

Chapter 2

Hurdle Technology in Food Preservation

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2.1 Introduction

Most of the food products in the market are preserved (i.e. retained its stability) based on more than one hurdle or preservation method. In order to determine the food stability, two questions need to be asked: what target attribute(s) needs to be achieved in the microbial, chemical, bio-chemical and physical changes; and what is the required time frame of stability? When considering stability, the microbial and chemical safety aspects must be considered first before sensory properties. The microbial stability and safety of the most traditional and novel foods is based on a combination of several preservation factors (called hurdles), and the microorganisms present in food are unable to overcome. This is illustrated by the so-called hurdle effect, first highlighted by Leistner (1978). The critical limits are being used by the industry when each hurdle such as heat treatment, water content, pH and storage temperature is applied alone. Fundamental based theoretical concepts of F-value (hurdle: heat treatment), water activity (hurdle: water content) and glass transition (hurdle: glassy state; depending on water, storage temperature, and structure) are the most successful in determining food stability during food processing and storage. These concepts (i.e. each hurdle) are usually applied to specific types of products, for examples F-value to canned foods (i.e. high moisture); and water activity and glass transition for dried and frozen foods. The F-value is based on commercial sterility, water activity by state of water (i.e. bound or free) and glass-rubber transition by structural mobility. However, more than 60 hurdles may involve in food preservation (Leistner 2000a). The details of the important hurdles used in establishing food stability are discussed in the IFT/FDA Report (2003) and Leistner (2007).

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In achieving the desired safety by only one hurdle, high severity in processing needs to be applied. This caused significant damages to the nutritional and sensory quality of foods. For this reason, it is important to have multi-hurdles approach for developing safe and wholesome food products. The hurdle effect has fundamental importance for the preservation of foods, since the hurdles provide a control to microbial spoilage, food-poisoning and other undesired changes. The advantages of hurdle concepts are (1) it can avoid the severity of one hurdle for preservation, (2) it can give synergy of combination, and (3) many of the hurdles come from past experience (i.e. tradition or culture). Currently huge numbers of products are being developed based on the multi-hurdles. The combinations and the levels of hurdles are determined based on the empirical experiments. However, it is a challenge to food scientists and engineers to have unified concept or approach for determining food stability considering multi-hurdles, such as heat treatment, water content, pH, salt, spices, preservatives, packaging and storage temperature. Stability map was proposed based on the state diagram (i.e. states and/or phases of a food as a function of water or solids content and temperature) (Levine and Slade 1986; Rahman 2012). Recently macro-micro region concept in the state diagram has been proposed and relative stability map is postulated in the 13 micro-regions. In order to achieve safety, the proposed micro-region concept showed potential to combine multi-hurdles, or to provide a guide on the hurdles need to be used in each micro-region (Rahman 2009). The objective of this chapter is to highlight the recent development in achieving food stability by intelligent use of multi-hurdles and theoretical concepts.

2.2 Guide Lines for pH and Salt

2.2.1 *pH Value*

The minimum pH for the growth and toxin production of microorganisms are compiled by IFT/FDA Report (2003) and Rahman (2007). The literature tabulations include a pH lower than 4.6 to inhibit the growth of many pathogens and this limit is considered as safe or low risk (Brown and Booth 1991). It is generally accepted that the limiting pH of 4.6 provides a good margin of safety against the hazards of *botulism* in acidified foods, and such products are given relatively mild heat treatment. The critical limit of pH 4.6 is commonly used to categorize the low risk and high risk foods. Based on a comprehensive review of the literature, the IFT panel concluded that a pH of 4.6 is appropriate to control spore-forming pathogens and a pH of 4.2 is appropriate to control vegetative pathogens (IFT/FDA Report 2003).

2.2.2 *Salt (i.e. Sodium Chloride)*

Salt is one of the most common preservatives. Life at high salt concentration is energetically expensive. Oren (2011) identified thermodynamic limits to microbial life at high salt concentration. They identified that 346 g/L (i.e. 34.6 %) was the

limit to stop all microbial process, thus only salt as a hurdle could be impossible to implement due to the negative impact on health and sensory. For this reason, most of the cases salt is used in combination with other hurdles. Most processed meat products contain sodium chloride from 2.8 % in cooked sausages to 4.5 % in cured meat products (Komarik et al. 1974) and have been maligned as a heavy salt contributor to the diet. However, in many products salt in combination with other hurdles showed high potential.

