**



- ❖ A light source is placed 50 cm away facing the test tube and is powered on, a 5 minutes lapse is allowed to enable the plant adjust to the light intensity.
- ❖ The length of gas bubble evolved in 10 second, 30 second, and 1minute intervals is measured by pulling the syringe plunger to draw the bubble slowly along the capillary tube.
- ❖ Steps **above** are repeated with the light source placed at 40 cm from the test tube with the plant, then 30 cm, 20 cm, and finally 10 cm.
- ❖ a control experiment is set up using natural room lighting and repeating the above steps.

Observation / results	Explanation
A colorless gas which relights a glowing splint evolves from the cut end of the plant.	The gas is oxygen released from Photosynthetic reactions.

❖ The rate of gas evolution is directly proportional to light intensity up to a certain illumination i.e. the closer the light source is to the plant; the more oxygen bubbles evolve up to a certain light intensity then remains relatively constant and may decrease. **<u>Determination of amount of gas released</u>** a) if scale is marked in mm^3 or cm^3: read volume directly b) if scale is marked in mm: calculate volume from $\pi r^2 h$ π=3.14, r=capillary tube radius, h=distance bubble covers	❖ This is because of the increased light intensity which provides more energy for photo-activation of electron flow. ❖ Increased illumination may not cause any further evolution of oxygen because ❖ of light saturation ❖ other factors limit the process ❖ Increased illumination may cause a decrease in bubble evolution because chlorophyll gets **bleached** with increased illumination.

Precautions to avoid experimental inaccuracies / errors	**Explanation / Remedy**
❖ Temperature fluctuation of the water in the beaker	❖ Thermostatically controlled bath should be used to maintain temperature constant since it affects photosynthetic activity.
❖ The experiment must be conducted in total darkness	❖ To avoid effects of external light fluctuations on photosynthesis
❖ There must be periodical refilling of HCO_3^- solution	❖ To avoid depletion of carbon dioxide
❖ The water should be aerated first.	❖ To saturate the water with oxygen such that the oxygen evolved does not dissolve into water.
❖ Each time the light position is adjusted, a 5-minute lapse must be allowed before bubble counting	❖ To allow the plant equilibrate (adjust) to the new light intensity.
❖ Light intensity fluctuation	❖ Use voltage that gives constant light for a long time
❖ Trapped gas bubbles	❖ Swirl the water weed to release them

NOTE:

❖ Instead of measuring the length of bubble, bubbles can be counted, but this has several disadvantages

(i) Some bubbles may not be seen due to variations in size, which can be avoided by adding a little detergent to lower the surface tension

(ii) Bubbles may evolve very fast to be counted, especially in much illumination.

- The percentage of oxygen in the evolved gas is **only about 40%** because of dilution by
  - (i) dissolved N_2 or other gases released from solution
  - (ii) CO_2 which had accumulated from respiration, and is first displaced into the capillary tubing, especially if the plant had been kept in the dark

FACTORS INFLUENCING THE RATE OF PHOTOSYNTHESIS

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

Environmental factors

- Carbon dioxide concentration
- Light intensity
- Temperature
- oxygen concentration
- Some air pollutants e.g. Sulphur dioxide
- Altitude
- Salinity

Internal factors include

- Chlorophyll concentration
- Water and dissolved nutrients
- Enzyme inhibitors e.g. cyanide, dichlorophenol dimethyl urea – DCMU

The level of each factor determines the yield of material by a plant; therefore, it is necessary to first consider the interaction of factors controlling photosynthesis

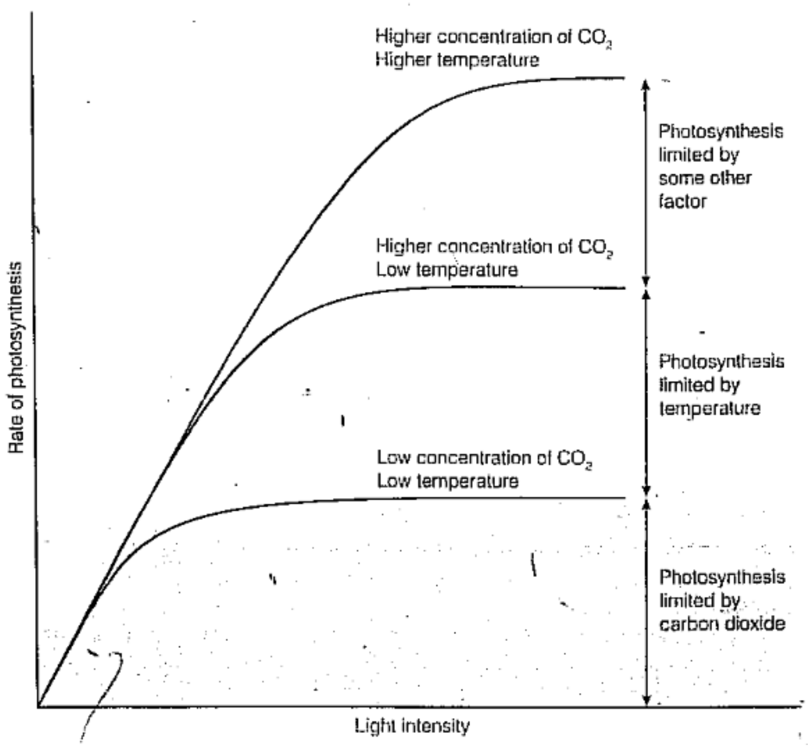
THE PRINCIPLE OF LIMITING FACTORS

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.

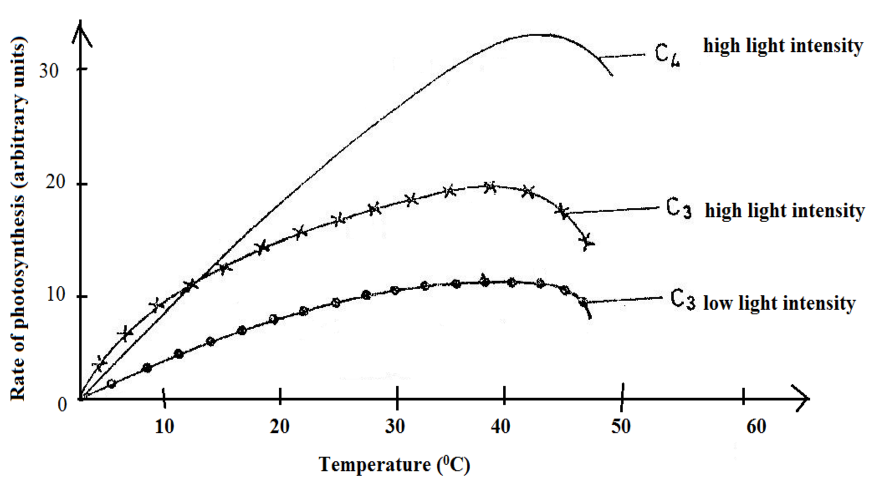
Therefore, the rate of photosynthesis can be increased further by increasing either temperature of carbon dioxide concentration which are limiting factors.

(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 catalysed by enzymes which, like all enzymes are sensitive to temperature.

Note:

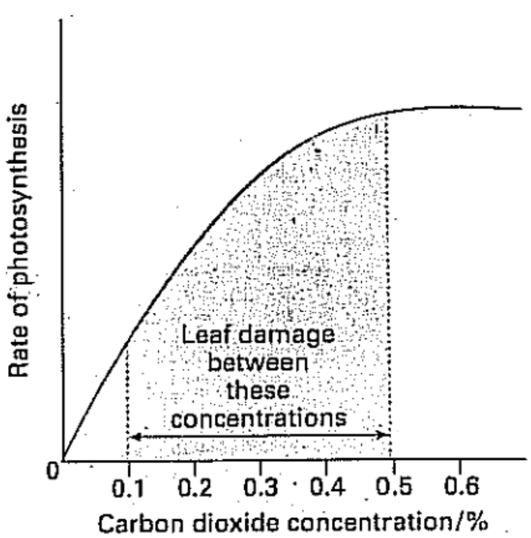
- the effect of temperature on these reactions is similar to its effect on other enzymes
- The optimum temperature varies for each species, but many temperate plants have an optimum temperature ranging from 25°C to 35°C.



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

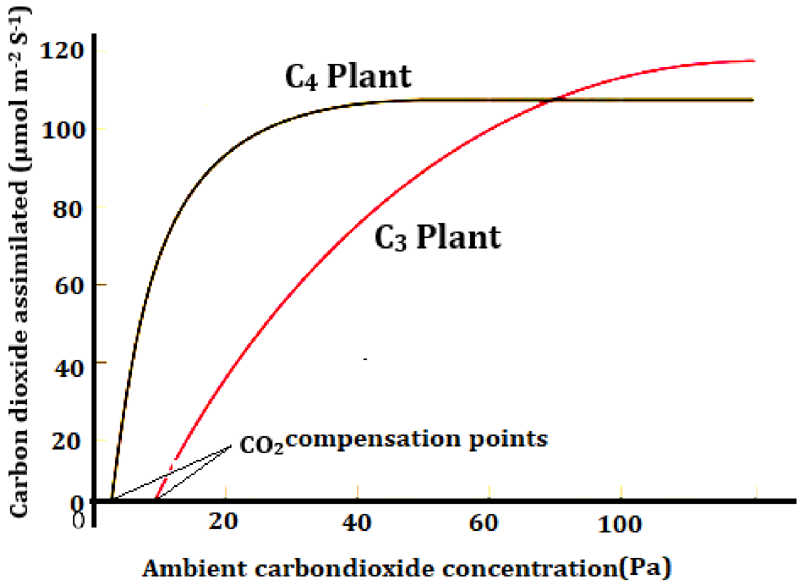
In the atmosphere, the concentration of carbon dioxide ranges from 0.03 to 0.04 %. However, it is found that 0.1% of carbon dioxide in the atmosphere increases the rate of photosynthesis significantly. As long as there is no other facto limiting photosynthesis, an increase in carbon dioxide concentration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

Qn. Mention other ways the carbon dioxide concentration of the environment can be increased



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	❖ **At** 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.

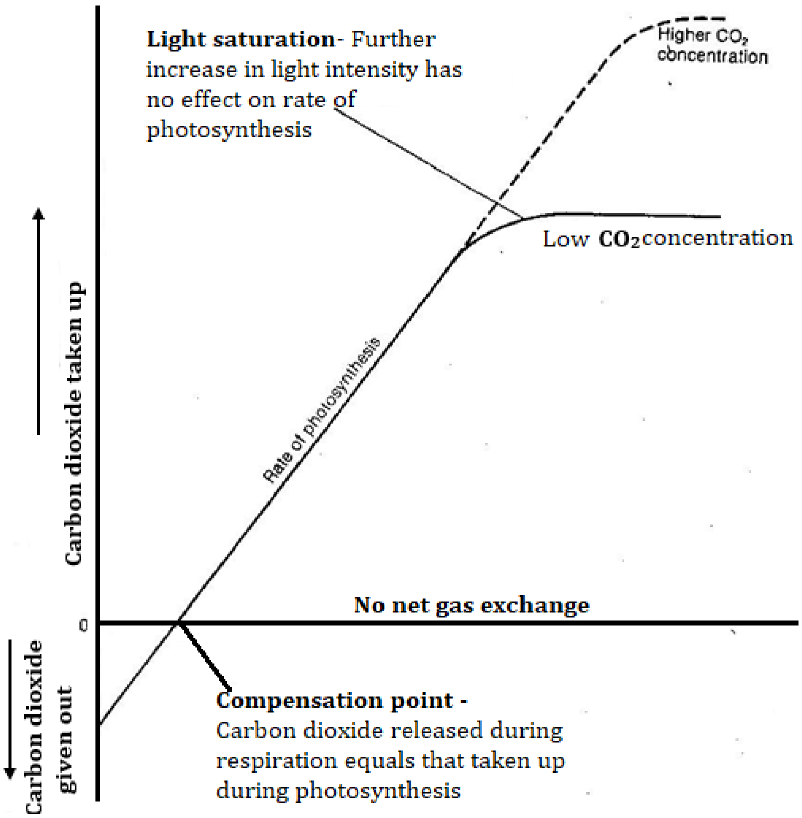
(iii) Light intensity

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**. It occurs during early morning or late evenings. This varies for different plants.

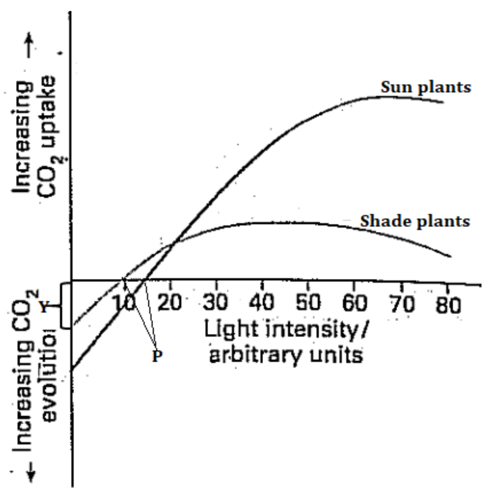


However, after reaching a certain light intensity further increase in light intensity has no effect on the rate because photosynthetic pigments have become saturated with light, and some other factor either availability of carbon dioxide, amount of chlorophyll or temperature stops the reaction from going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

SUN AND SHADE PLANTS

Sun plant are those with leaves growing on branches exposed to direct sunlight while shade plants are those with leaves growing 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.



- At very low light intensity, shade plants have higher CO_2 uptake; these photosynthesise best at low light intensities which reduces with illumination.
- sun plants have a higher light compensation point than shade plants;
- shade plants have relatively low light compensation point this is a physiological adaptation which enables shade plants to make efficient use of light of low intensity.
- P represents compensation point at which CO_2 uptake equals CO_2 output.
- At Y biomass decreases because the rate of respiration exceeds that of photosynthesis.

