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

TYPES OF HETEROTROPHIC NUTRITION
(a) Holozoic nutrition
(b) Saprotrophic nutrition (Saprophytic nutrition)
(c) Symbiosis: **(i)** Parasitism **(ii)** Mutualism **(iii)** Commensalism

HOLOZOIC NUTRITION
This is the type of nutrition in which complex organic food is taken in and broken down inside the body of an organism into simple soluble molecules which are then absorbed and assimilated.

BASIC PROCESSES INVOLVED IN HOLOZOIC NUTRITION
1. ***Obtaining food:*** May involve movements to capture or find new food sources from the environment.
2. ***Ingestion***: The intake of food into the body (feeding mechanisms).
3. ***Digestion***: Chemical breakdown (by enzymes) and physical breakdown (by teeth, gizzard, mandibles, radula) of large insoluble molecules of food into small soluble molecules.
4. ***Absorption***: The uptake of nutrient molecules into the cells of the digestive tract and, from there, into the bloodstream
5. ***Defecation (Egestion)***: elimination of undigested residue.
6. ***Assimilation:*** The utilization of the absorbed soluble food substances to form energy or materials which are incorporated into the body tissues.

FEEDING MECHANISMS OF ANIMALS

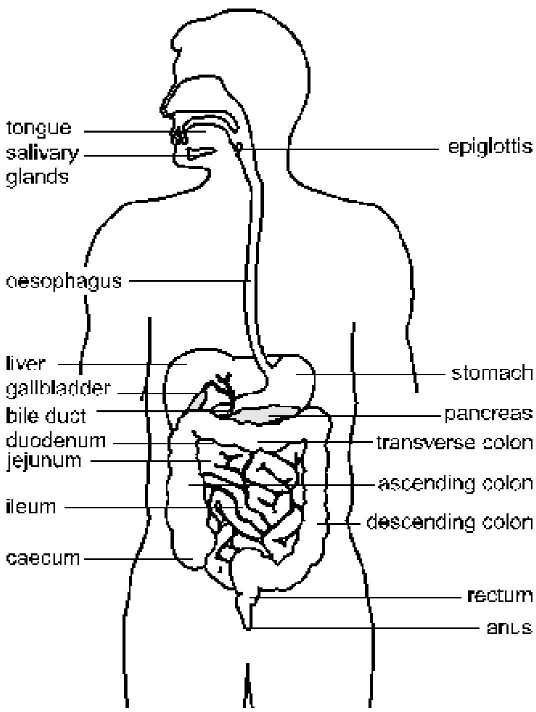
Nature of food	***Mechanism***	***Organisms***	***Description***
Small particles	filter feeding / microphagous feeding;	Whales, sharks, flamingo, herring;	Body appendages (gills/beaks/keratinous plates) filter planktons/blue green algae suspended in water into body cavity /mouth then digestion occurs.
	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

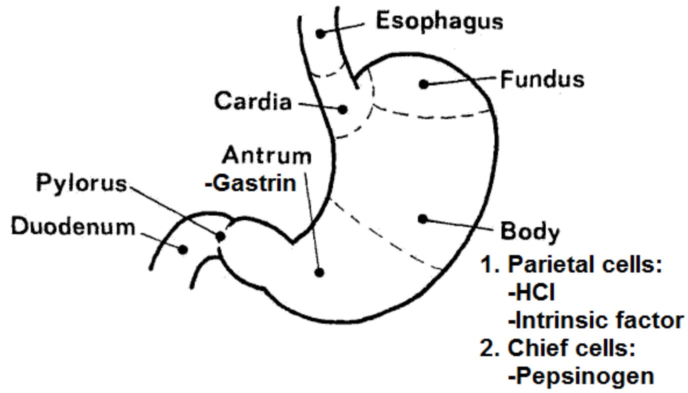
The human digestive system consists of:

1. Alimentary canal: Mouth, throat, oesophagus, stomach, small intestine (duodenum, jejunum and ileum), large intestine (colon, caecum and appendix), rectum and anus.

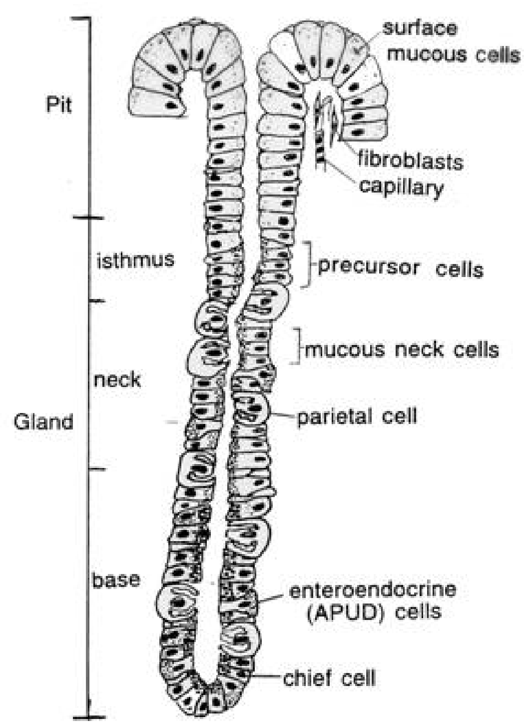
2. Accessory structures: Teeth, tongue, salivary glands, liver, gall balder and pancreas. These are organs, glands, and tissues that enable digestive processes, e.g. by secreting fluids /chemicals, but the food does not actually pass through them.



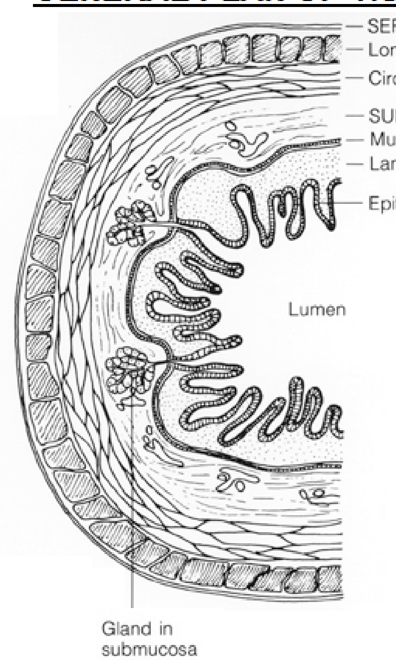
Details of the stomach region



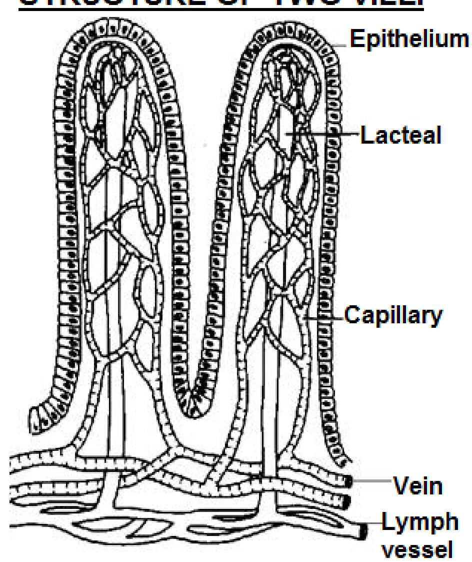
Structure of Gastric gland



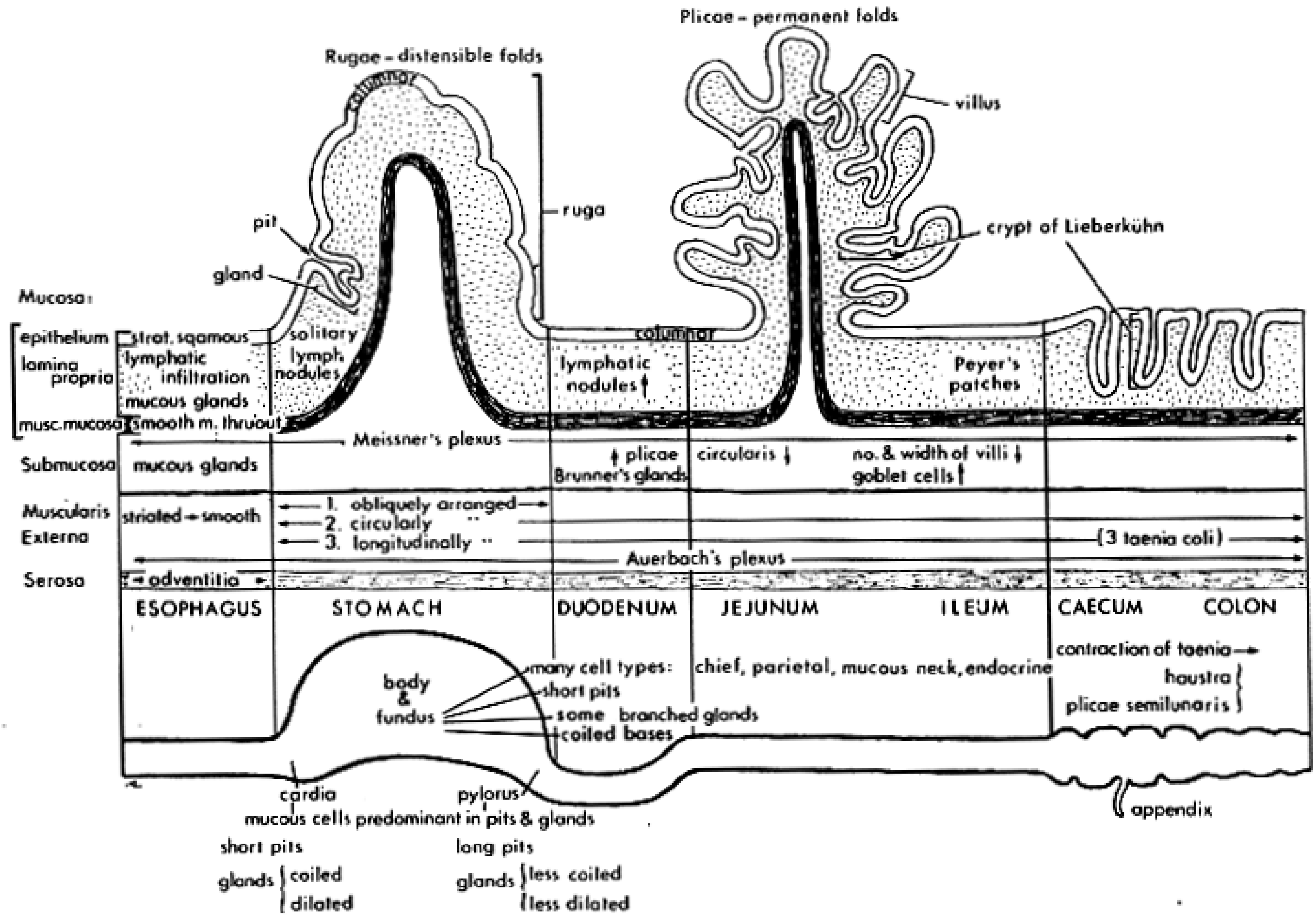
GENERAL PLAN OF T.S OF ALIMENTARY CANAL



STRUCTURE OF TWO VILLI



VERTICAL SECTION THROUGH THE ALIMENTARY CANAL



COMPARISON OF HISTOLOGY OF GASTROINTESTINAL TRACT REGIONS

WALL LAYER	STOMACH	DUODENUM	ILEUM	COLON
Serosa (Adventitia)	●Areolar 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.			
Muscularis externa	●Consists of three muscle layers: **(i)** inner oblique layer **(ii)** middle circular layer **(iii)** outer longitudinal layer			
Auerbach's plexus (Myenteric plexus)	●Network of **unmyelinated** nerve fibers and ganglia between Muscularis externa longitudinal and circular muscles ●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			
Submucosa	●Consists of loose connective tissue, collagen, large arteries and veins, lymph vessels and nerves			
	● **Brunner's glands** absent. ●No **goblet cells**	●**Brunner's glands** present ●Brunner's glands secrete alkaline mucus to neutralize acidic chyme from the stomach ●Brunner's glands are compound, tubular, mucous ●**Goblet cells** present	● **Brunner's glands** absent. ●**Goblet cells** present	● **Brunner's glands** absent.
Meissner's plexus (Submucosal plexus)	●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.			

<table>
<tr><th>WALL LAYER</th><th>STOMACH</th><th>DUODENUM</th><th>ILEUM</th><th>COLON</th></tr>
<tr><td rowspan="3">Mucosa</td><td colspan="4">1. Muscularis mucosa:
● Thin layer of smooth muscle at the boundary between mucosa and submucosa.
● Contains both circular and longitudinal muscles
● Functionally, the Muscularis mucosa presumably causes stirring at mucosal surface for increased secretion and nutrient absorption</td></tr>
<tr><td colspan="4">2. Lamina propria:
● Formed by a very cell-rich loose connective tissue (fibroblasts, lymphocytes, plasma cells, macrophages, eosinophilic leucocytes and mast cells).
● Lamina propria 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).
● Lamina propria of intestinal villi may include smooth muscle fibers.
● In oral cavity and oesophagus, lamina propria is located immediately beneath a stratified squamous epithelium</td></tr>
<tr><td colspan="4">3. Surface epithelium:
● Mucosal epithelium is highly differentiated along the several regions of the GI 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
● In the stomach, surface epithelium contains mucous cells that secrete protective, alkaline mucus
(a) Plicae of the small intestine are permanent folds in the mucosa supported by a core of submucosa. Plicae increase the absorptive surface area of the mucosa.
(b) Gastric pits are shallow indentations in surface epithelium of stomach mucosa into which gastric glands open.
(c) Intestinal crypts (crypts of Lieberkühn) contain secretory Paneth cells at the deep end, which secrete lysosomal enzymes that contribute to protecting cells in the crypt lining.
(d) Villi are very small, typically densely-packed, invaginations of a mucosa that increase the surface area for absorption. In the stomach – no villi, duodenum – many, leaf-like villi, ileum – few, finger-like villi.
(e) Rugae are distensible folds in the gastric mucosa.</td></tr>
</table>

SECRETIONS FROM CELLS LOCATED IN THE GASTRIC WALL

The secretions of the mucous cells, chief cells, and parietal cells are known collectively as ***gastric juice***, whose components include: ***mucus***, ***pepsinogen***, ***hydrochloric acid*** and ***intrinsic factor***

<table>
<tr><th>Type of Cell</th><th>Secretion</th><th>Stimulus for secretion</th><th>Function</th></tr>
<tr><td rowspan="2">Mucous Cells
(i) Mucous surface cells
(ii) Mucous neck cells</td><td>Mucus</td><td>Tonic secretion, with irritation of mucosa</td><td>Physical barrier between lumen and stomach lining.</td></tr>
<tr><td>Bicarbonate</td><td>Secreted with mucus</td><td>Buffers gastric acid to prevent damage to epithelium</td></tr>
<tr><td rowspan="3">Chief / Peptic / zymogenic cells</td><td>Pepsinogen</td><td rowspan="3">Acetylcholine, acid secretion.</td><td>Pepsin digests protein, including collagen</td></tr>
<tr><td>Gastric lipase</td><td>Digests lipids</td></tr>
<tr><td>Prochymosin (Prorennin)</td><td>Rennin curdles soluble Caseinogen (milk protein) into insoluble casein whose slow flow enables digestion</td></tr>
<tr><td rowspan="2">Parietal / oxyntic cells</td><td>Hydrochloric acid</td><td rowspan="2">Acetylcholine, gastrin, histamine</td><td>(i) Activates pepsinogen to pepsin, Prorennin to rennin
(ii) Kills bacteria. Only Helicobacter pylori, that cause gastritis and gastric ulcers survive in the stomach</td></tr>
<tr><td>Intrinsic factor</td><td>● Complexes with vitamin B_{12} to enable absorption of Vitamin B_{12} necessary for red blood cell formation
● Vitamin B12 is a cofactor of enzymes which synthesise tetrahydrofolic acid, which, in turn, is needed for the synthesis of DNA components
● Little intrinsic factor causes pernicious anemia</td></tr>
<tr><td colspan="4">Enteroendocrine cells (APUD-cells: amine precursor uptake and decarboxylation cells)</td></tr>
<tr><td>(a) G cells
(Gastrin-producing cells)</td><td>Gastrin hormone</td><td>Acetylcholine, peptides, and amino acids</td><td>(i) Stimulates secretion of gastric juice
(ii) Increases contractions of gastro-intestinal tract
(iii) Relaxes the pyloric sphincter.</td></tr>
<tr><td>(b) D cells
(Somatostatin-producing cells)</td><td>Somatostatin hormone</td><td>Acid in stomach</td><td>(i) Inhibits stomach secretion of gastrin and HCl
(ii) Inhibits duodenal secretion of secretin and cholecystokinin
(iii) Inhibits pancreas secretion of glucagon</td></tr>
<tr><td>(c)VIP-producing cells (vasoactive intestinal peptide)</td><td>Vasoactive intestinal peptide</td><td>Distension of the stomach wall</td><td>(i) Induces smooth muscle relaxation
(ii) Inhibits gastric acid secretion
(iii) Stimulates pepsinogen secretion by chief cells</td></tr>
<tr><td>(d) Enterochromaffin cells
(Serotonin-containing cells)</td><td>Histamine</td><td>Acetylcholine, gastrin</td><td>Stimulates gastric acid secretion</td></tr>
</table>

DIGESTION

Digestion is the process by which large food molecules are broken down into small soluble molecules which can be absorbed and assimilated into the tissues of the body.
Digestion includes two types of processes:
Mechanical processes: which include the chewing and grinding of food by the teeth and also the churning and mixing of the contents of the stomach to expose more surface area to the enzymes that finish the digestive process.
Chemical processes: which include hydrolysis action of digestive enzymes, bile, acids.

DIGESTION IN THE MOUTH

It starts with chewing (mastication), which breaks food into pieces small enough to be swallowed and also increases the surface area of food to digestive enzymes.
The sight, taste, smell and thought of food induces salivary glands to secrete saliva, a watery fluid with PH of 6.8 to 7.0.
During chewing, saliva mixes with food and the different saliva components perform different functions:
(i) **Salivary amylase (ptyalin)** enzyme catalyses the breakdown of **amylose** of cooked **starch** into **maltose**.
(ii) **Water** moistens food and binding it together for swallowing
(iii) **Mucin** binds and lubricates food; to enable swallowing.
(iv) **Chloride ions** activate salivary amylase
(v) **Lysozymes** kill bacteria in the buccal cavity.

NOTE:
- Amount of **amylase** secreted in saliva depends on **amount of starch** the animal regularly feeds on in diet.

1. Amylase is usually absent in the saliva of carnivores because of absence of cooked starch in the diet.
2. In separate human groups, the relative amounts of amylase (in arbitrary units) produced in saliva were as follows: **Tswana: 248, Bushmen 22, European: 101**. Which human group's diet is largely made of flesh?

SWALLOWING

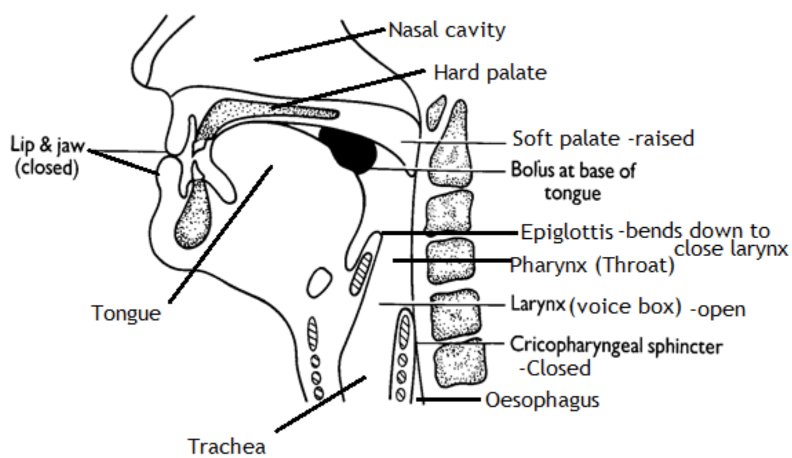
This is a reflex action, which lasts less than 10 seconds.

STAGES OF SWALLOWING

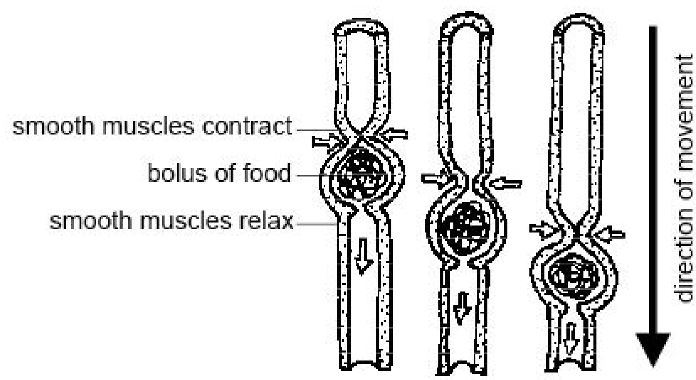
- **Tongue** contracts to push the bolus towards the throat, forcing the **soft palate** upwards to close the **nasopharynx**
- **Larynx** and **hyoid bone** move anteriorly and upwards.
- **Epiglottis** bends downwards to close **larynx** (trachea entrance) to prevent food from entering the trachea.

***NB:** Any food that enters into trachea is expelled out by coughing reflex.*

- Breathing briefly stops due to closure of **glottis**.
- **Pharynx** shortens.
- **Upper oesophageal sphincter** (Cricopharyngeal sphincter) relaxes, to allow the bolus enter into **oesophagus**
- In oesophagus the food bolus moves by **peristalsis**, a sequence of wave-like contractions that squeeze food down the oesophagus.
- **Lower oesophageal sphincter** (**cardiac sphincter)** relaxes to allow food into stomach.



PERISTALSIS IN OESOPHAGUS



TYPICAL EXAMINATION QUESTION
(a) Describe the process of swallowing food in humans. (10 marks)
(b) Explain the role of gastric juice during food digestion in adult humans (10 marks)

DIGESTION IN THE STOMACH

● Arrival of food in the stomach stimulates secretion of **gastrin hormone** from **G-cells** 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 follows:

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	Buffers gastric acid to prevent damage to epithelium
Chief / Peptic / zymogenic cells	Pepsinogen	Pepsinogen on activation to pepsin digests protein to polypeptides
	Gastric lipase	Digests lipids to fatty acids and glycerol
	Prochymosin (Prorennin)	Rennin coagulates soluble milk protein **Caseinogen** into insoluble **casein** in babies, whose slowed flow enables digestion by **pepsin**.
	Gastric lipase	Gastric lipase **weakly** hydrolyses **fats** to **fatty acids** and **glycerol**
Parietal / oxyntic cells	Hydrochloric acid	(i) Activates pepsinogen to pepsin, Prorennin to rennin (ii) Kills most bacteria in the stomach. (iii) Provides optimum acidic pH for pepsin to hydrolyse proteins into polypeptides. (v) 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**

MECHANISM OF HYDROCHLORIC ACID SECRETION IN PARIETAL CELLS

● Hydrochloric acid is produced by **parietal** cells through a complex series of reactions.

