TOPIC 1: CELL BIOLOGY/CYTOLOGY

Competency: The learner evaluates cells and tissues, by analyzing and relating their structure to function, as a basis for medical research in order to improve health.

Learning Outcomes: The learner should be able to: Analyze the properties and functions of chemical compounds (water, lipids, proteins including enzymes from mammals) in a cell, focusing on their roles in maintaining cellular structure and metabolic processes in living organisms.(s, gs)

SUBTOPIC: CHEMICALS OF LIFE

These are chemical substances/molecules that are essential for the survival and maintenance of life processes. These chemicals ensure that metabolic processes take place efficiently and also take part in determining/ forming cellular components.

Major categories of chemicals of life

The chemical substances in living organisms can be categorized into two major groups;

- **Organic chemicals of life** such as proteins, lipids, nucleic acids and carbohydrates.
- **Inorganic chemicals of life** such as water, minerals, acids.

1.1 WATER AS A CHEMICAL OF LIFE

Key guiding questions. In groups, Research and discuss the following;

- What atoms make up water molecule and how are they bonded together/what type of bond holds its atoms and molecule?
- Why water is considered a polar molecule?
- How does the shape, size and polarity of water as well its nature of bonding between the water molecules influence its properties/behaviors?
- What are the unique properties of water and how do they relate with the biological roles/functions of water in biological systems?
- Explain the interactions of water with polar and non-polar molecules?

INTRODUCTION

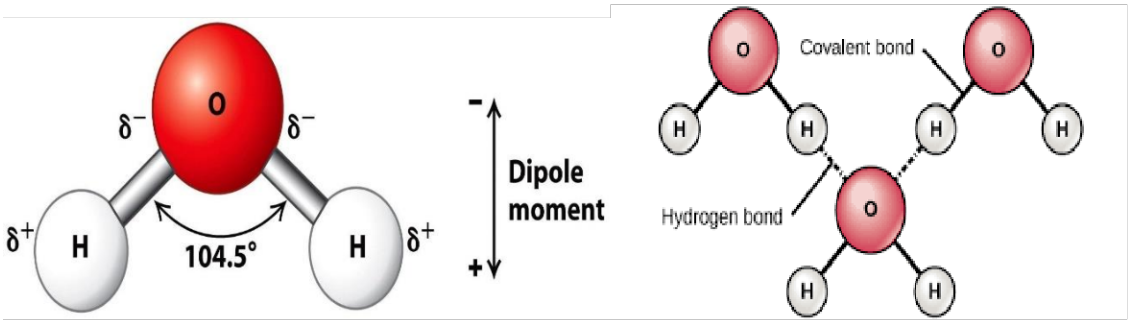
Do you know that without water, life could not exist on this planet?

Water is the most essential molecule for life, making up about **60-70%** of the human body weight and plays a crucial role in biological systems. The unique physical and chemical properties of water that allow it to support life processes arise from its structure (size & shape), polarity and nature of bonding that exist between its molecules.

Structure of Water and its nature of bonding

A water molecule (H_2O) consists of two hydrogen atoms bonded to one oxygen atom, forming a bent (V- shape) with an angle of about 104.5° between the hydrogen atoms. This configuration coupled with the difference in the electronegativity between the Oxygen atom

and hydrogen atom results in unequal charge distribution within the molecule, making water **a polar (dipole) molecule**. The Oxygen atom being more electronegative than hydrogen atom (*O atom has a greater electron attracting power than H atom*), acquires a partial negative charge while the hydrogen atom acquires a partial positive charge. Therefore in water, one pole or part is slightly positive and the other is slightly negative and this is known as a dipole. The dipole/polar nature of water allows it to form hydrogen bonds between its molecules, enabling the water molecules to have weak attractions for each other, with the opposite charges coming together and causing them to behave as if they were "sticky".



NB: Hydrogen bonds are not as strong as ionic or covalent bonds and so, they are constantly being formed, broken and reformed in water. Although these bonds are individually weak, their collective effect is responsible for a number of unusual physical properties of water.

How the structure and the nature of bonding of water molecules influences its properties

- The bent shape creates unequal charge distribution, which makes water polar. This polarity allows water molecules to attract each other via hydrogen bonding leading to properties like cohesion, adhesion, surface tension, solvent properties, density anomaly, and capillarity action as well as thermal properties like high specific heat capacity and latent heat of vaporization.
- The small size allows water to move easily through biological membranes and tiny spaces in tissues. This contributes to properties like low viscosity, high density in liquid form, rapid diffusion, high surface tension etc.