2.3 Progress in Developing Guidelines

The stability guidelines are mainly based on the pH, water activity, and thermal processing. FDA's Good Manufacturing Practice Regulations governing the processing requirements and the classification of foods are shown in Fig. 2.1 (Johnston and Lin 1987). Low acid (i.e. high pH) foods packaged in hermetically sealed containers must achieve commercial sterility conditions either by retorting or combined treatment of pasteurization and water activity or a combined treatment of pasteurization and acidification. It could be seen that pH 4.6 and a_w 0.85 are the critical limits. In 1962 the US Public Health Service in the “Food Service Sanitation Manual” issued the potentially hazardous food (PHF) as any perishable food which consists in whole or in part of milk products, eggs, meat, poultry, fish or other ingredients capable of supporting the rapid and progressive growth of infectious or toxigenic microorganisms. The progress of the definition of PHF is discussed in the IFT/FDA Report (IFT/FDA 2003). FDA Food Code in 1999 defined PHF food as it

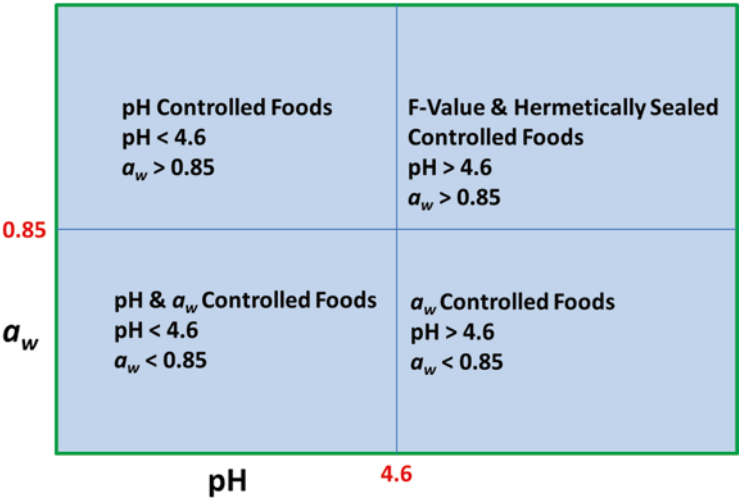


Fig. 2.1 FDA Good Manufacturing Practice Regulations governing processing requirements and classification of foods (Adapted from Johnston and Lin 1987)

Table 2.1 Control of spores: product treated to control vegetative cells and protected from recontamination

Critical a_w Values	Critical pH Values		
	pH ≤ 4.6	$4.6 < \text{pH} < 5.6$	pH ≥ 5.6
$a_w \leq 0.92$	Non-TCS	Non-TCS	?
$0.92 < a_w < 0.95$	Non-TCS	Non-TCS	?
$a_w > 0.95$	Non-TCS	?	?

Note: ? means stability is question, thus number of measures need to be taken

Table 2.2 Control of vegetative cells and spores: product not treated or treated but not protected from recontamination

Critical a_w Values	Critical pH Values			
	pH < 4.2	$4.2 < \text{pH} < 4.6$	$4.6 < \text{pH} < 5.0$	pH > 5.0
$a_w < 0.88$	Non-TCS	Non-TCS	Non-TCS	Non-TCS
$0.88 < a_w < 0.90$	Non-TCS	Non-TCS	Non-TCS	?
$0.90 < a_w < 0.92$	Non-TCS	Non-TCS	?	?
$a_w > 0.92$	Non-TCS	?	?	?

Note: ? means stability is question, thus number of measures need to be taken

must be kept cold or hot, because the food (i.e. temperature controlled for safety, TCS) has the necessary intrinsic factors to support the growth of pathogens. The TCS foods require time/temperature control to limit pathogen growth or toxin formation that constitutes a threat to public health. A science-based framework was proposed by the IFT/FDA panel (IFT/FDA Report 2003). The framework contains two steps:

- Step 1: Was the food treated to destroy vegetative cells of potentially pathogens and packaged to avoid recontamination? If yes, position your product in Table 2.1 according to its pH and water activity (a_w). If not, position your product in Table 2.2 according to its pH and a_w .
- Step 2: If the food is classified as a non-TCS food according to Step 1 above, it may be stored and held safely without regard to time or temperature. If the need for time/temperature control is questionable, the food should be held either hot or cold for safety or subjected to a product assessment as the next step in determining the appropriate classification.