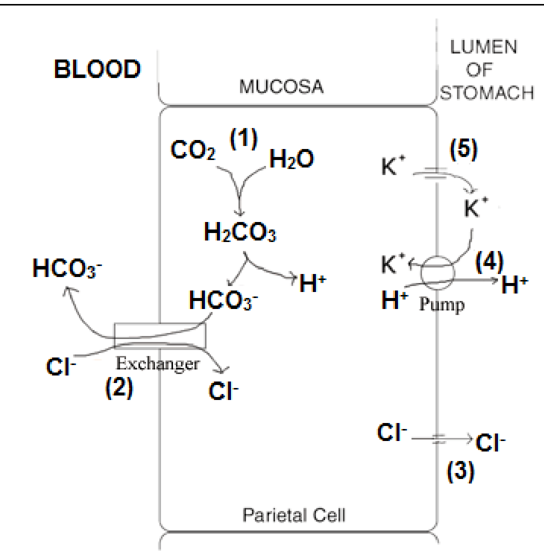
● Catalysed by the enzyme **carbonic anhydrase**, **carbon dioxide** (which diffused from capillaries) reacts with **water** to form **carbonic acid**, which dissociates into **bicarbonate ion** and **hydrogen ion**.

● **Bicarbonate ion** is transported into the blood stream by an **ion exchange molecule** in plasma membrane which exchanges **bicarbonate ions** exiting parietal cells for **chloride ions** entering.

● **Hydrogen ions** are **actively pumped** into the **duct** of **gastric gland** and the **negatively charged chloride ions diffuse** with the **positively charged hydrogen ions**.

● **Potassium ions** are **counter pumped** into the parietal cell in exchange for **hydrogen ions**.

● The net result is production of hydrochloric acid in the **parietal cells** and its secretion into the **duct** of **gastric gland**.



● Due to churning by the stomach wall (alternate contractions and relaxations), **VIP-producing cells** are stimulated to secrete the hormone called **vasoactive intestinal peptide**, which causes relaxation of **pyloric sphincter muscle** to allow the semi solid **chyme** flow from the stomach into the duodenum, after a maximum of about **four hours**.

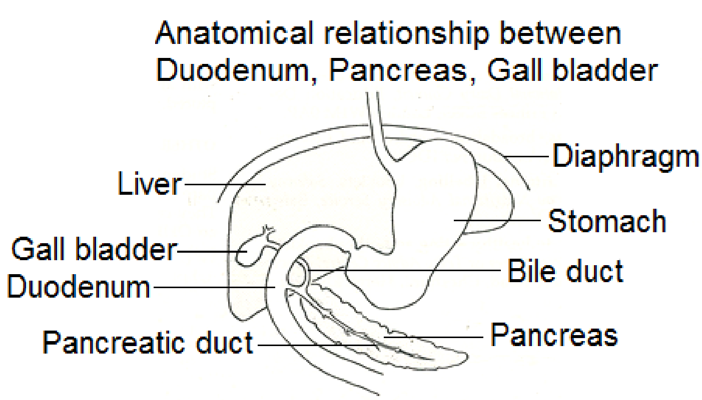
DIGESTION IN THE DUODENUM

Arrival of **partially digested, acid food** mixture in the duodenum stimulates **endocrine cells** in duodenal walls to secrete the hormones: **Secretin, Enterogastrone, Cholecystokinin (CCK)** formerly **Cholecystokinin-Pancreozymin (CCK-PZ), Villikinin** and **Enterocrinin**. These hormones coordinate activities of the stomach, pancreas, gall bladder and ileum as follows:

Hormone	Stimulus for secretion	Effect
Secretin hormone	Acid chyme in duodenum	●Stimulates the **liver** to secrete **bile** into the **gall bladder**. ●Stimulates pancreatic secretion of **non-enzymatic** substances (**hydrogen carbonate ions)** from **acinar cells.** HCO_3^- neutralise the acid from the stomach to provide an alkaline pH optimum for pancreatic enzymes. ●Inhibits secretion of **HCl** by **oxyntic cells** as chyme leaves the stomach.
Enterogastrone hormone	Acid and fat in the duodenum	●Reduces stomach motility ●Inhibits oxyntic cells from secreting hydrochloric acid in order to provide an optimum pH for pancreatic enzymes. ●Signals the stomach to empty slowly when fat is present, allowing much time for digestion of fat already emptied. **NOTE**: High fat diets stimulate enterogastrone production, which prolongs food stay in the stomach, and is therefore useful in treating duodenal ulcer.
Cholecystokinin hormone (CCK) formerly called **Cholecystokinin**	Partially digested **fat** and **protein** in the duodenum	●Stimulates contraction of **gall bladder** to release **bile** into **duodenum**. **(i)** Bile salts (sodium glycocholate) emulsify fats i.e. fats physically break into droplets due to reduced surface tension, which increases their surface area ●Stimulates the pancreas to secrete **pancreatic enzymes**: (i) **Pancreatic amylase** which catalyses the hydrolysis of **starch** into **maltose** (ii) **Enterokinase**, a non-digestive enzyme which activates **Trypsinogen** to **Trypsin.** (iii) **Trypsinogen**, which is activated by **enterokinase** to **Trypsin.** **Trypsin:** **(1)** Catalyses hydrolysis of **polypeptides** to **peptides.** **(2)** Activates **chymotrypsinogen** to **chymotrypsin**. (iii) **Chymotrypsinogen,** which is activated to **chymotrypsin** by **Trypsin.** **Chymotrypsin** catalyses hydrolysis of **casein** / **polypeptides** into **peptides**.
Villikinin (Motilin)	**Alkaline pH** in the duodenum	●Increases peristalsis in the small intestine and ileum villi movements, in preparation for incoming food.

NOTE:
1. Some sources indicate that **enterogastrone** refers to any of the hormones secreted by the mucosa of the duodenum in the lower gastrointestinal tract in response to dietary lipids to inhibit churning e.g. **(i)** Secretin **(ii)** Cholecystokinin
2. All **proteolytic** (protein digesting) enzymes along the gut are secreted in **inactive (precursor)** form to prevent **autolysis** (self-digestion) of gut tissues, which are protein in nature.

The churning action of duodenal walls turns the semi-solid **Chyme** into a thin, milky-looking alkaline fluid called **Chyle**.



DIGESTION IN THE ILEUM

Distention of the small intestine by food / **tactile stimulus** / **irritating stimulus** stimulates the secretion of **intestinal juice** (**Succus entericus**), which consists of a mixture of substances from **crypts of Lieberkühn** and **Brunner's glands**. Some of the components of **Succus entericus** include the following enzymes:

●***Peptidases*:** catalyse hydrolysis of **peptides** into **amino acids**, thereby completing the digestion of proteins.
●***Nucleotidases*:** catalyse hydrolysis of **nucleotides** into **phosphoric acid, nitrogenous bases** and **pentose sugars**.
●**Maltase**: catalyses hydrolysis of **maltose** into **glucose** molecules, thereby completing starch digestion.
●***Sucrase (invertase)***: catalyses hydrolysis of **sucrose** into **glucose** and **fructose** molecules.
●***Lactase***: catalyses hydrolysis of **lactose** into **glucose** and **galactose** molecules.
●***Intestinal lipase***: catalyses hydrolysis of **lipids** into **fatty acids** and **glycerol**.
●***Intestinal amylase***: catalyses hydrolysis of **starch** into **maltose**.

FOOD ABSORPTION

It is the process by which soluble food substances are absorbed across the **gut epithelium** into **blood circulatory system** or **lymphatic system** to be carried to all body cells.

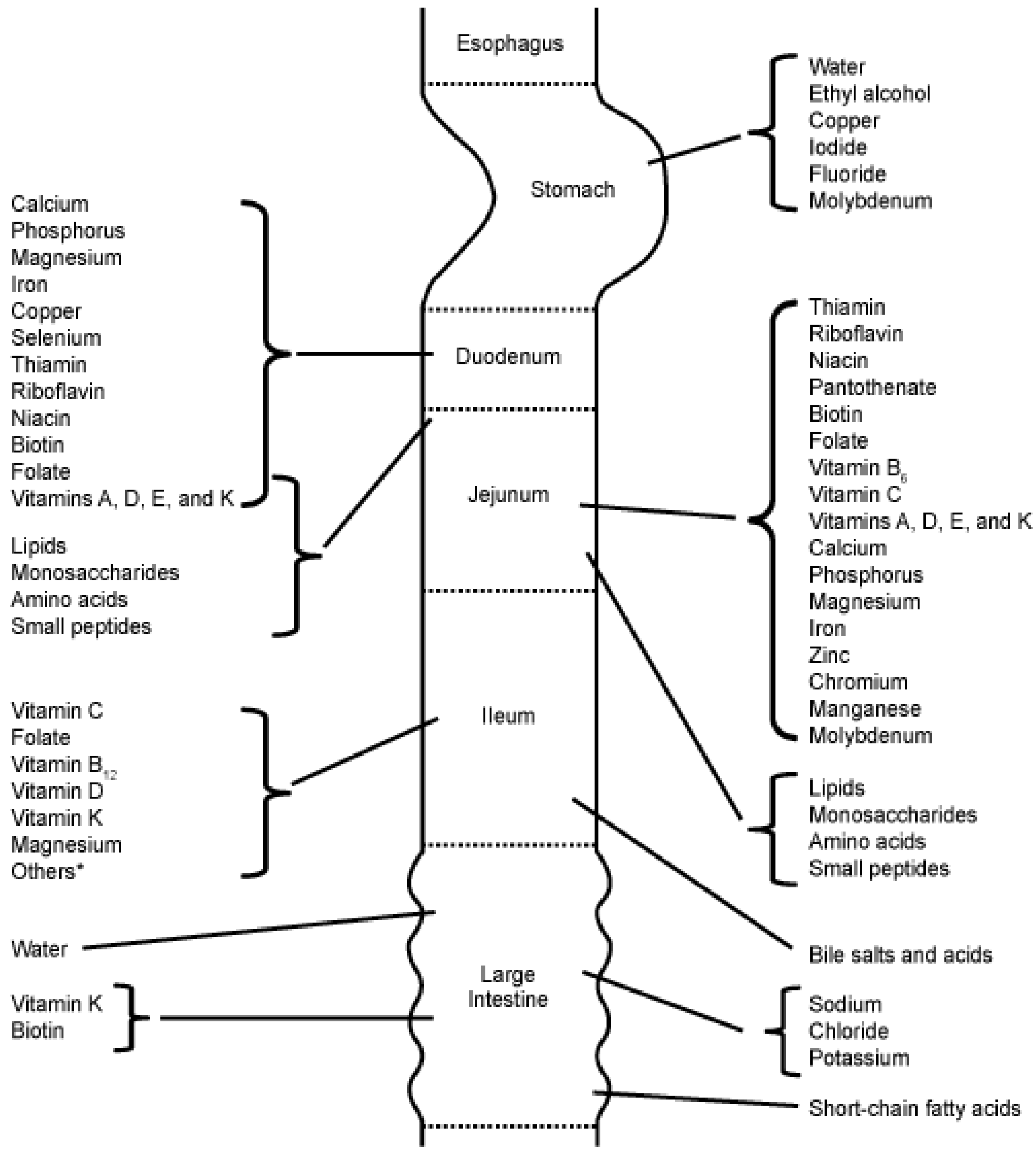
During absorption, substances move as follows:

(i) From **intestinal lumen** across the free end / **apical** end / **mucosal** end of the absorbing cell.

(ii) Across the base / **basilar** end / **serosal** end of absorbing cell into the **subcellular space**, and finally into **blood circulatory system** or **lymphatic system**.

NOTE: Substances entering at the apical surface may be metabolized or within the cell or may appear at the basilar surface when changed into another form.

MAIN SITES OF NUTRIENT ABSORPTION



*Many additional nutrients may be absorbed from the ileum depending on transit time.

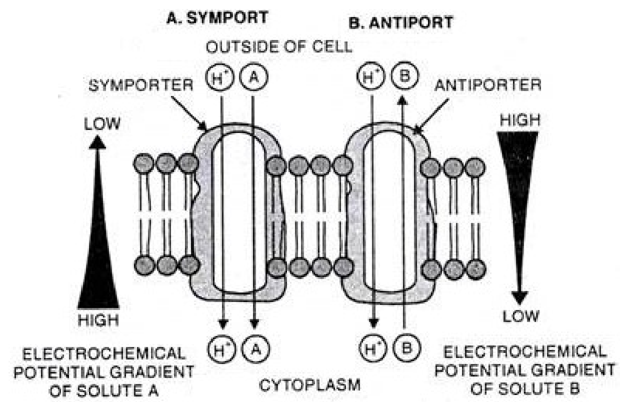
PROCESSES INVOLVED IN ABSORBING DIGESTED FOOD
(1) Simple diffusion **(2)** Facilitated diffusion **(3)** Active transport**: Direct** active transport and **Secondary** active transport

SECONDARY ACTIVE TRANSPORT
A form of active transport across a biological membrane in which a transporter protein couples the movement of an ion (e.g. Na^+ or H^+) **down** its electrochemical gradient to the **uphill** movement of another molecule or ion **against** a concentration/electrochemical gradient. Thus, energy stored in the electrochemical gradient of an ion is used to drive the transport of another solute against a concentration or electrochemical gradient.

TYPES OF SECONDARY ACTIVE TRANSPORT
1. Cotransport (also known as **Symport**) **2. Exchange** (also known as **Antiport**)

1. COTRANSPORT: The direction of transport is the same for both the driving ion and driven ion/molecule.
Examples:
(i) The Na^+/glucose cotransporter in **enterocytes** (small intestine epithelial cell) and kidney proximal tubule epithelial cells simultaneously transports 2 Na^+ ions and 1 glucose molecule into the cell across the plasma membrane.
(ii) The H^+/dipeptide or tripeptide cotransporter in epithelial cells of small intestine couples the downhill movement of H^+ across the plasma membrane to the uphill transport of dipeptides and tripeptides into the cell against a concentration gradient.

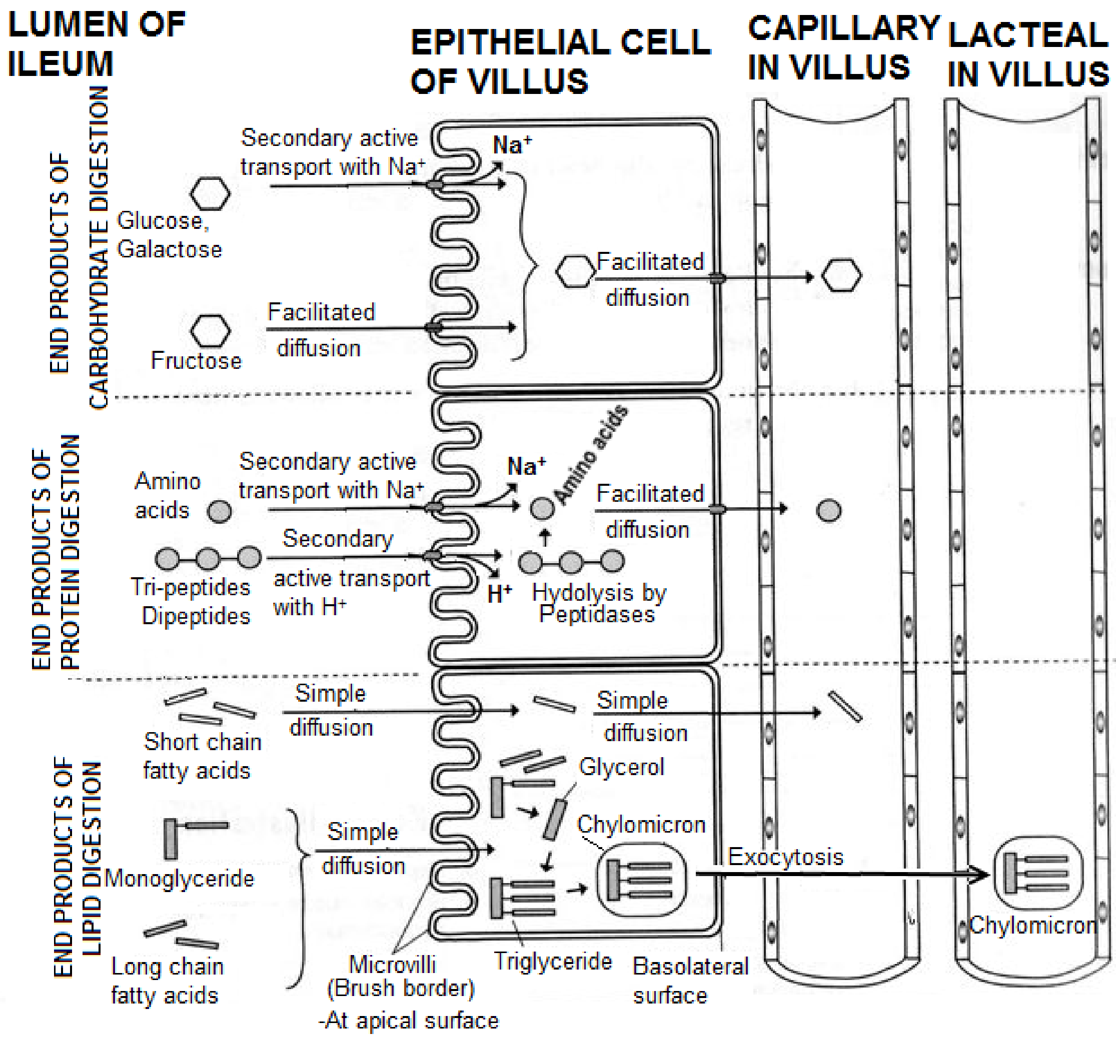
2. EXCHANGE: The driving ion and driven ion/molecule move in opposite directions.
Example:
The Na^+/Ca^{2+} exchanger in cardiac muscle cells transports 3 Na^+ ions into the cell in exchange for 1 Ca^{2+} ion transported out of the cell.



MECHANISMS OF ABSORBING DIGESTED FOOD IN THE ILEUM

Digested food	Mechanism	Description of the mechanism
Glucose and galactose	Secondary **active transport** with Na^+ (**Cotransport with Na^+**)	Glucose and galactose are **cotransported** into epithelial cells of villi with **Na^+** ions, then exported into blood capillaries by **facilitated diffusion**.
Fructose	Facilitated diffusion	Fructose moves into epithelial cells of villi by **facilitated diffusion**, then exported into blood capillaries by **facilitated diffusion**.
Amino acids	Secondary **active transport** with Na^+ (**Cotransport with Na^+**)	Amino acids are **cotransported** from intestinal lumen into small intestinal epithelial cells with **Na^+** ions, then exported to capillaries by **facilitated diffusion**.
Dipeptides and Tripeptides (Oligopeptides)	Secondary **active transport** with H^+ (**Cotransport with H^+**)	Oligopeptides (dipeptides and tripeptides) are **cotransported** from intestinal lumen into villi epithelial cells with **protons (H+)** Oligopeptides are then **hydrolysed by cytoplasmic peptidases** into **amino acids**, which are exported from the villi epithelial cells into blood capillaries by **facilitated diffusion**.
Short chain fatty acids	Simple diffusion	Short chain fatty acids move into epithelial cells of villi by **simple diffusion**, then are exported into blood capillaries by **simple diffusion**.
Monoglycerides and Long chain fatty acids	Simple diffusion	Monoglycerides and long chain fatty acids **diffuse** into columnar epithelia of villi, **recombine** to form **lipids**, then combine with **proteins** to form water soluble **lipoproteins** called **chylomicrons**, which are exported by **exocytosis** to lacteals.

NOTE:
1. Absorption of **whole proteins** occurs only in a few circumstances e.g. **newborns** when suckling absorb **antibodies** (**immunoglobulins**) from the mother's milk (colostral milk) to acquire **passive immunity**.
2. In adults, absorption of whole protein can cause **allergic reaction** due to presence of **foreign protein** in blood.



ILEUM – THE MAJOR SITE FOR ABSORPTION

Adaptations of the ileum to absorption of food

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

TYPICAL EXAMINATION QUESTIONS

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

- Large surface area by microvilli / protrusion of exposed parts for fast uptake of soluble substances.
- Epithelium only one layer thick to reduce diffusion distance.
- Protein channels allow facilitated diffusion and active transport.
- Numerous mitochondria provide much ATP for active uptake of some nutrients like glucose and salts.
- Blood capillaries close to epithelium/ surface to reduce diffusion distance during absorption of glucose/ amino acids
- Lacteal / lymphatic vessel is permeable/has large surface area at centre to absorb fatty acids and glycerol.
- Tight junctions between adjacent villi enable controlling absorption of substances

(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.

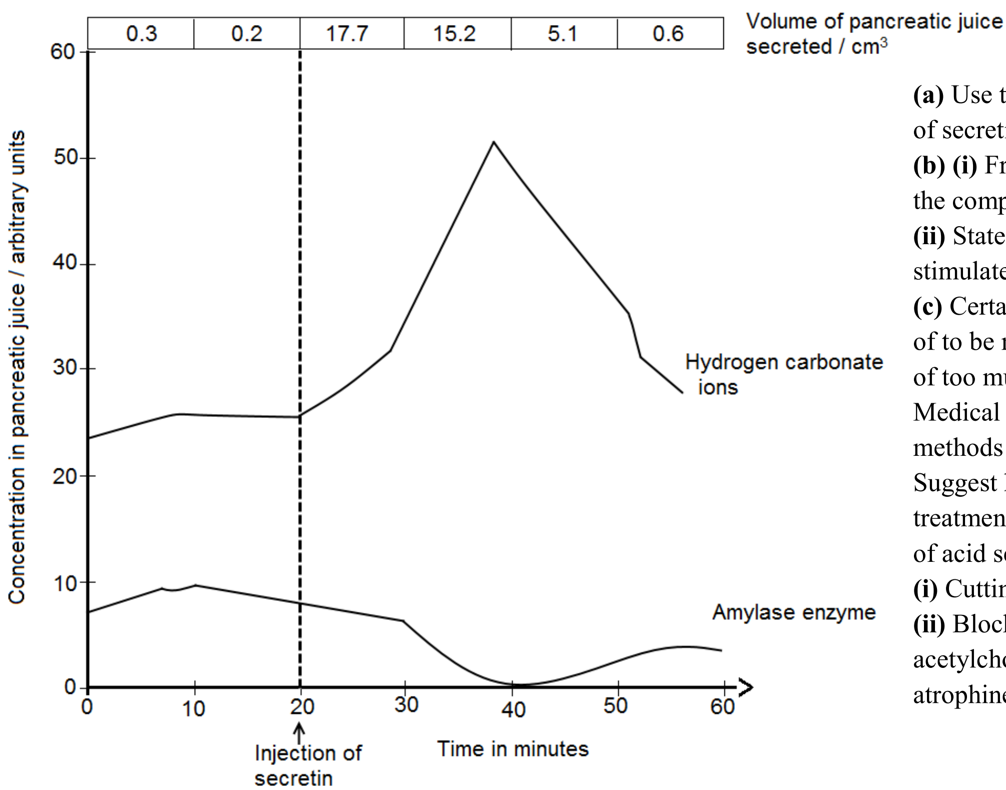
	Rate of absorption	
	By living intestine	By poisoned intestine
Glucose	1.00	0.33
Galactose	1.10	0.53
Fructose	0.43	0.37
Xylose	0.31	0.31
Arabinose	0.29	0.29

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

●The rate of absorption of glucose and galactose is faster in living intestine**;** but much slower in poisoned intestine**; because** absorption of these sugars is **active transport** requiring ATP whose formation depends on enzymes**;** which are **inhibited** by respiratory inhibitor **cyanide;** To a small extent, the two sugars are absorbed **passively;**

●Rate of absorption of fructose, xylose and arabinose is the same or relatively the same in living intestine and in poisoned intestine**; because** absorption of these sugars is **facilitated diffusion** which **does not** require ATP**;** therefore **not inhibited** by respiratory poison **cyanide;**

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 atrophine.

