WATER ACTIVITY: WHY IT IS IMPORTANT FOR FOOD SAFETY*

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The single most important property of water in food systems is the water activity (a_w) of food. Throughout history the importance of controlling water in food by drying, freezing or addition of sugar or salt was recognized for preserving and controlling food quality. Water activity is the ratio of the vapor pressure of water in equilibrium with a food to the saturation vapor pressure of water at the same temperature. The water activity of a food describes the degree to which the water is "bound" in the food and hence its availability to act as a solvent and participate in chemical/biochemical reactions and growth of microorganisms. It is an important property that can be used to predict the stability and safety of food with respect to microbial growth, rates of deteriorative reactions and chemical/physical properties. The water activity principle has been incorporated by various regulatory agencies (FDA CFR Title 21) in definitions of safety regulations regarding the growth and proliferation of undesirable microorganisms, standards of several preserved foods, and packaging requirements. New instrumentation has improved the speed, accuracy and reliability of water activity measurements and is definitely a needed tool for food safety. The AquaLab, a chilled mirror dew point instrument, measures water activity values between 0.030 and 1.000 a_w in less than five minutes. It attains a resolution and precision of ± 0.001 a_w with an accuracy of ± 0.003 a_w.

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Introduction

There are two basic types of water analysis. The first, water content, is a quantitative or volumetric analysis to determine the total amount of water present in a food. The second type measures the water activity, a_w. It indicates how tightly water is bound, structurally or chemically, in food products. Water activity is the relative humidity of air in equilibrium with a sample in a sealed measurement chamber. It is therefore the ratio of the water vapor pressure (p) over a food to that over pure water (p_o) at a given temperature. Multiplication of the a_w by 100 gives the percent equilibrium relative humidity (ERH) of the atmosphere in equilibrium with the food.

$$a_w = \frac{p}{p_o} = \frac{\%ERH}{100}$$

The single most important property of water in a food is the water activity (Taoukis, 1988). The water activity of a food describes the energy status of water in a food and hence its availability to act as a solvent and participate in chemical or biochemical reactions (Labuza, 1977). Figure 1 is a global stability map of foods, showing stability as a function of a_w (Labuza, 1970). Water's ability to act as a solvent, medium and reactant increases with increasing water activity (Labuza, 1975).

The concept of water activity (a_w) is an important property for food safety. It predicts food safety and stability with respect to microbial growth, chemical/biochemical reaction rates, and physical properties (Figure 1). By measuring the water activity of foodstuffs, it is possible to predict which microorganisms will be potential sources of spoilage and infection. Controlling water activity is an important way to maintain the chemical stability of foods. Non-enzymatic browning reactions and