The product assessment was performed based on the factors, such as ingredients, processing, change of acids used to lower pH, preservatives, and formulation. The final decision on the hurdles could be based on challenge testing and available predictive models. The panel used their proposed framework to determine its applicability to a specific example(s) from selected class of food product categories. Additional examples of the determination of TCS are provided in the report developed by Texas Department of State Health Services (TCS Guidance 2006). They also identified the pathogens of concern for different classes of food products and potential hurdles alone or combination to be used. Scientific sound criteria for

determining whether foods require time/temperature control for safety could consider the interaction of pH, a_w and other factors from microbial growth models. For example, USDA pathogen model could identify the critical boundary for growth of specific bacteria when both pH and a_w are used. The panel pointed that framework should be validated for a broad variety of products, and predictive models of pathogens as a function of several parameters, such as packaging atmosphere, redox potential, pH, a_w , preservatives and ingredients should be developed. In addition, synergistic factors and variations of results in the real product and challenged test should also be explored.

2.4 Concepts of Food Stability Determination

2.4.1 *F-Value*

In 1795 Nicolas Appart, a chef took up a challenge and established a theory that if fresh foods were put in airtight containers and sufficient heat applied, then food would last longer. He proposed his preservation method after 14 years of experimentation without understanding the role of bacterial spoilage. A theoretical understanding of the benefits of canning did not come until Louis Pasteur observed the relationships between microorganisms and food spoilage after 50 years later (Rahman 2009). The sterilization of canned foods has a long tradition and it is most likely that it will continue to be popular because of its convenience and extended shelf-life (1–4 years at ambient temperature).

The time of sterilization process is estimated based on F-value concept. The F-value was originally developed by Bigelow et al. (1920) and subsequently by Ball and Olson (1957). By the 1860s the time required to process food in can was reduced from 6 h to 30 min through numbers of inventions and improvements (Simpson et al. 2012). The inactivation target in sterilization process depends on the types of heat resistance bacteria and pH of foods. It is possible to classify food products into three groups according to pH: low-acid ($\text{pH} \geq 4.6$), medium-acid ($3.7 \leq \text{pH} \leq 4.6$), and high-acid foods ($\text{pH} \leq 3.7$). The target microorganism in the thermal processing of low-acid food ($\text{pH} \geq 4.6$) is *Clostridium botulinum*. The processing time based on first order kinetics can be estimated as (Bigelow 1921; Singh and Heldman 2009):

$$t = -\frac{1}{k} \ln \left(\frac{N_F}{N_o} \right) = \left(\frac{D}{2.303} \right) \ln \left(\frac{N_F}{N_o} \right) \quad (2.1)$$

where k is the destruction rate (s^{-1}), N_o and N_F are the initial and final numbers of micro-organisms, and D is the decimal reduction time (s), respectively. Equation (2.1) for microbial death indicates that final concentration tends to zero when time tends to infinity, thus it would not be possible practically to reach a final concentration of zero for the target micro-organism. Considering this point, the commercial

sterilization criterion should be defined so that it is possible to design a process that is safe but occurs within a finite time and which is economically and practically feasible (Simpson et al. 2012). According to Stumbo (1973) the commercial sterilization criterion was established arbitrarily. The commercial sterilization criterion states that the minimum thermal process should reduce initial micro-organism concentration by 10^{12} . This is well known as 12D concept or “botulinum cook”. Teixeira (2002) discussed the origins of the 12D concept and outlined the original work of Esty and Meyer (1922). They concluded that Stumbo (1948) was the first to recognize the logarithmic nature of time temperature curve. The commercial sterilization was used for several reasons (1) safety margins, (2) cooking requirements, and (3) to prevent the growth of thermophilic spoilage microorganisms. The probability argument says, in 12D treatment there will be one spore in 10^{12} cans (Singh and Heldman 2009). Considering 100 million cans consumed per day, an estimate over a 100-year period worldwide consumption will be 3.65×10^{12} cans and the 12D criterion would predict three to four outbreaks every 100 years (Simpson et al. 2012).