PROBABLE SOLUTIONS

(a) ●Secretin injection causes a rapid increase in the volume of **pancreatic juice** from 20 minutes to 30 minutes**;** followed by gradual decrease to 40 minutes**;** then a rapid decrease to 60 minutes**;**

●Secretin injection causes gradual increase in the concentration of bicarbonate ions from 20 minutes to 30 minutes**;** followed by rapid increase to a peak at 40 minutes**;** then rapid decrease until 60 minutes**;**

●Secretin injection causes gradual decrease in concentration of amylase from 20 minutes to 30 minutes**;** followed by rapid decrease to a minimum at 40 minutes**;** then gradual increase until 55 minutes and thereafter remains constant until 60 minutes**;**

●Upon injection into blood, secretin hormone circulates to reach the pancreas and liver, first in **low concentration** from 20 minutes to 30 minutes**;** gradually stimulating pancreatic secretion of **watery hydrogen carbonate ions** from **acinar cells** and **gradually stimulating** secretion of **somatostatin hormone** which **gradually inhibits** secretion of pancreatic amylase enzyme**.**

●From 30 minutes to 40 minutes, there is now **much secretin concentration** in blood circulation**;** which rapidly stimulates pancreatic acinar cells to rapidly secrete **hydrogen carbonate ions** and **also** greatly stimulates secretion of **somatostatin hormone** which **rapidly inhibits** secretion of pancreatic amylase enzyme**;**

●From 40 minutes to 60 minutes, high PH (alkalinity) due to **hydrogen carbonate ions** inhibits the working of secretin hormone; causing less stimulation of acinar cells hence rapid decrease in secretion of hydrogen carbonate ions. **Somatostatin hormone** secretion decreases hence decreasing the inhibition of pancreatic exocrine cells causing increased amylase enzyme secretion**;**

(b) (i) Pancreatic juice is mainly composed of **substances** (like water), **hydrogen carbonate ions,** and small amounts of enzymes like **amylase**.

(ii) Secretion of **bile** in liver cells, stored in the gall bladder which when released in the duodenum emulsifies fats into droplets, which is physical digestion.

(c) (i) Conditioned reflexes from vagal centre in the brain fail to stimulate secretion of acetylcholine, no secretion of gastrin hormone, no secretion of gastric juice (HCl) during the cephalic phase (before food reaches the stomach) hence the stomach wall will be less irritated.

(ii) Blocking the action of acetylcholine using atrophine **inhibits** the secretion of **gastrin hormone**; hence secretion of gastric juice (HCl) is inhibited.

COLON

●In the colon, there is mainly absorption of:

(i) Water into the blood capillaries by **osmosis.**

(ii) Vitamins Biotin (B_7) and K, which is synthesised by *Escherichia coli* bacteria that live in the colon.

(iii) Na^+, Cl^- and K^+

NOTE: The colon wall contains mucus secreting cells for lubricating the movement of undigested food through the colon.

APPENDIX AND CAECUM

●In ruminants like cattle and in non-ruminants like rabbits, **mutualistic bacteria** secrete **cellulase enzyme** which digests **cellulose** to **glucose,** which is lost along with faeces. In the process described as **coprophagy (coprophagia)**, rabbits eat own faecal pellets while dung beetles feed on cow dung to enable absorption of glucose at the ileum.

●In humans, appendix and caecum have no obvious role.

RECTUM

●In the rectum, food is stored temporarily to enable osmotic absorption of water into blood capillaries.

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

(i) Secretion of digestive juices depends on respiratory energy, therefore unnecessary secretion must be prevented to avoid wastage of respiratory substrates.

(ii) Secretion of **proteolytic enzymes** in inactive form prevents **autolysis** (self-digestion of tissues).

MECHANISMS OF CONTROLLING DIGESTION IN HUMANS

●Involves a combination of **hormonal** and **nervous; stimulations** and **inhibitions** of the gut; that **regulate** the secretion of digestive juices in the gut;

●The digestive juices secreted include **saliva** in the buccal cavity; **gastric** juice in the stomach; **pancreatic** juice and **bile** in the duodenum; **intestinal** juice in the ileum;

CONTROL IN THE MOUTH

●Sight / smell / thought of food **stimulate** conditioned reflexes involving the **cerebral cortex, hypothalamus** and **medulla oblongata;** which **stimulate** salivary glands to secrete saliva.

●Contact of food with tongue taste receptors **stimulates** nerve impulses via sensory neurons to the **hypothalamus** and **medulla oblongata;** relayed along motor neurons to **stimulate** salivary glands to secrete saliva.

-Salivary amylase in saliva causes hydrolysis of starch to maltose.

●Loss of appetite / depression **inhibit** cerebral cortex**;** parasympathetic centre is **not stimulated**, no secretion of saliva**;**

CONTROL IN THE STOMACH

Occurs in 3 phases: **cephalic; gastric;** and **intestinal** phases;

Cephalic phase / Nervous phase:

It occurs before food enters the stomach;

●Sight / smell / thought of food **stimulate** conditioned and unconditioned reflexes**;** involving the **cerebral cortex, hypothalamus** and **medulla oblongata;** which **stimulate** the **vagus nerve** causing the release of **acetylcholine**; which **stimulates** the secretion of the **hormone gastrin**; whose effects are:

(i) Stimulates secretion of gastric juice.

(ii) Increases contractions of gastro-intestinal tract

(iii) Relaxes the pyloric sphincter to let in bolus of food from the gullet;

●Loss of appetite / depression **inhibit** cerebral cortex**;** parasympathetic centre is **not stimulated**, no gastric secretion**;**

NOTE:

Secretion of nervous phase lasts for about one hour during which gastric juice secretion reaches a maximum, after which there is a rapid decrease from 1 hour to 1.5 hours.

Therefore, nervous secretion is: **(i)** short lasting and **(ii)** rapid as compared to the hormonal phase.

Gastric phase:

● Arrival of food bolus distends / stretches the stomach wall which activates **stretch receptors** to fire impulses to the **Meissner's plexus** in the stomach wall to cause the following effects:
(i) Stimulate local secretory reflexes in the stomach wall to activate gastric glands secrete **pepsinogen** and **HCl**;
(ii) Stimulate reflexes in the medulla, via the **vagus nerve** to activate gastric glands wall to secrete **pepsinogen** and **HCl**;
(iii) Stimulate **enteroendocrine** cells / G-cells to secrete **gastrin hormone;** which stimulates secretion of **gastric juice;**
(iv) Stimulate **enteroendocrine /enterochromaffin** cells to secrete **histamine;** which activates secretion of **gastric juice;**

● Partially digested proteins especially peptides / decrease in pH activates **chemoreceptors**, which stimulate G-cells to secrete **gastrin hormone;** which stimulates secretion of **gastric juice;**

● Excessive acidity (PH of less than 2) **inhibits G-cells** hence **gastric juice** secretion reduces;

● Emotional upset activates **sympathetic nervous system** whose effects override the **parasympathetic nervous system**;

NOTE:
The gastric glands are stimulated by hormones to secrete gastric juice for about four hours.
Therefore, hormonal secretion is: **(i)** longer lasting and **(ii)** gradual as compared to the cephalic phase.

Intestinal phase:

● Distension of duodenum / presence of acid chyme / partially digested food stimulates the secretion of **intestinal** (**enteric**) **gastrin hormone**; which stimulates secretion of **gastric juice** in the stomach**;**

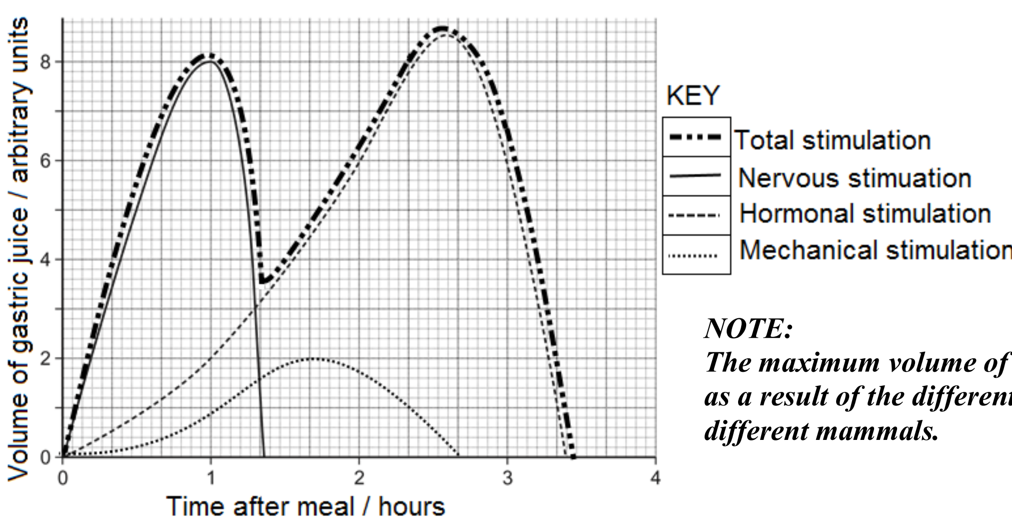
● Distension of duodenum / presence of acid chyme / fatty acids / irritants / in the duodenum stimulates the secretion of Intestinal hormones:
(i) **Secretin**; which stimulates the release of **bile** from the liver and **hydrogen bicarbonate ions** in pancreatic juice;
(ii) **Cholecystokinin**; which stimulates the pancreas to secrete its enzymes;
(iii) **Enterogastrone**; which inhibits/suppresses gastric activity (any further secretion of acid by the stomach);
(iv) **Vasoactive intestinal peptide** inhibits gastric acid secretion.

● Distension of duodenum / presence of acid chyme / fatty acids / irritants / in the duodenum initiates gastric-inhibitory impulses in the enterogastric reflex causing suppression of gastric activity; and emptying of stomach;

CONTROL IN THE ILEUM

Contact of food with intestinal lining stimulates the intestinal glands; to secrete intestinal juice composed of enzymes responsible for completion of digestion of food substrates;

Variations in volume of gastric juice produced by nervous, hormonal and mechanical stimulations with time after eating food



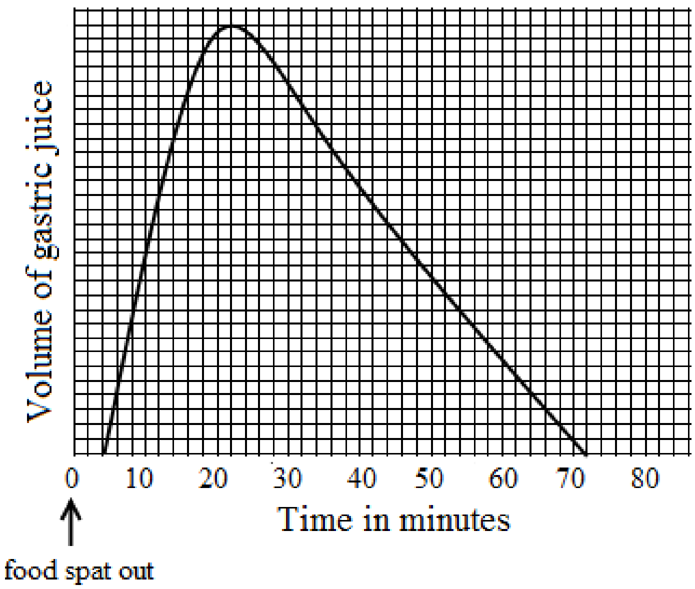
NOTE:
The maximum volume of gastric juice produced as a result of the different stimulations varies in different mammals.

OBSERVATIONS / DESCRIPTION

1. Volume of gastric juice produced during nervous stimulation increases rapidly from 0 hour to a maximum at 1 hour, then decreases rapidly and ceases at 1.5 hours. Nervous secretion is: (i) shorter lasting (ii) instantly rapid as compared to hormonal and mechanical phases.
2. Volume of gastric juice produced during hormonal stimulation increases gradually from 0 hour to 1 hour, then increases rapidly to a maximum at about 2.5 hours, then decreases rapidly and ceases at about 3.3 hours.
Therefore, hormonal secretion is: **(i)** longer lasting and **(ii)** initially gradual as compared to the cephalic phase.
3. Volume of gastric juice produced during **mechanical stimulation (food stretching stomach and duodenal wall)** increases gradually from 0 hour to 0.7 hour, then increases rapidly to a maximum at about 1.6 hours, then decreases rapidly and ceases at about 2.6 hours

TYPICAL EXAMINATION QUESTION

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.
(d) 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.

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

TYPICAL EAMINATION QUESTION

(a) What roles do the liver and pancreas play in: (i) food digestion (ii) metabolism of absorbed products

(b) How can the diet of raw liver prevent the disease pernicious anaemia?

	Digestion	**Metabolism of absorbed products**
Pancreas	On stimulation by **cholecystokinin hormone**, the pancreas secretes enzymes whose effects are as follows: (i) Amylase catalyses hydrolysis of starch into maltose (ii) Enterokinase enzyme which activates Trypsinogen to Trypsin. (iii) Trypsin: (1) Catalyses hydrolysis of polypeptides to peptides. (2) Activates chymotrypsinogen to chymotrypsin. (iii) Chymotrypsin catalyses hydrolysis of casein / polypeptides into peptides. (iv) Lipase hydrolyses fats to fatty acids and glycerol (v) Nuclease hydrolyses nucleic acids to nucleotides (vi) Polypeptidase hydrolyses polypeptides to amino acids. On stimulation by secretin hormone, the pancreas secretes hydrogen carbonate ions from acinar cells, which neutralise the acid chyme from the stomach to provide an alkaline pH optimum for pancreatic enzymes.	(i) If in excess (above 90mg/100cm^3), the pancreas is stimulated to secrete insulin hormone which causes conversion of glucose to glycogen for storage, fat or metabolizing it to energy and CO_2. (ii) If little (below 90mg/100cm^3), the pancreas is stimulated to secrete glucagon hormone which causes conversion of glucagon to glucose hence increasing the blood glucose level.
Liver	On stimulation by secretin hormone, the liver secretes **bile** into the **gall bladder**. On stimulation by CCK hormone, **gall bladder** contracts to release bile salts which emulsify fats i.e. fats physically break into droplets due to reduced surface tension, which increases their surface area	**1. The Liver regulates blood glucose:** (i) If in excess (above 90mg/100cm^3), glucose is converted into glycogen for storage. (ii) If little (below 90mg/100cm^3), glycogen is converted into glucose for use. **2. The liver regulates amino acids in the body:** Excess amino acids are not stored in the body, but undergo deamination process. i.e. the amino group (-NH_2) from the amino acid is removed to form ammonia, which later forms urea that is carried in blood to kidneys for excretion. **3. The liver regulates lipids (fats) in the body:** It synthesizes and degrades phospholipids and cholesterol. 4. The liver forms red blood cells in foetus and breaks down worn out red blood cells in adults. 5. The liver forms plasma proteins from amino acids 6. The liver stores fat soluble vitamins A, D, E, K and water soluble vitamins B_{12} and C 7. The liver stores minerals like Iron, potassium, copper, zinc and trace elements. 8. The liver detoxifies poisonous substances i.e. toxic substances are turned harmless by the liver cells e.g. alcohol, cholesterol and hydrogen peroxide.

(b) Raw liver is rich in vitamin B_{12} which is essential for formation of red blood cells (erythrocytes), whose absence causes pernicious anaemia characterised by paleness, slowness and death.

FOOD AND DIET IN HUMANS

Food: Any substance taken in to nourish the body and sustain life. Food provides energy and nutrients.
Nutrient: is a substance which is needed for **growth**, **repair** and **metabolism**.
The three main nutrients are: **(1)** carbohydrates **(2)** proteins **(3)** lipids (fats and oils)

MEASURING FOOD ENERGY CONTENT

The energy content in a food sample can be measured by **simple calorimetry.**
Calorimetry: Measuring the amount of heat given out or taken in by a process, such as the combustion of a fuel.

PROCEDURE OF CALORIMETRY

(i) Pour cold water into a boiling tube / small beaker / metal can
(ii) Record the starting temperature of the water
(iii) Measure accurately the mass of the food sample in a crucible
(iv) Heat the food until it catches fire.
(v) Heat the water using the flame from the burning food
(vi) Record the final temperature of the water and calculate the temperature difference.

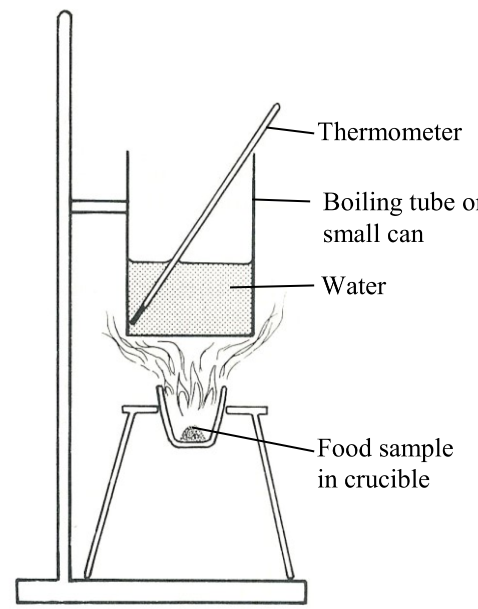
NB: The experiment above can be done more accurately using a **food calorimeter,** though it costs more money to purchase.

Calculations
Work out the energy transferred to the water in joules or in calories
Energy transferred (J) =
Mass of water (g) × 4.2 (J/g°C) × temperature increase (°C)

Note: 4.2kJ (1 cal.) of energy are required to raise the temperature of 1 kg of water through 1^0C

Worked example
When 0.5 g of food is burned, 10 cm^3 of water warms up by 20°C. What is the energy content of the food in J/g?

Solution
1 cm^3 of water has a mass of 1 g
Energy transferred to water = 10 × 4.2 × 20 = 840 J
Energy content of food = 840 ÷ 0.5 = 1680 J/g
To find the energy value of sugar, 1g of sugar is burnt in a crucible, the flame produced is used to heat 100 g water in a metal can and the rise in temperature of the water measured.



COMPARISON OF ENERGY VALUES

Carbohydrate: 1 gram contains 17 kJ
Fat: 1 gram contains 39 kJ
Protein: 1 gram contains 18 Kj

ENERGY UNITS

Energy units are joules, no longer calories
4.18 joules = 1 calorie
1000 calories = 1 kilocalorie (kcal.) = 1 Cal
1000 joule = 1 kJ (kilojoule) = 1 joule
1000 kJ = MJ (megajoule)

PRECAUTIONS

When comparing different foods, it is important to carry out a fair test by keeping other variables constant:
(1) Starting temperature of water **(2)** temperature increase **(3)** distance of the flame from the boiling tube
● More reliable results can be obtained by repeating the experiment.

SOURCES OF ERROR IN CALORIMETRY

(a) Inaccurate weighing of sugar
(b) Incomplete combustion of the sugar
(c) Inability to measure the temperature difference accurately enough
(d) Heat from the burning sugar escaping without heating the water.

ENERGY-FOOD INTAKE AND CONSUMPTION

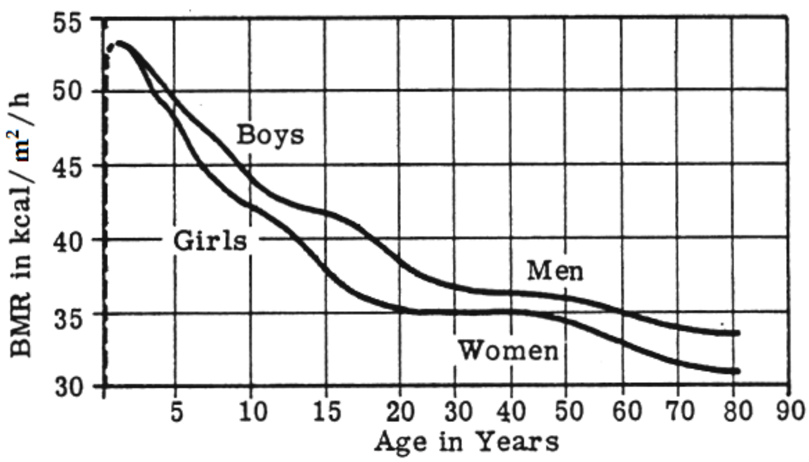
The body needs energy for **three main** reasons:

(i) 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.
(ii) Sustain body activities like muscle contraction during movement, locomotion, etc.
(iii) Generation of heat to maintain body temperature at about 37^0C

NOTE: BMR accounts for about 65% of the energy used in the body each day.

FACTORS WHICH DETERMINE BASAL METABOLIC RATE

Age, Sex, Body mass, Nature of physical activity engaged in, Muscle mass, Diet, Drugs, Environmental factors e.g. temperature, Hormonal factors e.g. during pregnancy and lactation, Genetics.



(a) (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.

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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.

BALANCED DIET

Balanced diet is one which contains the correct proportions and quantity of protein, carbohydrate, lipids, vitamins, mineral salts, water and dietary fibre/roughage required to maintain health.

- Mainly, carbohydrates and lipids are for energy production, proteins are for growth and repair, vitamins and mineral salts are for protection of good health, water is a solvent while roughage stimulates peristalsis to prevent constipation.
- An unbalanced diet can lead to **deficiency diseases**.

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: (1) the extra mass causes a person to get tired quickly **(2)** increases chances of stroke/heart attack.
How an obese person can lose weight: (1) Eating less energy food **(2)** Taking more exercises to increase energy output

BODY MASS INDEX (BMI)

This is one of the ways of determining whether a person is **underweight** or **overweight**.
BMI can be calculated using the formula:

$$BMI = \frac{\text{Mass in kg}}{(\text{Height in m})^2}$$

Qn. Calculate the BMI of a female of mass 69 kg and height of 1.67m
Another way of determining whether a person is underweight or overweight is to use a graph showing the relationship between height and body mass.