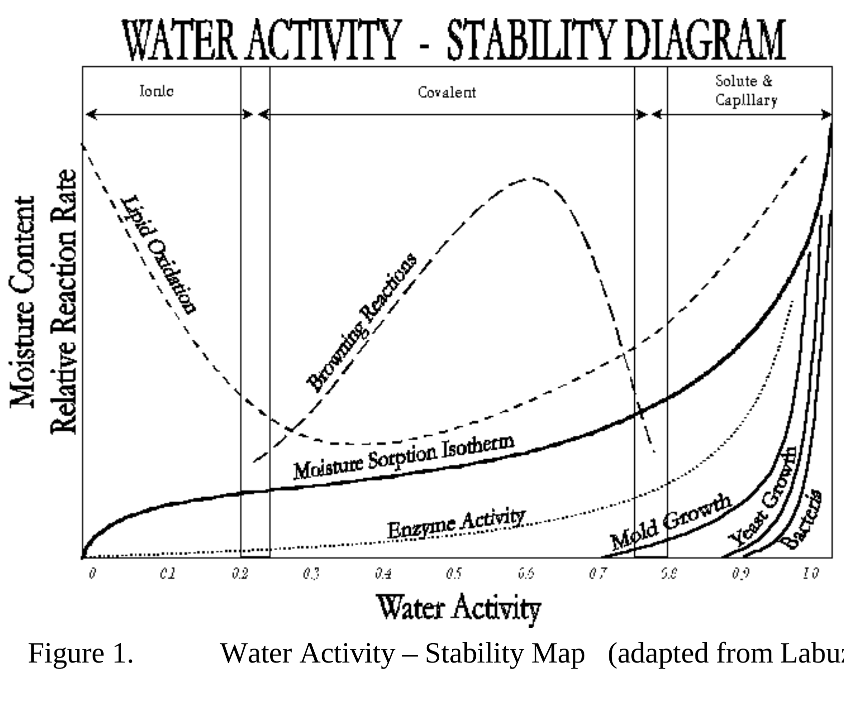

Figure 1. Water Activity – Stability Map (adapted from Labuza)

spontaneous autocatalytic lipid oxidation reactions are strongly influenced by water activity. Water activity can play a significant role in determining the activity of enzymes and vitamins in food. Finally, a_w plays a significant role in the physical properties such as texture and shelf-life of foods.

Microbial Safety

One purpose of food safety is to prevent growth and toxin production from harmful microorganisms. According to the 1995 trends in the United States survey, American consumers' confidence in the safety of the food supply has increased. In fact, 77% of shoppers are now completely or mostly satisfied that supermarket foods are safe. The top concerns regarding the food supply are spoilage and bacterial contamination. Incidentally, 77% of all traceable foodborne illness outbreaks result from improper handling in foodservice establishments, 20% from improper handling in the home, and only 3% from manufacturing errors (Slone, 1995).

Scott (1957) showed that microorganisms have a limiting water activity level below which they will not grow. Water activity, not water content, determines the lower limit of available water for microbial growth. The lowest a_w at which the vast majority of food spoilage bacteria will grow is about 0.90. *Staphylococcus aureus* under anaerobic conditions is inhibited at an a_w of 0.91, but aerobically the a_w level is 0.86. The a_w for molds and yeasts growth is about 0.61 with the lower limit for growth of mycotoxigenic molds at 0.78 a_w (Beuchat 1981). Table 1 lists the water activity limits for growth of microorganisms significant to public health and examples of foods in those ranges.

In addition to the relationship between microbial growth and water activity, a number of other aspects of food microbiology are influenced by water activity. The effect of a_w on sporulation, germination, and mycotoxin production of microorganisms is complex (Beuchat, 1983). Generally for yeast, a higher a_w is required for sporulation than spore germination. The minimum a_w for toxin production are generally higher than the minimum a_w growth level.

Chemical/Biochemical Reactivity

Water activity influences not only microbial spoilage but also chemical and enzymatic reactivity. Water may influence chemical reactivity in different ways. It may act as a solvent, reactant or change the mobility of the reactants by affecting the viscosity of the food system (Leung, 1987). Water activity influences non-enzymatic browning, lipid oxidation, degradation of vitamins, enzymatic reactions, protein denaturation, starch gelatinization, and starch retrogradation.

The likelihood of non-enzymatic browning increases with increasing a_w , reaching a maximum at a_w in the range of 0.6 to 0.7 (Figure 1). Generally, further increases in water activity will hinder browning reactions. Lipid oxidation has a minimum in the intermediate a_w range and increases at both high and low a_w values, although due to different mechanisms. This type of food spoilage results in the formation of highly objectionable flavors and odors. Water soluble vitamin degradation in food systems increases with increasing a_w values (Kirk, 1981). Enzyme and protein stability is influenced significantly by water activity due to their relatively fragile nature. Most enzymes and proteins must maintain conformation to remain active. Maintaining critical a_w levels to prevent or entice conformational changes is important to food quality. Most enzymatic reactions are slowed down at water activities below 0.8, but some reactions occur even at very low a_w values. Water activity influences the gelatinization temperature and retrogradation rate of starch.

