DEPARTMENT OF BIOCHEMISTRY
FEDERAL UNIVERSITY WUKARI

2021/2022 SECOND SEMESTER BCH 242: GENERAL BIOCHEMISTRY II
COURSE DISTRIBUTION

S/N	TOPICS	LECTURER	DURATION
1	• A survey of physical and chemical factors that affect biochemical systems which include;		
	i. Water, solutions, acids, bases, pH, buffers and their effects on cellular activities.	Dr Tatah	2 weeks
	ii. Acidity and alkalinity (pH and pKa values and their effects on cellular activities)	Mida	2 weeks
2	i. Chemical kinetics, equilibrium and thermodynamics ii. Electrochemical and redox reactions in relation to energy transduction.	Abu	3 weeks
3	iii. Biological oxidation and bioenergetics. iv. Gibb's equation, chemical coupling, phosphorylation, ATPnand NADH cycles.	Ale	3 weeks
	v. Introduction to metabolism of carbohydrates and lipids	Moses	2 weeks
4	• Revision and tests	All	1 weeks

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(Coordinator)

Biological Roles of Water: Why is water necessary for life?

Water makes up 60-75% of human body weight. A loss of just 4% of total body water leads to dehydration, and a loss of 15% can be fatal. Likewise, a person could survive a month without food but wouldn't survive 3 days without water. This crucial dependence on water broadly governs all life forms. Clearly water is vital for survival, but what makes it so necessary?

The Molecular Make-up of Water

Many of water's roles in supporting life are due to its molecular structure and a few special properties. Water is a simple molecule composed of two small, positively charged hydrogen atoms and one large negatively charged oxygen atom. When the hydrogens bind to the oxygen, it creates an asymmetrical molecule with positive charge on one side and negative charge on the other side (Figure 1). This charge differential is called polarity and dictates how water interacts with other molecules.

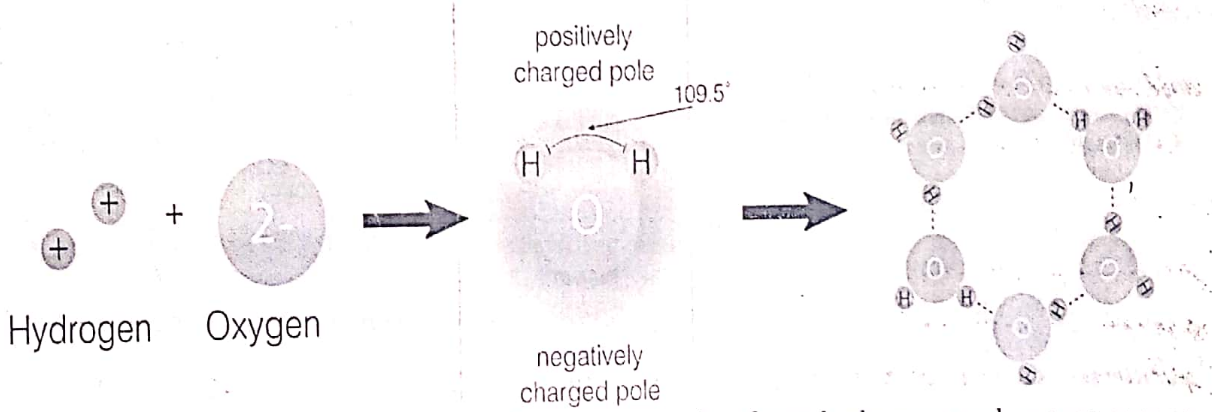

Figure 1: **Water Chemistry.** Water molecules are made of two hydrogens and one oxygen. These atoms are of different sizes and charges, which creates the asymmetry in the molecular structure and leads to strong bonds between water and other polar molecules, including water itself.

Water is the "Universal Solvent"

As a polar molecule, water interacts best with other polar molecules, such as itself. This is because of the phenomenon wherein opposite charges attract one another: because each individual water molecule has both a negative portion and a positive portion, each side is attracted to molecules of the opposite charge. This attraction allows water to form relatively strong connections, called bonds, with other polar molecules around it, including other water molecules. In this case, the positive hydrogen of one water molecule will bond with the negative oxygen of the adjacent molecule, whose own hydrogens are attracted to the next oxygen, and so on (Figure 1). Importantly, this bonding makes water molecules stick together in a property called cohesion. The cohesion of water molecules helps plants take up water at their roots. Cohesion also contributes to water's high boiling point, which helps animals regulate body temperature.