CHANGES IN BODY ENERGY RESERVES DURING STARVATION

- **Starvation** results from the inadequate intake of nutrients or the inability to metabolize or absorb nutrients.

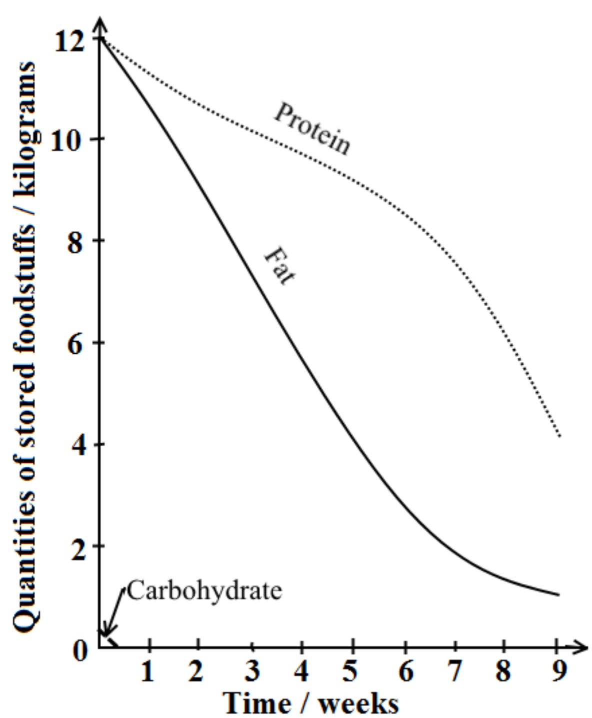
CAUSES OF STARVATION
Prolonged fasting, anorexia, deprivation, or disease
SYMPTOMS OF STARVATION
Weight loss, dehydration, apathy, listlessness, withdrawal, increased susceptibility to infectious disease, discoloured hair color, flaky skin, and massive edema in abdomen and lower limbs causing the abdomen to appear bloated.

ADVERSE EFFECTS OF STARVATION
(i) Marasmus: occurs on account of extreme energy deficiency, typically from inadequate amounts of protein and calories.
(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, giving the illusory impression that starving children are well fed.

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

DESCRIPTION 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.

TYPICAL EXAMINATION QUESTIONS

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)
They gained more body mass, fat and energy

(ii) Determine the average gain in mass of the cafetarian rats over the control rats during the 21 days
Average gain in mass = gain in body mass of cafeterian – gain in body mass of control rats = 131 – 103 = 28g

(iii) State three features of the two groups of rats which should be kept the same: Age, sex, species **(1½ marks)**

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

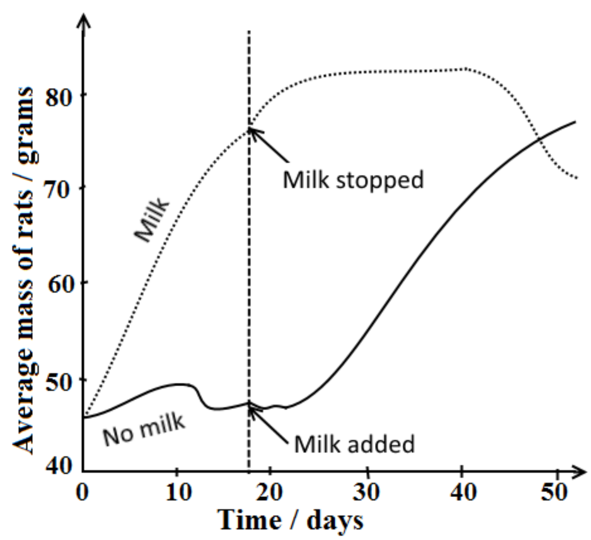
(c) Explain the observation that some people eat enormous amounts of foods without putting on weight where as others become over-weight on quite small food intake: Weight gain does not only depend on food intake, but on other factors like genetic makeup.

(d) Using evidence from the data, explain why cafetarian rats were able to gain more weight than control rats. (2 marks)
The difference between the energy content of food and energy used is higher in cafetarian rats; so unused food had to be converted to fat

(e) Why were control rats necessary in this experiment? For comparison of results **(1 mark)**

FEEDING EXPERIMENTS ILLUSTRATING THE IMPORTANCE OF VITAMINS IN NORMAL DIETARIES

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.

Why it was 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.

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.

Why while a diet of protein 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.

NUTRITION IN CARNIVORES AND HERBIVORES

(a) Carnivorous animals: are either **predators** or **scavengers** whose diet consists of mainly flesh obtained from **preys**.
(i) Predator: An animal that hunts and kills animals for food.
(ii) Prey: An animal that is hunted and killed for food.
(iii) Scavenger: An animal that eats dead animals, but doesn't kill them.
(b) Herbivore: An animal whose diet is mainly vegetation
(i) Grazers: Mainly feed on grass
(ii) Browsers: Mainly feed on leaves of shrubs and trees

	Carnivore	**Herbivore**
Adaptations for finding and capturing prey (**carnivores**) or grazing / browsing (**herbivores**)	● Well-developed sense of smell for locating prey ● Fast moving to outpace and capture prey ● Well-built body to manipulate and capture prey. ● Very sharp claws for gripping and killing prey. ● Keen eye sight for locating prey from a distance ● Foot pads enable stealth movement to ambush prey. ● Long, sticky tongue for reaching distant prey e.g. toads. ● Elongated canines for digging up prey e.g. walrus	● Upper jaw lacks incisors to provide a hard pad against which lower incisors press and cut grass. ● Tongue is highly muscular for manipulating food during chewing.
Adaptations for ingesting the food	● Sharp pointed canines for tearing the fresh of prey ● Flat molars to crush prey ● Incisors pointed for nipping and biting. ● Carnassial teeth present for shearing flesh. ● Upper jaw wider than lower jaw to facilitate shearing. ● Up-and-down jaw action only prevents lateral movement hence reducing the danger of dislocation ● Powerful jaw muscles provide much force for chewing	● Molars and premolars are ridged for maximum grinding of hard cellulose materials. ● Molars and premolars have large surface area for maximum grinding of the hard cellulose materials. ● Articulation of lower jaw permits lateral movement to enable maximum grinding of food. ● Well-developed jaw muscles provide much grinding power for crushing cellulose materials. ● Between the front and cheek teeth, there's a gap called diastema for separating crushed grass from uncrushed grass for effective chewing.
Adaptations for digesting the food	● No cellulose in diet hence less developed caecum and appendix to reduce on body weight to enable fast running. ● Relatively short alimentary canal reduces weight, since diet is entirely protein.	● Ruminant stomachs are four chambered to derive maximum nourishment from grass. ● Mutualistic bacteria in caecum and appendix enable chemical digestion of cellulose into glucose. ● Relatively long alimentary canal to digest vegetation

DIFFERENCES BETWEEN CARNIVORES AND HERBIVORES RELATED TO NUTRITION

Carnivores	Herbivores
●Closed pulp cavity in teeth	●Open pulp cavity in teeth
●Upper jaw incisors present	●Upper jaw incisors absent in most herbivores
●Canines present and well developed	●Canines small or absent to create a diastema
●Carnassial teeth present	●Carnassial teeth absent
●Cheek teeth pointed	●Cheek teeth flattened with enamel ridges and dentine grooves
●Articulation of lower jaw prevents lateral movement	●Articulation of lower jaw permits lateral movement
●Relatively short alimentary canal	●Relatively long alimentary canal
●No cellulose digestion	●Cellulose digestion occurs in caecum

EXAMPLES OF SYMBIOTIC ASSOCIATIONS IN ANIMALS

●**Symbiosis:** Ecological relationship between two or more organisms living together with some form of feeding relationship.

●**Mutualism:** Close relationship where two organisms of different species depend on each other for reciprocal benefit, without any harm e.g. pollination flowers by insects, **Trichonympha** and **termites,** cellulase producing bacteria and herbivores, etc.

●**Commensalism:** Loose relationship in which two organisms of different species live together, only one organism benefits while the other remains unharmed e.g. sea anemone and clown fish.

●**Parasitism:** Close relationship between organisms of different species in which one organism called **parasite** obtains nutrients from and harms a larger living organism called host.

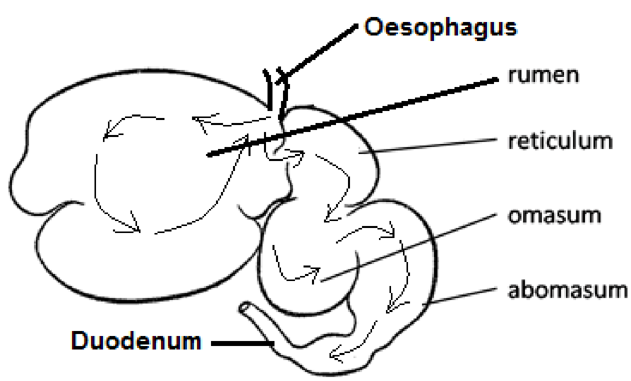
DIGESTION IN RUMINANT MAMMALS

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.

Four-chambered stomach showing food movement during feeding



1. Rumen (Paunch): Bacteria and protozoa in the rumen secrete **cellulase enzyme** which breaks down cellulose into glucose which undergoes fermentation to form **organic acids**, **carbon dioxide** and **ethane**. The fermentation process produces heat that keeps ruminants warm.

2. Reticulum (Honeycomb bag): Here any foreign objects that may have been accidentally swallowed with food settle out in the **honeycomb** structure of the reticulum's walls. Reticulum is sometimes called **"hardware stomach".**

3. Omasum (Psalterium / Manyplies): Absorbs water from food and also absorbs more nutrients called volatile fatty acids that supply ruminants with energy.

4. Abomasum (Reed / True stomach): Here, the food particles are digested by hydrochloric acid in the same way it occurs in human stomachs. The remaining particles are then passed on to the small intestine where most of the nutrients are absorbed by the body and made available to the ruminant.

CELLULOSE DIGESTION IN TERMITES

Guts of wood-eating termites contain a micro-organism called **Trichonympha,** which secretes **cellulase enzyme** to digest cellulose in wood. The termite absorbs some of the products of digestion (**glucose**), while **Trichonympha** gets sheltered.

CELLULOSE DIGESTION IN RABBITS (NON RUMINANTS)

The caecum and appendix of a rabbit contain bacteria that secrete **cellulase enzyme** for digesting **cellulose** into **glucose**. The herbivore gains **glucose** while the bacteria get **shelter**.

In the process described as **coprophagy (coprophagia)**, rabbits eat own faecal pellets while dung beetles feed on cow dung to enable absorption of glucose at the ileum.

PARASITISM

Close relationship between organisms of different species in which one organism called **parasite** obtains nutrients from and harms a larger living organism called host.

Challenges / Dangers faced by ectoparasites	Challenges / Dangers faced by endoparasites
● Failure to cling on the host to avoid being dislodged. ● Failure to obtain nutritive molecules from the host. ● Failure to find the right host for dispersal to their final host	● Failure to penetrate the host ● Failure to obtain nutritive molecules from the host. ● Destruction by the digestive enzymes and immune responses of the hosts. ● Complete elimination or extinction. ● Fluctuating environment e.g. low oxygen tensions, excess heat, solute concentration, darkness etc. ● Failure to find the right host for dispersal to their final host

GENERAL ADAPTATIONS OF PARASITES

Structural adaptations	Physiological adaptations	Reproductive adaptations
● Possession of penetrative devices for host entry e.g. fungal haustoria, cutting teeth in hook worms *Ancylostoma duodenale*) ● Possession of nutrient suckers e.g. leech ● Development of digestive-resistant outer covering to avoid host's enzyme attack e.g. *Ascaris* and *Taenia* etc. ● Camouflaging morphology to increase survival chances e.g. brown ticks on brown cattle. ● Possession of specialised mouth parts in some ecto-parasites to suck hosts e.g. sharp stylets in aphids and tsetse flies. ● Possession of specialised haustorial structures in Cuscuta (Dodder plants) for obtaining nutrients from the host ● Degeneration of non-essential organs e.g. no feeding organs, no locomotory organs, no alimentary canal to reduce body size and fit in intestines /blood vessels and for reducing energy expenditure on such organs for example *Fasciola hepatica* (liver fluke), tape worm, hook worm etc.	● Production of enzymes to digest the host's tissues during penetration into the host e.g. fungi and plasmodium ● Production of anticoagulants by blood feeding parasitic animals such as mosquitoes and ticks to avoid blood clotting during feeding. ● Highly tolerant to fluctuating environment e.g. anaerobic respiration in areas of low oxygen tensions, high temperatures, darkness and pH changes in places where they live e.g. most endoparasites. ● Rapid means of escape which increases their chances of survival e.g. fleas and mosquitoes. ● Production of much mucus for resisting digestion by host's enzymes. ● Some endoparasites produce chemicals to protect themselves against the immune response of the host.	● Some are hermaphrodites with the ability to carry out self fertilisation to increase the rate of reproduction e.g. *Fasciola*, *Taenia*. ● Some asexually reproduce for high rate of reproduction to avoid extinction. ● Release of sexually mature forms of the parasites as free living organisms e.g. in some parasitic animals such as the horse hair worms ● Production of large number of infective agents such as eggs, cysts, and spores which increase survival chances to avoid extinction e.g. tape worms. ● Development of reproductive bodies that are highly resistant when out of the host to survive adverse conditions e.g. cysts in amoeba, fungal spores, etc. ● Use of intermediate host (vector) for their transfer to primary host e.g. plasmodium in female anopheles mosquito to man. ● Some parasites localise the strategic points for propagation to the next host e.g. HIV which causes AIDS is localised in the sex organs. ● Some use hereditary transmission for increased spreading i.e. some parasites infect the ovary of primary host which lays parasite infected eggs.

COMMON PARASITES

Definitive host (final host / primary host): a host in which a parasite attains sexual maturity.
Intermediate host (secondary host): a host in which a parasite passes one or more of its asexual stages; usually designated first and second, if there is more than one.

Phylum/division	Parasite	**Host**		**Effect on primary host**
		Primary	**Secondary**	
Platyhelminthes	*Fasciola hepatica* (liver Fluke)	Sheep, cattle	Pond snails	Liver rot
	Schistosoma mansoni (blood fluke)	Humans	Pigs	*Schistosomiasis* (Bilharzia)
	Taenia solium (Pork tape worm)	Humans	Pigs	**Taeniasis;** Anaemia, Weight loss Abdominal (intestinal) pain
	Taenia saginata (Cattle tapeworm)	Humans	Cattle	
Nematoda	*Ascaris lumbricoides (*roundworm*)*	Humans	None	*Ascariasis,* Intestinal obstruction
Spermatophyta (Seed plants)	Dodder plant (Cuscuta)	Nettle, clover, tomato, potato	None	Damages tissues causing secondary infections
Spermatophyta (Seed plants)	*Striga* sp. (witch weeds)	Maize, millet, groundnut, etc.	None	Stunted growth, wilting, and chlorosis
Heterokontophyta	*Phytophthora infestans*	Tomato leaves	None	Late blight of potato and tomato (Black leaf spots, tuber rot)
Arthropoda	*Plasmodiun*	Female Anopheles	Humans	Malaria fever

LIFECYCLES OF SELECTED PARASITES

Lifecycle of *Ascaris lumbricoides (*roundworm*)*	Adaptations of *Ascaris* to parasitic life
● Adult female in lumen of ileum lays about 200,000 eggs daily, which are passed out in faeces. ● Fertile eggs **embryonate** and become infective after about **three** weeks, (***optimum conditions:*** moist, warm, shaded soil). ● On being swallowed by humans, eggs hatch into larvae, which invade intestinal wall, and are carried via the portal, then systemic circulation to lungs. ● Larvae mature further in lungs (10 to 14 days), penetrate alveolar walls, ascend the bronchi to the throat, and are swallowed into gut. ● Upon reaching the ileum, they develop into adult worms. ● Between 2 and 3 months are required from ingestion of the infective eggs to **oviposition** by the adult female. ● Adult worms can live 1 to 2 years.	● Degeneration of structures reduces space occupied. ● Possession of digestive-resistant cuticle resists destruction by the host's enzymes. ● Ability to position itself in a habitat where it gains maximum nourishment. ● Eggs have protective/resistant shell which is their main ineffective and resistant stage. ● Tolerance to oxygen deficient environment ● Ability to copulate within the intestines followed by the laying of very many eggs increases survival chances.

Lifecycle of *Taenia sp. (*Tapeworm*)*	Adaptations of *Taenia* to parasitism
● Humans are the definitive hosts for *T. saginata* and *T. solium*. ● Eggs or **gravid proglottids** are passed out in faeces; ● Cattle (*T. saginata*) and pigs (*T. solium*) become infected by ingesting vegetation contaminated with eggs or gravid proglottids. ● In the animal's intestine, the **oncospheres** hatch, invade the intestinal wall, and migrate to striated muscles, where they develop into **cysticerci**. A cysticercus can survive for several years in the animal. ● Humans become infected by ingesting raw or undercooked infected meat. ● In the human intestine, the cysticercus develops over 2 months into an adult tapeworm, which can survive for years. ● Adult tapeworms attach and stay in small intestine by their scolex. ● The adults produce proglottids which mature, become gravid, detach from the tapeworm, and migrate to the anus or are passed in the stool (approx 6 per day). ● The eggs contained in the gravid proglottids are released after the proglottids are passed with the feces.	● Has hooks and suckers for holding tightly onto ileum wall. ● Flattened body increases surface area for absorbing its host's digested food ● Degeneration of structures reduces on space occupied. ● Lays many eggs to increase survival chances. ● Hooks for boring through the gut of the host ● Eggs have a thick shell for resisting enzyme destruction. ● Being hermaphrodite increases reproductive rate

Hygienic practices for controlling endoparasites
- Avoid eating infected under cooked meat
- Through proper disposal of sewage which prevents these worms from spreading
- Through cooking meat thoroughly for example prolonged heating destroys the tapeworm bladders
- Regular deworming to flush the worm out of the wall of the intestines in faeces.
- Through regular meat inspection before it is consumed by man.
- By prohibition of the discharge of raw sewage into inland waters and seas.

PLASMODIUM – THE MALARIA CAUSING PARASITE
There are approximately 156 named species of *Plasmodium* which infect various species of vertebrates. Four species are considered true parasites of humans, as they utilize humans almost exclusively as a natural intermediate host: *P. falciparum, P. vivax, P. ovale* and *P. malariae*.

LIFE CYCLE OF *PLASMODIUM*
- Malaria parasite life cycle involves **humans** as **intermediate** host and adult female **anopheles** mosquito as **definitive** host.
- During a blood meal, a malaria-infected female ***Anopheles*** mosquito releases **sporozoites** into human blood.
- On reaching the liver, **sporozoites** infect liver cells and mature into **schizonts**, which rupture and release **merozoites**.
- After this initial replication in the liver (**exo-erythrocytic schizogony**), the parasites undergo asexual multiplication in the erythrocytes (**erythrocytic schizogony**).
- **Merozoites** infect red blood cells, the ring stage **trophozoites** mature into **schizonts**, which rupture releasing **merozoites**.
- Some parasites differentiate into sexual **erythrocytic** stages (**gametocytes**).
- Blood stage parasites are responsible for the clinical manifestations of the disease.
- The gametocytes, male (**microgametocytes**) and female (**macrogametocytes**), are ingested by an *Anopheles* mosquito during a blood meal.
- The parasites' multiplication in the mosquito is known as the **sporogonic cycle**.

- While in the mosquito's stomach, the **microgametes** penetrate the **macrogametes-generating zygotes**.
- **Zygotes** become motile and elongated (ookinetes), invade the midgut wall of the mosquito to develop into **oocysts**.
- **Oocysts** grow, rupture, and release **sporozoites**, which enter the mosquito's salivary glands.
- Inoculation of the **sporozoites** into a new human host perpetuates the malaria life cycle.

LIFE CYCLE OF *PHYTOPHTHORA INFESTANS*

- *Phytophthora* produce two kinds of spore i.e. diploid **oospores**, formed sexually from fusion of haploid **antheridia** and **oogonia,** and **chlamydospores** formed asexually. Both types of spore have thick cell walls for surviving harsh conditions.
- Under cool wet conditions, *Phytophthora* spores (**oospores** or **chlamydospores**) germinate to form hyphae or directly produce sporangia.
- Sporangia release free swimming **biflagellated zoospores,** which travel in moisture at the surface of leaves, and in soil.
- On reaching plant root or leaf surface a zoospore forms a cyst.
- The encysted zoospore then germinates to form hyphae on the host surface, which penetrates plant leaf or root tissues to absorb nutrients.
- After *Phytophthora* infects the plant, it produces **sporangia** and **zoospores** which further infect other tissues of the same plant or nearby plants.
- Sexual reproduction occurs when positive and negative mating types are present.
- **Haploid nuclei** of **antheridium** and **oogonium** fuse together when the **antheridium** enters the **oogonium** to form a **diploid oospore**, which develops into a **sporangium** and the cycle will continue as is would asexually.

TYPICAL EXAMINATION QUESTION

1. The blood fluke, *Schistosoma mansoni* is an important helminth parasite that resides within the mesenteric veins of its definite host. Experiments were done and the graphs in figures 1, 2 and 3 below show the effect of temperature, light and salinity on the hatching of the eggs of *Schistosoma mansoni.* At hourly intervals, the number of eggs hatching was determined and expressed as a percentage of total hatch.

Figure 1 shows the effect of temperature on hatching. After 4 hours of treatment at the temperatures shown, the samples were incubated for a further two hours at 28^{0}C at constant light and salinity.

Figure 2 shows the effect of light on hatching. One sample was kept in light for 6 hours while a second sample was first kept in the dark for 3 hours, then transferred to light for 3 hours at constant temperature and salinity.

Figure 3 shows the effect of salinity on hatching after treatment for 6 hours at constant temperature and light (percentage of total hatch is expressed as a % of number of eggs hatching in 0% saline).