Table 1. Water Activity and Growth of Microorganisms in Food*

Range of a_w	Microoranisms Generally Inhibited by Lowest a_w in This Range	Foods Generally within This Range
1.00 – 0.95	*Pseudomonas*, *Escherichia*, *Proteus*, *Shigells*, *Klebsiella*, *Bacillus*, *Clostridium perfringens*, some yeasts	Highly perishable (fresh) foods and canned fruits, vegetables, meat, fish, and milk; cooked sausages and breads; foods containing up to approximately 40% (w/w) sucrose or 7% sodium chloride
0.95 – 0.91	*Salmonella*, *Vibrio parahaemolyticus*, *C. botulinum*, *Serratia*, *Lactobacillus*, *Pediococcus*, some molds, yeasts (*Rhodotorula*, *Pichia*)	Some cheeses (Cheddar, Swiss, Muenster, Provolone), cured meat (ham), some fruit juice concentrates; foods containing 55% (w/w) sucrose or 12% sodium chloride
0.91 – 0.87	Many yeasts (*Candida*, *Torulopsis*, *Hansenula*), *Micrococcus*	Fermented sausage (salami), sponge cakes, dry cheeses, margarine; foods containting 65% (w/w) sucrose (saturated) or 15% sodium chloride
0.87 – 0.80	Most molds (mycotoxigenic penicillia), *Staphyloccocus aureus*, most *Saccharomyces* (bailii) spp., *Debaryomyces*	Most fruit juice concentrates, sweetened condensed milk, chocolate syrup, maple and fruit syrups; flour, rice, pulses containing 15-17% moisture; fruit cake; country-style ham, fondants, high-ratio cakes
0.80 – 0.75	Most halophilic bacteria, mycotoxigenic aspergilli	Jam, marmalade, marzipan, glacé fruits, some marshmallows
0.75 – 0.65	Xerophilic molds (*Aspergillus chevalieri*, *A. candidus*, *Wallemia sebi*), *Saccharomyces bisporus*	Rolled oats containing approximately 10% moisture, grained nougats, fudge, marshmallows, jelly, molasses, raw cane sugar, some dried fruits, nuts
0.65 – 0.60	Osmophilic yeasts (*Saccharomyces rouxii*), few molds (*Aspergillus echinulatus*, *Monascus bisporus*)	Dried fruits containing 15-20% moisture; some toffees and caramels; honey
0.50	No microbial proliferation	Pasta containing approximately 12% moisture; spices containing approximately 10% moisture
0.40	No microbial proliferation	Whole egg powder containing approximately 5% moisture
0.30	No microbial proliferation	Cookies, crackers, bread crusts, etc. containing 3-5% moisture
0.20	No microbial proliferation	Whole milk powder containing 2-3% moisture; dried vegetables containing approximately 5% moistrue; corn flakes containing approximately 5% moisture; fruit cake; country-style cookies, crackers

* Adapted from Beuchat (1981).

Physical Properties

In addition to predicting the rates of various chemical and enzymatic reactions, water activity effects the textural properties of foods. Foods with high a_w have a texture that is described as moist, juicy, tender and chewy (Bourne, 1987). When the water activity of these product is lowered undesirable textural attributes such as hard, dry, stale and tough are used. Low a_w foods normally have texture attributes described as crisp and crunchy, while at higher a_w the texture changes to soggy. Also, water activity affects the flow, caking and clumping properties of powders and granulations.

Water activity is an important parameter in controlling water migration of multicomponent products. Some foods contain components at different water activity levels, such as cream filled snack cakes or cereals with dried fruits. By definition water activity defines that moisture will migrate from the region of high a_w to the region of lower a_w, but the rate of migration depends on many factors. Undesirable textural changes are the result of moisture migration in multicomponent foods. For example moisture migrating from the higher a_w dried fruit into the lower a_w cereal, causes the fruit to become hard and dry while the cereal becomes soggy (Brandt, 1996).

Government Regulations

The United States has one of the safest food supplies of any country in the world. The FDA's Good Manufacturing Practice Regulations incorporates water activity guidelines in defining food safety regulations. The purpose of GMP regulations are to detail the specific requirements and practices to be followed by industry to assure that foods are produced under sanitary conditions and are pure, wholesome, and safe to eat (Johnston, 1987). Specific parts and paragraphs of applicable GMP regulations from Title 21 of the Code of Federal Regulations using a_w in relation to control measures and food safety are listed in Table 2. However, neither GMP's alone nor activities of regulatory agencies alone can guarantee a completely safe food supply (Vetter, 1996). A science based system, Hazard Analysis and Critical Control Points (HACCP), will improve food safety and reduce the incidence of foodborne illness.