ADAPTATIONS TO PHOTOSYNTHESISE IN SUN AND SHADE

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

Shade plant	Sun plants
▪ Abundant chlorophyll ***b*** (low chlorophyll *a* to chlorophyll *b* ratio) which gives leaves dark green colour to increase light absorption in the dark; ▪ Palisade/ spongy mesophyll ratio low to allow maximum light penetration; ▪ Mesophyll cell surface / leaf area ratio low to maximise light trapping; ▪ Leaf orientation horizontal to maximise light trapping; ▪ Reddish leaf undersides to enhance reflectance back up ▪ through the photosynthetic tissue; giving the plant a second chance to utilize the light. ▪ Stomatal density low to avoid over cooling; ▪ Thin leaves to maximise light penetration; ▪ Stomatal size large to allow loss of excess water; ▪ Elongated internodes for increased access to light; ▪ Chloroplast size large to increase the surface area for storage of photosynthetic pigments.	▪ Abundant chlorophyll ***a*** (high chlorophyll *a* to chlorophyll *b* ratio) to increase light absorption; ▪ Palisade/ spongy mesophyll ratio high to minimise light penetration; ▪ Mesophyll cell surface / leaf area ratio high to minimize excessive light and transpiration; ▪ Leaf orientation erect to minimise light trapping; ▪ Stomatal density high to avoid over heating; ▪ Much carotenoids to prevent damage to chlorophyll from very bright light. ▪ Thick leaves to minimise light penetration; ▪ Stomatal size small to minimise water loss; ***Other features*** (i) RuBISCO and soluble protein content /mass higher (ii) Chlorophyll / soluble protein ratio high (iii) Chloroplast size small

Exercise 4

1. The table 1 below shows the rate at which carbon dioxide is taken up (+) and released (-) from stem of an herbaceous plant and from a single leaf of the same species at different light intensities.

Light intensity (arbitrary units)	UPTAKE (+) AND RELEASE (-) OF CARBONDIOXIDE /$mg50cm^{-2}h^{-1}$	
	STEM	LEAF
0.0	-0.5	-0.5
1.0	-0.2	+0.6
2.5	+0.3	+2.8
4.0	+0.7	+4.6
5.0	+1.0	+5.3
7.0	+1.6	+6.0
11.0	+2.5	+6.3

(a) Present the data provided in the table above in a suitable graph. (06 marks)
(b) Calculate the rate at which carbon dioxide is used in photosynthesis by $50cm^2$ of the plant organ at light intensity of 3 arbitrary units. (03 marks)
(c) Explain,
(i) the rate of uptake and release of carbon dioxide of the leaf of a plant as light intensity increases. (14 marks)
(ii) the difference in the rate of uptake of carbon dioxide of leaf and stem of plants. (06 marks)
(iii) From your graph, the difference in the light compensation points of the leaf and stem of plants. (04 marks)
(d) Suggest any three practical difficulties you would meet in conducting an experiment to obtain data of the kind given in the table. (03 marks)
(e) State physiological problems likely to be faced by a plant beyond light intensity of 3 arbitrary units. (04 marks)

(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.

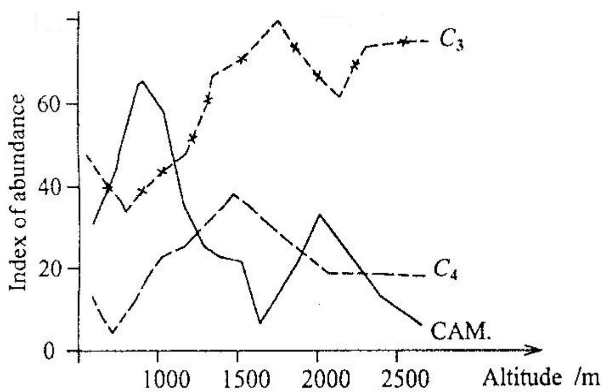
(vi) Water

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 vapour through them.

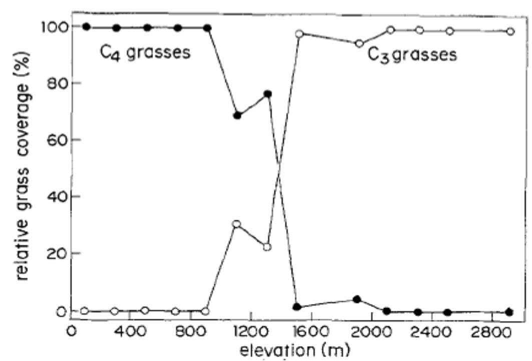
(vii) Pollution

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	***Explanation***
❖ C3 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 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.

Exercise 5

1. a) Explain the significance of pigments and light in photosynthesis. (12 marks)
   (b) How does altitude affect distribution of C_3 and C_4 plants? (08marks)

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 photorespire and have very short compensation periods. E.g. C4 plants such as sugar cane and maize have a much grater 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.

Exercise 6

1. The figure below shows the changes in leaf area index (ratio of leaf surface to soil surface (m^2cm^{-2}) of two species of clover, *Triforium ripens* and *Triforium fragiferum*, growing in a pure and mixed stand.

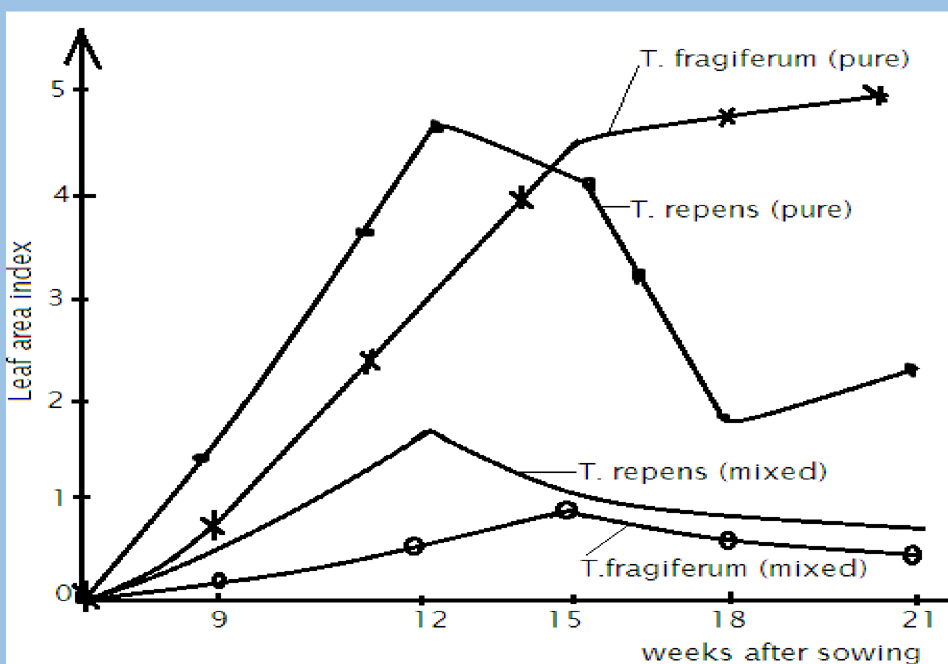


Table 1: shows the characteristics of the petioles and leaf size of the two species of clover.

	Characteristics	
	T. fragiferum	T.repens
Petiole length	Long	Short

Leaf size	Large	Small

Use the information in the figure and table to answer the questions that follow,

(a) Compare the leaf area index of *Trifolium repens* and *T.fragiferum* in the,
   (i) pure stands.(06 marks) (ii) mixed stands. (06 marks)

(b) Explain the trend in leaf area index for *Trifolium repens* in pure stands. (10 marks)

(c) Explain the differences in growth rate of the two species in mixed stands. (07 marks)

(d) Explain why *Trifolium fragiferum* continues to grow after the peak of *Trifolium repens*? (04 marks)

(e) What conclusion can you draw from the results in a mixed stand? (04 marks)

(f) What other factors are likely to have caused the difference in growth rate of the two species in mixed stand? (03 marks)

S6 BIOLOGY NOTES CONTINUED……

HETEROTROPHIC NUTRITION

This is the type of nutrition in which organisms take in readymade organic food substances made by autotrophs (producers).

TYPES OF HETEROTROPHIC NUTRITION

1. **Holozoic nutrition:** involving feeding on solid organic materials obtained from the bodies of other organisms. This occurs in all animals, some protists and some specialised plants
2. **Saprotrophic nutrition (Saprophytic nutrition):** involves feeding on soluble organic compounds obtained from dead animals and plants. This occurs in many protists, fungi and bacteria and in some animals.
3. **Symbiosis:** the living together in close association of two or more organisms of different species involving nutrition. There are common types of symbiotic relationships i.e.
   - Parasitism
   - Mutualism
   - Commensalism

NUTRIENTS, FOOD AND DIET

Organisms have two basic nutritional requirements i.e. energy and building materials which are supplied in the form of chemicals known as **nutrients**. Such nutrients are categorized into

- Organic nutrients: these include carbohydrates, lipids, proteins and vitamins
- Inorganic nutrients: these include mineral salts.

Such nutrients are found in the food we eat.

DIET

Diet is the quantity and nature of the food we eat i.e. which nutrients and how much of each.

Balanced diet

Is one which contains the correct proportions and quantity of the various nutrients, water and dietary fibre required to maintain health.

The essential nutrients for the balanced diet provide of a mammal consists of the following components.

- Carbohydrates and fats in relatively large quantities as sources of energy
- Proteins in large quantities for growth and repair processes
- Vitamins and minerals in smaller quantities for protection of good health and prevention of deficiency diseases.

NUTRIENT	FOOD SOURCE COMPOSITION	FUNCTIONS	DEFICIENCY DISEASE, SIGNS AND SYMPTOMS
Carbohydrates	Starch e.g. tubers, grains and pulses Sugars from corns, honey, root vegetables, milk, dairy products, fruits and canes Dietary fiber or roughage from	Starch and sugars provide energy to cells in the body once metabolized and oxidised. Starch and sugars such as glycogen stores energy in the body Presence of sugars is essential for sparing proteins in tissues and lipids in the body.	May contribute to **marasmus.** Nausea, dizziness, constipation, lethargy, dehydration, bad breath, loss of appetite Body becomes weak and thin

	cereals, fruits, vegetables, wheat , barley, legumes	sugars are building blocks for more complex molecules such as nucleic acids, nucleotides (e.g. ATP and NAD) formation of structure e.g. cellulose in plant cell wall and glycol proteins in cell membranes and chitin in exoskeleton of arthropods dietary fibers increase the bulk of stool and softens it to make bowel movements easier	
Lipids	Margarine, milk, cheese, eggs, butter, G.nuts, sim sim, fish, avocado	Source of energy upon their oxidation. Store excess energy from food in fatty tissue (adipose tissue) Glycolipids are essential for formation of cell membranes Form fatty membranes of the myelin sheath around certain nerves for faster nerve impulse propagation Heat insulators keeping the body worm Offer protection to vital organs in bodies of animals For absorption and transport of micronutrients such as fat-soluble nutrients.	Dry and scaly skin Dry eyes Feeling constantly cold Dry hair or hair loss Hormonal problems Inability to feel full Mental fatigue Constant fatigue Deficiencies in fat-soluble vitamins
Proteins	Animal products such as meat, eggs, milk, chicken, fish yoghurt and cheese Plant products e.g. soya bean, beans and nuts	Source of energy if the diet is deficient in carbohydrates and fat e.g. during starvation and fasting. Source of amino acids for synthesis of new proteins for growth and repair. For formation of structures e.g. cell membranes, hair, muscles and nails Constituent of protoplasm of cells They are regulators of body processes when they form enzymes and hormones	**Kwashiorkor** in children **Symptoms** General body weakness Pot belly Brown hair Loss of appetite Stunted growth Cracked skin around the ears and mouth Swollen legs, hands and feet

VITAMINS

These are essential non-protein organic compounds which are needed in small amounts for normal growth and metabolism. If the diet lacks a particular vitamin, a disorder called deficiency disease results. Vitamins are normally classified into two basing on their solubility: -

(a) Water soluble vitamins: these are soluble in water e.g. vitamins B and C, these are readily excreted in urine and must therefore be consumed regularly.

VITAMIN	MAIN FOOD SOURCES	FUNCTIONS IN BODY	SYMPTOMS OF DEFICIENCY
Vitamin B_1 (Thiamin)	Liver, lean meat, eggs, unpolished rice, yeast extract	Helps release energy form carbohydrates	**Beri beri** **Symptoms** • Decreased appetite • Gastrointestinal disturbance • Nerve and muscle disorder
Vitamin B_2 (Riboflavin)	Whole grain cereals, meat, liver, yeast extract	Component of FAD a coenzyme in respiratory metabolism Maintenance of healthy skin and mucosa	**Ariboflavinosis** **Symptoms** • Skin lesions such as cracks in the corners of the mouth • Blurred vision • Abnormal utilization of oxygen
Vitamin B_3 (niacin or nicotinic acid)	Meat, fish, liver, whole grain products, unpolished rice, nuts, yeast extract	Component of coenzymes NAD and NADP important in respiration and photosynthesis respectively	**Pellagra** **Symptoms** • Skin and gut lesions • Muscle weakness • Loss of appetite • Pigmentation of exposed areas of the chest
Vitamin B_5 (pantothenic acid)	Most foods but especially liver, egg and legumes	Component of vitamin A Carbohydrate and fat metabolism	▪ Fatigue ▪ Numbness ▪ Tingling in the hands and feet (burning feet syndrome)
Vitamin B_6 (pyridoxine)	Meats, vegetables, wholegrain cereals, yeast extracts	Forms coenzymes in amino acid metabolism	▪ Convulsions ▪ Kidney stones ▪ Sores in eyes and mouth ▪ Poor motor coordination
Vitamin B_{12} (cobalamin)	Liver, kidney, milk, eggs, cheese and meat	Form coenzymes in DNA metabolism Needed for maturation of red blood cells	**Pernicious anaemia** Malfunction of nerves due to the degeneration of axons of spinal cord Weight loss defective formation of red blood cells Muscle twitching
Biotin	Liver, yeast, vegetables, liver, kidney Synthesized by intestinal bacteria	Coenzyme in carboxylation reactions Coenzyme in fat, protein and carbohydrate metabolism	▪ Dermatitis ▪ Loss of appetite ▪ Nerve and muscle disorders
Folic acid	Green vegetables, nuts, yeast, liver, pulses, fish, legumes	Coenzyme in DNA synthesis and amino acid metabolism	Anaemia Gastrointestinal problems

Vitamin C (ascorbic acid)	Citrus fruits, dark green vegetables, potatoes	Stimulates synthesis of collagen fibres e.g. bones, cartilage and gums Antioxidant Improves iron absorption An electron carrier in respiration	Scurvy ▪ Bleeding gums ▪ Loosening of teeth ▪ Anaemia ▪ Red spots in the skin ▪ Degeneration of muscles and cartilage ▪ Joint pains ▪ Poor wound healing ▪ Increased susceptibility to infection

(b) Fat soluble vitamins: these are ones that are soluble in lipids e.g. vitamins A, D, E and K. fat-soluble vitamins tend to accumulate in fatty tissues of the body, and may even build up to lethal concentrations if taken in excess.