The processing time to achieve 12D can be estimated when D_T value of target micro-organism at the temperature T is known. However, the processing time varies with the size of a can. Considering $D_{121.1} = 0.21$ min for *C. botulinum*, one spore per g and can size of 0.1 L (density: 1 g/cm³), the processing time (t) to achieve 12D is 2.94 min from Eq. (2.1) (Simpson et al. 2012). Similarly if the can size is 5 L, the processing time is 3.29 min. Since thermal process could not be performed at a specific temperature instead a varied temperature range during heating and cooling time, thus thermal death time, F_r is defined for processing as (Holdsworth and Simpson 2008):

$$F_r = \int_0^t 10^{\frac{T-T_r}{z}} dt \quad (2.2)$$

where F_r is the processing time at a reference temperature (s), T_r is the reference temperature (°C) and z is the thermal constant or z -value. If reference temperature T_r is 121.1 °C, then F_r is termed as F_o as:

$$F_o = \int_0^t 10^{\frac{T-121.1}{z}} dt \quad (2.3)$$

Currently, a common commercial sterilization treatment for *C. botulinum* F_o is in the range of 6–8 min, although some companies use F_o of 10 min or higher. Considering this processing time, 5 L can size and the minimum time requirement (6 min) at 121.1 °C, indicated 1.335×10^{-25} spores per package. Applying the probability concept, we should expect one outbreak in several billion years (to be precise, one hundred thousand billion years). In fact, at least in the past 50 years no outbreak has been directly related to the sterilization criterion (Simpson et al. 2012). However, there is no theoretical method available for the prediction of F_o , if other hurdles are used in combination.

2.4.2 Water Activity

W.J. Scott, an Australian scientist, proposed that the active water could be much more important to the stability of a food than the total amount of water present. The legacy of Scott allowed scientist to develop generalized rules or limits for the stability of foods using water activity (Scott 1953). In general the rules of water activity concept are (1) food products are most stable at their “BET-monolayer” content or “BET-monolayer water activity” and unstable above or below BET-monolayer; (2) there are a critical water activity limit for a specific micro-organism or a class of micro-organism for their growth or toxin production, and biochemical reactions (Scott 1953; Labuza et al. 1970). For example, there is a critical water activity level below which no microorganisms can grow. Pathogenic bacteria cannot grow below a water activity of 0.85, whereas yeasts and molds are more tolerant to reduced water activity, but usually no growth occurs below a water activity of about 0.6. Labuza et al. (1972) proposed the food stability map based on the water activity concept containing growth of micro-organisms and different types of bio-chemical reactions. In the recent food stability map, Rahman (2009) showed the trends of microbial growth, bio-chemical reactions and mechanical characteristics in the three zones of water activity (zone 1: BET-monolayer, zone 2: adsorbed multi-layer, zone 3: matrix or solvent water) (Fig. 6.5). In fact, the BET-monolayer could be only achieved in the cases of dried foods. The limitations of water activity concept are reviewed by Rahman (2010). However, food industries are now widely used this concept for determining the stability of their dried products.

2.4.3 Glass Transition

Considering the limitations of water activity concept, the hypothesis of glass transition concept was put forward. White and Cakebread (1966) first highlighted the importance of the glassy state of foods in determining its structural stability. The significant applications of the glass transition concept emerged in food processing in the 1980s, when Levine and Slade (1986) and Slade and Levine (1988) identified its major merits and wide applications. The rules of the glass transition concept are (1) the food is most stable at and below its glass transition (i.e. T_g or T_g'), and (2) the higher the $T-T_g$ or T/T_g (i.e. above glass transition), the higher the deterioration or reaction rates (Levine and Slade 1986). Detailed Reviews on the food stability in relation to glass transition, molecular relaxation and mobility are available in the literature (Champion et al. 2000; Le Meste et al. 2002; Rahman 2006, 2010). It is clear from the literature that all experimental results could not be explained by the above rules (Rahman 2009; Levine and Slade 1986), thus further developments are necessary. The limitations of water activity and glass transition concepts would not invalidate the concepts completely rather make it difficult to apply universally. The water activity concept is based on the binding nature of water molecules in the matrix.

When water is bound (i.e. unavailable to take part in reactions) to the solid matrix or non-solvent, then no deterioration reactions could be expected. The glass transition concept is based on the molecular mobility of the reacting components at micro-level in a matrix, thus diffusion of the reactants through the system is very slow and stability is achieved. Thus a successful combination of water activity and glass transition could open more precise and unified determination of stability criteria (Rahman 2010).

