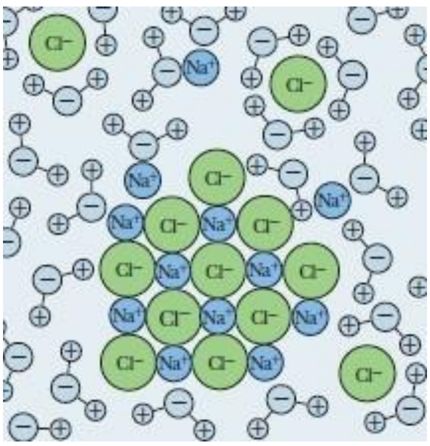
Water as a biological solvent

Introduction

Water is the most important substance of life. It provides an environment for many species. All cells contain a minimum of 85% of water, with most fluids inside and outside of the cell likely to have at least 90% water. Both transportation of molecules and chemical reactions take place in dissolved water. Water acts as a metabolite in many reactions, either as a reactant or as a product of a reaction. It is involved in many reactions like photosynthesis, digestion and aerobic respiration. A wide range of biomolecules are dissolve in water including sugars, amino acid, small nucleic acids and proteins. Only non-polar lipids and large polymers like polysaccharides, large proteins do not dissolve. Cells host a huge range of chemical reaction. 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 relative high specific heat capacity .It also helps transport dissolved compounds into and out of cells. Many compounds dissolve and transfer a proton to a water molecule. Almost all biological macromolecules proteins and DNAs are inactive in the absence of water. Hydration of a protein is particularly important for the stability of the structure and for the function, especially the recognition at a specific site. Water is strongly dipolar, this property makes water a very effective solvent, particularly for crystalline salts. So, water is the solvent of the body and it regulates all functions, including the activity of everything it dissolves and circulates

Water as a biological solvent

Water is a versatile solvent due to its polarity, which allows it to form hydrogen bonds easily. When an ionic compound is dissolved in water, each ion is surrounded by a sphere of water molecules called a hydration shell. As shown in the figure below.



Hydration shells surrounding ions in solution. Water molecules orient so the electrical charge on the ion are sequestered by the water dipole. Water dissolves inorganic and organic compounds alike, simultaneously serving as both good and poor solvent for biological macromolecules such as proteins, those with molecular weights in excess of 10^6g per mole. Blood is an example of proteinaceous milieu containing 0.1M sodium chloride with a wide variety of proteins. On the other hand, water is a rather poor solvent for nonpolar macromolecules. This is largely responsible for the self assembly of lipids into the bilayer structure building blocks of living cells. Otherwise lipids would dissolve in water, failing to organise into any entity whatsoever, and proteins would not form the secondary or tertiary structures so essential to enzyme activity. The peculiar feature of this sparing hydrocarbon solubility in water is that it is temperature independent. If this were not the case a slight change in temperature would cause water to become a more aggressive solvent, possibly corroding life by dissolving lipid and protein assemblies.

Weak acids and bases

According to the Bronsted-Lowry, an acid is a proton donor and a base is a proton acceptor. Weak acids and bases are ubiquitous in biological system and play important roles in metabolism and its regulation. Water is amphoteric i.e it has the ability to act as either an acid or a base in chemical reactions.A weak acid is an acid that do not dissociates completely, releasing only some of its hydrogen atoms into the solution. The majority of acids are weak .On average, only about 1 percent of a weak acid solution dissociates in water in a 0.1 mol/L solution. Therefore, the concentration of hydrogen ions in a weak acid solution is always less than the concentration of the un dissociated species. Thus it is less capable than a strong acids at donating protons. Weak acids have very small values for K_a and therefore higher values pK_a compared to strong acids, which have very large Ka values and slightly negative pK_a values. Examples of weak acids include acetic acid, phosphoric acid and oxalic acid. The strength of a weak acid is represented as an equilibrium constant or as a percent dissociation. The equilibrium concentrations of reactants and products are related by the acid dissociation constant expression, $K_{a.}$ The greater the value of $K_{a,}$ the more the formation of hydrogen ion is favoured, and the lower the pH of the solution. The K_a of weak acids varies between acids with K_a less than 1.8×10^{-16} are weaker acid than water. All weak acids in solution exist in equilibrium. The equilibrium is between the molecular form of the acid and the ionized form of the acid.

$$\rightleftharpoons \quad HA(aq) + H_2O(l) \quad H_3O^+(aq) + A^-(aq)$$

For all acids this equilibrium lies predominantly on left. Most of the acid is in the molecular form. This results in all weak acids having an equilibrium constant that is less than 1.The largest equilibrium constant is 10^{-2}.The smallest is about 10^{-13}.The equilibrium expression for all monoprotic weak acids is

$$K_a = \frac{[H^+][A^-]}{[HA]}$$

where K_a is the acid-ionization constant.