PROPERTIES OF WATER

Water has unique physical and chemical properties that make it essential for life. These properties are unusual and are mostly due to its **small size**, **its polarity** and **hydrogen bonding** between its molecules. The properties of water can be directly linked to a number of biological functions performed by water in biological systems. Below are some of the properties of water and how they relate with biological functions in biological systems;

Property of water	How they relate with their biological roles
Universal solvent/solvent abilities: Water is an excellent solvent and so dissolves many polar/ionic substances.	• It provides a medium for biochemical reactions. • Allows distribution/transportation of nutrients and removal of waste materials (excretion)/serves as a transport medium.
A liquid at room temperature	• It provides a liquid medium inside the cells and aquatic environments for organisms to live in.
Transparency/colorless: water has a high transmission of visible light/allows light to pass through it.	• This allows photosynthetic organisms in aquatic ecosystems to photosynthesize at depth in water. • Facilitates navigation of aquatic animals which allows them to look for food or escape danger like predators.
Ice is less dense than liquid water, so ice floats.	• This insulates the water below allowing aquatic animals in cold environments to survive.
Has a low viscosity: water molecules can slide over each other very easily.	• Water flows freely through narrow vessels allowing distribution of materials. • Watery solutions can also act as lubricants like mucus allows food to move down the oesophogus.
Has a higher density than air; Liquid water is denser than air.	• This provides buoyancy to aquatic animals/supports weight of large aquatic organisms enabling them to move. • It also supports and disperses reproductive structures such as larvae and large fruits
High compressibility; Water is difficult to compress.	• This allows it to provide structural support through acting as a skeleton (hydrostatic skeletons). • Provides turgor pressure in plant cells, which maintains rigidity and shape.
Has a high surface tension; water forms a skin at its surface.	• Allows some aquatic animals like pond skaters to land on the surface of water and move over it.
Has strong cohesive and adhesive forces which prevent it from breaking under tension. This is due to the hydrogen bonds which cause water molecules to stick together (cohesion), leading to high	• This facilitates capillarity action which is essential for water transport in the xylem vessels of plants.

surface tension. Water also adheres to other substances (adhesion).	
Has a high tensile strength; water columns never break or pull apart easily.	• This allows continuous stream of water to be pulled up the stem xylem during transpiration.
Water as a reactant/reagent; water can take part in chemical reactions of metabolism	• Serves as a raw material for photosynthesis. • It also takes part in many digestive reactions, breaking down food by hydrolysis.
Thermal properties not required as per their syllabus, but learners can think about their roles in biological systems.	

Other biological functions of water

- It provides a medium through which sperms swim enabling fertilization to take place.
- It enables germination of seeds by activating hydrolytic enzymes, transportation of hydrolyzed stored food reserves and softening of the testa.
- It also plays a role in the regulation of pH.
- It facilitates in temperature regulation through cooling by evaporation.
- Plays a role in lubrication like synovial fluid in joints allowing movement without friction.
- Plays a role in osmoregulation.
- It enables dispersal of seeds, fruits, gametes and larvae stages in aquatic organisms.
- It is important in translocation of organic molecules in plants.
- It offers support in hydrostatic skeleton in organisms such as in earthworms.
- It enables migration of organisms to occur as a result of river flow or ocean currents.
- Water acts as a habitat for some organisms and supports organisms that live in it.
- The amniotic fluid supports and protects the mammalian fetus during development from mechanical damage.
- The watery endolymph and perilymph in the mammalian ear plays a significant role in hearing and balancing.
- The watery aqueous and vitreous humors gives to the eyeball.
- The pressure of blood plasma makes the penis erect enabling copulation to take place.

Roles of Water in maintaining cellular and metabolic processes

Cellular Structure	Metabolic Processes
• **Maintains cell shape** – Water provides turgor pressure in plant cells, keeping them rigid and so maintains the cell shape. • **Component of cytoplasm** – The cytoplasm is mostly water, ensuring a	• **Solvent for biochemical reactions**- water provides a medium for biochemical reactions, enabling chemical processes to take place normally. • **Serves as a reactant in metabolism** – Water participates directly in hydrolysis

stable environment for organelles where they are suspended. • **Structural support in macromolecules** – Water aids in maintaining the proper folding and functioning of proteins and nucleic acids. • **Acts as a cushion** – Water absorbs mechanical shocks, protecting cells and tissues from mechanical/physical damage.	reactions and in photosynthesis as a reactant. • **Transport medium**- It facilitates in transportation of nutrients, wastes, and gases in cells and the entire body. • **Temperature regulation** – Water's high specific heat capacity stabilizes internal cellular temperatures by buffering the temperature fluctuations. • **Facilitates enzyme function** – Water maintains the optimal environment for enzymatic activity.