2.4.4 Critical Temperature Concept and Molecular Mobility

It is expected that there should be a break in the plot of k (i.e. reaction rate) versus T/T_g (i.e. change in slope between above and below the critical ratio) at T/T_g equal to 1, if glass transition concept is valid or X_w/X_b equal to 1, if water activity concept is valid. Buitink et al. (2000) measured molecular mobility by ST-EPR and ^1H -NMR, and observed two distinct changes: first one minor shift just close to T_g and second abrupt decrease due to solid-like to liquid-like defined as T_c . In the case of sugars, T_c was observed at 17–35 °C higher than T_g and for biological materials it was more than 50 °C. This variation was also explained by the density of hydrogen bond and molecular packing measured by FTIR. This higher T_c was also correlated with the observed collapse or softening of sugars at 10–17 °C above glass transition (Levine and Slade 1988; Roos 1995; Sun et al. 1996) and crystallization above 30 °C. It is generally believed that crystallization over practical time scale occurred above glass transition, although some report showed it was below 30 °C than glass temperature (Le Meste et al. 2002). α -amylase was more stable in rubbery matrices of lactose or trehalose than in a glassy PVP matrix and the protective efficiency of saccharides, maltodextrins and PVPs did not increase with their respective glass transition temperature (Rossi et al. 1997; Terebiznik et al. 1998). In addition dielectric and other spectroscopy determine α , β and γ relaxations below glass transition (Adrjanowicz et al. 2009). However it is not clear how these could be related or linked to determine the stability of foods. Considering the fact that glass transition is not the critical limit, Rahman (2010) tested the hypothesis that there is a critical temperature as a ratio of T_c/T_g (T_c is the critical temperature) which could vary with moisture content. Above the critical temperature, an increase in the water content or temperature significantly increased the reaction rate while below the critical temperature the rate was relatively less affected by water content and temperature. He observed values of T_c/T_g varied from 0.78 to 1.5 depending on the types of reaction and the matrices. In some instances, the values of T_c/T_g were close to 1.0 indicating only glass transition could explain the process. Moreover, the deviations of T_c/T_g from 1 explain why in many instances in the literature both stability and un-stability were observed above and below glass transition. The glass transition by thermal or mechanical relaxations measure mobility in a 20–300 nm range, while other relaxation techniques, such as Nuclear magnetic Nuclear Magnetic Resonance (NMR) measures the molecular relaxation in a 1–2 nm range (McBrierty and Packer 1993).

Recently, tremendous progress has been achieved in understanding multidimensional aspects of the molecular mobility. Although it is not yet very clear how these knowledge could be applied in determining the stability of foods.

2.4.5 *State Diagram*

The glass transition concept was further advanced by developing state diagrams for foods. A state diagram is a stability map of different states and phases of a food as a function of water or solids content and temperature. Most probably, Levine and Slade (1986) presented the first state diagram in the food science literature by illustrating glass line, freezing curve, and intersection of these lines as T_g'' by extrapolation of the extended freezing curve by maintaining similar curvature. The main advantage of drawing a map is to help understanding the complex changes when the water content and temperature of foods are changed. It also assists in identifying stability of foods during storage as well as selecting a suitable condition of temperature and moisture content for processing. The state diagram based on freezing curve and glass transition provided four macro-regions: region I (i.e. below glass transition), region II (above glass transition and below maximal-freeze-concentration, i.e. completely frozen), region III (above maximal-freeze-concentration condition and below freezing curve, i.e. partially frozen), and region IV (i.e. above glass transition and above freezing curve) (Levine and Slade 1986). Rahman (2006) combined water activity and glass transition concepts in the state diagram by plotting BET monolayer as a function of temperature. This makes four regions: below BET-monolayer, one above and one below; and above BET-monolayer, one above and another below. In the literature it was emphasized that a combination of water activity and glass transition concepts could be a powerful tool in predicting food stability. The approaches to combine both concepts are reviewed by Rahman (2010, 2012). However, Rahman (2006) combined glass transition and water activity concepts in the state diagram by plotting BET-monolayer values as a function of temperature.