VITAMIN	MAJOR FOOD SOURCES	FUNCTIONS IN BODY	SYMPTOMS OF DEFICIENCY
Vitamin A (retinol)	Oranges, paw paw, green vegetables, carrots, liver, dairy food	Maintenance of normal epithelial structure Needed for formation of visual pigments	Night blindness Increased risk of infections especially of the mucous membranes Dry skin **Xerophthalmia** (drying and degeneration of cornea)
Vitamin D (calciferol)	Liver, fish oils, dairy products, action of sunlight on lipids in the skin	Absorption and metabolism of calcium and phoshorous Formation of bones	**Rickets** in children Weak bones Deformed bones **Osteomalacia** in adults Softening of bones
Vitamin E (tocopherols)	Liver, green vegetables, wheat germ oil, sunflower oil, peanuts	Antioxidant (prevents damage to phospholipids in cell membranes) Involved in formation of DNA, RNA and red blood cells Promotes fertility in rats Prevents haemolysis of RBC	Haemolytic anaemia Sterility in rats
Vitamin K (phylloquinone)	Green vegetables, synthesized by intestinal bacteria	Blood clotting	Failure of blood to clot

AN EXPERIMENT TO ILLUSTRATE THE IMPORTANCE OF VITAMINS IN DIET OF MAMMALS

In his investigations exploring the relationship between diet and growth in rats, **Frederick Gowland Hopkins** found that a diet consisting of protein, salts, fats, and carbohydrates **could not alone** support growth.

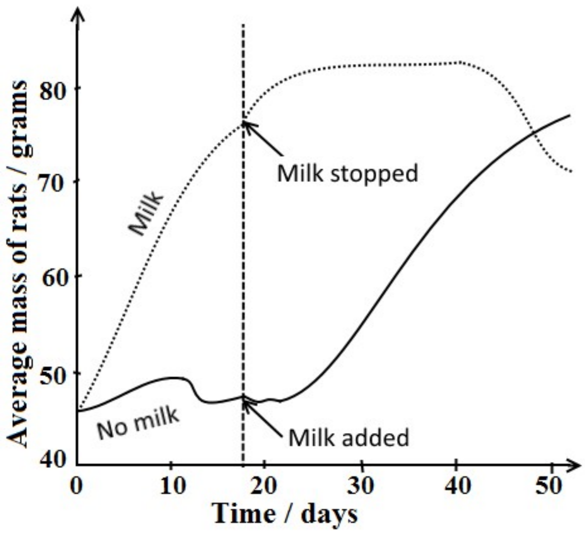
EXPERIMENT

Two groups of young rats were used.

Group A were fed on a diet of purified casein, starch, glucose, lard, minerals and water only for the first 18 days.

Group B were fed on a diet of purified casein, starch, glucose, lard, minerals and water **plus** an extra of $3cm^3$ of milk daily for the first 18 days.

After 18 days milk was given to group A rats and removed from group B's diet.



OBSERVATIONS

Group A rats increased in mass gradually from 0 day to 10 days, mass decreased gradually until about 12 days, mass remained relatively constant up to 22 days, then mass increased rapidly from about 22 days to 50 days

Group B rats increased rapidly in mass from 0 day to 18 days, then gradually increased in mass from 18 days to about 23 days, stopped growing from about 23 days to 40 days and gradually decreased in mass/lost weight thereafter.

CONCLUSION: Hopkins's experiments revealed that, to grow, animals needed small amounts of other substances he called **"accessory food factors"**- now known as **vitamins**.

EXPLANATION

Group A rats resumed growth and increased in weight after 18 days while **group B** rats stopped growing and lost weight after 18 days. While the $3cm^3$ of milk had an insignificant food value in terms of carbohydrate, fat, protein and minerals, the milk contains an extra nutrient which the rats needed to be able to grow and develop.

Related questions

1. **Why was it necessary to transfer milk from group B to group A half way through the experiment?**
   To ensure that all groups of rats are subjected to identical conditions e.g. feeding them on identical food so as to establish the effect of milk on growth while eliminating the possibility of other factors being responsible the observed differences in results e.g. choice of rats in one group (group A) may have been more sickly than those in group B etc.
2. **Why feeding rats on one type of protein (casein), not a variety is ruled out as a possible cause of growth stoppage and weight loss?**
   Although proteins are essential for growth and there are different types, proteins are hydrolysed in the body into different amino acids, and the body is able to make some amino acids for itself. Therefore, even though the rats were only getting casein this was enough to not have an effect on growth.
3. **Why while a diet of milk alone is sufficient for young animals, it is inadequate for adults?**
   Much as milk contains all the nutritional requirements like protein, carbohydrates (lactose), lipids, mineral salts, vitamins and water, some amounts may be nutritionally insufficient to meet the metabolic demands of adults.

Some people who are lactose intolerant can't digest the main sugar (lactose) in milk. In normal humans, production of lactase enzyme that digests lactose stops between ages of two and five years, which would result in insufficient ATP production.

MINERAL IONS

Minerals are inorganic nutrients which are involved in a wide variety of body functions. Some minerals called **macronutrients** are needed in relatively large quantities others called **trace elements (micronutrients)** are needed in small quantities.
The principle minerals required in the human diet, and their sources are as shown in the table below

(a) Macronutrients

Mineral	Major food source	Function(s)
Calcium (Ca^{2+})	Dairy foods, eggs, green vegetables	Constituent of bone and teeth; Needed in blood clotting; Needed in muscle contraction; Are enzyme activators
Chloride (Cl^{-})	Table salt	Maintenance of anion/cation balance; formation of hydrochloric acid in the stomach; maintenance of water balance.
Magnesium (Mg^{2+})	Meat, green vegetables	Component of bones and teeth; Enzyme activator.
Phosphate (PO_4^{3-})	Dairy foods, eggs, meat, vegetables	Constituent of nucleic acids, ATP, phospholipids (in cell membranes), bones and teeth.
Potassium (K^{+})	Meat, fruits and vegetables	Needed for nerve and muscle action and in protein synthesis
Sodium (Na^{+})	Table salt, dairy foods, meat, eggs, vegetables	Needed for nerve and muscle action; maintain anion/cation balance.
Sulphate (SO_4^{2-})	Meat, eggs, dairy foods	Components of proteins and enzymes

(b) Micronutrients

Mineral	Major food source	Function(s)
Cobalt (Co^{2+})	Meat	Component of vitamin B_{12} which is needed for the formation of red blood cells *Deficiency in diet leads to pernicious anaemia*
Copper (Cu^{2+})	Liver, meat, fish	Constituent of many enzymes; needed for bone and haemoglobin formation
Fluoride (F^{-})	Many water supplies	Improves resistance to tooth decay
Iodide (I^{-})	Fish, shellfish, iodised salt	Component of growth hormone, thyroxin *Deficiency in diet leads to Goitre; cretinism in children*
Iron (Fe^{3+} or Fe^{2+})	Liver, meat, green vegetables	Constituent of many enzymes, electron carriers, haemoglobin and myoglobin. *Deficiency leads to anaemia*
Manganese (Mn^{2+})	Liver, kidney, tea and coffee	Enzyme activator and growth factor in bone development *Deficiency leads to poor bone development*
Molybdenum (Mo^{4+})	Liver, kidney, green vegetables	Essential for metabolism of enzymes involved in DNA metabolism.
Zinc (Zn^{2+})	Liver, fish, shellfish	Enzyme activator, involved in the physiology of insulin

WATER

This makes up about 70% of the total body weight of mammals and serves a wide variety of important functions which were discussed in CHEMICALS OF LIFE

Note:

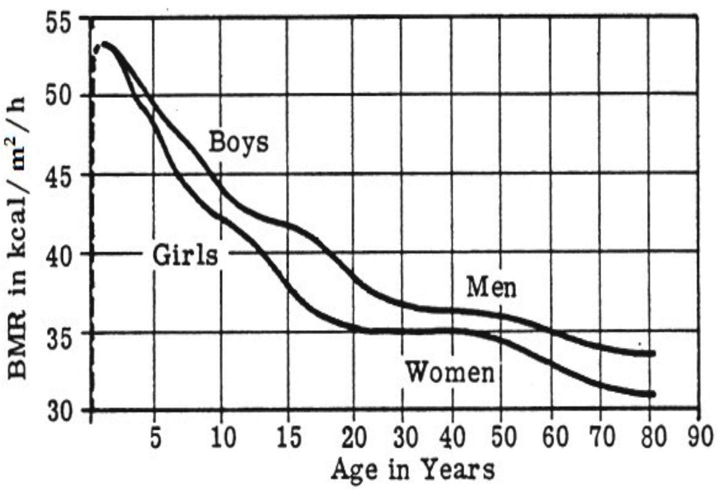
- ❖ Failure to replace water results in dehydration which can adversely affect physiological performance.
- ❖ Drinking too much water in a short time can lead to water intoxication, as water dilutes the tissue fluid and inflates cells. This can lead to metabolic disorders e.g. nausea, vomiting, muscle cramps and in extreme cases, death.

ENERGY-FOOD INTAKE AND CONSUMPTION

The body needs energy for **three main** reasons:

- ❖ Maintain the **basal metabolic rate** (**BMR**) – minimum energy a body requires at rest to perform vital functions like beating of the heart, breathing, peristalsis, impulse transmission, synthesis of biological molecules like proteins, etc.
- ❖ Sustain body activities like muscle contraction during movement, locomotion, etc.
- ❖ Generation of heat to maintain body temperature at about 37^0C

The graph below shows the variation in BMR of males and female with time



(a) state the

(i) Factors shown in the graph, which affect BMR: Age and sex

(ii) Other factors not shown in the graph, which affect BMR:

Muscle mass, Body size, level of physical activity, and Pregnancy and lactation, Diet, Drugs, Environmental factors e.g. temperature, Hormonal factors e.g. during pregnancy and lactation, Genetics

Explanation of variation in BMR with the factors in (a) (i) above.

Variation in BMR with sex

- ❖ At about 2.5 years and below, BMR in males is equivalent to BMR in females **because** infants have basically identical composition of carbohydrates, fats and protein.
- ❖ From about 2.5 years throughout life, BMR is slightly higher in males than in females **because** males usually have more body muscle than females while females usually have more fat than males per unit body mass and surface area. The more muscle tissue in the body, the more energy the body needs just to function e.g. to conduct impulses and biosynthesis compared to fat cells that largely store fat, with little biosynthesis.

Variation in BMR with age

- ❖ Infants and children have relatively high BMR than old-aged adults **because** at infancy and childhood much of the energy consumed is used in biosynthesis of cellular components required for growth. At adulthood, biosynthesis is greatly reduced since growth has stopped.

- From the age BMR was **first** determined to about 20 years of age, BMR decreases rapidly, then remains constant up to about 50 years of age and thereafter decreases slowly.
- From infancy to maturity at 20 years of age, biosynthesis of cellular components required for growth decreases rapidly, then remains constant by middle age until 50 years of age and thereafter decreases slowly, partly because of loss of muscle tissue, and also because of hormonal and neurological changes. Only repair and replacement of worn out cells occurs at slow rate by adulthood.

Explanation of variation in BMR with the factors in (a) (ii) above.

- **Muscle mass** (amount of muscle tissue in the body). Muscle requires more energy to function than fat. The more muscle tissue in the body, the more energy the body needs just to exist.
- **Body size:** Larger bodies tend to have a higher BMR because they usually have larger internal organs and fluid volume to maintain. Taller people have a larger skin surface, therefore have higher metabolism to maintain a constant temperature.
- **Genetics:** Genotypes and genetic disorders determine the rate of BMR.
- **Physical activity:** Regular exercise increases muscle mass and causes the body to burn kilojoules at a faster rate, even when at rest.
- **Hormonal factors (e.g. during pregnancy and lactation):** Hormonal imbalances caused by certain conditions, including hypo- and hyperthyroidism, can affect the metabolism. Expectant and lactating mothers require more energy to support foetal and baby growth respectively.
- **Environmental factors (e.g. temperature):** Weather can also have an effect on body metabolism; if it is very cold or very hot, the body works harder to maintain its normal temperature and that increases the metabolic rate.
- **Drug content in the body:** Caffeine and nicotine can increase your metabolic rate, while medications including some antidepressants and anabolic steroids can contribute to weight gain regardless of what you eat.
- **Diet:** Certain aspects of one's diet can also affect metabolism e.g. inadequate intake of iodine for optimal thyroid function can slow down body metabolism.

EFFECTS OF UNDERFEEDING AND OVERFEEDING

- If energy output exceeds energy input, carbohydrate reserves (glycogen) and fat reserves (adipose tissue) are respired and the person's body mass decreases. When carbohydrate and fat reserves exhaust, tissue protein is respired and the body wastes away.
- If energy intake exceeds energy usage over a period of time, carbohydrate is turned into fat and the person's body mass increases leading to **obesity** (overweight).

Disadvantages of obesity:

- the extra mass causes a person to get tired quickly
- increases chances of stroke/heart attack.