Figure 1

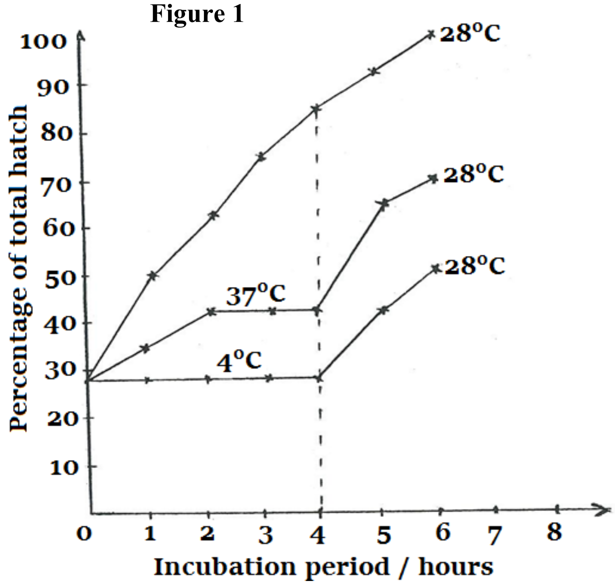
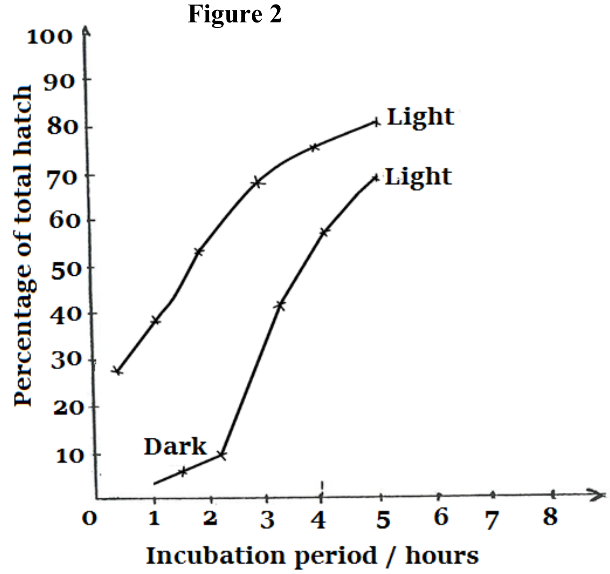


Figure 2



The eggs kept in 0.8% saline for 6 hours as in figure 3 above were removed, divided equally into four lots and placed in a range of saline solutions for a further 6 hours. The results are as shown in **table 1** below:

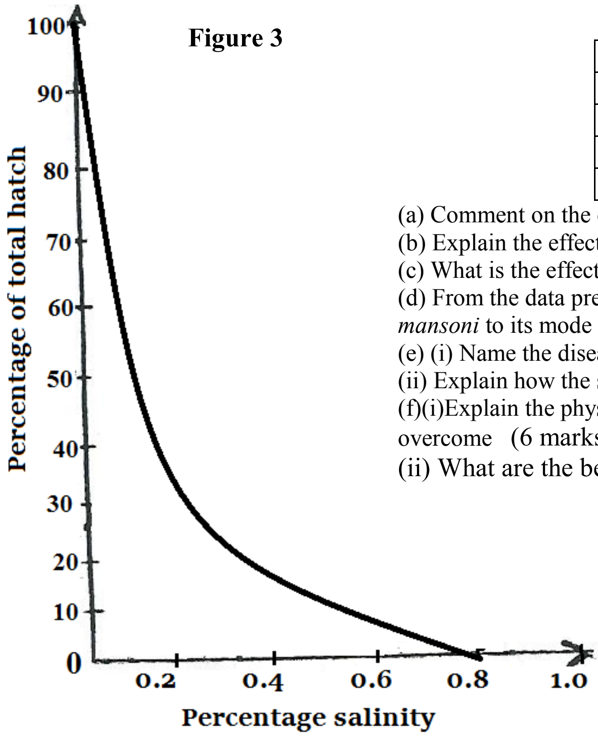


Table 1

Salinity (%)	Total hatch after 6 hours (%)
0.0	100
0.2	40
0.4	20
0.6	8

(a) Comment on the effect of temperature on hatching of *Schistosoma mansoni* eggs. (7 marks)
(b) Explain the effect of light on percentage hatch of eggs. (6 marks)
(c) What is the effect of salinity on percentage hatch of the eggs? (4 marks)
(d) From the data presented and restricting yourself to egg stage only, discuss adaptations of *S. mansoni* to its mode of life. (10 marks)
(e) (i) Name the disease caused by this blood fluke to man (1 mark)
(ii) Explain how the spread of disease can be controlled (4 marks)
(f)(i)Explain the physiological challenges facing human endo-parasites and how they are overcome (6 marks)
(ii) What are the benefits of parasitic nutrition to organisms that exhibit it? (2 marks)

PROBABLE SOLUTIONS

(a) Comment on the effect of temperature on the hatching of the eggs of *Schistosoma mansoni.* (7 marks)

- At constant light, salinity and temperature of 28^0C; ✓ eggs hatched rapidly; ✓ to completion; ✓
- At higher temperature of 37^0C and lower temperature of 4^0C; ✓hatching is just slightly stimulated (greatly inhibited); ✓
- Restoring temperature from 37^0C and 4^0C to 28^0C; ✓stimulates rapid hatching; ✓

(b) Explain the effect of light on the percentage of the total hatch of the eggs. (6 marks)

- The lot of eggs exposed to light hatch rapidly to completion; ✓ because light stimulates / activates a hatching substance/enzyme; ✓ which digests/breaks down the egg membranes to enable emergence of larvae; ✓
- Darkness generally inhibits hatching; ✓ because the hatching substance is inactive; ✓ however in this case a little hatching occurred in the dark probably due to experimental errors which resulted in some illumination of eggs;✓

(c) What is the effect of salinity on the percentage of total hatch of the eggs? (4 marks)

- In fresh water (at 0% salinity) all eggs hatched; ✓ at 0.8% salinity no eggs hatched (hatching was inhibited); ✓ increase in salinity; ✓ causes a rapid decrease in hatching; ✓

(d) From the data presented and restricting yourself to the egg stage only, discuss the adaptation of *S. mansoni*
(For more information, see MBV Roberts; functional approach, pg. 552-553)

- In the mesenteric veins of the main host of *Schistosoma mansoni*; ✓ there is total darkness and temperature is about 37^0C; ✓both of which prevent hatching of eggs into miracidia (larvae) in man; ✓because they would die; ✓
- When faeces with eggs reach fresh water bodies; ✓where there is much illumination (light), lower temperature and very low salinity; ✓ all of which favour rapid hatching of eggs; ✓ many larvae (miracidia) are formed; ✓ which infect water snails; ✓ (intermediate host) and form more larvae (cercariae) that infect man; ✓

(e) (i) Name the disease caused by this blood fluke to man (1 mark)

Bilharzia (Schistosomiasis); ✓

(ii) Explain how the spread of the disease can be controlled (method and its purpose = 01 mark x 4)

- Disposal of faeces in latrines/toilets to avoid their contact with fresh water bodies; ✓
- Deworming to kill adult worms in humans; ✓
- Wearing gear (boots/shoes) that shield/protect feet from larvae (cercaria) infection; ✓
- Use molluscides to kill larvae's (miracidia) intermediate hosts (adult snails) in water; ✓
- Biological control in which some fish and ducks are introduced in water to feed on larvae /snails; ✓

(f)(i) Explain the physiological challenges facing human endo-parasites and how they are overcome
(Any 3, @ challenge – 1 mark, how overcome – 1 mark = 06 marks)

Challenge	How it is overcome
• Digestion by the host's enzymes; ✓	• Development of thick cuticle/secretion of inhibitory substances /mucus✓
• Osmotic changes in the habitat; ✓	• Increased chemosensitivity in order to equilibrate with host✓
• Inhibitory chemical environment; ✓	• Secretion of anti-inhibitory substances; ✓
• Anaerobic conditions; ✓	• Ability to respire anaerobically; ✓
• Attack by host's immune system; ✓	• Development of protective structures against the host's immune attack✓

(ii) Importance of parasitic nutrition (2 marks)

- A variety of nutrients required for growth, development and body maintenance may be obtained from one meal

Less development of digestive system since most nutrients obtained are fully /partially digested.

SAPROTROPHISM (SAPROTROPHIC NUTRITION)

The process of obtaining soluble organic substances from extracellular digestion of dead or decayed organic matter.
Saprotroph: An organism that absorbs soluble nutrients from extracellular digestion of dead/decaying organic matter.

EXAMPLES OF SAPROTROPHS

(i) Saprobes: fungi like mushrooms, yeasts and moulds
(ii) Saprophytes: **saprotrophic plants** e.g. sugar stick, gnome plant, Indian-pipe and **putrefying bacteria** which convert complex organic substances into simpler compounds e.g. **Zygomonas** bacterium ferments **glucose** producing **alcohol, lactic acid and carbon dioxide**, **Clostridium aceto-butylicum** forms **butyl alcohol** from **carbohydrates**, **Lactobacillus** converts **sugars** into **lactic acid**.
(iii) Saprophages: Animal scavengers, such as dung beetles and vultures

DESCRIPTION OF SAPROTROPHISM IN FUNGAL MOULD LIKE MUCOR/RHIZOPUS

●Under suitable conditions (moisture / water, oxygen, neutral / mildly acidic pH, temperature of about 25 °C) the saprotroph secretes different enzymes into the dead animal/plant body; proteases, lipases, carbohydrases e.g. amylase which break down insoluble complex organic substances into simple soluble substances as follows:
-**Proteases** break down **proteins** into **amino acids**
-**Lipases** break down **lipids** into **fatty acids** and **glycerol**
-**Carbohydrases** e.g. **Amylases** break down **starch** into **maltose**/**simple disaccharides**
●The end products of extra-cellular digestion such as **fatty acids** and **glycerol, glucose, amino acids** plus other nutrients like **vitamins** e.g. **thiamine** and **ions** e.g. **potassium, phosphorus, and magnesium** are re-absorbed into the hypha through the cell wall by **endocytosis / simple diffusion / facilitated diffusion / active transport** and passed on throughout the mycelium complex to enable growth and repair.

COMPARISON OF SAPROPHYTES WITH PARASITES

Similarities

Both: **(1)** are heterotrophs **(2)** absorb soluble food **(3)** have simple digestive systems **(4)** have sexual and asexual phases in their reproduction **(5)** produce large numbers of offspring.

Differences

Parasites	Saprophytes
●Energy derived from living organisms	●Energy derived from dead organisms
●Many stages in lifecycle	●Usually a single adult stage, with spores inclusive
●Very specific to their host	●Use a variety of food sources
●Nutritionally highly adapted	●Simple methods of nutrition
●Most plant and animal groups have representatives	●Almost totally fungi and bacteria
●Most are aerobic	●Anaerobic and aerobic

IMPORTANCE OF SAPROPHYTES
●Recycling of materials e.g. carbon, nitrogen, phosphorus
●Brewing and baking e.g. yeast (*Saccharomyces*)
●Making antibiotics e.g. Penicillin
●Decomposition of wastes e.g. sewage
●Production of yoghurt and cheese
●Food source e.g. mushrooms
●Industrial applications e.g. leather tanning, production of vitamins, etc.

AUTOTROPHIC NUTRITION

Autotrophic (Greek: *auto* – 'self'; *trophic* – 'feeding') organisms take in inorganic carbon e.g. carbon dioxide and energy, to form complex organic compounds.

Types of Autotrophs
(1) ***Phototrophs*** - organisms which synthesize organic compounds using light energy. *e.g. all green plants, algae, cyanobacteria, blue-green bacteria, green sulphur bacteria, purple sulphur bacteria, colourless sulphur bacteria.*
(2) C***hemotrophs -*** organisms which synthesize organic compounds using energy extracted from oxidation of inorganic chemicals by the process called **chemosynthesis** e.g. *Nitrosomonas* and *Nitrobacter*

CHEMOSYNTHESIS

Chemosynthesis: chemical process in which inorganic chemicals are oxidized to provide energy to living organisms for the synthesis of organic compounds.

Chemosynthetic bacteria	***Substrate***	***Main product***	***Habitat***
Nitrosomonas and Nitrococcus	Ammonium (NH_4^+)	Nitrite (NO_2^-)	Soil
Nitrobacter	Nitrite (NO_2^-)	Nitrate ((NO_3^-)	Soil
Thiobacillus	Sulphur (H_2S)	Sulphate (SO_4^{2-})	Decaying organic matter
Ferrobacillus / Iron bacteria	Ferrous (Fe^{2+})	Ferric (Fe^{3+})	Streams flowing over iron rocks
Hydrogenomonas	Hydrogen (H_2)	Water (H_2O)	Soil

Importance of chemosynthesis
The chemical activities of the organisms involved bring about nutrient cycling; for example:
- *Nitrosomonas* and *Nitrobacter* bacteria are involved in nitrification in plants.
- *Thiobacillus* catalyse the conversion of sulphur containing compounds to sulphates which are directly useful to plants.

Mechanism of chemosynthesis in some bacteria

$$NH_3 + 3O_2 \xrightarrow{\textit{Nitrosomonas}} HNO_2 + H_2O + \text{energy (79 kcals)}$$

$$HNO_2 + O_2 \xrightarrow{\textit{Nitrobacter}} HNO_3 + \text{energy (22 kcals)}$$

$$H_2S + 2O_2 \xrightarrow{\textit{Thiobacillus}} SO_4^{2-} + 2H^+ + \text{Energy}$$

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

$$6CO_2 + 12H_2S \longrightarrow C_6H_{12}O_6 + 6H_2O + 12S$$

PHOTOSYNTHESIS

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

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

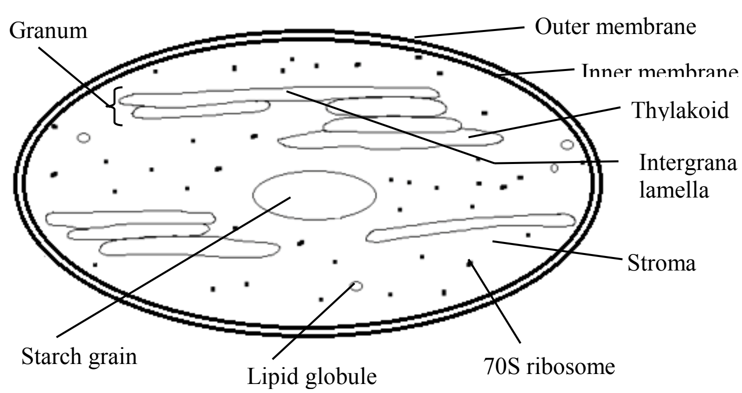
GENERAL ADAPTATIONS OF LEAVES FOR PHOTOSYNTHESIS

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

Adaptations for gas entry and exit	*Adaptations for liquid entry and exit*
1. Numerous stomata are present in the epidermis of leaves to enable entry and exit of gases. **2.** The guard cells bordering stomata pores can be opened and closed to regulate the uptake of carbon dioxide and the loss of water. **3.** Spongy mesophyll possesses many airspaces to enable faster and uninterrupted diffusion of gases between the atmosphere and the palisade mesophyll which wouldn't happen if the gases were to diffuse through the cells themselves, a process which would be much slower.	**1.** A large central midrib containing a large vascular bundle comprising xylem and phloem tissue is possessed by most dicotyledonous leaves for the entry and transport of water and mineral salts, and the phloem for carrying away sugar solution, usually in the form of sucrose. **2.** A network of small veins is found throughout the leaf to ensure that every cell is close to xylem vessel or phloem sieve tube for constant supply of water for photosynthesis and a means of removing the sugars they produce.

CHLOROPLAST STRUCTURE

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



Adaptations of chloroplast for its functions
- Outer membrane is semi- permeable to regulate entry and exit of substances for maintaining internal chloroplast environment.
- Abundant light trapping pigments for photosynthesis
- Abundant enzymes catalyse photosynthetic reactions in the stroma.
- Extensive network of thylakoid membranes increase surface area for photosynthesis.
- Narrow intermembrane space enables H^+ ion concentration gradient to be rapidly established for chemiosmosis to occur
- Inner membrane contains molecules for electron transport pathway
- DNA presence codes for protein synthesis, including enzymes.
- Many ribosomes for protein synthesis to reduce on importing proteins from cytoplasm.
- Outer membrane is permeable to gases like carbon dioxide which is a raw material for photosynthesis.

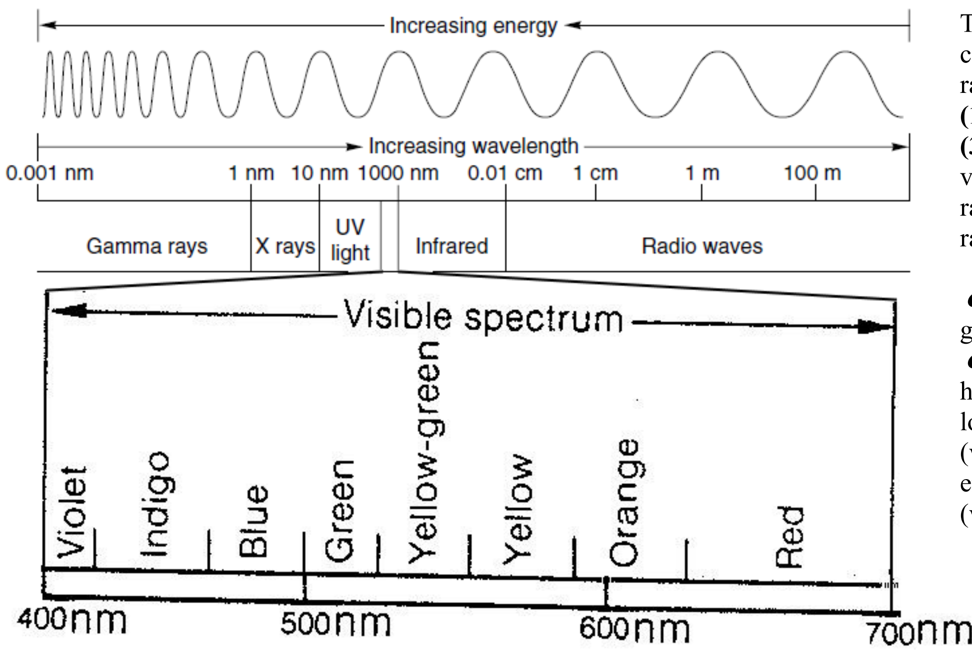
CONDITIONS NECESSARY FOR PHOTOSYNTHESIS

1. Carbon dioxide, 2. Water, 3. Light, 4. Photosynthetic pigments

Condition	Explanatory notes
1. Carbon Dioxide	●Land plants obtain CO_2 **(1)** by diffusion via stomata **(2)** by absorbing CO_3^{2-} from soil via roots. ●Aquatic plants absorb dissolved bicarbonates through their general surface to carbon dioxide. ●Air contains about 0.04% (400 ppm) by volume carbon dioxide while it is variable in water
2. Water	Water provides the H^+ ions (protons) and electrons for the reduction of carbon dioxide. $2\,H_2O \longrightarrow O_2 + 4(H)$ $4(H) + CO_2 \longrightarrow CH_2O + H_2O$
3. Light	Three important properties of light: **(i) quality**/colour **(ii) intensity**/brightness **(iii) duration**/time. Light is **electromagnetic** energy propagated in discrete particles called **photons or quanta**

ELECTROMAGNETIC RADIATION

Electromagnetic radiation is a form of energy transmitted through a vacuum (empty space) or a medium (such as glass) in which electric and magnetic fields are propagated as waves.



The electromagnetic spectrum consists of ***eight types*** of radiations:
(1) Cosmic rays **(2)** gamma rays **(3)** x-rays **(4)** ultra-violet rays **(5)** visible light spectrum **(6)** infrared rays **(7)** electric rays and **(8)** radio rays.

●The shorter the wavelength, the greater the frequency.
●Light with a short wavelength has more energy than light with longer wavelength e.g. Blue light (wavelength 400nm) has more energy than a photon of red light (wavelength 700nm).

ORIGINS OF PHOTOSYNTHETIC LIGHT

1. Incandescence: The emission of light from hot matter e.g. the sun. The hotter the material, the shorter the wavelengths of emitted light, the more the energy.
2. Luminescence: The emission of light when 'excited' electrons fall to a lower energy, emitting a photon e.g. the light-emitting diode bulbs in school labs, fluorescent lights, light from leaf extracts, etc.

NATURE OF LIGHT

Visible light is the part of the electromagnetic spectrum between the wavelengths of 400 nm and 740 nm, known as the **photosynthetically active radiation (PAR)**.

FATE OF LIGHT THAT HITS A LEAF

Light interacts with a leaf in three ways:
1. Reflection (Reflectance): light can simply rebound off the leaf surface and hence never utilized in leaf photosynthesis.
2. Transmission (Transmittance) through the leaf, exiting from the underside.
3. Absorbance by the leaf, in which case the light might be used in photosynthesis.
●Of the absorbed visible radiation, 70%, is used in photosynthesis while 30% is transmitted through the leaf.
● **Blue** and **red** are the most **absorbed** wavelengths, and **green** and **far infrared** wavelengths pass through.
●Transmission depends on the thickness of the leaf; thin leaves transmit more light than thick leaves.

LIGHT IN A FOREST (SHADY ENVIRONMENT)

●The amount of **sunlight decreases** as light penetrates down the vegetation layers because the amount of **leaf area** increases. **Leaf area index** is the one-sided leaf area per unit area of ground.

●The leaf area index (LAI): **LAI = m^2 leaf area/m^2 ground area**

E.g.: 3 m^2 leaf area/m^2 ground area means there are 3 square meters of leaf area over each square meter of ground area.

●The greater the leaf area over a surface, the lower the quantity of light reaching that surface.

FATE OF LIGHT IN A FOREST (SHADY ENVIRONMENT)

The graph beside shows the energy in light of different wavelengths reaching the ground in a forest.

Energy was measured in:

(1) Direct sunlight that passed through canopy gaps.

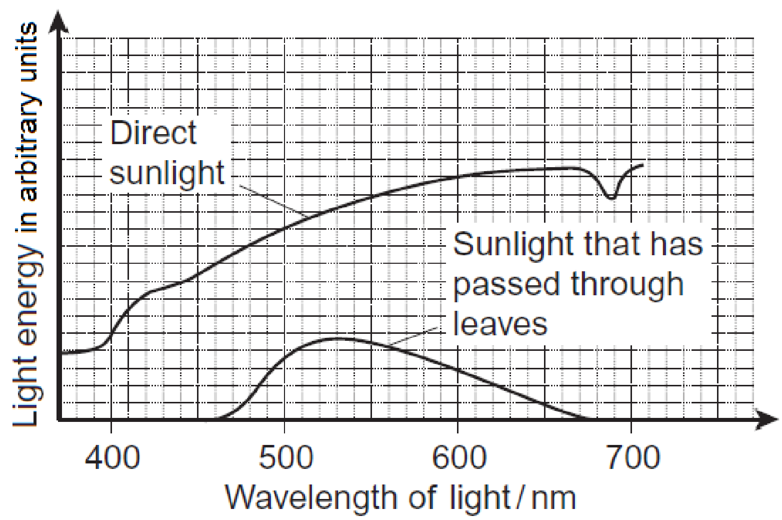
(2) Sunlight that had passed through tree leaves.

●As light penetrates the canopy, different wavelengths are filtered out – **light becomes attenuated (reduced)**:

(i) The denser (thicker) the canopy, the more weakening of light occurs.

(ii) Leaves with whitish hairs and cuticle reflect more light than deep green leaves

(iii) The smaller the size of gaps in the canopy, the more weakening of light.