Furthermore, since most biological molecules have some electrical asymmetry, they too are polar and water molecules can form bonds with and surround both their positive and negative regions. In the act of surrounding the polar molecules of another substance, water wriggles its way into all the nooks and crannies between molecules, effectively breaking it apart are dissolving it. This is what happens when you put sugar crystals into water: both water and sugar are polar, allowing individual water molecules to surround individual sugar molecules, breaking apart the sugar and dissolving it. Similar to polarity, some molecules are made of ions, or oppositely charged particles. Water breaks apart these ionic molecules as well by interacting with both the positively and negatively charged particles. This is what happens when you put salt in water, because salt is composed of sodium and chloride ions.

Water's extensive capability to dissolve a variety of molecules has earned it the designation of "universal solvent," and it is this ability that makes water such an invaluable life-sustaining force. On a biological level, water's role as a solvent helps cells transport and use substances like oxygen or nutrients. Water-based solutions like blood help carry molecules to the necessary locations. Thus, water's role as a solvent facilitates the transport of molecules like oxygen for respiration and has a major impact on the ability of drugs to reach their targets in the body.

Water Supports Cellular Structure

Water also has an important structural role in biology. Visually, water fills cells to help maintain shape and structure (Figure 2). The water inside many cells (including those that make up the human body) creates pressure that opposes external forces, similar to putting air in a balloon. However, even some plants, which can maintain their cell structure without water, still require water to survive. Water allows everything inside cells to have the right shape at the molecular level. As shape is critical for biochemical processes, this is also one of water's most important roles.

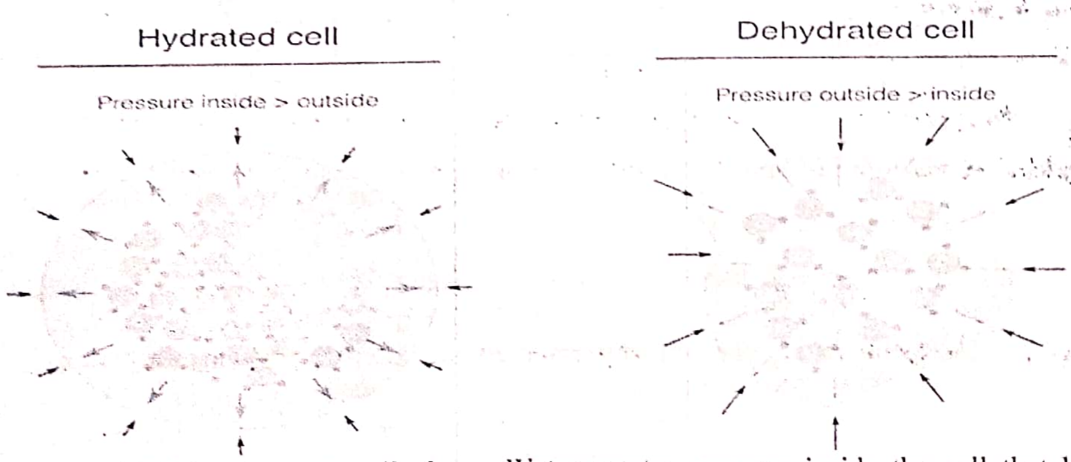

Figure 2: **Water impacts cell shape.** Water creates pressure inside the cell that helps it maintain shape. In the hydrated cell (left), the water pushes outward and the cell maintains a round shape. In the dehydrated cell, there is less water pushing outward so the cell becomes wrinkled.

Water also contributes to the formation of membranes surrounding cells. Every cell on Earth is surrounded by a membrane, most of which are formed by two layers of molecules called phospholipids (Figure 3). The phospholipids, like water, have two distinct components: a polar "head" and a nonpolar "tail." Due to this, the polar heads interact with water, while the nonpolar tails try to avoid water and interact with each other instead. Seeking these favorable interactions, phospholipids spontaneously form bilayers with the heads facing outward towards the surrounding water and the tails facing inward, excluding water. The bilayer surrounds cells and selectively allows substances like salts and nutrients to enter and exit the cell. The interactions involved in forming the membrane are strong enough that the membranes form spontaneously and aren't easily disrupted. Without water, cell membranes would lack structure, and without proper membrane structure, cells would be unable to keep important molecules inside the cell and harmful molecules outside the cell.