HACCP is a way for industry to control and prevent problems, and ensure safe food by controlling the production process from beginning to end, rather than detecting problems at the end of the line. It identifies where hazards might occur in the food production process and puts into place actions to prevent the hazards from occurring. For example, a target water activity must be established to prevent hazardous organisms from growing. By controlling major food risks, such as microbiological, chemical and physical contaminants, the industry can better assure consumers that its products are safe.

Measurement of Water Activity

In the past, measuring water activity of foodstuffs was a time consuming and difficult process. Methods for water activity determinations are detailed in the Official Methods of Analysis of AOAC International (1995), Method 978.18. New instrument technologies have vastly improved speed, accuracy and reliability of measurements. Reliable laboratory instrumentation is required to guarantee the safety of food products and enforce government regulations.

Table 2. Annual Code of Federal Regulations, Title 21 Subpart References to Water Activity

110 Current good manufacturing practice in manufacturing, packing, or holding human food	
110.3(n)	Safe-moisture level is a level of moisture low enough to prevent the growth of undesirable microorganisms in the finished product under the intended conditions of manufacturing, storage, and distribution. The maximum safe moisture level for food is based on its water activity (a_w). An a_w will be considered safe for a food if adequate data are available that demonstrate that the food at or below the given a_w will not support the growth of undesirable microorganisms.
110.3(r)	Water activity (a_w) is a measure of the free moisture in a food and is the quotient of the water vapor pressure of the substance divided by the vapor pressure of pure water at the same temperature.
110.40(f)	Instruments and controls used for measuring, regulating, or recording temperatures, pH, acidity, water activity, or other conditions that control or prevent the growth of undesirable microorganisms in food shall be accurate and adequately maintained, and adequate in number for their designated uses.
110.80(b)(2)	All food manufacturing, including packaging and storage, shall be conducted under such conditions and controls as are necessary to minimize the potential for the growth of microorganisms, or for the contamination of food. One way to comply with this requirement is careful monitoring of physical factors such as time, temperature, humidity, a_w, pH, pressure, flow rate, and manufacturing operations…
110.80(b)(4)	Measures such as sterlilzing, irradiating,pasteurizing, freezing, refrigerating, controlling pH or controlling a_w that are taken to destroy or prevent the growth of undesirable microorganisms, particularly those of public health significance, shall be adequate under the conditions of manufacture, handling, and distribution to prevent food from being adulterated within the meaning of the act.
110.80(b)(14)	Food such as, but not limited to, dry mixes, nuts, intermediate moisture food, and dehydrated food, that relies on the control of a_w for preventing the growth of undesirable microorganisms shall be processed to and maintained at a safe moisture level. Compliance with this requirement may be accomplished by any effective means, including employment of one or more of the following practices: (i) monitoring the a_w of food (ii) controlling the soluble solids-water ratio in finished food (iii) protecting finished food from moisture pickup, by the use of a moisture barrier or by other means, so that the a_w of the food does not increase to an unsafe level.
108.35 & 113 Thermally processed low-acid foods packaged in hermetically sealed containers	
113.3(e)(ii)	By the control of water activity and the application of heat, which renders the food free of microorganisms capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution.
113.3(n)	Low-acid foods means any foods, other than alcoholic beverages, with a finished equilibrium pH greater than 4.6 and a water activity (a_w) greater than 0.85. Tomatoes and tomato products having a finished equilibrium pH less than 4.7 are not classed as low-acid foods.
113.3(w)	Water activity (a_w) is a measure of the free moisture in a product and is the quotient of the water vapor pressure of the substance divided by the vapor pressure of pure water at the same temperature.
113.40(i)	Equipment and procedures for thermal processing of foods wherein critical factors such as water activity are used in conjunction with thermal processing. ….
113.81(f)	…. When normally low-acid foods require sufficient solute to permit safe processing at low temperatures, such as in boiling water, there shall be careful supervision to ensure that the equilibrium water activity (a_w) of the finished product meets that of the scheduled process. The scheduled thermal processes for foods having an a_w greater than 0.85 and less than the a_w that would allow the growth of spores of microorganisms of public health significance shall be sufficient to render the food free of microorganisms capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution.
113.100(a)(6)	Food preservation methods wherein critical factors such as water activity are used in conjunction with thermal processing. Product formulation and scheduled processes used, including the thermal process, its associated critical factors, as well as other critical factors, and results of a_w determinations.
114 Acidified foods	
114.3(b)	Acidified foods means low-acid foods to which acid(s) or acid food(s) are added; these foods include, but are not limited to, beans, cucumbers, cabbage, artichokes, cauliflower, puddings, peppers, tropical fruits, and fish, singly or in any combination. They have a water activity (a_w) greater than 0.85 and have a finished equilibrium pH of 4.6 or below. …
114.3(d)	Low-acid foods means any foods, other than alcoholic beverages, with a finished equilibrium pH greater than 4.6 and a water activity (a_w) greater than 0.85. Tomatoes and tomato products having a finished equilibrium pH less than 4.7 are not classed as low-acid foods.