Interactions of water with polar and non-polar molecules

Water's interactions with other molecules depend on its polarity. Since water is polar, it interacts differently with polar and non-polar molecules.

a) With polar molecules;

Polar molecules include ionic substances like salts which contain charged particles(ions), and non-ionic substances like sugar and some proteins which contain slightly negative hydroxyl group(-OH). Water molecules interacts with these molecules through dipole to dipole forces and hydrogen bonding.

How the interaction occurs: On contact with water, ions and polar groups are surrounded by water molecules which separate (dissociate) the ions or molecules from each other. Once the substance is in solution, its molecules or ions can move freely making it chemically reactive than when in solid state.

b) With non-polar molecules:

Non polar molecules like lipids have no charged regions and so, don't form hydrogen bonds or dipole interactions with water. Once in water, they are repelled by the water and usually group together. Therefore, non polar molecules are hydrophobic (water hating).

1.2 LIPIDS AS CHEMICALS OF LIFE

Key guiding questions; Research and in groups, discuss the following;

- What are the basic elements that make up lipids? How do lipids differ from other macromolecules in terms of composition?
- What are the major categories of lipids and their chemical compositions?
- What are the properties of simple and conjugated lipids? How do their properties relate to their biological functions?
- How are simple and conjugated lipids important in maintaining cellular structure and metabolic processes?

INTRODUCTION

Lipids are large organic compounds composed of the elements: carbon (C), hydrogen (H), and oxygen (O). Unlike proteins and carbohydrates, lipids have a much higher proportion of hydrogen and carbon relative to oxygen, making them more hydrophobic (water insoluble). They are insoluble in water but soluble in organic solvents like ether, ethanol etc.

Note that lipids are not macromolecules /polymers (*since they are not made up of many repeating units*) but because of their hydrophobic properties, the molecules associate/aggregate into globules.

PROPERTIES OF LIPIDS

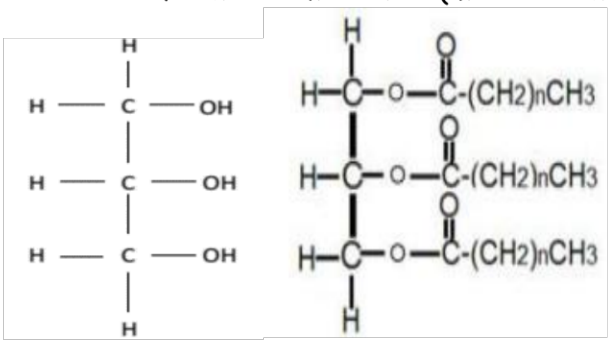
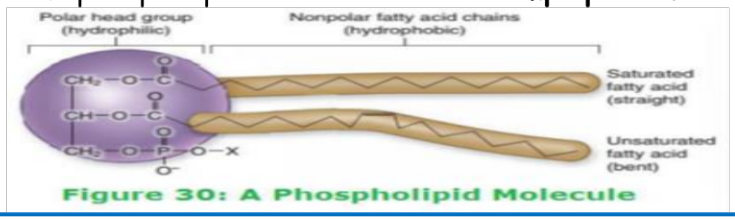
- They are insoluble in water but soluble in non-polar solvents like benzene, chloroform, ether, ethanol etc. Their low solubility is due to the low oxygen content which results into a small number of polar hydroxyl groups in lipids hence very few hydrogen bonds formed.
- They have a high proportion of hydrogen and a low proportion of oxygen content in their molecules.
- They are non-polar compounds, i.e. they have no **uneven** distribution within the molecule, meaning that they don't form hydrogen bonds with water molecules and therefore, don't dissolve in water.
- They are less dense than water and therefore float on water.
- They can be solids or liquids at room temperature.
- Their melting point increases with increase in saturation.
- They undergo high oxidation in respiration to yield large amounts of energy/have a high calorific value due to their higher proportion of hydrogen atoms.
- They are poor conductors of heat.