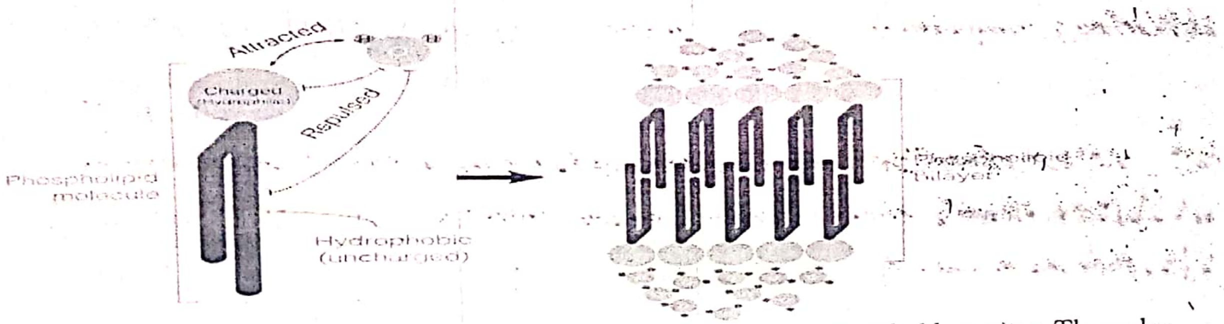

Figure 3: **Phospholipid bilayers.** Phospholipids form bilayers surrounded by water. The polar heads face outward to interact with water and the hydrophobic tails face inward to avoid interacting with water.

In addition to influencing the overall shape of cells, water also impacts some fundamental components of every cell: DNA and proteins. Proteins are produced as a long chain of building blocks called amino acids and need to fold into a specific shape to function correctly. Water drives the folding of amino acid chains as different types of amino acids seek and avoid interacting with water. Proteins provide structure, receive signals, and catalyze chemical reactions in the cell. In this way, proteins are the workhorses of cells. Ultimately proteins drive contraction of muscles, communication, digestion of nutrients, and many other vital functions. Without the proper shape, proteins would be unable to perform these functions and a cell (let alone an entire human) could not survive. Similarly, DNA needs to be in a specific shape for its instructions to be properly decoded. Proteins that read or copy DNA can only bind DNA that has a particular shape. Water molecules surround DNA in an ordered fashion to support its characteristic double-helix conformation. Without this shape, cells would be unable to follow the careful instructions encoded by DNA or to pass the instructions onto future cells, making human growth, reproduction, and, ultimately, survival infeasible.

Chemical Reactions of Water

Water is directly involved in many chemical reactions to build and break down important components of the cell. Photosynthesis, the process in plants that creates sugars for all life forms, requires water. Water also participates in building larger molecules in cells. Molecules like DNA and proteins are made of repetitive units of smaller molecules. Putting these small molecules together occurs through a reaction that produces water. Conversely, water is required for the reverse reaction that breaks down these molecules, allowing cells to obtain nutrients or repurpose pieces of big molecules.

Additionally, water buffers cells from the dangerous effects of acids and bases. Highly acidic or basic substances, like bleach or hydrochloric acid, are corrosive to even the most durable materials. This is because acids and bases release excess hydrogens or take up excess hydrogens, respectively, from the surrounding materials. Losing or gaining positively-charged hydrogens disrupts the structure of molecules. As we've learned, proteins require a specific structure to function properly, so it's important to protect them from acids and bases. Water does this by acting as both an acid and a base. Although the chemical bonds within a water molecule are very stable, it's possible for a water molecule to give up a hydrogen and become OH–, thus acting as a base, or accept another hydrogen and become H3O+, thus acting as an acid. This adaptability allows water to combat drastic changes of pH due to acidic or basic substances in the body in a process called buffering. Ultimately, this protects proteins and other molecules in the cell.

In summary, water is vital for all life. Its versatility and adaptability help perform important chemical reactions. Its simple molecular structure helps maintain important shapes for cells' inner components and outer membrane. No other molecule matches water when it comes to unique properties that support life. Excitingly, researchers continue to establish new properties of water such as additional effects of its asymmetrical structure. Scientists have yet to determine the physiological impacts of these properties. It's amazing how a simple molecule is universally important for organisms with diverse needs.

More details on the Roles of Water and living organisms

Water has a number of roles in living organisms:. solvent temperature buffer metabolite living environment. These, roles can be explained once we have understood the structure and bonding in a water molecule, and between water molecules.

A molecular compound

Water is a molecular compound, with molecular formula H2O. The atoms in a water molecule are held together by strong covalent bonds. These are very difficult to break.