How an obese person can lose weight:

- Eating less energy food
- Taking more exercises to increase energy output

STARVATION AND GENERAL UNDEREATING

Starvation results from the inadequate intake of nutrients or the inability to metabolize or absorb nutrients this can be due to:

  - Prolonged fasting
  - Anorexia

- Deprivation of food
- Disease

SYMPTOMS OF STARVATION

Weight loss, dehydration, apathy, listlessness, withdrawal, increased susceptibility to infectious disease, discoloured hair color, flaky skin, and massive edema in abdomen and lower limbs causing the abdomen to appear bloated.

ADVERSE EFFECTS OF STARVATION

(i) Marasmus: occurs on account of extreme energy deficiency, typically from inadequate amounts of protein and calories.

Task: ***Describe the signs and symptoms of a child suffering from marasmus.***

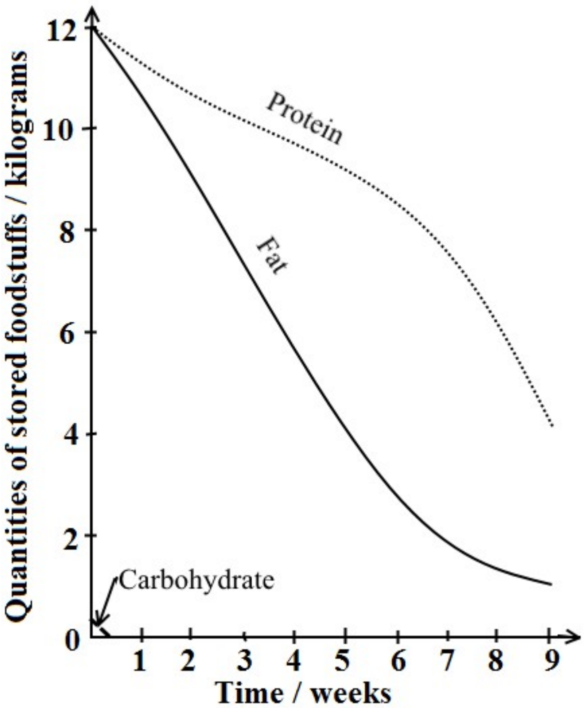
(ii) Kwashiorkor: is related to marasmus, affects children who are protein-energy deficient, and can result in edema (fluidic inflammation) and an enlarged fatty liver, resulting in the counterintuitive distending of bellies.

Task: ***Describe the signs and symptoms of a child suffering from Kwashiorkor.***

INTERVENTIONS AGAINST STARVATION

- Rehydration and feeding the starving person low-bulk food with much proteins, much energy and fortified with vitamins and minerals.
- Avoid foods high in bulk but low in protein content

The graph below shows changes in body energy reserves during starvation



Explanation of changes in energy reserves

- Glycogen, proteins, and fats are all metabolized during starvation.
- Exhaustion of blood glucose stimulates **glucagon** secretion and **insulin** secretion is inhibited.
- Within the first 24 hours, the very low glycogen amount stored in the liver and muscles decreases rapidly to depletion **because** glycogen is broken down into glucose for oxidation to release energy, while the amounts of fats and protein remain high. Anaerobic breakdown of glycogen in skeletal muscle is also stimulated.
- Within week 1, a few hours after depletion of carbohydrate/glycogen, the amount of fats decreases rapidly while the amount of protein decreases gradually until about 6 weeks of starvation.

✓ This is because fats are hydrolysed rapidly into fatty acids and glycerol while oxidation of amino acids releases energy.

✓ The liver metabolizes fatty acids into **ketone bodies** that are degraded to release energy. Accumulation of ketones causes **ketosis,** by condition characterised by blood becoming **acidic**

✓ Fatty acids in skeletal muscles are broken down to release energy, thus decreasing the use of glucose by tissues other than the brain.

✓ Glycerol is converted into small amount of glucose, but most of the glucose is formed from the amino acids of proteins.

✓ The brain begins to use ketone bodies, as wells as glucose, for energy.

- ✓ Dependency on fats for energy release decreases the demand for glucose, protein breakdown reduces but does not stop.
- ✓ The liver degrades **non-essential proteins** into glucose for the brain in a process called **gluconeogenesis,** which involves converting carbon skeletons into pyruvate or Krebs' cycle intermediates and excreting amino groups from the body as urea.

- From 6 weeks to 8 weeks, amount of fat decreases slowly to very low levels, while amount of protein decreases rapidly.
  - ✓ This is because as fat reserves / stores are getting depleted, metabolism of fats to release energy occurs gradually and the body begins to rapidly break down **essential proteins**, leading to loss of liver and heart function as these organs are broken down for fuel metabolizing proteins as the major energy source.
  - ✓ Muscles, the largest source of protein in the body are rapidly depleted.

Exercise 1

1. A group of rats were encouraged to over eat by feeding them with unlimited supplies of processed foods such as chocolate and cakes over a three-week period. These rats were called cafetarian rats. Over the same period, another group of control rats fed on unlimited supplies of their natural food.

	Average over 21 days	
	Cafetarian rats	Control rats
Energy content of food eaten(kj)	11670	6480
Gain in the body mass (g)	131	103
Gain in body fat (g)	66	40
Energy used (kj)	9440	4690

(i) What was the effect of feeding the rats on food other than their natural food? (1½ marks)

(ii) Determine the average gain in mass of the cafetarian rats over the control rats during the 21 days (03 marks)

(iii) State three features of the two groups of rats which should be kept the same (1½ marks)

(iv) Which chemical of life in the rats would have been responsible for most of the gain in mass? (½ mark)

(b) Explain the observation that some people eat enormous amounts of foods without putting on weight where as others become over-weight on quite small food intake:

(c) Using evidence from the data, explain why cafetarian rats were able to gain more weight than control rats. (2 marks)

(d) Why were control rats necessary in this experiment? (1 mark)

1. HOLOZOIC NUTRITION

This involves the consumption of complex organic food which is broken down inside the organisms into simple soluble molecules which are then absorbed and assimilated. It is mainly used by animals which have a specialized digestive tract, the alimentary canal.

BASIC PROCESSES INVOLVED IN HOLOZOIC NUTRITION

(i) Ingestion-is the taking in of food into the body. Organisms use a variety of feeding mechanisms which depend on the size and nature of food.

(ii) Digestion-is the breakdown of large organic molecules into smaller, simpler soluble molecules. This can be categorized basing on

(a) Mechanism of breakdown of food

- **<u>Mechanical (physical) digestion</u>**: This involves mechanical breakage of food by a variety of structures including teeth, radula, gizzard and rhythmic contraction of the muscles of the gut wall.
- **<u>Chemical digestion</u>**: This involves breakdown of food by a chemical process catalysed by enzymes. The type of chemical process which these enzymes catalyse during digestion is hydrolysis.

(b) Where digestion is taking place

- **<u>Extracellular digestion</u>**: where chemical digestion of food is completed outside the cells for example in mammals, food is digested in the alimenatry canal before it is taken up by the cells lining the gut.
- **<u>Intracellular digestion</u>**: where solid food particles are taken up by phagocytosis and then digested in the food vacuole with in the cell e.g. protists such as amoeba, paramecia and sponges. Intracellular digestion is more premitive since it is associated with simpler organisms.

(iii) Absorption: is the uptake of the useful soluble molecules from the digestive region, across a membrane into the body tissue proper.

(iv) Assimilation: is the utilization of the absorbed food molecules to provide either energy or materials to be incorporated into the body.

(v) Egestion: is the elimination/removal of undigested waste food materials from the body.

Holozoic organisms can be classified according to the type of food ingested:

- **Herbivores**: feed on plants.
- **Carnivores**: Feed on animals.
- **Omnivores**: Feed on a mixed diet of animals and plant materials.

Holozoic organisms can also be classified according to the form of food they ingest:

- **Microphagus feeders**: these are animals that take in food in the form of relatively small particles for example earthworms and filter feeders like mussels
- **Fluid feeders**: these ingest food in fluid form for example aphids, butterflies and mosquitoes.
- **Macrophagous feeders**: these take in food in the form of relatively large pieces, for example Hydra and sea anemones, which use tentacles to catch their prey, and large carnivores such as sharks.

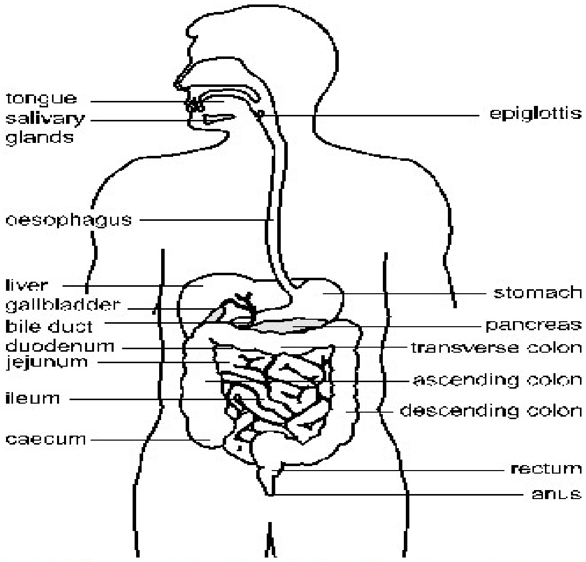
FEEDING MECHANISMS OF ANIMALS

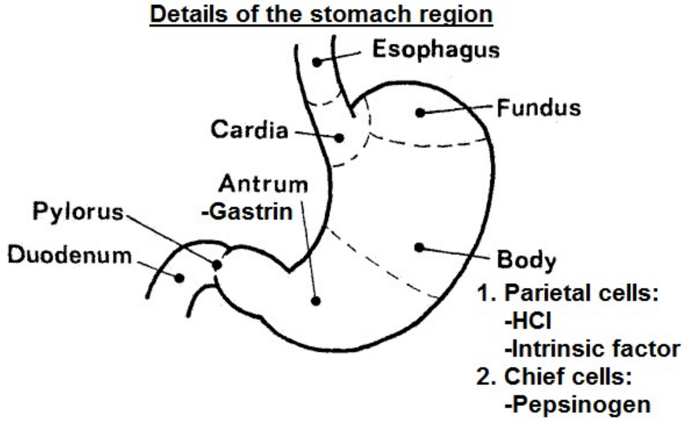
Nature of Food	***Mechanism***	***Organisms***	***Description***
Small particles	filter feeding / microphagous feeding;	Whales, sharks, flamingo, herring;	Body appendages (gills/beaks/keratinous plates) filter planktons/blue green algae suspended in water into body cavity /mouth then digestion occurs.
	Pseudopodial feeding	Amoeba	Pseudopodia enclose the food particle to form **food vacuoles** which on associating with **primary lysosomes** form **secondary lysosomes,** and after digestion, soluble products simply/facilitatively diffuse /actively move into the cytoplasm while undigested wastes are egested by **exocytosis**.
	Flagellate feeding	Euglena, sponges	Flagellar beating directs microscopic food particles to the region of ingestion, then intracellular digestion occurs.
	Ciliary feeding	Paramecium, *Amphioxus*	Cilia beating directs microscopic food particles to the region of ingestion, then intracellular digestion occurs.
	Tentacular Feeding	Sea cucumber	Mucus on tentacles traps food particles
	Setous feeding	Water flea (*Daphnia)*, culex mosquito larvae	Setae on appendages trap and direct small food particles into the digestive system.
	Mucoid feeding	Some molluscs	Mucus layer traps food particles, later swallowed and new layer formed.
Fluids or soft tissues	Fluid feeding;	Aphids, leeches, fleas, lice, mosquitoes, housefly, vampire bats/ Tapeworm, *Trypanosoma*;	Nutrient-rich fluid from the living host; is sucked by modified mouth parts; Already digested food is absorbed across the integument;
Large particles	Substrate feeding / deposit feeding;	Insect larvae / earthworms;	Non-selective swallowing of mud, silt, sand, etc after burrowing their way through the food / organic material;
	Bulk feeding / macrophagous feeding;	Land snail, caterpillar, termites, snakes, birds, seals, squids, many mammals, spiders, blowfly larvae, crabs, dragonfly, etc.	May involve scraping and boring (termites, snails) / Capturing and swallowing (snakes, birds, dogfish, seals) / Capturing, chewing and swallowing (squid, mammals) / Capturing, digesting externally and ingesting (spider, starfish, blowfly); using appendages like tentacles/pincers, claws/ poisonous fangs and jaws/ mandibles;