2.4.6 *Macro-Micro Region in the State Diagram*

Using state diagram, Rahman (2009) hypothesized 13 micro-regions having the highest to the lowest stability based on the location from the glass and BET-monolayer lines (Fig. 2.2). For example, region-1 (relatively non-reacting zone, below the BET-monolayer line and glass line) is the most stable and region-13 (highly reacting zone, far from BET-monolayer line and glass line) is the least stable. The stability decreased as the zone number increased. Applications of this hypothesis in food processing are presented by Rahman (2006, 2010, 2012). Schebor et al. (1995) studied sucrose hydrolysis in the micro-regions 1 and 2, and evidenced the validity of the hypothesis. Advantages of micro-region concept are as follows

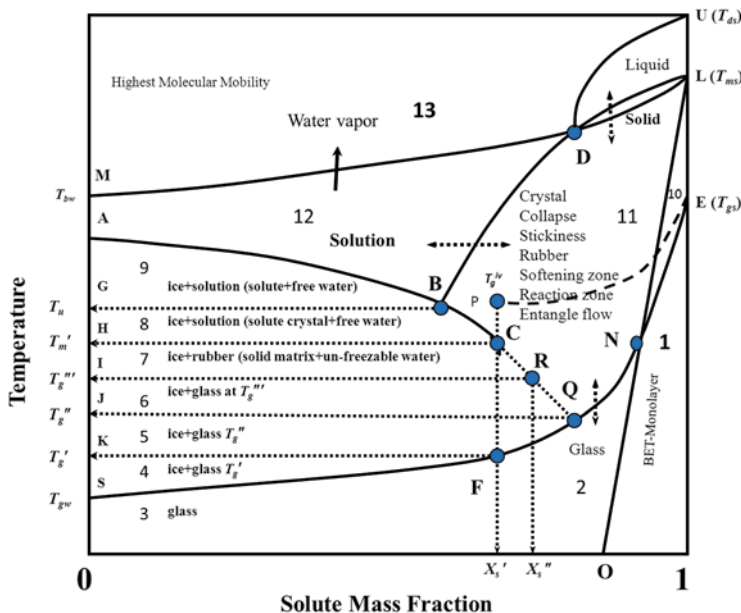


Fig. 2.2 State diagram showing different regions and state of foods [updated from Rahman (2006, 2009)] T_{ds} : solids-decomposition temperature, T_{ms} : solids melting temperature, T_{gs} : solids–glass transition temperature, T_g^{iv} : end of solids-plasticization temperature, T_{gw} : glass transition of water, T_u (solute crystallization temperature during freeze-concentration), T_m' (maximal-freeze-concentration condition, i.e. end point of freezing), T_g''' (glass transition of the solids matrix in the frozen sample as determined by Differential Scanning Calorimetry (DSC)), T_g'' (intersection of the freezing curve to the glass line by maintaining the similar curvature of the freezing curve), and T_g' (glass transition at maximal-freeze-concentration, i.e. at the end point of freezing), T_{bw} : boiling temperature of water (Rahman 2012)

(1) stability rules could be developed for each micro-region (i.e. narrow moisture and temperature range) as compared to the macro-region (i.e. broad moisture and temperature region), and (2) the states or phases of the material could be identified in each micro-region. A reference point could be identified where BET-monolayer line and glass line intersect and any location in the state diagram could be assessed in relation to the reference point.

2.5 Progress in Microbial Reaction in Relation to Hurdle Concept

Hurdles are deliberately combined to improve the microbial and chemical stability, and the sensory quality of foods as well as their nutritional properties and economic cost. Thus it improves the total quality of foods by application of an intelligent mix

of hurdles (Leistner 1985, 2000b). The main advantage of the hurdle technology is its synergistic effect (i.e. non additive). Previously hurdle technology (i.e., a combination of preservation methods) was used empirically without much knowledge of the governing principles. Progress in principles of the major preservative factors on the physiology and behavior of microorganisms in foods could allow more intelligent applications of hurdles (Leistner 2000b). These are: homeostasis, metabolic exhaust, and stress reactions. Homeostasis is the tendency to achieve uniformity and stability in the internal status of organisms (Gould 1988). For instance, the maintenance of a defined pH is a prerequisite and feature of living cells, and this applies to higher organisms as well as microorganisms (Haussinger 1988). When homeostasis of bacteria is altered, the bacterial cells react by spending their energy in maintaining their physiological status rather than in multiplying, thus repair needs more energy. In this case microorganisms remain in the lag phase or even die before their homeostasis is reestablished by repair (Leistner 1995a). Energy restrictions for microorganisms are caused by anaerobic conditions, such as vacuum or modified atmosphere and low a_w , pH and redox potential, and these act synergistically in combination when applied in foods (Gould 1995).