Most polyprotic acids are weak. A polyprotic acid has a K_a for each acidic proton on the acid. Each successive K_a is smaller than the previous one. $pK_a$was introduced as an index to express the acidity of weak acids, where $pK_a$is defined as

$$pK_a=-\log_{10}K_a$$

pK_a is defined as the negative logarithm to the base 10 of the K_a in g ions /L or as logarithm to the base 10 of the reciprocal of K_a..The pK_a value is directly proportional to the standard Gibbs free energy change for the reaction. The value of pK_a changes with temperature. When the reaction is endothermic, K_a increases and pK_a decreases with increasing temperature. And for exothermic reactions K_a decreases and pK_a increases with increasing temperature. The value of pK_a also depends on molecular structure of the acid in many ways. The quantitative behaviour of acids and bases in solution can be understood only if their pK_a values are known. In particular, the pH of a solution can be predicted when the analytical concentration and pK_a values of all acids and bases are known.

A weak base is a chemical base that does not ionize fully in an aqueous solution. This results in a relatively low pH compared to strong base. Weak base are almost always derivatives of the Ammonia molecule. Weak bases in water undergo hydrolysis.

$$NH_3(aq) + H_2O(l)\ NH_{4(aq)} + OH^-(aq)$$

The equilibrium expression for this is

$$K_b = \frac{[NH_4^+][OH^-]}{[NH_3]}$$

K_b is called the base-ionization constant. pK_b is the negative base-10 logarithm of the base dissociation constant of a solution. It is used to determine the strength of a base or alkaline solution.

$$pK_b=-\log_{10}K_b$$

The methods for determining K_b can also be used to determine the pH of a solution of a weak base. Weak bases do not completely dissociate at equilibrium in water. So calculating the pH of these solution requires consideration of a unique ionization constant and equilibrium concentrations.

Determination of K_a

K_a can be determined in a variety of ways. The most common is by measuring the pH of a solution of the weak acid in question. This method works for monoprotic acids, but for polyprotic acids,the result is a combination of the various K's for each acidic proton. Titration method works well for either polyprotic acids. Measuring the pH at various points in the titration and plotting the pH vs.The volume of the base added gives an indication of the K's for the acid.

The relationship between K_a and K_b

When acid strength increases conjugate base strength decreases, and base strenght increases, conjugate acid strength decreases. This relationship can be illustrated mathematically using the K_a and K_b expressions for a conjugate acid –base pair.

Weak acid:$HA(aq) + H_2O \rightleftharpoons A^-(aq) + H_3O^+$

$K_{a=} [H_3O^+][A^-]/ [HA]$

Conjugate base: $A^-(aq) + H_2O \rightleftharpoons HA(aq) + OH^-(aq)$

$K_{b=} [HA][OH^-]/ [A^-]$

Multiplying the two equilibrium expressions and simplifying gives

$K_a \times K_b = [H_3O^+][A^-]/ [HA]\times [HA][OH^-]/ [A^-]$

$K_a \times K_b = [H_3O^+] [OH^-]$

Therefore, $K_a \times K_b = K_w = 1\times10^{-14}$ at 25˚C

Notice that as K_a increases, acid strength increases and K_b for the conjugate base must decrease. Thus stronger acids have weak conjugate bases, and stronger bases have weak conjugate acids. This relationship can be used to determine ,for example, the K_b For weak base if the K_a for the conjugate acid is known.

pH

pH is the measurement of the hydrogen ion concentration. pH may be defined as the negative logarithm of the hydrogen ion concentration or pH of the solution is the logarithm of the reciprocal of hydrogen ion concentration. This definition of pH was introduced by the Danish Biochemist, Soren Peter in 1909 .Every aqueous solution can be measured to determine its pH value. This value ranges from 0 to 14 pH.pH 7 is the centre of the measurement scale, it is neither acidic nor basic, it is called neutral pH. Measurement of pH is one of the most important and frequently used procedures in Biochemistry. Almost all processes containing water have a need for pH measurement. Drinking water with a pH between 6.5 and 8.5 is generally satisfactory. Acidic waters with pH below 6 are corrosive to plumbing and faucets. Alkaline waters are less corrosive. Most living things depend on a proper pH level to sustain life. The pH affects the structure and activity of biological macromolecules. For example, the catalytic activity of enzymes is strongly dependent on pH. All human beings and animals rely on internal mechanism to maintain the pH level of their blood. The blood flowing through our veins must have a pH between 7.35 and 7.45.Exceding this range by as little as one –tenth of a pH unit could prove fatal.