THE HUMAN DIGESTIVE SYSTEM

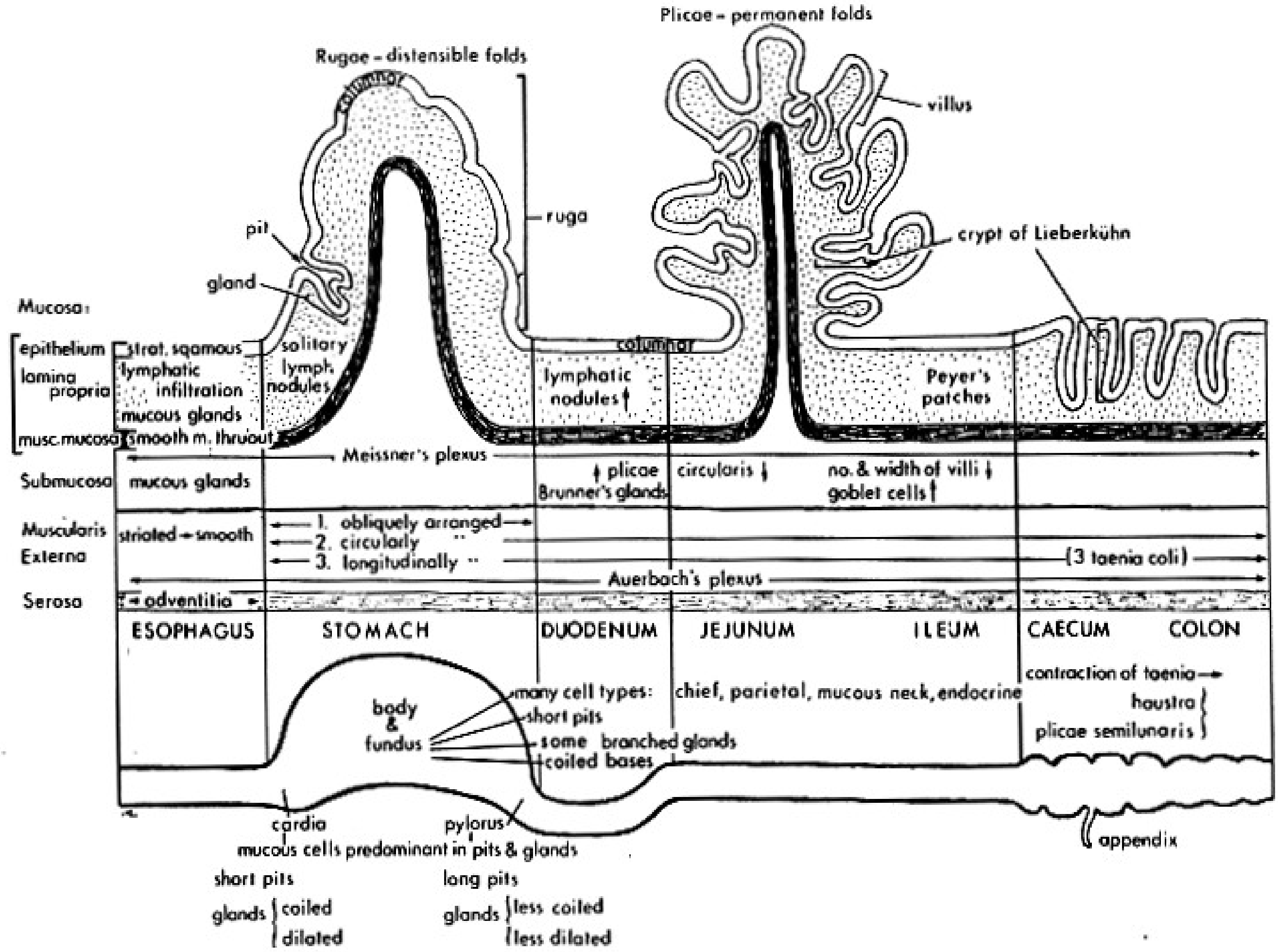
The human digestive system consists of:

1. **Alimentary canal:** Mouth, throat, oesophagus, stomach, small intestine (duodenum, jejunum and ileum), large intestine (colon, caecum and appendix), rectum and anus.
2. **Accessory structures:** Teeth, tongue, salivary glands, liver, gall balder and pancreas. These are organs, glands, and tissues that enable digestive processes, e.g. by secreting fluids /chemicals, but the food does not actually pass through them.





VERTICAL SECTION THROUGH THE ALIMENTARY CANAL



HISTOLOGY OF THE DIGESTIVE TRACT REGIONS

Although each different region of the gut possesses its own special characteristics, all have a basic common structure consisting of **four** distinct layers, the mucosa, submucosa, muscularis externa and serosa.

(i) **<u>Serosa (Adventitia):</u> this is the outer most layer made up of a**reolar connective tissue, same composition as mesenteries. It is called **serosa** when the outermost layer lies adjacent to the peritoneal cavity. it is called **adventitia** when the outermost layer is attached to surrounding tissue.

(ii) **<u>Muscularis externa:</u>** this consists of three muscle layers:

- ❖ inner oblique layer
- ❖ middle circular layer
- ❖ outer longitudinal layer

(iii) **<u>Auerbach's plexus (Myenteric plexus):</u>** these form a network of **unmyelinated** nerve fibers and ganglia between Muscularis externa longitudinal and circular muscles

Functions

- ❖ Brings about **peristalsis** when stimulated by pressure of food in the gut.
- ❖ Receives impulses from the **vagus nerve**
- ❖ Control of nerve impulses is **involuntary**
- ❖ Promotes secretion of intestinal juices
- ❖ Causes sphincter muscles to open, thus permitting food to pass from one part of the digestive system to another

(iv) **<u>Submucosa:</u>** this consists of loose connective tissue, collagen, large arteries and veins, lymph vessels, nerves and glands such as Brunner's glands present in the duodenum and Goblet cells present in the duodenum and ileum. Brunner's glands secrete alkaline mucus to neutralize acidic chyme from the stomach

(v) **<u>Meissner's plexus (Submucosal plexus):</u>** these form the nerve network of unmyelinated nerve fibres and associated ganglia located with the submucosa. it is believed to work against the myenteric plexus to control the muscular contractions more finely. In intestines, it works with Auerbach's plexus in producing peristaltic waves and increasing digestive secretions.

(vi) Mucosa: this is the inner most layer of the wall, it is divided into three layers i.e.

1. ***Muscularis mucosa: a t***hin layer of smooth muscle at the boundary between mucosa and submucosa, it contains both circular and longitudinal muscles
2. ***Lamina propria:*** this is formed by a very cell-rich loose connective tissue (fibroblasts, lymphocytes, plasma cells, macrophages, eosinophilic leucocytes and mast cells), it contains numerous cells with **immune function** to provide an effective **secondary line of defense** e.g. **Peyer's patches** which are lymphoid structures located in the ileum. Lamina propria of **villi** includes **lacteals** (**lymphatic capillaries**) while that of **intestinal villi** may include smooth muscle fibers. In **oral cavity** and **oesophagus**, lamina propria is located immediately beneath a stratified squamous epithelium
3. ***Surface epithelium***:Mucosal epithelium is highly differentiated along the several regions of the digestive tract. At the upper and lower ends of the tract, the epithelium is protective, **stratified squamous**, along the lining of the stomach, small intestine, and colon, the epithelium is **simple columnar** while in the stomach, surface epithelium contains mucous cells that secrete protective, alkaline mucus

   This is highly modified along the alimentary canal to form

- **Gastric pits:** the shallow indentations in surface epithelium of stomach mucosa into which gastric glands open.
- **Intestinal crypts** (**crypts of Lieberkühn**): these contain secretory **Paneth cells** at the deep end, which secrete lysosomal enzymes that contribute to protecting cells in the crypt lining.
- **Villi:** these are very small, typically densely-packed, invaginations of a mucosa that increase the surface area for absorption. These occur in the duodenum and ileum.
- **Rugae** are distensible folds in the **gastric** mucosa in the stomach

PRINCIPLES OF DIGESTION

Food obtained by organisms must be processed into small soluble molecules for absorption into the body tissue.

With the aid of structures such teeth, tentacles, claws, pincers, food is taken into the gut or alimentary canal or gastro-intestinal tract by the act of ingestion.

The food is then subjected to digestion which converts solid food into soluble compounds capable of being absorbed.

Digestion in humans is extracellular, this starts with physical digestion and then followed by chemical digestion. The digestive enzymes are secreted by the glands which are either outside the gut e.g. salivary gland and pancreas or located within the gut wall itself.

Physical and chemical processes of digestion go hand in hand i.e. Mechanical digestion chop up the solid lump of food into smaller pieces providing a larger surface area which aid chemical digestion Variable quantities of acids or alkali are also secreted to provide the correct PH for optimum functioning of enzymes.

DIGESTIVE ENZYMES

Digestive enzymes are broadly divided into three groups, though their details vary in different animals. They include:

(i) **Carbohydrases** which catalyses the breakdown carbohydrates
(ii) **Lipases** which catalyse the breakdown lipids (fats and oils).
(iii) **Proteases** which catalyze the break down proteins

HOW DIGESTIVE ENZYMES WORK

Enzymes are specific in the reactions they catalyse and therefore many enzymes are required to completely break down a large macromolecule. One enzyme breaks up a molecule into smaller sections and then others reduce these parts to their basic components.

For example:

Proteins are first attached by enzymes which break the peptide bonds/links in the interior of the molecule. Such enzymes called **endopeptidase** spilt the proteins and larger polypeptides into smaller pepetides. Examples of endopeptidases in human gut include pepsin and trypsin.

The smaller peptides are then attached by enzymes which break off their terminal amino acids. These enzymes are called **exopeptidase** and are of two types: the **aminopeptidases** which break off amino acids at the end of the polypeptide chain which has the amino(-NH_2) group and the **carboxypeptidase** which attach the end of the polypeptide chain with free carboxyl (-COOH) group. The same principle applies to the carbohydrases.

Certain enzymes break the glycosidic bonds in the interior of the polypeptin chain forming shorter polypeptides and other enzymes then attach the end of these polypeptide chains liberating free monosaccharides.
Fats, being smaller molecules, are broken down into fatty acids and glyceraol by single enzyme lipase. (check illustrations; BS pg 246)

THE PROCESS OF DIGESTION

Digestion in buccal cavity

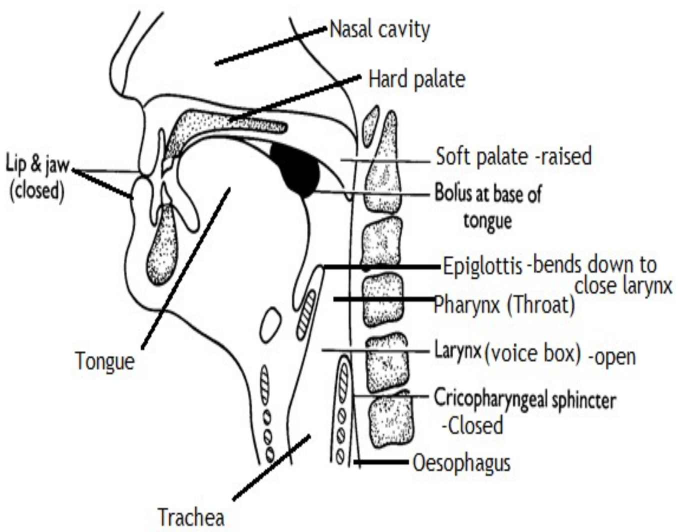
In the buccal cavity the food is subjected to the chewing action of the teeth (mastication). During chewing the muscular tongue moves food around the mouth and mixes and moistens it with saliva secreted by the salivary glands.
The secretion of saliva is initiated by sight, smell, taste or thought of food. The receptors on the taste buds on the tongue, the eyes and the olfactory (smell) receptors in the nose trigger the reflexes that bring about salivation. Saliva is a watery secretion which contains:

- **Enzymes salivary amylase (ptyalin):** This starts the chemical digestion of starch. It catalyses the hydrolysis of starch to disaccharide maltose
- Lysozyme: kills bacteria in the buccal cavity.
- **Mucous**: moistens and lubricates food in preparations for its passage down the oesophagus.
- Various **mineral salts:** including **sodium hydrogen carbonate** which maintains PH at around 6.5-7.5, the optimum pH for salivary amylase and **chloride ions** which speed up the activity of salivary amylase.

Towards the back of the buccal cavity the semi-solid, partially digested food particles are stuck together and moulded into a **bolus.**

Swallowing

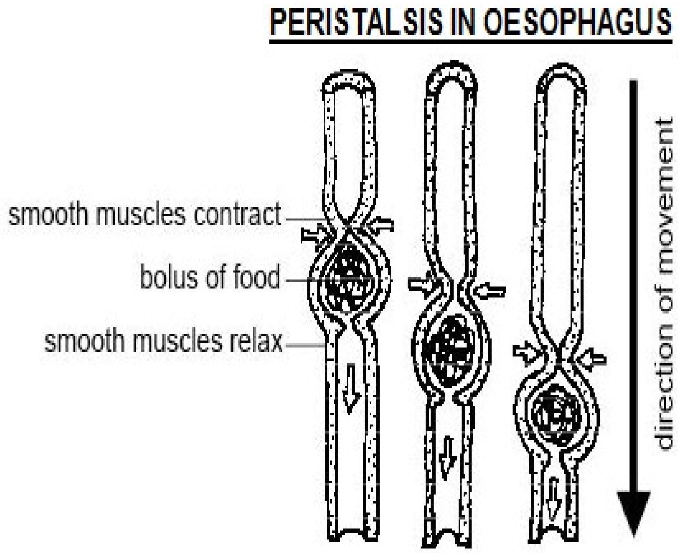
By the action of the tongue the bolus is pushed towards the pharynx. From here as result of reflex action it is swallowed into the oesophagus through the pharynx.



Note:

- Triggered by tactile stimulation of the soft palate and wall of the pharynx, swallowing is a reflex in which contraction of the tongue forces the bolus against the soft palate thereby closing the nasal cavity. The opening into the larynx, the glottis, is closed by the valve-like epiglottis, so the bolus enters the oesophagus. While all this is happening respiration is momentarily inhibited.
- The nerve centre responsible for controlling this swallowing reflex is located in the hind brain.

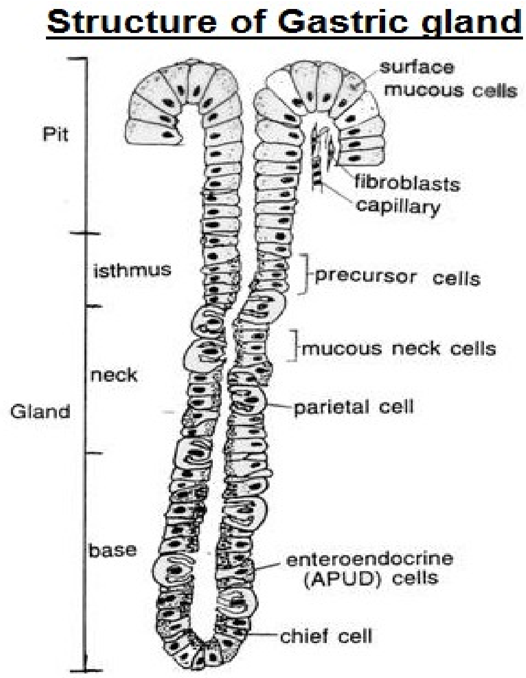
The bolus is propelled down the oesophagus to the stomach by **peristalsis.** The passage of food to the stomach is controlled by a narrow sphincter made up of smooth muscles called the **cardiac sphincter.**



During peristalsis, food is pushed through the gut by two layers of smooth muscles, the outer longitudinal and inner circular layer of muscle in the gut wall. The circular muscle contracts behind the bolus, narrowing the oesophagus and pushing the bolus down while the longitudinal muscles contract in front of the bolus, shortening this section and pulling it past the advancing bolus.