Metabolic exhaustion is the “auto-sterilization”. It was first observed that in a mildly heated sausage inoculated with *Clostrial* spores and adjusted to different water activity by addition of salt and fat, and stored 37 °C. *Clostrial* spores surviving during the heat treatment vanished in the product during storage, especially unrefrigerated (Leistner and Karan-Djurdjic 1970). Further experimental evidence showed that auto-sterilization occurred in the unrefrigerated conditions, and more hurdles accelerated metabolic exhaustion (Leistner 2000b). More examples of “auto-sterilization” are presented by Leistner (2007). The traditional “air-dried” fermented sausages from Germany showed a good record of safety due to the fermentation at low temperature (<15 °C) and to extensive aging, which was compensated the requirement of higher levels of acids, and antimicrobial nitrite (Lucke and Vogeley 2012).

Some bacteria become more resistant or even more virulent under stress (i.e. stress reaction), since they generate stress shock proteins. The synthesis of protective stress shock proteins is induced by heat, pH, a_w , ethanol, and oxidative compounds as well as by starvation. Therefore, multi-target preservation of foods could be the key to avoiding synthesis of stress shock proteins, which otherwise could jeopardize the microbial stability and safety of hurdle technology (Leistner 1995b). Nevertheless, further research in stress shock proteins and different mechanisms that switches them on or could inactivate them warranted, in relation to hurdle technology (Leistner 2007).

The multi-target preservation of foods should be the ultimate goal for a gentle but most effective preservation of foods (Leistner 1996). Leistner (2000b) proposed that food microbiologist could learn from pharmacology and medicine. For example, at least 12 classes of biocides are already known which have different targets, and sometimes more than one, within microbial cell. Often the primary target is the cell membrane and it becomes leaky due to the disruption of cell wall.

In addition, biocides also impair synthesis of enzymes, proteins, and DNA (Denyer and Hugo 1991). Multi-drug attack has proven successful in the medical field to fight bacterial infections (i.e. tuberculosis) as well as viral infections (i.e. aids), thus a multi-target attack on microorganisms should also be a promising approach in food microbiology (Leistner 2000b).

Leistner (2007) provided an example of hurdle technology in the case of Indian *paneer*. It is a traditional cottage-cheese-type product fried in cubes with oil and onions and sauce containing salt, spices, and often tomatoes are added. However, *paneer* spoils bacteriologically within 1–2 days at room temperature (which in India can reach 35 °C), and this is a strong drawback for its industrial production. Sterilized paneer in cans showed severe sensory limitations with regard to flavour, texture and color. Table 2.3 shows how hurdle technology can use to develop paneer with long shelf life. Another example on the La Chang (i.e. a meat product in China) is also presented by Leistner and the combinations of hurdles and the shelf life are shown in Table 2.3.

Table 2.3 Examples of hurdle products

Product	Hurdles	Shelf-life
La Chang (meat) China	a_w : 0.85–0.70	2–3 months
	pH: 5.9–5.7	
	NaCl: 3–5 %	
	Sugar: 4–20 %	
	Refrigeration: No	
	Total count < 10 ⁶ /g	
La Chang (meat) China	a_w : 0.85–0.70	4–5 months
	pH: 5.9–5.7	
	NaCl: 3–5 %	
	Sugar: 4–20 %	
	Packaged: vacuum	
	Refrigeration: No	
Fresh Paneer (India)	Storage: 35 °C	1–2 days
Paneer (India)	a_w : 0.97	Several weeks
	pH: 5.0	
	F_o : 0.8 min	
	Storage: 35 °C	
Paneer in gravy (India)	a_w : 0.95	2 weeks (Storage: 45 °C)
	pH: 5.0	1 month (Storage: 30 °C)
	F_o : 0.8 min	3 months (Storage: 15 °C)
	Potassium sorbate: 0.1 %	

Summarized from Leistner (2007)

2.6 Prediction for Multi-hurdles

In predicting or modelling stability, two approaches could be used in identifying the boundary or limit of the growth/no-growth (reaction or no-reaction) within a time frame, and then predicting the rate of growth or reaction within the growth or reacting region. Bigelow (1921) developed a mathematical model to describe the logarithm nature of thermal death. Nevertheless it was not until the 1980s when mathematical models predicting the behavior of microorganisms experienced a great development. A new field emerged in the food microbiology area: predictive microbiology. Different types of empirical growth models for microorganism are widely used. These are specific to the types of microorganism, physico-chemical properties of food, and the used hurdles. Davey et al. (1978) developed thermal inactivation rate (i.e. $\ln k$) of *Cl. Botulinum* as a linear function of $1/T$, pH and pH^2 . Similarly Cerf et al. (1996) also developed the regression correlations of $\ln k$ as a function of $1/T$, pH, pH^2 , and a_w . The non-monotonous changes of pH and a_w make it more difficultly to predict the effect of hurdles in combination. Velugoti et al. (2011) generated growth data of *Salmonella* in sterile pork at various isothermal conditions, and dynamic models were developed within storage temperature (10–45 °C).