The dot-and-cross diagram for a water molecule shows there are two **bonding pairs' of electrons** and two **non-bonding pairs of electrons**. The four pairs repel one another, forming a tetrahedral pattern. In this way they are as far from one another as possible. The molecule itself (the spatial distribution of atoms) is described as 'bent', 'angular' or 'non-linear'. The two electrons in each oxygen-hydrogen bond are not shared equally. They are more strongly attracted to the oxygen atom. The bond is **polar**, it has a 'negative end' (the oxygen atom) and a 'positive end' (the hydrogen atom). A **hydrogen bond** forms between a non-bonding pair of electrons on the oxygen atom of one water molecule and the hydrogen atom ('positive end') of another water molecule. The hydrogen bond is about ten times weaker than a single covalent bond. With this understanding we can begin to understand how water fulfils its various roles in biological systems.

Solvent

Most compounds with **ionic bonding**, e.g. metal salts, dissolve in water. The oxygen atoms of water molecules are attracted to cations (ions with a positive charge) and water molecules surround it. These water molecules attract more water molecules and hydrogen-bonds form between them. The result is a cluster of water molecules around the ion. We say the ion is hydrated. Similarly anions (ions with a negative charge) become surrounded by clusters of water molecules.

This time it is the positive ends of the water molecule, the hydrogen atoms, that are attracted to the anion. A wide range of molecular compounds also dissolve in water, including sugars, amino acids, small nucleic acids and proteins. All these molecules are **polar**. This means they have a positive end and a negative end as the result of polar covalent bonds within them. Of the important biological molecules only the non-polar lipids (fats and oils) and large polymers (e.g. polysaccharides, large proteins and DNA) do not dissolve. The water acts as a solvent for chemical reactions and also helps transport dissolved compounds into and out of cells.

Another important property is that many compounds dissolve and transfer a proton (a hydrogen nucleus) to a water molecule. The result is an acidic solution with pH < 7. Compounds that release a proton in this way are called **acids**. For example,

CH_3COOH (aq) + H_2O (aq) CH_3COO^- (aq) + H_3O^+ (aq)

H_3O^+(aq) is called a **hydroxonium ion** and is responsible for the acidic properties of the solution.

pH= $-\log 10[H_3O^+]$

Some molecules receive a proton from a water molecule. The result is an alkaline solution with pH >7. Compounds that accept a proton in this way are called **bases**. For example, OH^-(aq) is called a **hydroxide ion** and is responsible for the alkaline properties of the solution.

Temperature buffer

Cells host a huge range of chemical reactions. Many of these are catalysed by Enzymes. Enzyme activity is sensitive to temperature and reactions only occur in a narrow range of temperatures. Water helps to buffer temperature changes because of its relatively high **specific heat capacity** (the heat required to raise 1 kg of water by 1 °C). It also has relatively large **enthalpy of vaporization** (heat energy required to convert a liquid to a gas) and **enthalpy of fusion** (heat energy required to convert a solid to a liquid). This is reflected in the unusually high boiling and melting points of water: These properties are a consequence of hydrogen bonding.

Metabolite

Chemical reactions take place in cells. Collectively these reactions together are called **metabolism**, i.e. all the chemical and physical processes within a cell. The chemicals involved are called **metabolites**. Water is a metabolite in many reactions, either as a reactant or as a product of reaction. For example, it's involved in **photosynthesis**, **digestion** and **aerobic respiration**. When water reacts with a chemical to break it into smaller molecules the reaction is described as **hydrolysis**.

When water is formed as one of the products when two molecules join together the reaction is described as **condensation**.

Living environment

Many organisms, such as fish, live in water and cannot survive out of it. They have adapted to living in it. Ice floats on water. This is because ice is less dense than water. The reason is that ice has a giant structure with every oxygen atom at the centre of a tetrahedral arrangement of hydrogen atoms (two are covalently bonded and two are hydrogen-bonded). In freezing weather, ice forms on the surface of ponds and lakes forming an insulating layer above the water below. This provides a living environment for some organisms until the ice melts. Organisms can also live under the ice. The surfaces of ponds and lakes (and other forms of water) are covered in a 'skin' of water molecules. While most objects break through this skin, it is strong enough to support small insects such as pond skaters. The skin forms because of the increased attraction between water molecules (**cohesive forces**) at the surface.

MAINTAINING CELLULAR CONDITIONS: pH AND BUFFERS

Water is the universal solvent inside all cells and extracellular fluids. Water molecules (H_2O) can dissociate into hydroxide ions (OH^-) and hydrogen ions (H^+). Other molecules or parts of molecules have the ability to either give up hydrogen ions, acids, or accept hydrogen ions, bases. Consequently, we can characterize any aqueous solution by the concentration of positively charged hydrogen ions and negatively charged hydroxide ions.