Digestion in the stomach

The stomach is highly elastic and muscular organ which can expand easily to hold large amount of food. The stomach wall is thick, highly folded and is dotted with numerous pits, the gastric pits leading to tubular **gastric glands**. The gastric glands secrete the **gastric juice.**
Arrival of food in the stomach stimulates secretion of **gastrin hormone** into the blood stream, which stimulates the **gastric glands** to secrete **gastric juice**, whose components include: ***mucus*****,** ***pepsinogen*****,** ***hydrochloric acid*** **and** ***intrinsic factor.***
The components of gastric juice are secreted by different cells and perform different roles as illustrated in the table below



Type of Cell	Secretion	Function
Mucous cells (i) Mucous surface cells (ii) Mucous neck cells	Mucus	Forms a barrier at the stomach lining, to prevent tissue digestion.
	Bicarbonate salts	Buffers gastric acid to prevent damage to epithelium
	Pepsinogen	Pepsinogen on activation to pepsin catalyses hydrolysis of protein to polypeptides

Chief / Peptic / zymogen Cells	Prorennin	Rennin coagulates soluble milk protein **Caseinogen** into insoluble **casein** in babies, whose slowed flow enables digestion by **pepsin**.
Parietal / oxyntic cells	Hydrochloric acid	❖ Activate pepsinogen to pepsin and prorennin to rennin. ❖ Provides the optimum PH for the action of the gastric enzymes. ❖ Kills bacteria thus acting as a defense mechanism. ❖ Denatures many proteins, their tertiary structure is altered making them easier to digest. ❖ Begins the hydrolysis of sucrose to glucose and fructose. ❖ Stops the working of salivary amylase enzyme
	Intrinsic factor	❖ Forms a complex which enables absorption of vitamin B_{12} that is necessary in red blood cell formation ❖ Little *intrinsic factor* causes **pernicious anemia**

Note:

- ❖ Pepsinogen is also activated by pepsin itself this is also termed as autocatalysis.
- ❖ These enzymes are secreted in an inactive form because they are proteolytic enzymes and might otherwise attack the tissues themselves before being released.
- ❖ Once secreted, the active forms of the enzymes are prevented from attacking the tissues by the mucus lining the stomach wall. The mucus is secreted by the **mucous-secreting cells** situated towards the neck of the gastric glands.

While the enzymes are working, mechanical digestion of the food by the churning action of the thick muscular wall of the stomach pound the food into a semi-fluid state called **chyme.**
The cardiac and pyloric sphincter prevents the uncontrolled exit of food from the stomach. Both act as valves and retain food in the stomach for periods of up to four hours. Relaxation of the pyloric sphincter releases small quantities of the food into the duodenum at regular intervals.

Assignment:

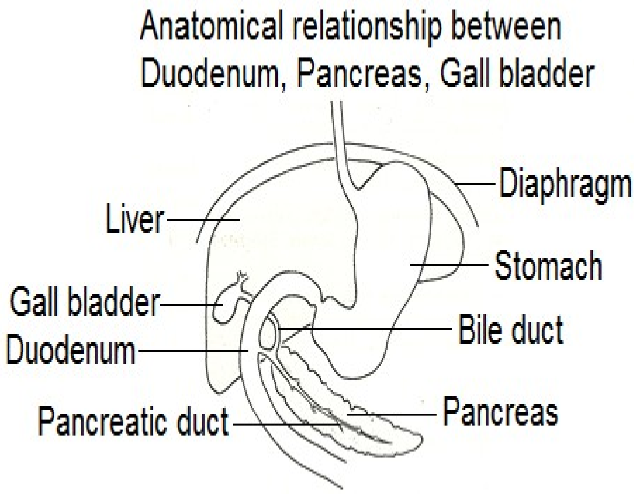
1. Give the functions of the stomach in the process of digestion.
2. How is the structure of the stomach related to its functions?
3. What are the functions of gastric juice?
4. Read and write notes about how HCl produced by oxyntic cells is formed. Ref. FA pg 128)

Digestion in the small intestine

The first part of the small intestine is the **duodenum**. It short, about 25cm long and the pancreatic and bile duct opens in it. The duodenum leads to the **ileum** which is long (3m long). The submucosa and mucosa together are folded.

(a) The duodenum

Peristaltic contraction of the stomach keeps the chyme moving toward the duodenum.
The passage of food into the duodenum is controlled by a ring of muscle, the **pyloric sphincter**, situated immediately between the far end of the stomach and the duodenum.
The duodenum is the main seat of chemical digestion in the gut. The agents of digestion are from three sources: **the liver**, **pancreas** and **wall of the small intestine**.
The liver produces **bile** which is stored in the gall bladder. From the gall bladder the bile flows through the bile duct into the duodenum.



Bile is a mixture of substances, not all of which are involved in digestion. The digestive components are:

- ❖ The **bile salts**, sodium taurocholate and glycocholate. These emulsify fats by lowering their surface tension, causing them to break up into numerous tiny droplets. This increases the total surface area of the fat, thereby facilitating the digestive action of the enzyme lipase.
- ❖ **Sodium bicarbonate**, which neutralizes the acid from the stomach. This makes the pH of small intestine distinctly alkaline which favours the action of the various enzymes.

Note: Bile salts are not enzymes: they are not proteins and have no chemical effect on fats, only physical effect of emulsifying them.
The **pancreas** secretes pancreatic juice containing digestive enzymes into the duodenum via the pancreatic duct. These enzymes are produced by groups of cells within pancreas. They include:

- **Pancreatic amylase**- complete the hydrolysis of starch to maltose which began in the mouth
- **Pancreatic Lipase**-breaks down lipids (fats and oils) to fatty acids and glycerol
- **Trypsinogen**-which when converted to trypsin by **enterokinase** secreted from microvilli, digests proteins into smaller polypeptides and activates more trypsinogen into trypsin
- C**hymotrypsinogen**-which is converted to chymotrypsin that digests proteins to amino acids.
- **Carboxypeptidases**-that converts peptides to amino acids
- **Nucleases**-break down nucleic acids to nucleotides

Note: The pancreatic juice has a variety of peptidases which release free amino acids from polypeptide chains. However, protein digestion is completed mainly by enzymes produced in the wall of the small intestine.
Pancreatic juice also contains **mineral salts** (e.g. sodium hydrogen carbonate) which neutralizes acid chyme from the stomach and so provide a more neutral pH in which the intestinal enzymes can operate.

(b) The ileum

The secretory cells in the wall of the small intestine produce mucus and a variety of enzymes (intestinal juice/succus entericus) whose collective function is to complete the digestion of the various compounds already started by the other secretions. These enzymes include:

- **Maltase** which hydrolyses maltose to glucose, thus completing the digestion of starch.
- **peptidases** which break down polypeptides to free amino acids thereby completing the digestion of proteins.
- **Sucrase** which hydrolyses sucrose (cane sugar) to glucose and fructose;
- **Lactase** which hydrolyses lactose (milk sugar) to glucose and galactose, and nucleotidases which split nucleotides into their constituent subunits.
- **Enterokinase**-which activates trypsinogen.

Note:

1. Alkaline fluid (due to sodium hydrogen carbonate) and mucus of the intestinal juice are secreted by coiled **Brunner's glands** whereas the enzymes are produced by cells at the bottom of the narrow tubes called **crypts of Lieberkühn.**
2. **Crypts of Lieberkühn** are formed when the epithelium folds at the base of the villi. It is here that new epithelial cells are made to replace those which are constantly being shed from the villi (the average life of these cells is about five days). The cells secrete most of their enzymes as they move up the sides of the villus.
3. All the enzymes involved in digestion in the small intestine, apart from those made by pancreas are bound to the cell surface membranes of the microvilli of the epithelium or located within the epithelial cells. Therefore it is at these sites that final breakdown of carbohydrate (disaccharides to monosacharides), and protein (dipeptides and some tripeptides to amino acids) occurs. (*Check illustration: BS pg 247; fig 8.23*)
4. The **Paneth** cells at the base of the crypts secrete lysozyme, the antibacterial enzyme.
5. Throughout the small intestine, are special epithelial cells called **goblet cells** which secrete mucus.

How is the flow of the secretions into the small intestine controlled? (See control of digestive secretions)

Assignment 1:

1. Describe how each of the following parts of the human digestive system their structure is related to their function(s)

(i) **Mouth (ii) Stomach (iii) Intestine (iv) Liver (v) pancreas**

FOOD ABSORPTION

Absorption of the soluble end-products of digestion occurs through the **villi** of the ileum.

A large surface area is required for efficient absorption to occur. The wall of the ileum achieves this in the following ways:

- *It is very long*
- *Its walls are folded (folds of Kerkring) to provide a large internal projection,*
- *The folds themselves have numerous finger-like projection called villi*
- *The epithelial cells lining the villi bear numerous microvilli which further increase the surface area for absorption*. (check illustration: BS pg 245 fig. 8.2)

The villi contain smooth muscles which enable them to contract and expand, this bringing them into contact with newly-digested food.

The walls of the villi are richly supplied with blood capillaries to carry away the absorbed food.

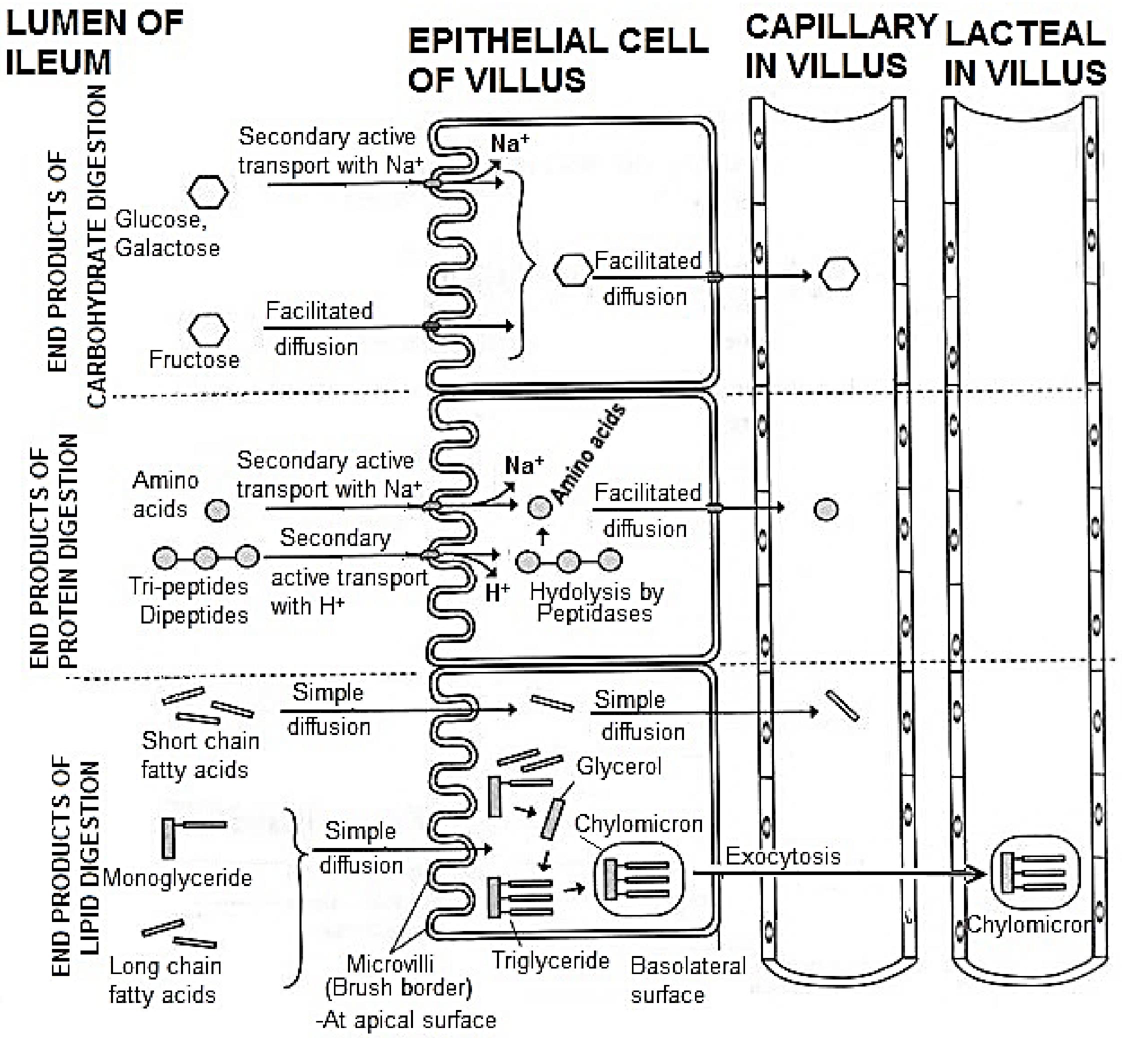
Structure of the villus *(Draw and label the structure of villus; use any advanced biology text book)*

Monosaccharide and amino acids are absorbed are absorbed either by diffusion or active transport across the epithelial lining of the villi into the blood capillaries beneath. The blood capillaries join to form the hepatic portal vein which delivers the absorbed food the liver.

Fatty acids and glycerol are absorbed into the columnar epithelial cells lining the villi where they are reconverted into lipids. Proteins present in the epithelial cells coat the lipid molecules to form lipoprotein droplets called chylomicrons. These pass out of the epithelium cells by exocytosis into the lymphatic vessels in the villi as white emulsion of minute globules. This gives the lymph vessels a milky appearance, for which reason they are known as lacteals.

The lipoprotein droplets are carried by the lymph in the lymphatic system to veins near the heart where they eventually enter into blood plasma. An enzyme in the blood plasma then hydrolyses the lipids back to fatty acids and glycerol in which form they are taken up by the cells.