In 1970s the “probability model” for the prediction of germination of spores, population growth, survival, and toxin production within a specified period of time under defined conditions of storage and product composition was emerged (Carrasco et al. 2012). The “growth/no-growth” or “interface” modeling are progressed. One of the first attempts to Growth/no-Growth (G/NG) modeling was developed by Pitt (1992). He related the boundary by an empirical equation with the temperature and water activity limits for *Aspergillus* spp. growth. Carrasco et al. (2012) reviewed the methodology of development of a probability or growth/no-growth (G/NG) models. The logistic regression approach has been widely adopted for probability and G/NG modelling. In general, probability models are devoted to the data which can be measured as “positive” or “negative”. For example, if we consider the variable “detection of toxin”, only two responses are possible: “detectable” or “not detectable” and responses can be coded as 1 (positive response) or 0 (negative response), or even better, if response replicates are obtained, a number between 0 and 1 can be given to the response, calculated as the average of the scores (0 or 1) of the replicates. The number obtained is considered as the probability of occurrence of the phenomenon studied. This probability can be related to independent variables such as temperature or pH by some mathematical function using regression techniques. In logistic regression, the probability (P) can be expressed as “logit” as:

$$\text{logit } P = \log \left(\frac{P}{1-P} \right) \quad (2.4)$$

Mertens et al. (2012) developed G/NG model by linear logistic regression and *logit* was correlated as a function of a_w , pH, sodium chloride and acetic acid. A simplified

G/NG model conceptually derived from the Gamma model. Logit was related to the variables or factors in order to determine the boundary. Polese et al. (2011) developed G/NG boundary using gamma function and observed a limited numbers of fail dangerous prediction, thus he suggested simplified G/NG model could be used as a first estimate method when experimental data are missing or insufficient. In addition, a practical time frame usually used to generate the boundary data, thus it ignores stability for longer period. In general, extrapolation in prediction, especially in foods, is not straightforward because of the complexity of the food matrix (Pinon et al. 2004).

2.7 Conclusion

Currently most of the stable food products are based on more than one hurdle. Examples of these hurdles are thermal treatment, moisture, salt, low temperature storage, and preservatives. It is a challenge to the food scientists and engineers to have unified concepts for determining food stability. The individual assessment of each product can be performed using logical tree based on their hurdles as proposed by IFT/FDA. The fundamental based prediction or the required rules for determining stability of multi-hurdle foods are limited, thus empirical approaches based on the specific experimental data are mainly used. Theoretical concepts of F-value, water activity and glass transition are the most successful in determining food stability criteria for thermal treatment, moisture content, and moisture-temperature structure control, respectively. The water activity and glass transition concepts are combined in the state diagram. Recently macro-micro region concept in the state diagram is proposed in order to handle the real challenges in combining different hurdles in food preservation. Finally the progress in microbial reaction, prediction models, molecular mobility, and guidelines from authorities are discussed in relation to the intelligent applications of hurdles. It was emphasized that further progress needs to be achieved in developing generic prediction models (boundary and dynamic) and fundamental understanding on the microbial responses to the hurdles in order to develop a classification of hurdles and their modes of attack.

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Nomenclature

- a_w Water activity
- D Decimal reduction time (s)
- F_r Thermal death time at reference temperature (s)
- F_o Thermal death time at reference temperature 121.1 °C (s)

G	Growth
k	Destruction rate (s^{-1})
N_o	Initial number of microorganisms
N_F	Final number of microorganisms
NG	No-growth
P	Probability
pH	Negative log hydrogen ion concentration
T	Temperature ($^{\circ}C$)
T_c	Critical temperature ($^{\circ}C$ or K)
T_g	Glass transition temperature ($^{\circ}C$)
t	Time (s)
X_b	BET-monolayer water content (g/g sample)
X_w	Water content (g/g sample)
z	Microbial thermal constant ($^{\circ}C$)

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