Observations

1. All the wavelengths of direct light reach the ground because this light passes through gaps left by leaves hence no wavelength is filtered out.
2. Of the light that passes through leaves, only wavelengths in the range 460 nm – 670 nm reach the ground (high transmittance to the ground) because of low/no absorption by chlorophylls in the leaves.
3. Wavelengths of visible light below 460 nm and above 670 nm do not reach the ground after passing through leaves (no transmittance) because of much absorption by photosynthetic pigments e.g. chlorophylls.
4. Of the light that passes through leaves, wavelength 525 nm reaches the ground with most energy because it is least absorbed by photosynthetic pigments.

4. PHOTOSYNTHETIC PIGMENTS

●**Chlorophylls** and **carotenoids** absorb light energy required in photosynthesis.

●**Carotenoids** also protect chlorophyll from photo damage.

Photosynthetic Pigment	***Distribution (occurrence)***	***Properties***
Chlorophyll ***a***	All photosynthetic plants i.e. It is the most abundant	●Bluish green in pure state ●Very soluble in ether, and also soluble in lipid solvents e.g. chloroform, carbon tetrachloride, alcohols, etc
Chlorophyll ***b***	Higher plants	●Olive green (yellow green) in pure state. ●Very soluble in methyl alcohol and also soluble in lipid solvents e.g. chloroform, carbon tetrachloride, etc
Bacteriochlorophyll	(1) Purple sulphur Bacteria, (3) Green sulfur bacteria	● Are related to chlorophylls ●Conduct photosynthesis, but do not produce oxygen. ●Absorbs wavelengths of light not absorbed by plants
CAROTENOIDS (a) ***xanthophylls*** e.g. lutein (b) ***carotenes*** e.g. α-carotene, lycopene	Occur in chloroplasts of plants, algae, some bacteria, and some types of fungi	●Xanthophylls are often yellow, Carotenes vary in colour: pale yellow, bright orange, deep red. ● Are soluble in fat solvents e.g. ether, chloroform, acetone. ●Carotenes are closely related to the vitamin A

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

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

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

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

SUN AND SHADE LEAVES

- Sun leaves are those that grow on branches exposed to direct sunlight while shade leaves grow on branches exposed to light that has passed through leaves.
- In **low light**, plants need to maximise light absorption for photosynthesis to exceed respiration if they are to survive.
- In **high light** environment, plants maximise their capacity for utilising abundant light energy, while at the same time dealing with excess sunlight which can bleach chlorophyll.

ADAPTATIONS TO PHOTOSYNTHESIZE IN SUN AND SHADE

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

Shade plant	Sun plants
1. Abundant chlorophyll ***b*** (low chlorophyll *a* to chlorophyll *b* ratio) which gives leaves dark green colour to increase light absorption in the dark; 2. Palisade/ spongy mesophyll ratio low to allow maximum light penetration; 3. Mesophyll cell surface / leaf area ratio low to maximise light trapping; 4. Leaf orientation horizontal to maximise light trapping; 5. Reddish leaf undersides to enhance reflectance back up through the photosynthetic tissue; giving the plant a second chance to utilize the light. 6. Stomatal density low to avoid over cooling; 7. Thin leaves to maximise light penetration; 8. Stomatal size large to allow loss of excess water; 9. Elongated internodes for increased access to light; 10. Chloroplast size large to increase the surface area for storage of photosynthetic pigments.	1. Abundant chlorophyll ***a*** (high chlorophyll *a* to chlorophyll *b* ratio) to increase light absorption; 2. Palisade/ spongy mesophyll ratio high to minimise light penetration; 3. Mesophyll cell surface / leaf area ratio high to minimise excessive light and transpiration; 4. Leaf orientation erect to minimise light trapping; 5. Stomatal density high to avoid over heating; 6. Much carotenoids to prevent damage to chlorophyll from very bright light. 7. Thick leaves to minimise light penetration; 8. 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

PHOTOSYNTHETIC PIGMENTS IN SUN LEAVES AND SHADE LEAVES OF BEECH TREE

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

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

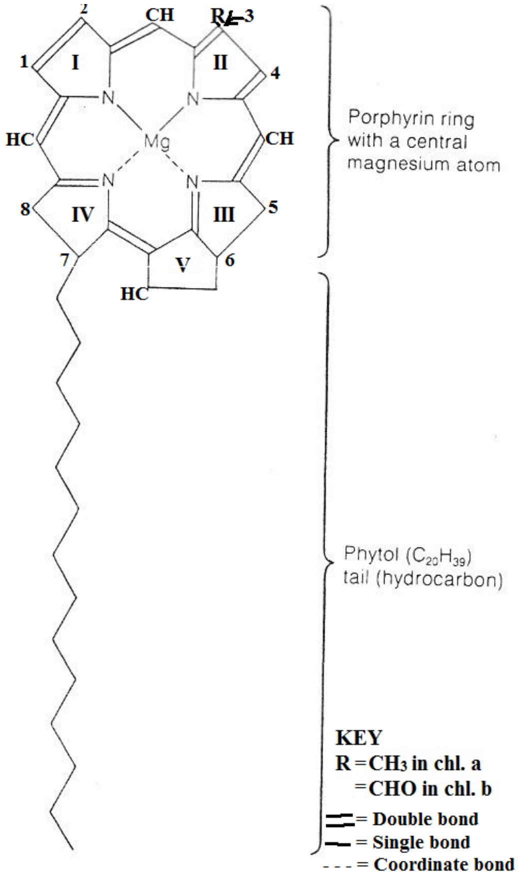
COMPARISON OF DISTRIBUTION OF PHOTOSYNTHETIC PIGMENTS

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

Why few species of plant can survive under shady habitats.

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

DESCRIPTION OF CHLOROPHYLL MOLECULE STRUCTURE



- Chlorophyll molecule has a ***tadpole-like*** structure, with a ***hydrophilic head*** called ***porphyrin*** and a ***hydrophobic tail*** made up of long chain alcohol called **phytol**.
- The ***flattened*** head is made up of ***four nitrogen*** containing ***pyrrole*** rings (labelled I-IV) which are linked by methine bridges (-CH=).
- The skeleton of each pyrrole ring is made up of 5 atoms - ***four carbon*** and ***one nitrogen***. The nitrogen lies towards the centre.
- A magnesium atom is held in the centre of porphyrin head by ***nitrogen atoms*** of pyrrole rings using ***2 covalent*** and ***2 coordinate bonds***.
- Chlorophyll b differs from chlorophyll a in having the group (-CHO) instead of a methyl group (-CH_3) at position **R** (carbon 3).

NB: The phytol tail ***anchors*** and ***orients*** the chlorophyll molecule in the chloroplast's thylakoid membrane

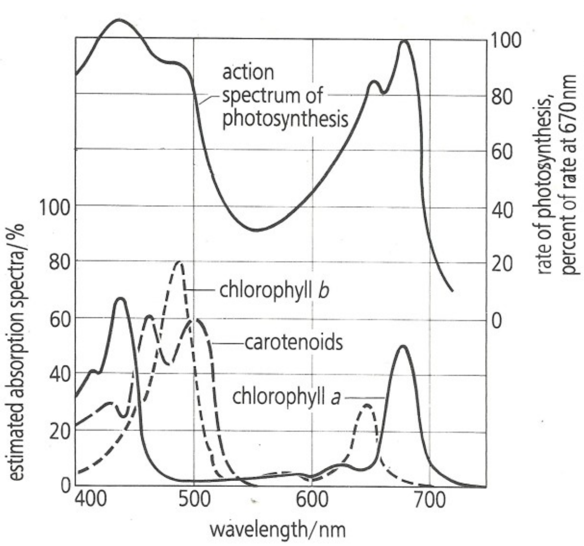
ABSORPTION SPECTRUM OF PHOTOSYNTHETIC PIGMENTS

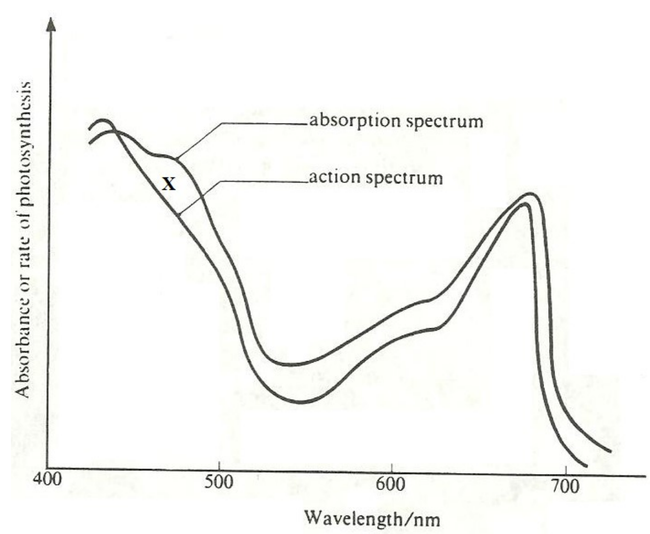
It is a graph of the relative absorption of different wavelength of light by a pigments like chlorophyll. It is measured by a **spectrophotometer**

ACTION SPECTRUM OF PHOTOSYNTHESIS

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

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





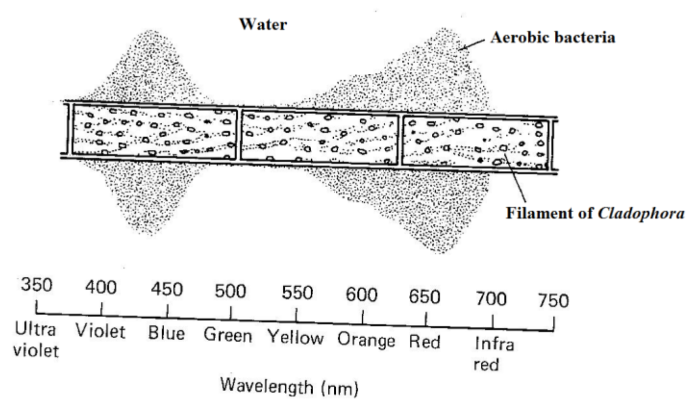
Observations	*Explanation*
● The action spectrum of photosynthesis corresponds closely to the absorption spectra of chlorophyll **a** and **b**.	● This indicates that most of the wavelengths of light absorbed by chlorophyll are used in photosynthesis.
● There is non-correspondence of action spectrum of photosynthesis with absorption spectra at point marked **'X'**	● This is because it is at '**X**' where there is maximum absorption by carotenoids, which are not used in photosynthesis.
● The wave lengths of about 550 nm to 620 nm have the lowest absorption and action spectra for all the photosynthetic pigments.	● The unabsorbed (reflected light) appears green, thus making chlorophyll, the chloroplasts and the leaves that contain it appear green to our eye.
● There are two absorption maxima of *lambda* = 430 nm and *lambda* = 662 nm for chlorophyll **a**, and 453 nm and 642 nm for chlorophyll **b**, but only one maximum for carotenoids at about 510 nm.	● This shows that chlorophyll a as well as b are the main photosynthetic pigments, however, photosynthesis also occurs in the mid part of light spectrum where carotenoids are active.
● The action spectrum peaks within the blue-violet and red regions of the light spectrum.	● This shows that maximum photosynthesis occurs in red part and blue-violet part of visible light.

OTHER OBSERVATIONS

● ***Chlorophyll a*** absorption in red light is about twice that of ***chlorophyll b*** and the absorption peak is at a slightly longer wavelength (lower energy)

● Absorption of chlorophyll a in the blue is lower and shifted to a slightly shorter wavelength (higher energy).

ENGELMANN'S EXPERIMENT ON ACTION SPECTRUM OF PHOTOSYNTHESIS

Description of Engelmann's experiment	*Results of Engelmann's experiment*
●Filaments of the green alga ***Cladophora*** *of the genus* ***Pseudomonas*** are placed in a drop of water on a slide, then illuminated with light of different wavelengths and observed under the microscope. ●The control experiment involves mounting the alga on a slide in water with aerobic bacteria in total darkness and thereafter exposing the slide to light. ● ***Observation 1:*** The motile aerobic bacteria cluster near to the filaments in the region of blue light (450 nm) and red light (650 nm). ● ***Deduction 1:*** Since the distribution of aerobic bacteria is in response to the concentration of oxygen which is a by-product of photosynthesis, then red and blue light are the most effective for photosynthesis. ● ***Observation 2:*** Motile aerobic bacteria cluster around the edge of the cells adjacent to the chloroplast. ● ***Deduction 2:*** Oxygen is more concentrated near the chloroplast which shows that the chloroplast is the sight of photosynthesis. ● ***Observation 3:*** The aerobic bacteria of the slide previously in the dark are immobile but later cluster around the alga filament on exposure to light.	 ● ***Deduction 3:*** Darkness prevents photosynthesis, which stops evolution of oxygen resulting in anaerobic conditions that **donot** favour aerobic bacterial activity ● ***Observation 4:*** There is hardly any aerobic bacteria in the ultra-violet, green and infra-red regions of the spectrum. ● ***Deduction 4:*** Light from ultra-violet, green and infra-red regions of the spectrum is hardly absorbed by chlorophylls hence least used in photosynthesis, with no / little evolution of oxygen.

MECHANISM OF PHOTOSYNTHESIS

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

PHASES OF PHOTOSYNTHESIS

[1] Light stage (**Photochemical** reactions or **Hill** reaction)   **[2]** Dark stage (**Biochemical** reactions**)**.

LIGHT DEPENDENT PHASE

● It takes place in the thylakoid membranes of chloroplasts.

The main functions are:

(1) ***Photophosphorylation*** i.e. addition of an inorganic phosphate to Adenosine diphosphate (ADP) to form Adenosine triphosphate (ATP) using light energy.

(2) Formation of $NADPH^+$ which is the reduced form of ***Nicotinamide adenine dinucleotide phosphate***.

DESCRIPTION OF LIGHT STAGE OF PHOTOSYNTHESIS

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

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<tr><th>THE Z-SCHEME SUMMARISING LIGHT STAGE</th><th>OPERATIONS OF PHOTOSYSTEMS I AND II</th></tr>
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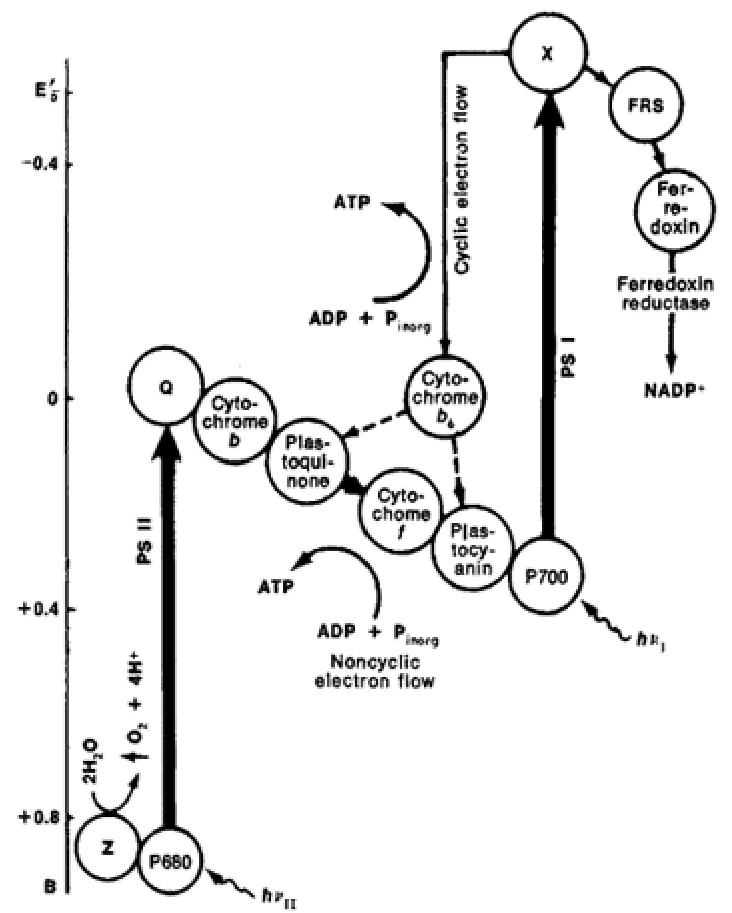

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● Chlorophyll molecules of PSII and PSI are excited by light of wavelength 680 nm and 700 nm respectively; causing the loss of electrons to a chain of electron carriers in a series of reduction-oxidation reactions as follows:

(i) From PSI, some electrons may flow:

(1) Cyclically to iron-protein complex, cytochromes b_6, plastoquinone, cytochrome-**f,** plastocyanin and back to P-700, during which electrons lose energy to form ATP from ADP and P*i*.

(2) Non-cyclically (Unidirectionally) to unknown molecule A, iron-protein complex, Ferrodoxin, Flavin-Adenine Dinucleotide (FAD) which becomes reduced (FADH), finally to NADP to form reduced NADP (NADPH).

(ii) From PSII to the unknown molecule Q, substance B, plastoquinone (PQ), cytochrome f, plastocyanin, (a copper enzyme), and finally to PSI, to replace the electrons earlier lost. During this flow, electrons lose energy to **phosphorylate** ADP to form ATP.

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

● ***At the same time, photolysis of water:***

(1) Causes accumulation of H^+ **inside the thylakoid space.**

(2) Provides electrons to replace those lost from PSII, with evolution of oxygen molecule.

● ***Chemiosmosis*** occurs i.e. the highly concentrated H^+ inside the thylakoid space **diffuse** along the steep electrochemical gradient from the thylakoid space via the stalked particles into the stoma, thereby providing:

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

(2) H^+ for reducing NADP to form NADPH, which together with the ATP formed enter the dark stage.

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NOTE

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

WHAT IS MEANT BY?

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

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

COMPARISON OF CYCLIC AND NON-CYCLIC PHOTOPHORYLATION

Similarities

In both:

(1) there is flow of electrons through several electron carriers **(2)** there are pigment systems which accept and lose electrons **(3)** ATP is formed **(4)** pigment system I is involved **(5)** electron movement is located in the thylakoid membranes **(6)** protons are moved outwards of the thylakoids **(7)** protons (H^+) are actively pumped from stroma into thylakoid space **(8)** there is photo-excitation of electrons in the pigment systems.

Differences

NON-CYCLIC PHOTOPHORYLATION	CYCLIC PHOTOPHORYLATION
● Electrons flow unidirectionally (non-cyclically)	● Electrons flow cyclically
●First electron donor is (source of electrons) water	●First electron donor is pigment system I (PSI)
●Last electron acceptor is NADP	●Last electron acceptor is pigment system I (PSI)
●The products are ATP, NADPH and Oxygen	●The product is ATP only
●Involves both pigment systems I and II	●Involves only pigment system I
●Photolysis of water occurs	●No photolysis of water

ROLE OF WATER IN PHOTOSYNTHESIS

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

DARK REACTION [BIOSYNTHETIC PHASE OR BLACKMAN'S REACTION]

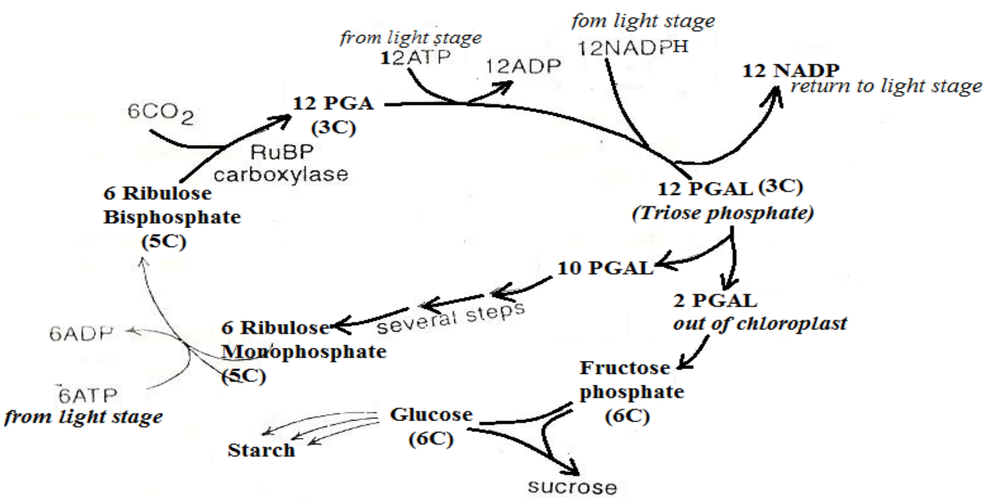
It's called **dark reaction** because does not require light, although can take place in light also. It occurs in the stroma of chloroplasts.

THE MAIN PATHWAYS FOR THE DARK REACTION

(l) Calvin-Benson cycle / C_3 pathway **(2)** Hatch-Slack pathway / C_4 pathway

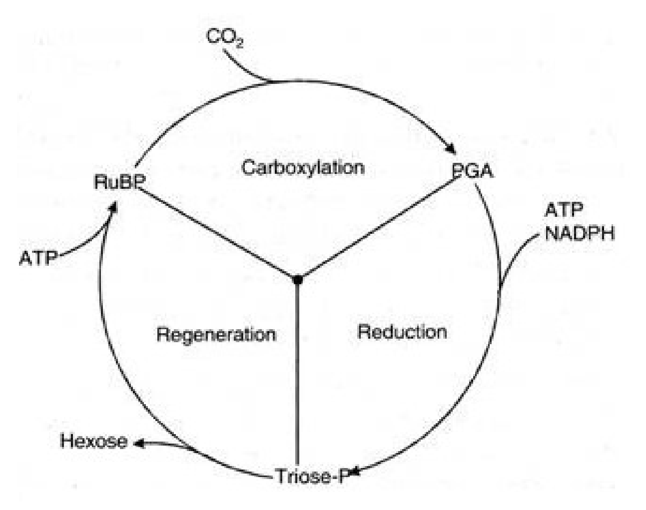
MAIN STAGES OF CALVIN-BENSON CYCLE (C_3 CYCLE)

C_3 Plants: Plants whose first stable product of photosynthesis is a 3-carbon organic compound called **glycerate-3-phosphate**



Triose phosphate (glyceraldehydes 3-phosphate) is the **end product** of the Calvin cycle / photosynthesis because all subsequent reactions can also occur in no-photosynthetic organisms like animals and fungi . **(Soper R. et al (1997). *Biological Science* n210:7.7)**

THREE MAIN STAGES OF THE CALVIN CYCLE



1. CARBOXYLATION

●Catalysed by RuBP carboxylase, 6 molecules of RuBP react with 6 molecules of CO_2, and 6 molecules of water forming 12 molecules of 3-phosphoglyceric acid (PGA), which is the **first carbohydrate made by C_3 plants.**

2. PHOSPHORYLATION AND REDUCTION

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

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

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

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

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

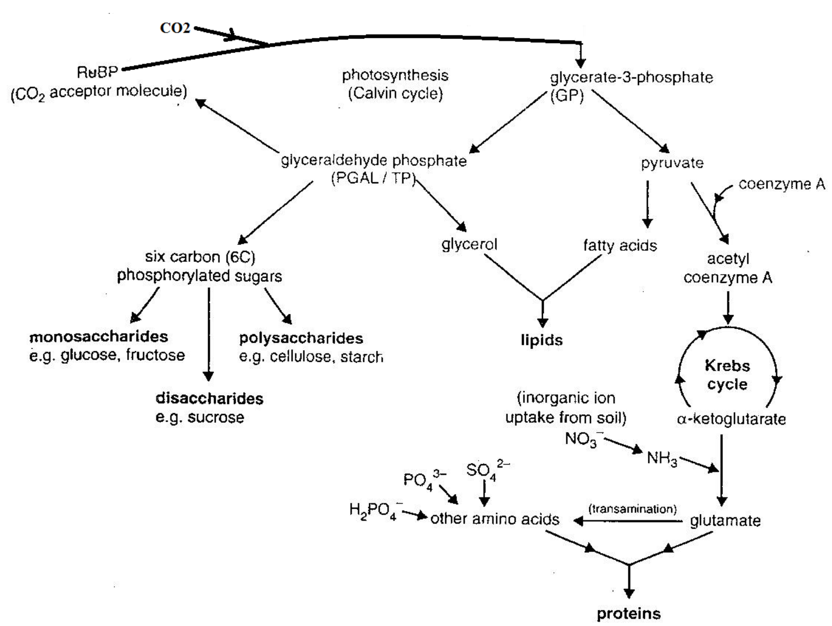
(a) Synthesis of carbohydrates: Glyceraldehyde-phosphate molecules are converted to form monosaccharides e.g. glucose, which may combine with fructose to form **sucrose**, transported in phloem sieve tubes or can be polymerized into starch for storage or cellulose.