A SUMMARY OF THE PROCESS OF ABSORPTION OF END PRODUCTS OF DIGESTION



In organic salts, vitamins and water are also absorbed in the small intestine.
Water is extensively absorbed in the **colon** whose wall is much folded for this purpose. Some metabolites and inorganic substances such as calcium and iron in excess in the body are exerted in the large intestine as salts. The colon also has symbiotic bacteria which synthesis amino acids and some vitamin, especially vitamin K, which are absorbed into bloodstream.
Thus, by the time it reaches the rectum, indigestible food is a semi-solid ready to be egested through the anus as **faeces**. This process is called **defaecation** and it is facilitated by the lubricative effect of large amounts of mucus which are secreted by the lining of the rectum.

Adaptations of the ileum to absorption of food

- long and highly folded for increased surface area in absorption of soluble food substances.
- has numerous finger-like projections called villi which increase the surface area for absorption of soluble food.
- Ileum epithelial cells have microvilli which further increase the surface area for efficient food absorption.
- epithelium is thin to reduce diffusion distance for soluble food substances to allow fast rate of diffusion.
- epithelium is permeable to allow movement of soluble food substances across with minimum resistance.
- Ileum villi have dense network of blood capillaries to rapidly carry away digested food from the absorption area which maintains a steep diffusion gradient.
- Ileum villi have permeable lacteal, a branch of the lymphatic system for carrying away fats
- Ileum epithelial cells have numerous mitochondria to generate ATP energy for active transport of some ions.
- Ileum inner surface is lined with a lot of mucus to prevent autolysis (self-digestion) by proteolytic enzymes.

Exercise 2

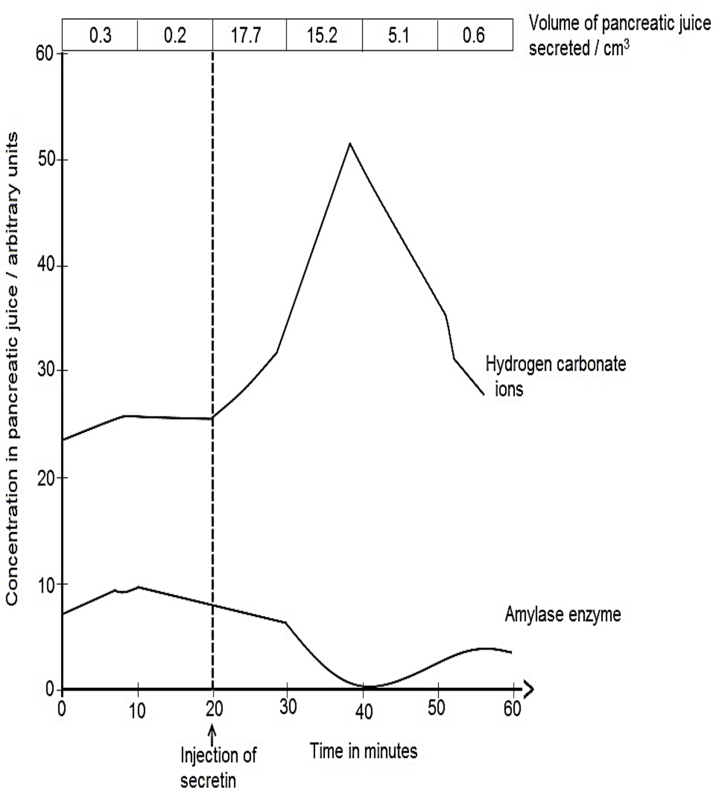
1. (a) Explain how the structure of villi in the small intestine is related to absorption of digested food.

(b) The table below shows experimental results of the rate of absorption of hexose sugars (Glucose, galactose and fructose), and pentose sugars (xylose and arabinose) by pieces of living intestine and by pieces of intestine poisoned with cyanide. The results are shown as relative to the rate for glucose.

	Rate of absorption	
	By living	**By poisoned**
Glucose	1.00	0.33
Galactose	1.10	0.53
Fructose	0.43	0.37
Xylose	0.31	0.31
Arabinose	0.29	0.29

Explain the observed rates of sugar absorption shown by the two tissues.

2. The graph below shows how an injection of secretin affects the secretion of pancreatic juice by the pancreas.



(a) Use the graph to explain the effect of secretin on pancreatic secretion.
(b) (i) From the graph, comment on the composition of pancreatic juice.
(ii) State any other digestive secretion stimulated by secretin.
(c) Certain types of ulcers are thought of to be made worse by the production of too much acid from the stomach. Medical doctors have used several methods to treat such ulcers. Suggest how each of the following treatments might reduce the amount of acid secreted by the stomach:
(i) Cutting the gastric vagus nerve.
(ii) Blocking the action of acetylcholine by giving the patient atropine.

. **(a)** Why are pepsin and trypsin secreted in an inactive form. (3 marks)
(b) Why are endopeptidases secreted earlier in the digestive system than exopeptidases? (3 marks)
(c) Explain how facilitated diffusion and active transport contribute to the absorption of glucose from the ileum. (4 marks)

CONTROL OF DIGESTION IN HUMANS

A combination of hormonal and nervous stimulations and inhibitions of the gut that regulate the secretion of digestive juices in the gut.

IMPORTANCE OF CONTROL OF DIGESTION

- ❖ Secretion of digestive juices depends on respiratory energy therefore unnecessary secretion must be prevented to avoid wastage of respiratory substrates.
- ❖ Secretion of **proteolytic enzymes** in inactive form prevents **autolysis** (self-digestion of tissues).

Nervous and hormonal control of digestive secretions

The production of digestive secretions must be timed to coincide with the presence of food in appropriate region of the gut. In mammals, the production of digestive secretions is under both nervous and hormonal control.

Saliva

Secretion of saliva into the buccal cavity from the salivary glands is controlled by two types of reflexe action: a **simple unconditional (inborn) reflex** and **conditioned reflex**.

- A simple unconditioned reflex occurs when food is present in the buccal cavity. Contact of food with the taste bads of the tongue stimulates receptors sensitive to sweet, salty and bitter tastes.

Sensory neurons carry nerve impulses from these receptors to the brain. Nerve impulses travel along motor neurons from the brain to the salivary glands, which are stimulated to secrete saliva.

- Conditioned reflexes of seeing/sight, smelling or thinking of food also operated in the same way as simple unconditioned reflex described. The eye, the ear and the olfactory (smell) receptors in the nose are the important receptors.

Gastric juice

Secretion of gastric juice occurs in three phases: nervous phase, gastric phase and intestinal phase.

1. **Nervous phase**: the presence of food in the buccal cavity and its swallowing trigger reflex nerve impulses which pass along the vagus nerve from the brain to the stomach. The sight, smell, taste and even the thought of food can trigger the same reflex. The gastric glands of the stomach are stimulated to secrete gastric juice. This takes place before the food has reached the stomach and therefore prepares it to receive food. This phase lasts for approximately one hour.
2. **Gastric phase**: takes place in the stomach and it involves both nervous and hormonal control.
    - Stretching of the stomach by the food it contains stimulate the stretch receptors in the wall of the stomach. These send nerve impulses to Meissner's plexus in the submucosa, which in turn sends impulses to the gastric glands, stimulating the flow of gastric juice.
    - Stretching of the stomach by the presence of food also stimulates special endocrine cells in the mucous to secrete the hormone **gastrin**. The gastrin travels via bloodstream to the gastric glands and stimulates them to produce gastric juice rich in hydrochloric acid.
    - Presence of fats in the stomach initiates the production of **enterogasterone** hormone from the stomach wall which reduces the churning motion of the stomach and reduces the flow of acid gastric juice.
3. **Intestinal phase:** When acidified chyme enters and makes contact with the walls of the duodenum, it triggers both nervous and hormonal response.
    - Receptors in the small are stimulated by the presence of food, the reflexes, which pass through the brain inhibit secretion of gastric juice and slow the release of chyme from the stomach. This prevents too much food being released into the small intestine at once.
    - In addition, the mucosa of the duodenum produces two hormones, **cholecystokinin** (CCK) also known as pancreozymin) and **secretin.** The two hormones are taken in bloodstream to the stomach, pancreas and the liver. In the stomach, secretin inhibits secretion of gastric juice and CCK inhibits stomach emptying.

Pancreatic juice and bile

Secretin and CCK are produced in the duodenum when acidified chyme enters it from the stomach. Secretin is produced in response to the acid whereas partially digested fats and protein stimulate CCK production.

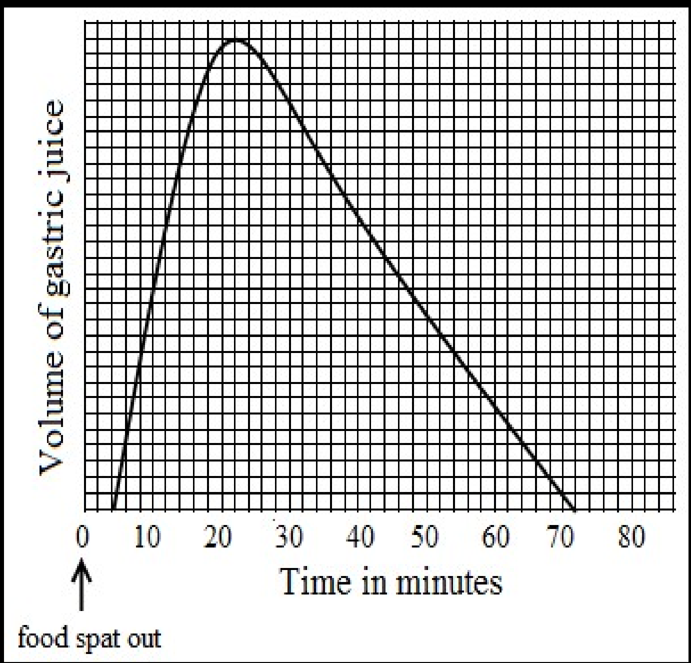
- **Secretin** is an anti-acid hormone and it stimulates the production of hydrogen carbonate ions in the pancreas and the liver making the pancreatic juice and the bile more alkaline. This helps to neutralize the acid from the stomach.
- **CCK** stimulates secretion of digestive enzymes by the pancreas and contraction of the gall bladder to release bile into the duodenum.

The secretion of bile and the pancreatic juice is also stimulated by nervous reflexes. During the nervous and gastric phases of gastric digestion, the vagus nerve also stimulates the liver to secrete bile and the pancreas to secrete enzymes.

(check summary of endocrine control BS pg 250, table 8.5)

Exercise 3

1. The graph below shows the amount of gastric juice produced by the stomach of an individual who had just chewed some food. The food was spat out after being chewed, and none was swallowed.



(a) Name two constituents of gastric juice

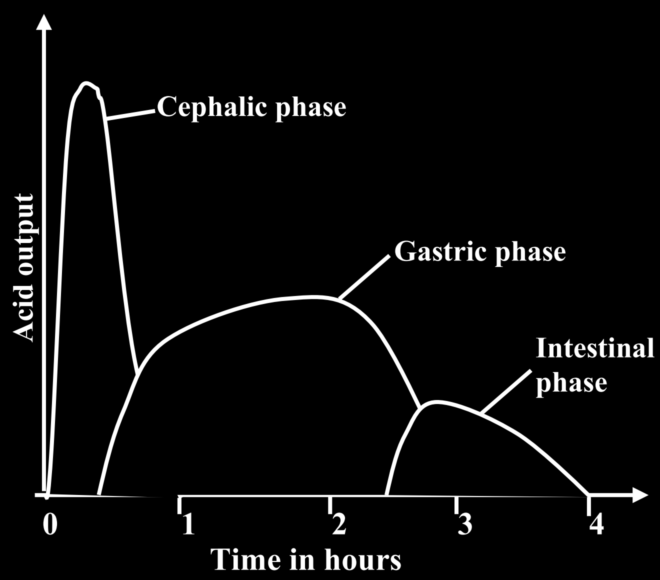
(b) Assuming that no traces of food got down into the stomach, explain how the secretion of gastric juice was brought about.

(c) (i) How much time elapsed between the moment the food was spat out and the moment gastric juice started to be produced?

(ii) Account for the delay in (c) (i) above.

(c) If the stomach of an adult person is surgically removed through an operation, suggest with reasons, the more suitable diet for such a person after recovery from the operation.

2. The figure below shows the phases of gastric secretion related to acid output in a human during digestion.



(a)Explain the changes in acid output as shown on the graph.

Cephalic phase (04 marks)

Gastric phase (03 marks)

(iii) Intestinal phase (04 marks)

(b) Suggest why the secretions of the digestive enzymes occur only when there is digestive work to be done. (01 mark)

3. (a) Explain the benefit of the secretion of saliva being controlled by both a simple reflex action and a conditioned reflex action. (3 marks)

(b) Explain the role of cholecystokinin in the control of the secretion of pancreatic juice.(3 marks)

4.(a) In what ways is auto digestion prevented in the human gut? (2marks)
(b) Describe the functions of the pancreatic secretions (13 marks)
(c) Explain how the release of pancreatic secretions is controlled (5 marks)

ASSIMLIATION OF FOOD

Assimilation: The process by which simple soluble food substances are absorbed and used by body cells in the various ways.

The products of digestion are brought directly through the hepatic portal vein to liver, which controls the amount of nutrients released into the mainstream blood circulatory system.

Assimilation supports growth, development, body renewal, and storing up of reserves used as a source of energy.

Metabolism: Chemical processes within cells of an organism. It involves:

(i) **Catabolism:** Break down of complex molecules into simpler molecules, with release of energy**.**

(ii) **Anabolism:** Assembly / building up of complex molecules from simple molecules using energy.

FOOD	HOW ABSORBED FOOD IS USED IN THE BODY	HOW BODY DEALS WITH EXCESS
Glucose	❖ ATP synthesis in respiration ❖ Formation of glycoproteins involved in cell to cell recognition mechanisms. ❖ For production of mucus ❖ Excess carbohydrates are stored in the form of glycogen in the liver and muscles.	❖ Stored in the liver as glycogen. ❖ Excess carbohydrates may be converted into fats for storage.
Amino acids	❖ Formation of protoplasm of cells during growth ❖ Production of enzymes and antibodies ❖ Formation of body structures such as hairs, nails, hooves, cell membranes ❖ Oxidised to release ATP energy during severe starvation i.e. in the absence of glucose and fats. ❖ Formation of hormones e.g. insulin ❖ Formation of plasma membrane components e.g. glycoproteins, channel proteins	❖ Deaminated in the liver to form urea, which is expelled by kidneys. ❖ Some amino acids are **transaminated** to produce a different amino acid
Fatty acids and glycerol	❖ The long chain fatty acids are desaturated in the liver and are then broken down to carbon dioxide and water by successive oxidations. ❖ Some of it can be converted into glucose ❖ Some used to form various structures which are components of cells e.g. phospholipids	❖ Stored as fat under the skin

ADAPTATION TO DIET

(a) Adaptations of a herbivore to its diet.