Importance: Many chemical reactions in living cells involve exchanges of hydrogen ions. Because changes in acidity can affect both the structure and chemical reactivity of cellular molecules, cells must constantly maintain an acid-base balance.

Questions: How do we quantify acidity? What affects the buffering capacity of acids and bases?

Variables:

Keq equilibrium constant [X], [Y] concentrations of reactants [A], [B] concentrations of products d fraction of a weak acid that is undissociated **Hydrogen ion concentration and pH**

The dissociation of water into hydroxide and hydrogen ions can be represented by the following reversible chemical equation: H_2O ---> $H^+ + OH$

The hydrogen ion is short-lived and combines with an H_2O molecule to form a hydronium ion (H_3O^+). The equilibrium constant of a chemical reaction is given by the ratio of products to reactants at equilibrium. For the general chemical equation X + Y ---> A + B, we can write the equilibrium constant as For the dissociation of water we get The equilibrium constant for the dissociation of water at 25° C has been measured as $K_{eq}=1.8\times10^{-16}$. This number is small because only a small fraction of water molecules dissociate. The concentration of water can be determined from the fact that 1 mole of water weighs 18g and 1 liter of water weighs 1000g. Hence, the concentration of pure water $[H_2O]$ is 1000g/L , 18 g/mol = 55.5 mol/L. By substituting these into the above equation, we find that $[H^+][OH^-]=1\times10^{-14}$ In pure water, the concentrations of hydrogen and hydroxide ions are about the same. Hence by taking the square root of 1×10^{-14} we find that $[H^+]$ and $[OH^-]$ are each about 10^{-7} M. This means that 1 liter of pure water contains about one ten-millionth of a mole of hydrogen or hydroxide ions. Other molecules, however, have the ability to donate or accept hydrogen ions. Consequently, when other substances are dissolved in water, the concentrations of H^+ and OH^- can change. As the concentration of hydrogen ions increases, the concentration of free hydroxide ions decreases in order to maintain an equilibrium. A convenient way to characterize aqueous solutions is to look at the hydrogen ion concentration. The pH scale allows biologists to define chemical solutions more conveniently: $pH = -\log[H^+]$

This method is convenient because it eliminates the need for exponential notation. We can see how pH changes with hydrogen ion concentration by plotting the equation for pH as a logarithmic function of $[H^+]$. We can more clearly see how $[H^+]$ affects pH by plotting this graph on a semi-log scale. This will make it easier for us to see values of pH at very low values of $[H^+]$. In the simplest terms, the value of pH simply gives us the absolute value of the exponent of the hydrogen ion concentration. On the pH scale, a 7 is considered to be neutral. Substances that can donate hydrogen ions, thus increasing $[H^+]$, are acids. Strong acids have pH much lower than 7. Molecules that accept hydrogen ions, thus decreasing $[H^+]$, are bases and have pH higher than 7.

Buffers

Cells must constantly maintain their pH in order to function properly. In animals, for example, the maintainence of blood pH is crucial for life. A slightly acidic pH (6.95) would result in coma and death. A slightly more basic pH (7.7) would result in convulsions and muscle spasms. As another example, the pH of cellular organelles such as lysosomes (around 5) is lower than the pH of the cytoplasm (around 7.2). Lysosomes contain enzymes that function optimally in an acidic environment. Such an acidic environment, however, would be detrimental to biological processes in the cytoplasm. Each must maintain the appropriate pH.

Methods: Cells can maintain pH chemically by using buffers. Buffers are molecules that easily interconvert between acidic and basic forms, donating or accepting protons as conditions change.

The dissociation of a simple acid HA can be described by the following chemical reaction:

$HA \dashrightarrow H^+ + A^-$

We can interpret this as a weak acid (HA) dissociating to form a hydrogen ion (H^+) and a conjugate base (A^-). Notice the reverse happens as well. Buffer solutions are typically mixtures of a weak acid and its conjugate base. Suppose we were to add a strong base, NaOH, to the buffer solution. NaOH would raply dissociate into Na^+ and OH^- ions. The hydroxide ions would rapidly accept the H^+ ions formed by the buffer. Similarly, if we added a strong acid, the conjugate base, A^-, would take up the additional hydrogen ions. In either case, the buffer (HA) would then continue to dissociate in order to maintain its original equilibrium.

Buffering ability depends on the ratio of conjugate base concentration to weak acid concentration.