Two main types of commercial instruments are available. One uses chilled mirror dew point technology while the other measures relative humidity with sensors that changes its electrical resistance or capacitance. Each has advantages and disadvantages. The methods vary in accuracy, repeatability, speed of measurement, stability in calibration, linearity and convenience of use.

Dew point is a primary approach to measurement of relative humidity that has been in use for decades (Harris, 1995). In a dew point instrument a sample is equilibrated with the headspace in a sealed chamber containing a mirror and a means of detecting condensation on the mirror. At equilibrium the relative humidity of the air in the chamber is the same as the water activity of the sample. The mirror temperature is precisely controlled by a thermoelectric (Peltier) cooler. Detection of the exact point at which condensation first appears is observed with a photoelectric cell. The photodetector senses the change in reflectance when condensation occurs on the mirror. A thermocouple attached to the mirror records the temperature at which condensation occurs.

Decagon Devices, manufacturer of the AquaLab (Figure 2), uses the dew point method to determine water activity. In addition to the technique described above the AquaLab uses an internal fan for air

Figure 2. Decagon Devices – AquaLab model Series 3

circulation to reduce equilibrium time. Also, the sample temperature is simultaneously measured along with the mirror temperature. Minor temperature changes in the system block do not affect accuracy because sample and mirror temperatures are part of the calculations. Using both temperatures eliminates the need for complete thermal equilibrium and reduce measurement times to less than five minutes. In this instrument, a_w measurements are accurate from 0.030 to 1.000 with an accuracy of ±0.003. Since the measurement is based on temperature determination calibration is not necessary, but proper functioning of the instrument is checked by running a standard salt solution. If there is a problem, the mirror is easily accessible and can be cleaned in a few minutes.

Other a_w sensors use resistance or capacitance to measure relative humidity. The sensor is made from a hygroscopic polymer and associated circuitry that gives a signal relative to the ERH. This ERH is equal to sample water activity only as long as the sample and sensor temperatures are equal. Capacitive sensors need between 30 to 90 minutes to come to temperature and vapor equilibrium. Accurate measures require good temperature control. Advantages of capacitance sensors include simple design and inexpensive implementation.

Conclusion

For many foods, water activity is an important property for food safety. It predicts food safety and stability with respect to microbial growth, chemical/biochemical reaction rates, and physical properties. The growing recognition of measuring water activity in foods is illustrated by the FDA's incorporation of the water activity principle into the Code of Federal Regulations. In the past, measuring water activity of foods was a frustrating experience. New instrument technologies have vastly improved speed, accuracy and reliability of a_w measurements. AquaLab is definitely a tool for ensuring food safety, stability and quality.

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