Plants material is relatively tough and largely indigestible by mammals without the aid of microorganisms. The first essential of its digestion is to grind up the vegetation, so disrupting the tissues and increasing its surface area. Animals such as cattle which consume predominantly plant material are called herbivores and they posses specialized dentition which may include the following features:

- ❖ A horny pad which replaces the upper front teeth (incisors and canines) against which the chisel-shaped lower incisors and canines bite when cropping grass.
- ❖ A pronounced gap, the diastema, between the incisors and premolars. This provides space in which the grass being chewed is kept separate from that which is freshly gathered.
- ❖ The cheek teeth (molars and premolars) have ridged surface which form an effective grinding surface.
- ❖ The jaws easily move from side to side to allow food to be broken down between teeth
- ❖ The teeth grow continuously throughout the herbivore's life. This essential as grinding action of the teeth wears them away.
- ❖ Large masseter muscle provides the power for grinding the vegetable matter.
- ❖ The alimentary canal is relatively long because digestion of plant material id difficult.
- ❖ The stomach of herbivorous ruminants is divided into a number of chambers, some of which produce digestive enzymes to break down food. Others including the rumen, house bacteria and protozoa which produce the enzyme cellulase essential to break down the cellulose which constitutes the bulk of the food ingested.

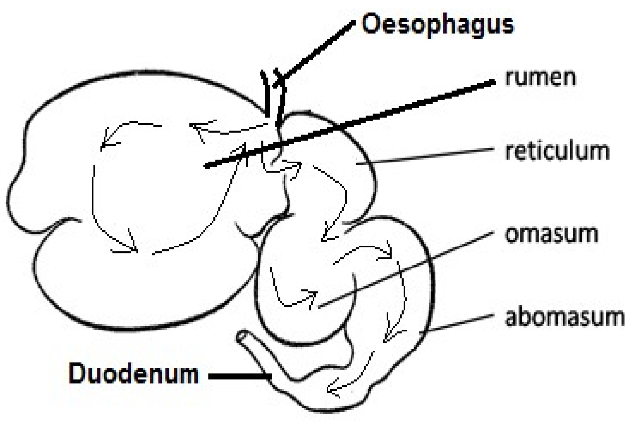
Digestion of cellulose in ruminants

Ruminants: are the mammals, which have a 4-chambered stomach for the digestion of plant-based food.

Rumination involves regurgitation of fermented grass known as **cud**, chewing and re-chewing it again to further break down plant matter and stimulate digestion. Ruminating mammals include cattle, goats, sheep, giraffes, deer, camels, antelope, etc.

The digestive system of a ruminant has complex stomach with four chambers i.e. **rumen**, **reticulum, omasum** and **abomasums.** The ruminant harbours millions of mutualistic (symbiotic) microorganisms in the first complex chamber, the rumen.

Four-chambered stomach showing food movement during feeding



Unchewed food is passed to the rumen by act of swallowing and later regurgitated bit by bit into the mouth for chewing.
In the rumen fluid, the cellulose-digesting bacteria digest cellulose by producing cellulase enzyme. Some of the products of digestion are absorbed by the microorganisms, the rest by the host. The bacteria are anaerobic (carry out fermentation in rumen) and the acids produced by them are neutralized by alkaline saliva, often produced in large quantities. The presence of microorganisms is essential to the ruminant since is unable to manufacture cellulase. The waste gases mainly carbon dioxide and methane produced as result of fermentation are expelled via mouth of the ruminant. Partially digested food 'cud' is passed to the second chamber, the **rectum** where it is formed into pellets. It is then regurgitated and thoroughly rechewed. This is called **rumination** or **'chewing curd'**. The food is then reswallowed and undergoes further fermentation. Then the partially digested food goes to the **omasum** which acts as a strainer-retaining large pieces requiring further breakdown and passing on the small particles to the **obomasum** (true stomach) which corresponds to the stomach in humans. From here onwards food undergoes digestion by usual mammalian digestive system.

Note:

- ❖ The relationship is mutualistic as both gain benefit. The ruminant acquires the products of cellulose breakdown which it would not obtain alone, and the microorganisms receive a constant supply of food and a warm, sheltered environment in which to live
- ❖ Because plant material is so difficult to digest, herbivorous mammals generally have much long alimentary canals than their carnivorous relatives
- ❖ In non-ruminants such as the rabbit, cellulose digestion is effected by the microorganisms in the caecum and appendix.
- ❖ In non-herbivorous mammals like humans, the caecum and appendix are functionless.

Assignment 2: ***Explain why a termite is able to digest wood.***

Adaptations of a carnivore to its diet

Carnivores such as a dog eat meat, which is mainly the muscle of another animal. This is rich in nutrients and therefore a much more concentrated source of food than plant material. Once captured and ingested, the digestion of meat presents little problem.

(b) Adaptations of carnivorous mammals to their diet

- ❖ The incisor teeth are sharp and used for nipping and biting.
- ❖ The canines are long and pointed for piercing and killing the prey and tearing flesh from the body
- ❖ The molars and premolars have a number of sharp pointed cusps. The last upper premolar and the first lower molar on each side of the mouth are particularly large and known as carnassials teeth
- ❖ The teeth of the upper jaw tend to overlap those of the lower jaw. The carnassials teeth therefore slide past one another and slice the meat into manageable pieces.
- ❖ The muscles of the jaw are well developed and powerful. This enables carnivores to grip the prey firmly during the kill and helps in crushing bone.
- ❖ There is no lateral jaw movement as in herbivore. Such movements lead to easier dislocation of the jaw, a distinct disadvantage when trying to grip struggling prey.
- ❖ Vertical movement of the jaw is less restricted, allowing wide gape for capturing and killing prey.
- ❖ The alimentary canal is short, reflecting the relative ease with which meat can be chemically digested.

2. SAPROTROPHIC NUTRITION –sometimes called saprobiontic or saprophytic.

This Involves feeding of complex organic food from the bodies of decaying organisms. Organisms which feed in this way are called **sprotrophs**/**saprophytes**/**saprobionts**. The saprotrophs either readily take up the food material which is already in soluble form or they secrete enzymes onto the solid food material, where it is digested externally into simple soluble molecules which are then absorbed and assimilated by the saprotrophs. It carried out by many fungi (e.g. mucor, Rhizopus and yeast), bacteria and protists.
Saprophytes do not have digestive system.
In nature saprotrophs are decomposers carrying out the decay of the corpses of animals and dead plants thereby degrading them into the component nutrients they contain which can be recycled
Assignment 3:
1. Describe the importance of decomposers in
(i) an ecosystem
(ii) carbon and nitrogen cycles
2. State the characteristics of saprophytism

Importance of saprophytes

- Saprotrophs contribute to the removal of dead organic remains of plants and animals by decomposing them.
- Saprotrophs provide important links in nutrient cycles. This is because the activities of saprotrophs bring about the decay of dead bodies and release from them elements that can be used by plants and various microorganisms to synthesise new organic substances. In this way they return the vital chemical elements from the dead bodies of organisms to living ones.
- Saprophytes have other importance including brewing e.g. yeast cells, food processing e.g. cheese and yoghurt, used as food e.g. mushroom, industrial processing e.g. leather tanning, sewage treatment and food spoilage.

3. SYMBIOSIS
Symbiosis is the living together in close association of two or more organisms of different species. Many associations involve three or more partners. Nutrition is commonly involved in symbiosis. The three common types of symbiotic relationships are:
(a) Mutualism
Mutualism is a close association between two living organisms of different species which is beneficial to both partners.
Examples include
(i) Bacteria and plants
Nitrogen fixing bacteria of genus *Rhizobium* form mutualistic association with roots of leguminous plants. In this association the bacteria gains sugars from the plants which they use to synthesise ATP needed in the conversion of ammonia to nitrates in the process of nitrogen fixation and also protection in the nodules, the legumes gain by absorbing nitrates produced by nitrogen fixation reactions of the bacteria

(ii) Mycorrhizas:

This is a relationship between fungi and the roots of plants. In this association, the fungus gains sugar from that being translocated to the roots of the plant, the plant gains

- Protection from bacteria and other parasites attacking by antibodies produced by the fungus
- Increased mineral absorption from the soil by utilizing some of the minerals absorbed by the fungus.

(iii) Algae and coelenterates

This is a symbiotic association between the common green hydra chlorohydra viridissima and a green alga known as Zoochlorella which lives inside its epidermal cells

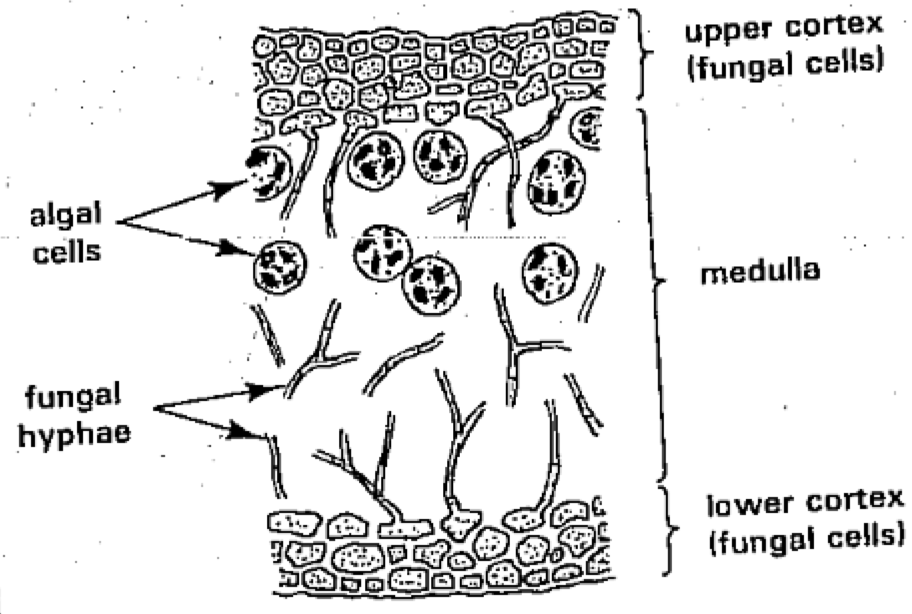
In this relationship the alga gains protection offered by the hydra in addition to the availability of carbon dioxide, nitrates and phosphates formed as excretory products by the hydra but which are useful raw materials for its photosynthesis while the hydra gains oxygen and other metabolites from the photosynthesis of the alga.

Note: this is an example of a loose mutualistic association where both organisms though benefiting can live independent lives.

(iv) Lichens

This is an association between a green alga and a fungus.the relationship is intimate that both organisms are often mistaken to be one.

A section through a lichen showing the fungal hyphae among the algal cells



In this association the fungus benefits from the products of the photosynthetic activity of the alga i.e. carbohydrates and oxygen which it uses for its own metabolism while the algae benefits from the structural support provided by the fungus and from the use of water and mineral salts absorbed by the fungus. These serve as its nutrients and in addition the water prevents it from drying out.

(v) Ruminants and bacteria and or protozoa (flagellates)

The flagellates secrete cellulase enzyme which digests cellulose of which the end products are absorbed by the ruminants for their metabolism also the bacteria synthesise vitamins B_1 and B_2 which are used by the ruminants while the bacteria gain protection, warmth and constant supply of food from the association.

(vi) Wood eating termites and flagellates (protozoans)

Protozoans like *Triconympha* in intestines of wood eating termite species produce the enzyme cellulase which they use to digest the cellulose in the wood they eat. In this association the flagellates gain protection and food from the termites while the termites gain from the use of the end products of cellulose digestion.

(vii) Non ruminants and bacteria

Horses and rabbits form a mutualistic association with bacteria which live in their caecum and appendix. The benefits for both organisms are similar to those of the ruminants and organisms in their rumen

(viii) Hermit crab *Pagurus* and the sea anemone *Adamsia palliata*

In this association; the crab gains shelter and protection from the anemone because it covers it and also has stinging cells in its tentacles with which it can sting enemies of both partners while the sea anemone obtains food from the crab and also free transport to wherever the crabs going which gives it the extra benefit of finding better food.

Significance of mutualistic associations in nature

- Increases efficiency of cellulose digestion in herbivores
- Brings about fixation of nitrogen into soil through symbiotic associations of bacteria and leguminous plants
- Enables colonization during terrestrial primary succession where the lichens constitute the pioneer species.

(iii)Commensalism

Commensalism is a close association between two living organisms of different species which is beneficial to one (the commensal) and the other is neither harmed nor benefits (the host).
For example, the colonial hydrozoan Hydractinia attaches itself to whelk shells inhabited by hermit crabs. It obtains nourishment from the scraps of food left by the crab after it has eaten. In this particular case the crab is totally unaffected by the association. Another example is an orchid or lichen (the commensal) growing on a tree (the host).

(iv)Parasitism (refer to ecology notes)

Exercise 4

1. (a) Compare *mutualism* and *parasitism*. (04 marks)
(b) Describe how
(i) Gut bacteria contribute to the well-being of herbivores (04 marks)
(ii) Nitrogen-fixing bacteria contribute to the well-being of herbivores (06 marks)
(c) Explain the mutualistic relationship between mammals and the micro-organisms in their alimentary tract. (08 marks)

2. (a) Distinguish between intracellular digestion and extracellular digestion (02 marks)
(b) Describe the role of digestive juices in the process of digestion in mammals (12 marks)
(c) Explain how chemical components in algae may end up into the cytoplasm of an amoeba (06 marks)