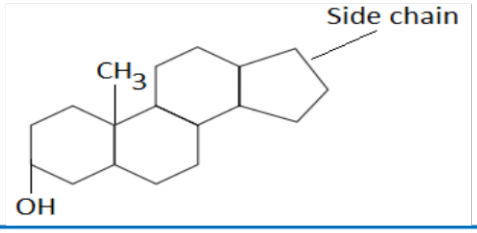
Major categories of lipids and their chemical composition

Lipids are categorized into simple and conjugated (complex) lipids based on their composition.

- **Simple lipids**: These are composed of only fatty acids and alcohol without additional groups like Triglycerides (fats and oils) and waxes.
- **Conjugated lipids**: These lipids contain additional groups such as phosphate, carbohydrates or proteins in addition to fatty acids and alcohol. They include; phospholipids, glycolipids, lipoproteins.

Lipids	Composition
Triacylglycerol/ Triglycerides: These include fats and oils. These are chemically similar	They are composed of three fatty acids and an alcohol, glycerol. Glycerol has 3(-OH) groups and each combines with a separate fatty acid to form an ester

but differ in their physical state at 20°C. Fats are solids are room temp while oils are liquids at room temp. Fats are common in animals while oils occur mainly in plants. **THINK** Triacylglycerols made of fatty acids with shorter hydrocarbon chains and containing one or more double bonds (unsaturated fats) have low melting points. **WHY?**	bond through a condensation reaction that leads to liberation of 3 water molecules (metabolic water).  **Glycerol** Triglyceride **Functions:** • Source of energy when oxidized. • Heat insulation/protection of body from heat loss. • Shock absorbers thus protect delicate organs. • Offer buoyancy in aquatic animals.
Waxes: These are esters of fatty acids, formed not with glycerol but with complex alcohols.	These are composed of fatty acids bonded to a long chain alcohol other than glycerol. They are usually relatively hard solids at 20°C. They are used to provide protection and also as offer waterproofing materials in both plants and animals. In plants, waxes occur on the cuticle of the leaves, fruits and seeds. In animals, they occur on the skins and feathers as well as a constituent of the exoskeleton of insects. They also form the combs of bees.
Phospholipids: These are lipids containing a phosphate group. They are formed when one of the fatty acid of a triacylglycerol is replaced by a phosphate group. **Functions:** • Act as a major component of the plasma membrane. • Affect the fluidity and permeability of the cell membrane. • Allow lipid soluble molecules to pass easily through them.	They are composed of two fatty acids, a phosphate group bonded to one glycerol. In their formation, a phosphate group is added to the third carbon atom in the position of the (-**OH**) group of the glycerol. The other two (-**OH**) groups of the glycerol react with fatty acids in a condensation reaction to form ester bonds/links. The phosphate group carries an electrical charge and is water soluble (hydrophilic) while the tails are insoluble in water (hydrophobic); thus phospholipids are described as **amphipathic**.  Figure 30: A Phospholipid Molecule

Glycolipids: They are predominately found on the outer surface of all eukaryotic cell membrane.	These are composed of a carbohydrate attached/bonded by a glycosidic bond to a lipid. The carbohydrate forms a polar head (hydrophilic) to the molecule which extends outwards and interacts with the extracellular environment. **Function:** • Serve as markers for cell-cell recognition and cell signaling. • Maintains membrane stability. • Participate in immune responses. • Determination of blood groups as antigens on RBCs
Lipoproteins: Such as chylomicrons, LDL, HDL, and VLDL.	These are composed of a protein molecule combined with a lipid molecule. **Function:** • Transports dietary fats from intestines to tissues. • Regulation of lipid metabolism • HDL removes excess cholesterol from blood/reduces the risks of atherosclerosis.
Steroids: **These** include cholesterol, bile salts, Steroid hormones (Oestrogen & Testosterone). These are not composed of fatty acids but only resemble other lipids in being insoluble in water but soluble in organic solvents.	These are composed of four fused rings of carbon and hydrogen atoms. Three of the rings are six numbered and one of them is five numbered. All together there are 17 carbon atoms, six of which are shared between the rings and they are saturated hydrocarbons. They cannot be hydrolyzed. Some are formed by the smooth ER of cell membranes. 