(b) Synthesis of lipids: (i) 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 th cytoplasm and chloroplast.

(ii) 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.

RELATIONSHIP BETWEEN PHOTOSYNTHESIS AND SYNTHESIS OF FOOD IN GREEN LANTS



QUESTION:

The enzyme RUBISCO, in spite of being the most common enzyme in the world, is very inefficient in photosynthesis. Explain this statement.

1. RUBISCO can add approximately $3CO_2$ to 3 molecules of RuBP each second, which is very slow for an enzyme. To make up for this, plants produce large quantities of RUBISCO, with it composing 50% of the protein in a chloroplast.
2. RUBISCO is not a very specific enzyme as it sometimes combines RuBP with oxygen rather than CO_2 because of a relatively non-specific active site, causing **photorespiration** which leads to the formation of a useless oxygenated intermediate, rather than carbon dioxide fixation.

WHAT IS PHOTORESPIRATION?

Oxygenation of RuBP by RuBP oxygenase (RUBP carboxylase) at high temperature, low carbon dioxide and high oxygen concentration to form phosphoglycolate which undergoes oxidation in peroxisomes and metabolism in mitochondria to release CO_2, thereby preventing carbon fixation in C3 plants.

HOW PHOTORESPIRATION AFFECTS PLANTS

When C3 plants are exposed to low carbondioxide concentration (or high oxygen concentration) e.g. when stomata close to reduce water loss, RuBP carboxylase catalyses the reaction between RuBP and oxygen to form a 2-carbon compound; **phosphoglycolate,** which is oxidized to release carbondioxide. Yet when the carbondioxide concentration is high, RUBISCO enzyme catalyses the reaction between RuBP and carbondioxide to form a 3-carbon compound; 3-**phosphoglyceric acid,** which undergoes several reactions to form sugar useful to the plant. It is estimated that Photorespiration **therefore reduces the potential yield of photosynthesis by 30-40%.**

THE HATCH-SLACK CYCLE OR C_4 PATHWAY

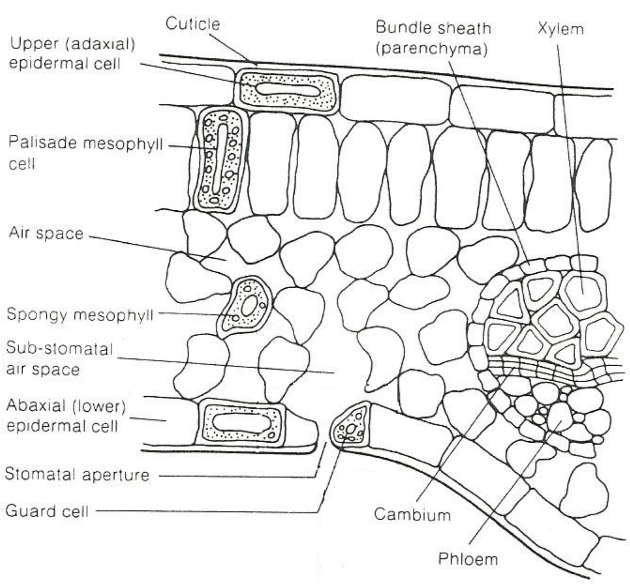
- ***C4 photosynthesis:*** type of photosynthesis in which the first stable product of CO_2 fixation is a four carbon compound called **oxaloacetate** (OAA) inside mesophyll cells, which is later reduced and exported into bundle sheath cells for further metabolism.
- ***Carbon 4 plants:*** plants in which the first product of carbon dioxide fixation is a four carbon compound called **oxaloacetate** (OAA) inside mesophyll cells, which is later reduced and exported into bundle sheath cells for further metabolism.
- ***Examples of C_4 plants***: maize, sorghum, *Amaranthus*, *Sugar cane*, paspalum, Bermuda grass, rhodes grass, nut grass.
- ***Fact:*** C_4 plants represent only 3% of the world's vascular plants yet they contribute about 20% to the global primary productivity because of their high productivity.
- ***Habitats:*** hot / arid / saline tropical habitats.
- ***Description of leaf anatomy:*** **Kranz**.

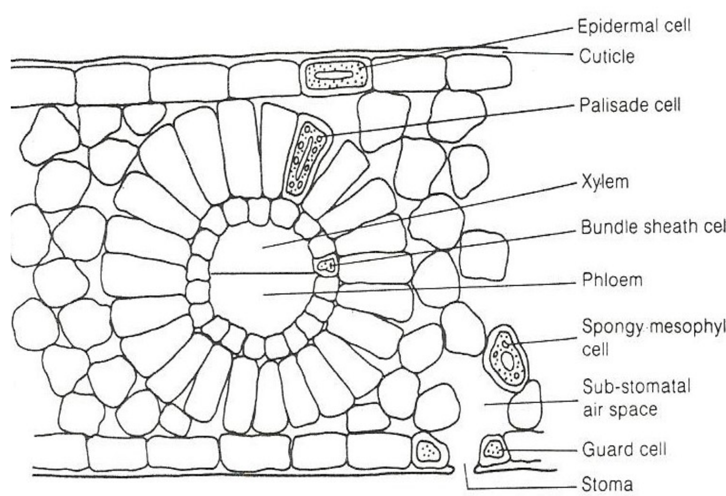
WHAT IS KRANZ LEAF ANATOMY?

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

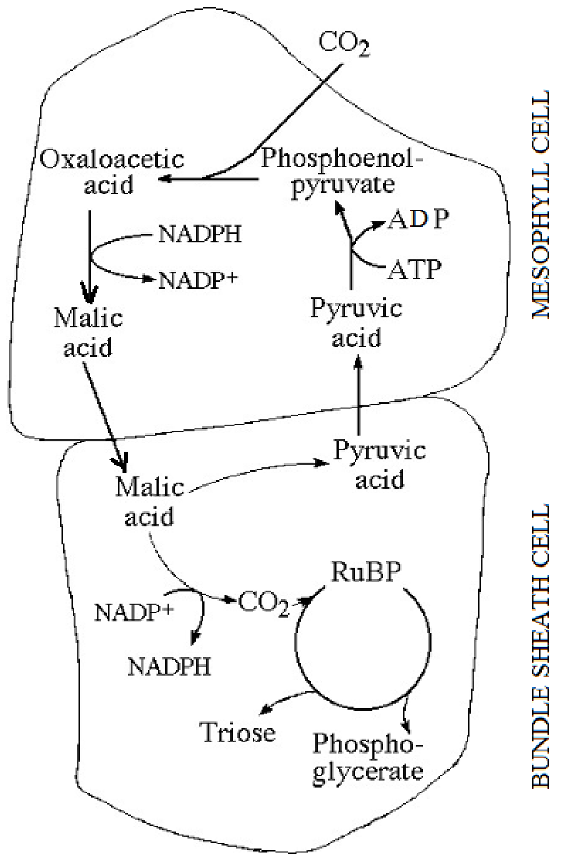
COMPARISON OF LEAF ANATOMY IN C_3 AND KRANZ ANATOMY IN C_4 PLANTS

Leaf anatomy in C_3 plants	***Kranz anatomy in C_4 plants***





DESCRIPTION OF C_4 CYCLE IN CO_2 FIXATION



1. In the presence of ***phosphenol pyruvic acid carboxylase*** enzyme, ***Phosphenol pyruvic acid*** is carboxylated inside the chloroplasts of mesophyll cells to form ***oxaloacetic acid***.
2. ***Oxaloacetic acid*** is reduced by NADPH to ***malic acid*** in the presence of ***malate dehydrogenase*** enzyme.
3. From chloroplasts of mesophyll cells, malic acid is translocated (shunted) to chloroplasts of bundle sheath cells where it is decarboxylated by NADP to form ***pyruvic acid*** and ***carbon dioxide***. The pyruvic acid produced returns to mesophyll cells for phosphorylation by ATP to regenerate **PEP;** the CO_2 acceptor.
4. Now the second carboxylation occurs in the chloroplasts of bundle sheath cells through Calvin cycle.

- RuBP of Calvin cycle is called ***final*** or ***secondary*** CO2 acceptor in C_4 plants.
- Ribulose bisphosphate accepts CO_2 produced in step 3 and to yield 3-phosphoglyceric acid as given in Calvin cycle.
- Some of the 3-phosphoglyceric acid is utilized in the formation of glucose-6-phosphate and sucrose while rest regenerates ribulose-1, 5 bisphosphate in the system.
- In the Calvin cycle 3 ATP molecules are required for the C_4 plants, 5 ATP molecules are required for the fixation of CO_2. For the formation of a glucose molecules, C_4 plants require 30 ATP while C_3 plants utilize only 18 ATP.

ADVANTAGES AND DISADVANTAGE OF C4 PATHWAY

Advantages	*Disadvantage*
●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 **(1)** the CO_2 fixing enzyme PEP carboxylase does not accept oxygen **(2)** 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:*** **(1)** of the increased rate of CO_2 uptake caused by **(i)** large internal leaf surface area **(ii)** short CO_2 diffusion distance **(iii)** CO_2 steep diffusion gradients **(2)** the bundle sheath cells in which dark reactions occur have **(i)** a large photosynthetic surface area enabled by un-usually large chloroplasts (ii) lack of grana on which O_2 would be produced, so ***no photorespiration***. **(3)** the Palisade cells in which light reactions occur have large grana to increase the photosynthetic surface area.	● The CO_2 fixing enzymes in C_4 plants are less active at cool, moist and low illumination conditions, therefore photosynthesis occurs slowly at high altitude with cool temperature and in low light intensity of temperate conditions. ***NB:*** *C4 plants grow better under hot, dry conditions when plants must close their stomata to conserve water – with stomata closed, CO2 levels in the interior of the leaf fall, and O2 levels rise*

QUESTION:

In spite of the higher productivity of C_4, which is almost four times greater than in C_3, majority of plants perform C3 photosynthesis. Explain this statement fully.

- CO_2 concentration is a major factor determining the pathway of carbon dioxide fixation.
- While C_4 plants are more productive at low CO_2 concentration, C_3 plants form the dominant plant life because they are effective at high CO_2, whose concentration is high in most environments and steadily increases due to increasing combustion of fossil fuels.
- Also considering that C_4 photosynthesis is more complex i.e. it involves many reactions both in bundle sheath cells and in mesophyll cell, and requires a specialized Kranz anatomy, most plants have simpler structures.
- *T*herefore, unless water loss is a significant issue, C_3 dominate since C3 photosynthesis is more effective.

COMPARISON OF C_3 AND C_4 PLANTS

Similarities

Both: (1) contain RUBISCO enzyme (2) depend on light for their reactions (3) show CO_2 fixation (4) have RuBP (5) form several same organic products e.g. PG, PGA, sucrose (6) have the calvin cycle

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

CRASSULACEAN ACID METABOLISM (CAM) PHOTOSYNTHESIS

Definition:

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.

CAM is a modified form of C_3 photosynthesis adopted by approximately 6% of vascular plant species as an adaptation to water deficit in terrestrial and epiphytic plants, with exceptions exhibited by submerged freshwater plants for other reasons.

Examples of CAM plants: Cacti, sisal, Opuntia, *Kalanchoe* (*Bryophyllum*), Vanilla*, pineapples,* and *Euphorbia milii*

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.

Example: Mesembryanthemum crystallinum usually uses C3 photosynthesis but during water or salt stressed it switches to CAM photosynthesis.

PHASES OF CAM THROUGH THE DIURNAL COURSE

Phase I: nocturnal CO_2 fixation (atmospheric + respiratory sources) mediated by PEPC and accumulation of malic acid within the vacuole.

Phase II: atmospheric CO_2 fixation at dawn which marks the transition between C_4 and C_3 activity.

Phase III: decarboxylation of malic acid and fixation of the regenerated CO_2 by Rubisco.

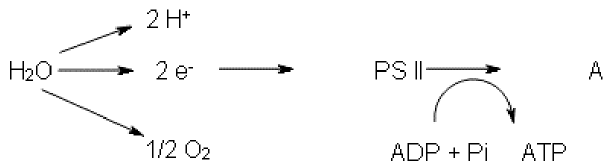
Phase IV: a period of atmospheric CO_2 fixation from the end of Phase III to dusk which latterly incorporates the shift from Rubisco to PEPC activity.

INVESTIGATING HILL REACTION OF PHOTOSYNTHESIS IN ISOLATED CHLOROPLASTS

Hill reaction: The photoreduction of an electron acceptor by the hydrogens of water, with the evolution of oxygen.

$$H_2O + A \xrightarrow[\textit{Chloroplasts}]{\textit{Light}} AH_2 + \tfrac{1}{2}O_2$$

This experiment investigates electron transfer in isolated chloroplasts using artificial electron acceptor, such as DCPIP, which intercepts electrons after Photosystem II (PS II) but before they reach Photosystem I (PS I). The path of electrons from water to the artificial acceptor (A) is, thus:



In this experiment, DCPIP (2,6-dichlorophenol-indophenol), a **blue** dye in oxidised form, acts as **an electron acceptor** and becomes **colourless** when **reduced**, allowing any **reducing agent produced by the chloroplasts** to be detected.

Procedure

(i) Small pieces of green spinach, lettuce or cabbage leaves (veins removed) are homogenated vigorously by grounding in a cold mortar or blended in cold blender containing 20 cm^3 of ice cold, isotonic buffered medium. The ice cold solution deactivated enzymes to prevent reactions. The **isotonic** solution prevents **rupturing** of chloroplasts which can result from osmotic influx or efflux of water. **Buffered** solution maintains pH to mimic chloroplast pH that's suitable for photosynthetic enzyme.
(ii) Filter into the beaker and pour the filtrate into pre-cooled centrifuge tubes supported in ice-water-salt bath.
(iii) Centrifuge the tubes for sufficient time to get a small pellet of chloroplasts. (e.g. 10 minutes at high speed).
(iv) Pour off the liquid (supernatant) into a boiling tube being careful not to lose the pellet.

Cuvettes are set up with the contents as listed below and monitored by a spectrophotometer
Cuvette 1 (leaf extract + DCPIP covered by aluminium foil)
Cuvette 2 (no leaf extract / boiled leaf extract + DCPIP + exposure to light)
Cuvette 3 (leaf extract + exposure to light + no DCPIP).
Cuvette 4 (leaf extract + DCPIP + Exposure to light).
(vi)When the DCPIP is added to the extracts, shake the Cuvette and note the time.
(vii)Time how long it takes to decolourise the DCPIP in each tube.

Sample results

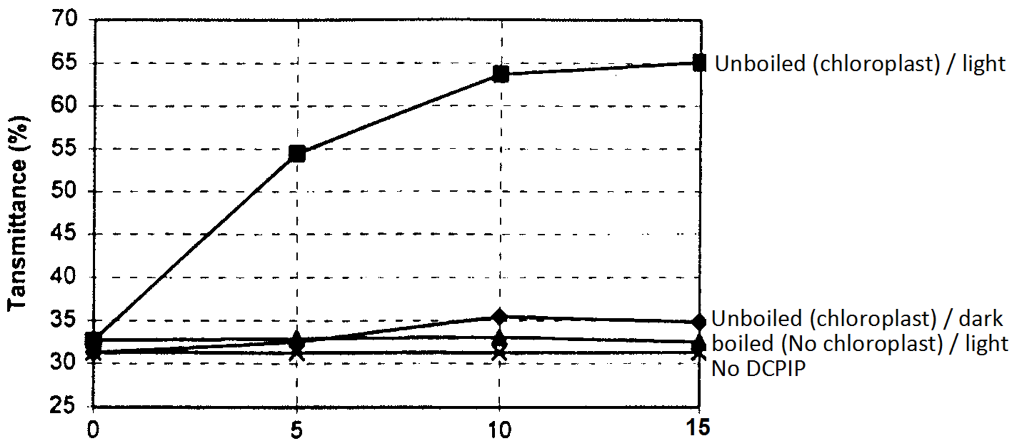
Time (sec)	Absorbance (arbitrary units)			
	Cuvette 1 (**Dark**)	Cuvette 2 (**No chloroplasts**)	Cuvette 3 (**No DCPIP**)	Cuvette 4 (**All conditions**)
0	1.08	1.37	0.80	1.07
20	1.06	1.37	0.80	0.90
40	1.06	1.37	0.80	0.81
60	1.06	1.37	0.80	0.71
80	1.05	1.37	0.80	0.57
100	1.05	1.37	0.80	0.47

On same axes, the results in the table above can be reflected graphically.

EXPLANATION FOR RESULTS IN THE TABLE ABOVE

Cuvettes	Observation / Description	Explanation
1	Absorbance decreases slightly from 0 second to 20 seconds, remains constant from 20 second to 60 seconds, decreases slightly from 60 seconds to 80 seconds, then remains constant thereafter.	There was no light hence no DCPIP reduction. The gradual decrease in the first 20 seconds is due to DCPIP being reduced when light hit the chloroplasts in the brief moment before the cuvette was wrapped by aluminium foil.
2	Absorbance remains constant from 0 seconds to 100 seconds	No reduction of DCPIP occurred, due to absence of chloroplasts.
3	Absorbance remains constant from 0 seconds to 100 seconds.	No reduction was detected without DCPIP hence the mixture didn't change from its original colour.
4	Absorbance of the reaction mixture decreases fast from 0 seconds to 100 seconds.	Presence of light enables the live chloroplasts to release electrons that were accepted by DCPIP to become reduced, which was shown by the colour change from blue to colourless hence enabling absorbance.

CONCLUSIONS
Cuvette 1: Light is necessary for DCPIP reduction.
Cuvette 2: Chloroplasts are necessary for reduction of DCPIP.
Cuvette 3: Chloroplasts do not affect the changes in absorption of the DCPIP solution.
Cuvette 4: Light is necessary for the release of electrons from live chloroplasts.
Cuvettes 1, 2, 3 work as control experiments.
If transmittance is used, the results can be reflected graphically as shown below



UNDERWATER PHOTOSYNTHESIS

Major photosynthetic challenges under water
(i) reduced carbon dioxide diffusion rate, which is overcome by supplementary use of HCO_3^- (bicarbonate ions)
(ii) low light penetration with depth.
- The rate of light penetration in a body of water depends on suspended substances and the turbidity of the water.

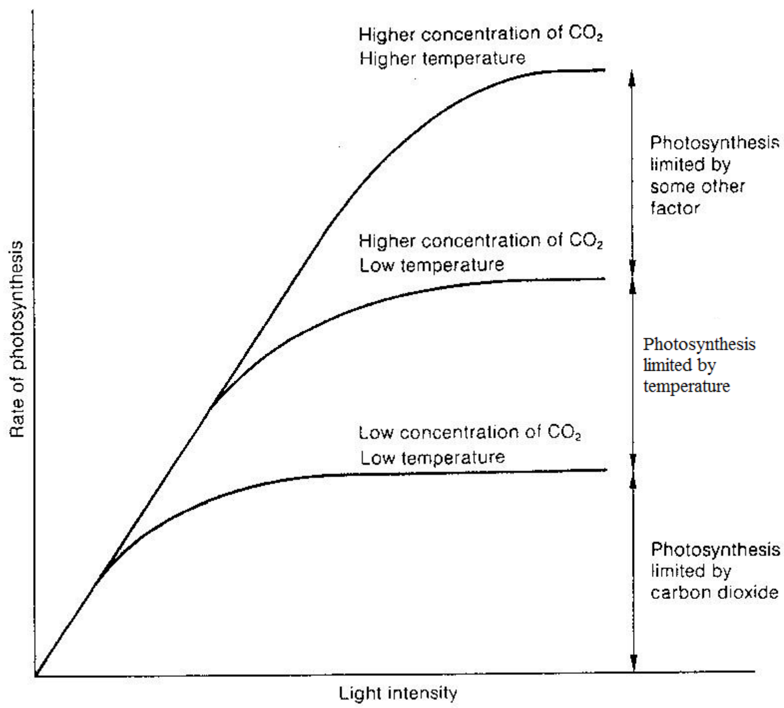
FACTORS WHICH AFFECT PHOTOSYNTHESIS

(1) carbondioxide concentration **(2)** Light intensity **(3)** Temperature **(4)** Chlorophyll concentration **(5)** oxygen concentration **(6)** Water and dissolved nutrients **(7)** Enzyme inhibitors e.g. cyanide, dichlorophenyl dimethyl urea – DCMU **(8)** Some air pollutants e.g. Sulphur dioxide **(9)** Altitude **(10)** Salinity

THE PRINCIPLE OF LIMITING FACTORS

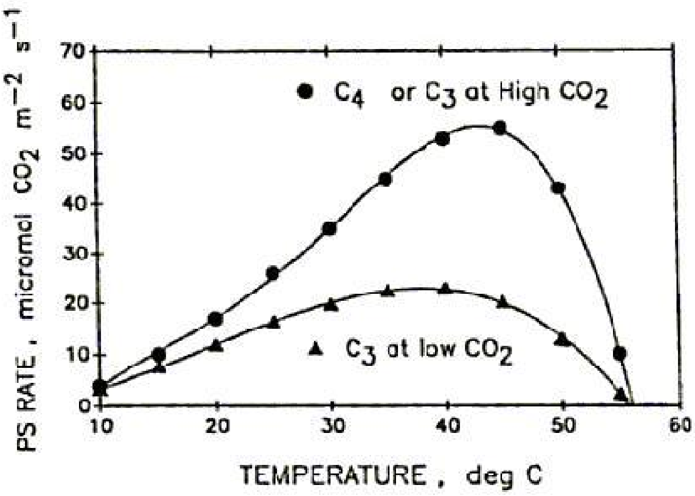
It states that: ***'At any given moment, the rate of a chemical process is limited by the one factor which is nearest its minimum value, and by that factor alone'***

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



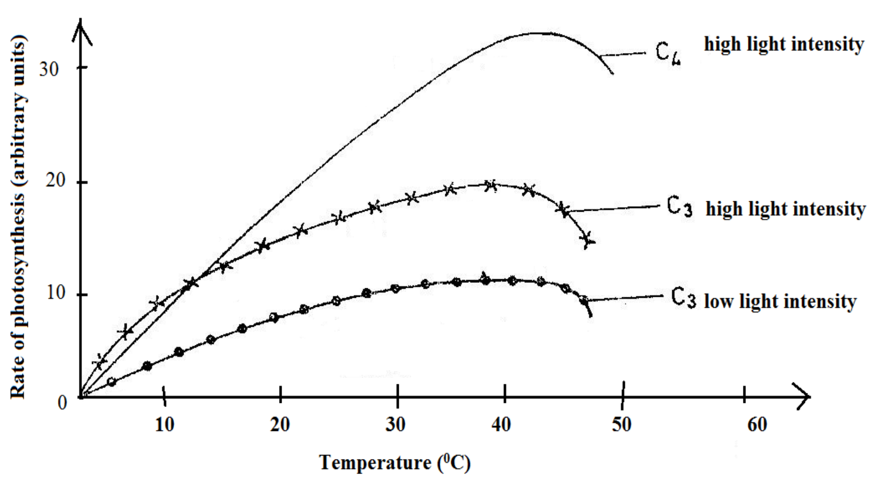
Salinity
One of the major effects of salinity is osmotic stress, and hence there are intimate relationships to drought stress or 'water stress'. This results in stomata closure in an effort to avoid desiccation, which reduces photosynthesis because uptake of CO_2 reduces.