It is expressed mathematically as :

$$pH=-\log [H^-]$$

pH is equal to negative log of hydrogen ion concentration. Hydrogen ion concentration is expressed in mol/L. The pH value is an expression of the ratioof hydrogen ion concentration to hydroxide ion concentration. Hence, if the hydrogen ion conc. is greater than hydroxyl ion concentration, the solution is acidic. Conversely, if the hydroxide ion is greater than the hydrogen ion concentration the solution is basic. At pH 7 the ratio of hydrogen ion to hydroxide ion is equal and, therefore, the solution is neutral. As shown in the equation below, pH is a logarithmic function. A change of one pH unit represents a 10 fold change in concentration of hydrogen ion.

pH scale

pH scale is used to describe whether a solution is acidic or basic. The pH scale designates the hydrogen ion and hydroxyl ion concentration. The ion product of water is the basis for the pH scale. As mentioned above that pH is equal to negative log of hydrogen ion concentration. The pH scale is logarithmic. If two solutions differ in pH by 1 pH unit then one solution has ten times the hydrogen concentration of the other. It does not tell us the absolute magnitude of the difference.

Ways of measuring pH

pH in an aqueous solution can be measured in a variety of ways. The most common way uses a pH sensitive electrode, a reference electrode and a pH meter.

Alternative methods for determining the pH of a solution are:

Indicators: Indicators are materials that are specifically designed to change color when exposed to different pH values. The color of a wetted sample paper is matched to a color on a color chart to infer a pH value. pH paper is available for narrow pH ranges and fairly wide pH ranges of 1 to 11. pH paper is used for preliminary and small volume measuring. It cannot be used for continuous monitoring of a process. Though pH paper is fairly inexpensive, it can be attacked by process solutions, which may interfere with the color change.

Colorimeter: This device uses a vial filled with an appropriate volume of sample to which a reagent is added. As the reagent is added, a color change takes place
.The color of this solution is then compared to a color wheel or spectral standard to interpolate the pH value. The colorimeter can be used for grab sample measuring, but not for continuous online measuring. Typically use to determine the pH value of water in swimming pools, spas, cooling towers, and boilers and river waters. A pH meter is always recommended for precise and continuous measuring. Most laboratories use a pH meter connected to a strip chart recorder or some other data acquisition device so that the reading can be recorded or stored electrically over a user defined time range.

Glossary:

Hydration shell: The sphere of water molecules around each dissolved ion.

Monoprotic acid :. A monoprotic acid is an acid that donates only one proton or hydrogen atom per molecule to an aqueous solution.

Polyprotic acid: A polyprotic acid is an acid that can donate more than one proton or hydrogen atom per molecule to an aqueous solution.

K_w : The water auto protolysis constant or auto ionization constant.

pK_a : pK_a is defined as the negative logarithm to the base 10 of the K_a in g ions /L.

pK_b: The negative logarithm, to the base 10, ofa base dissociation. constant.

pH: The negative logarithm of the hydrogen ion concentration.

FAQs:

Q1. What makes water a versatile solvent?

Ans: Water is a versatile solvent due to its polarity, which allows it to form hydrogen bonds easily.

Q2. What is a hydration shell?

Ans: A hydration shell is a salvation shell. It is the sphere of water molecules around each dissolved ion.

Q3. What is a weak acid ?

Ans: A weak acid is an acid that ionizes incompletely in aqueous solution.

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Q4.What is a weak base ?

Ans: A weak base is a base that only partially dissociates in water.

Q5.What is K_a?

Ans:K_a is the equilibrium constant for the ionization of an acid .It is also called the acid dissociation constant.

Q6.What is K_b?

Ans:K_b is the equilibrium constant for the ionization of a base .It is also called the base dissociation constant.

Q7. Define pH?

Ans: pH may be defined as the negative logarithm of the hydrogen ion concentration or pH of the solution is the logarithm of the reciprocal of hydrogen ion concentration. It is expressed mathematically as :

$$pH = -\log [H^-]$$

pH is equal to negative log of hydrogen ion concentration. Hydrogen ion concentration is expressed in mol/L.