Fatty acids as the building blocks of most lipids

Most of the lipids except steroids contain fatty acids as one of their chemical component. Each fatty acid contains an acidic group, the carboxyl group (-***COOH***) attached on a long unbranched hydrocarbon tail /chain (non-polar). The number of carbon atoms in most naturally occurring fatty acids is 14 to 22 and it is the nature of the hydrocarbon chain that determines the properties of lipids, including the insolubility in water. These tails are said to be hydrophobic (water hating).

Types of fatty acids

- **Saturated fatty acids**: These are fatty acids whose hydrocarbon chain has no/lacks double bonds/has only single bonds. All the carbon atoms in the chain have used all their valence electrons. Like stearic acids, palmitic acids etc.
- **Unsaturated fatty acids**: These are fatty acids whose hydrocarbon chain contains one or more double bonds (C=C). Some of the carbons in the chain don't use all their valence electrons. Like oleic acid, linoleic acid etc.

NOTE: Unsaturated fatty acids melt at much lower temperatures than saturated fatty acids. This is because the presence of double bonds form kinks which prevents close packing between the adjacent fatty acids chains thus lowering their melting points. The higher the number of unsaturated fatty acids in a lipid, the more likely they are to be liquids at a given temperature.

FUNCTIONS OF LIPIDS

Structural functions	Physiological/metabolic functions
• Phospholipids serve as major components of the plasma/cell membrane. • The fats form a subcutaneous layer in the dermis of the skin thus insulate the body/protect the body from heat loss since they are poor conductors of heat. • The waxes are components of the cuticle in plants and insects there by preventing water loss (desiccation). • They form a component of the myelin sheath of nerve cells thus facilitating impulse transmission. • Fats protect delicate organs like the heart and kidney from mechanical injury/serve as shock absorbers. • Waxes coat fur and feathers of some animals enabling them to repel water which would otherwise wet the organism. • They are component of adipose tissue.	• They provide a lot of energy through oxidation by respiration. • They are solvents for fat soluble vitamins (ADEK). • They are a good source of metabolic water to desert animals, young birds and reptiles while still in their shells. • They are a constituent of the brown adipose tissue which provides heat for temperature regulation (thermogenesis). • Phospholipids (form chylomicrons) facilitate transportation of fats between the gut and the liver. • Phospholipids are used in the formation of acetylcholine (a neurotransmitter substance) facilitating impulses transmission across the synapse. • Cholesterol is used in the synthesis of bile salts, sex hormones and the hormones of the adrenal cortex. • Steroids under human skin are used in the synthesis of vitamin D by the ultra-violet radiations from the sunlight.

Other functions of lipids

- Some lipids provide a scent in plants which attracts insects for pollination.
- Wax is used by bees to construct honey combs.
- Wax from bees is used in the manufacture of candles.
- Some seeds like castor seeds, sunflower seeds etc. store oils as their major food storage reserves.

What properties do lipids possess as energy storage compounds?

- They are compact thus take up little space whenever stored
- They are insoluble in water hence cannot be lost in solution.
- They are light and so can be stored in high concentrations with minimal effect on the body weight thus offering buoyancy to aquatic animals.
- They have a high calorific energy value.
- They have a high hydrogen-oxygen content hence can yield a lot of metabolic water upon oxidation.

NB: Although carbohydrates are the most direct source of energy in living things because they are quickly metabolized and used in both aerobic and anaerobic conditions, Triacylglycerols release roughly twice as much energy per gram of carbohydrates. However, body cells cannot oxidize fats in absence of oxygen (anaerobic conditions).

Assignments;

(a) Account for the following observations; Fats are common food stores in;
(i) Hibernating animals or animals living in extreme cold conditions.
(ii) Desert animals like camel and kangaroo rats.
(iii)In aquatic animals like seals, arctic fish.

(b) Why cells of poikilothermic animals usually have a higher proportion of unsaturated fatty acids than homoeothermic animals?

(c) Explain the reason and the significance of animals living in extreme cold conditions tending to store more unsaturated fats in their bodies than saturated fats.

(d) Explain why high cholesterol levels in blood are linked to certain heart diseases?

(e) What would be the advantages and disadvantages of trying to drastically lower the levels of cholesterol in the body?

(f) Why oils have a lower melting point than fats?

(g) Explain the role of steroids like cholesterol in maintaining the membrane fluidity?

1.3 PROTEINS AS CHEMICALS OF LIFE

To be continued……. Inshaa Allah