Effect of carbon dioxide
In the atmosphere, the concentration of carbon dioxide ranges from 0.03 to 0.04 %



Observation / description	***Explanation***
● Generally, the rate of photosynthesis increases rapidly with increasing CO_2 concentration to a maximum at 30 Pa in C4 plants and 90 Pa in C3 plants and thereafter remains constant.	● RuBISCO attaches carbon dioxide instead of oxygen, because the CO_2 concentration is higher than the oxygen concentration. ●More cells photosynthesize because of the increased carbon dioxide molecules available.
● The rate of photosynthesis is faster in C4 than C3.	PEPC of C_4 has a higher affinity for carbondioxide than RuBISCO of C_3 and hence acts faster.
● The overall photosynthetic products are greater in C3 than in C4	C4 needs more ATP than C3 which generally reduces photosynthetic out put
● The C4 plants are more efficient at lower CO_2 concentration while C3 more efficient at higher CO_2	● **A**t lower CO_2 concentration in C3 photorespiration reduces the photosynthesis efficiency yet PEPC has a high affinity for CO_2
● 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.
● At the CO_2 concentration of about 70 Pa, the rate of photosynthesis is equivalent in both plants	

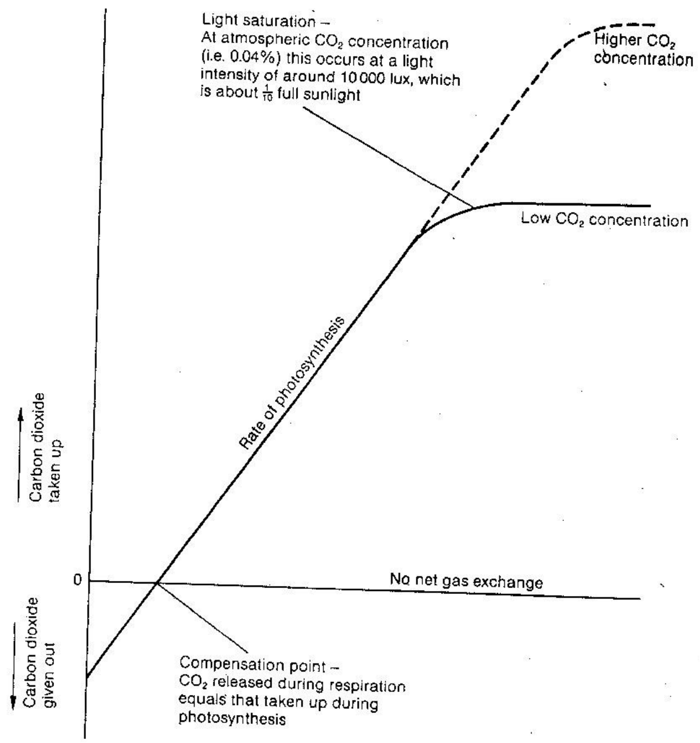
Chlorophyll Concentration
The concentration of chlorophyll affects the rate of reaction as they absorb the light energy without which the reactions cannot proceed.
Temperature
An optimum temperature ranging from 25°C to 35°C is required. At temperatures around 0°C the enzymes stop working and at very high temperatures the enzymes are denatured.



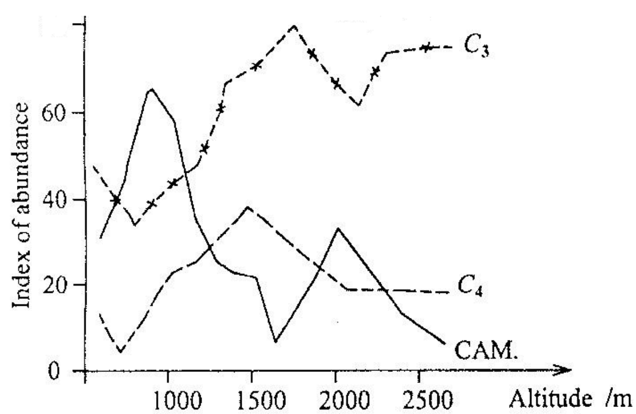
Observation / description	***Explanation***
●Below 10^0C, C_3 rate of photosynthesis is higher than in C_4 above 10^0C.	●C_4 photosynthetic enzymes are less active in the cold but become more active with increase in temperature.
●The maximum rate of photosynthesis attained in C_4 is much higher than 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
There is an initial increase in photosynthetic rate to a maximum at about $40\text{-}42^0C$, inspite 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.

Water: In response to drying, leaves close their stomata to conserve water being lost as water vapour through them.
Pollution: Soot blocks stomata and reduce the transparency of the leaves, which reduces photosynthesis.

Light intensity and Compensation Point
Low light intensity lowers the rate of photosynthesis. As the intensity is increased the rate also increases. At maximum intensity there is no effect on the rate. Very high intensity may, in fact, slow down the rate as it bleaches the chlorophyll.
Compensation point: The light intensity at which the photosynthetic intake of carbon dioxide is equal to the respiratory output of carbon dioxide. It occurs during early morning or late evenings



Effect of altitude (and oxygen)



Effect of altitude explained

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 the thus high osmotic value also a lot of water, are usually less frost resistant than C_3 plants.
●C4 plants are widely distributed at low altitude and slight elevation	●Enzymes are tolerant to high temperatures and the Kranz mesophyll anatomy shields RuBISCO in bundle sheath cells from much O_2 to avoid photorespiration.

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

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

OBSERVATION:

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

NOTE

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

MEASUREMENT OF RATE OF PHOTOSYNTHESIS

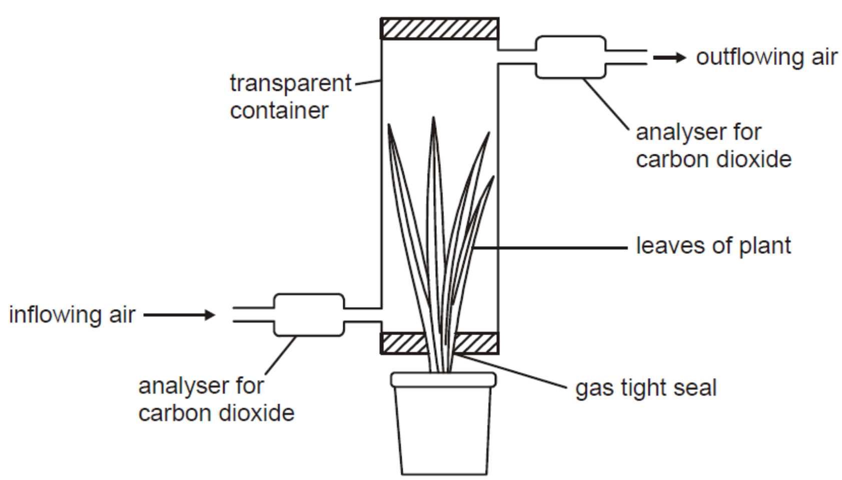
(i) Measure the uptake of CO_2 **(ii)** Measure the production of O_2 **(iii)** Measure the production of carbohydrates
(iv) Measure increase in dry mass

MEASURING THE UPTAKE OF CO_2

Uptake of CO_2 can be measured with the means of an Infra-Red Gas Analyser (IRGA) 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**

EXAMPLE

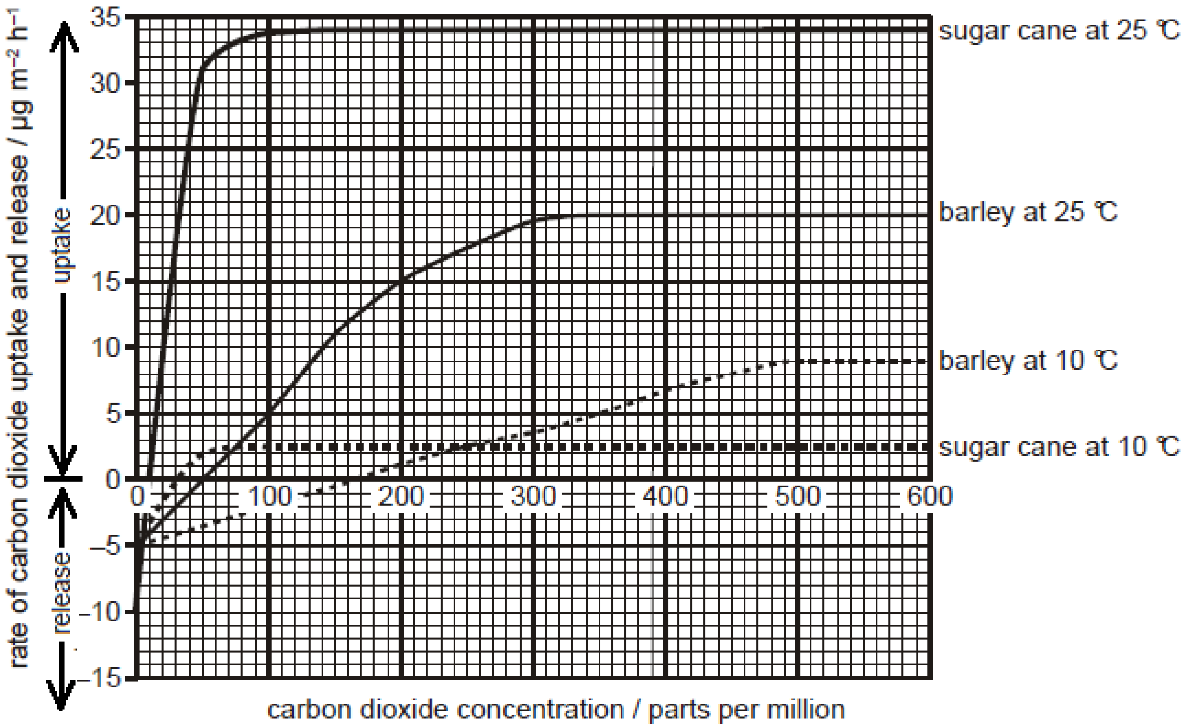
In an investigation of photosynthesis, the rate of carbon dioxide absorption by leaves of two plants, barley and sugar cane, was measured. The leaves were provided with air, moving at a constant rate, through an apparatus shown below:



EXPERMENTAL CONDITIONS

● Light intensity was kept constant and high, equivalent to full sunlight.
● Concentration of CO_2 in air entering the apparatus could be varied.
●The carbon dioxide taken up or given out by the leaves was determined by calculating the **difference** between the concentration in the inflowing and outflowing air.
● Leaves remained attached to the plants during the investigation.
●Two different temperatures, 10 °C and 25 °C, were used for each type of plant.

The results of the investigation



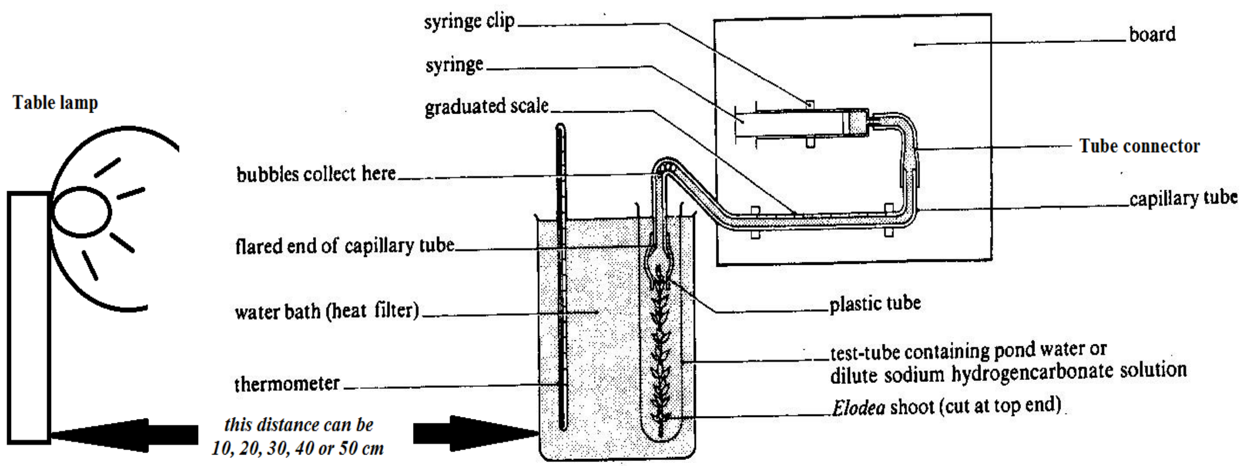
(a) For each plant species, describe the observed carbon dioxide uptake / release at the different temperatures (11 marks)
(b) Explain the observed carbon dioxide uptake / release in the two species at the different temperatures. (08 marks)
(c) Explain why all the measurements were made at the same light intensity.
(d) Suggest why it was important that the leaves remained attached to the plants while the measurements were made.
(e) Compare the response of the two species, sugar cane and barley, to differences in carbon dioxide concentration and temperature.

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

● ***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.
However, you can probably think of several inaccuracies in this method.

● ***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.

● ***Measuring the production of O_2***
Oxygen can be measured by (a) counting bubbles evolved from pond weed with the Audus apparatus
Requirements
(1) Previously well illuminated aquatic plant e.g. *Elodea* or *Cabomba* **(2)** Test tube **(3)** Watch **(4)** Water at room temperature **(5)** bench lamp to provide light (6) Knife **(7)** Ruler **(8)** 0.2 % sodium bicarbonate solution **(9)** plastic Syringe **(10)** 500 cm^3 glass beaker **(11)** capillary tube **(12)** plastic tube connector **(13)** graduated scale **(14)** retort stand **(15)** soft board **(16)** thermometer
Procedure:
Set up the apparatus as below in TOTAL DARKNESS



(1) A light source is placed 50 cm away facing the test tube, is powered on and a 5 minutes lapse is allowed to enable the plant adjust to the light intensity.
(2) The length of gas bubble evolved in 10 second, 30 second, and 1 minute intervals is measured by pulling the syringe plunger to draw the bubble slowly along the capillary tube.
(3) Steps **1** and **2** 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.
(4) Lastly the control experiment involves 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 **(1)** of light saturation **(2)** 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 affect 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 carbondioxide
● 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 fluaction	●Use voltage that gives constant light for a long time
●Trapped gas bubbles	●Swirl the water weed to release them
● Expel gas before taking another reading	●

NOTE:
● Instead of measuring the length of bubble, bubbles can be counted, but this has several disadvantages **(1)** 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 **(2)** 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 **(1)** dissolved N_2 or other gases released from solution and **(2)** 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

RELATIONSHIP BETWEEN PHOTOSYNTHESIS AND RESPIRATION

There is a close relationship between the activities of respiration and photosynthesis in living things. These two activities counteract each other in many ways, and a balance of the processes are necessary to maintain the favourable O_2/CO_2 ratio in the atmosphere.

- In the presence of light, plants respire aerobically to release carbon dioxide while consuming oxygen, and at the same time photosynthesise to release oxygen while consuming carbon dioxide, although photosynthesis far exceeds respiration.
- In darkness, plants respire aerobically to release carbon dioxide but photosynthesis is inhibited by absence of light.

SAMPLE QUESTIONS

1. Five small discs cut from spinach leaves were floated on a small volume of buffered hydrogen carbonate solution in a flask attached to a respirometer. The discs were first exposed to bright light, then to dim light and finally left in the dark. Oxygen release was recorded as positive values and oxygen uptake as negative values as given in the table below.

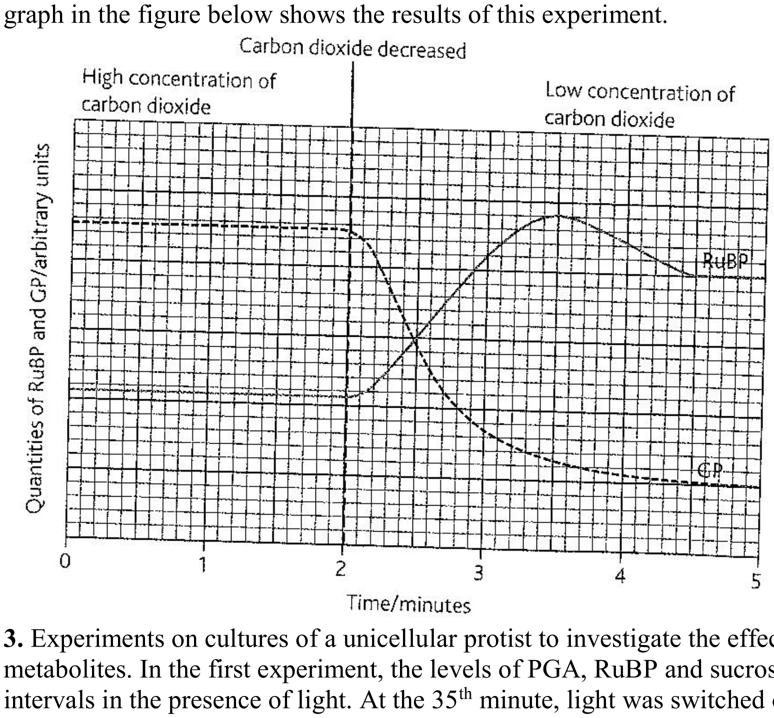
Light intensity	Time interval in minutes	Oxygen uptake or release in mm^3
Bright light	0 – 3 3 – 6 6 – 9 9 – 12	+57 +64 +58 +60
Dim light	12 – 15 15 – 18	+16 +3
Dark	18 – 21 21 – 24 24 – 27 27 – 30	- 16 - 12 - 15 - 14

(a) Present the data in a suitable graphical form

(b) (i) Calculate the mean rate of oxygen release in bright light
(ii) Explain the significance of the results obtained from this experiment.

(c) Explain the use of the following in the experiment above:
(i) Five small leaf discs, not one.
(ii) Hydrogen carbonate solution
(iii) Buffered hydrogen carbonate solution

2. 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 carbondioxide supplied was high. After 2 minutes, the concentration of carbondioxide was reduced. The graph in the figure below shows the results of this experiment.



Describe the effects of the decrease in carbondioxide after 2 minutes on:
(i) Glycerate 3-phosphate (GP)
(ii) Ribulose bisphosphate (RuBP)
(b) Suggest explanation for these changes to the levels of glycerate 3-phosphate (GP) and RuBP

3. 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

4. The rate of photosynthesis of *Digitaria bipartite*, a C4 plant and *Astropa belladonna*, a C3 plant was investigated under different intracellular carbon dioxide concentrations. The results are shown in the table below

Carbon dioxide concentration (ml per dm^3)	Rate of photosynthesis (mol of CO_2 assimilated per m^2 of leaf area per second)	
	Digitaria bipartite	*Digitaria bipartite*
0	0.0	0.0
25	12.5	0.0
50	35.0	5.0
75	37.5	14.0
100	37.5	25.0
150	37.5	40.0
200	37.5	47.5

(a) Present the data in the table above graphically
(b) Compare the rates of photosynthesis of two plants at the carbon dioxide concentrations shown in (a) above
(c) Explain your answer in (b) above
(d) Explain, in biochemical terms, the distribution of C_3, C_4 and CAM plants at their environments

5. The table below shows how the rate of photosynthesis of C4 and C3 plants vary with the temperature at different light intensities. The rate is in arbitrary unit.

Temperature/^{0}C	0	5	10	20	30	35	40
C_4 plants at high light intensity	0	5	12	25	28	32	38
C_3 plants at high light intensity	0	10	12	15	18	20	10
C_3 plants at low light intensity (Arbitrary units)	0	2	5	8	10	10	6

(a)Represent the above results graphically on the same axes.
(b) Explain how differently temperature affects photosynthesis in C_3 plants and C_4 plants.
(c) Explain the pattern of the graph obtained for C_3 plants under low light intensity.
(d) Explain the effect of light intensity on the following.
(i) Leaf colour (ii) Leaf size (iii) Internode length
(e) State three other factors that may limit the rate of photosynthesis.

6. The table below shows effect of temperature on rate of photosynthesis in two grasses, ***Agropyron*** and ***Bouteloua***

Leaf temperature (^{0}C)	**Rate of photosynthesis in arbitrary units**	
	Agropyron	Bouteloua
10	23	10
15	26	15
20	30	19
25	31	24
30	30	30
35	27	35
40	20	39
45	10	38

(a) Plot the data on a graph paper (b) Compare the rate of photosynthesis in the two plants.
(c) Account for the variation of the rate of photosynthesis in the two plants.
(d)(i) Describe the photosynthetic mechanism which is likely to occur in the cytoplasm of the mesophyll of Bouteloua
(ii) Explain the physiological significance of the mechanism described in (e) (i) above.

6. (a) Explain the effect of light intensity and temperature on the rate of photosynthesis.
(b) Explain photophosphorylation in terms of chemiosmosis.
(c) Explain the reactions involving the use of light energy that occur in the thylakoids of the chloroplast.

7. (a) Outline the light-independent reactions of photosynthesis.
(b) (i) 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.

8. (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.

9. (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.
(c) Explain the concept of limiting factors in photosynthesis, with reference to light intensity, temperature and concentration of carbon dioxide.