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ORIGINAL PAPER

Kinetics of Food Quality Changes During Thermal Processing: a Review

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Abstract Thermal treatments are extensively used in the food industry for control of pathogenic and spoilage microorganisms and spoilage enzymes. Food quality degradation during those treatments can be a major concern for consumer acceptance. Kinetic studies and mathematical models on quality changes of foods are essential in proper design of thermal treatments to ensure consumer satisfaction. This study provides a comprehensive review of recent progresses on quality kinetics for thermal treatments to inactivate microorganisms and enzymes in foods of both plant and animal origins. This paper mainly covers the theoretical basis for studying quality kinetics, common and special kinetic models to describe major quality attributes, such as appearance, texture, and nutrients, and potential applications of quality kinetic models to developing thermal treatment protocols. Finally, this review describes the challenges in quality kinetic studies and proposes recommendations for future research to maintain food quality and extend shelf life.

Keywords Thermal processing · Color · Texture · Nutrients · Kinetic model

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Introduction

Thermal sterilization, pasteurization, and blanching techniques have been extensively used in the food industry to control bacteria, fungi, and other microorganisms as well as undesirable enzymes in foods. To meet the food safety and shelf life-stable requirements, however, thermal processing may involve long time heating at high temperatures, promoting chemical and physical reactions in foods, and rendering the product unwholesome or causing quality degradation (Fellows 2009). For example, color changes, development of off-odors or off-taste, and loss of freshness or nutrients occur frequently during and after thermal processing (Liaotrakoon et al. 2013; Song et al. 2003; Wen et al. 2010; Zabbia et al. 2011). It is particularly true for prepackaged solid or semi-solid foods in which heat transfer is slow and the center temperature is difficult to raise when using conventional surface heating methods.

Novel thermal processing techniques hold potential in improving the heating efficiency and reducing quality losses. Electro-heating, such as ohmic (OH), microwave (MW), and radio frequency (RF) heating, has been considered to replace conventional heating for developing better foods (Liu et al. 2011; Pereira et al. 2008; Wang et al. 2012). Microwave energy has been used to control molds, yeasts, pathogens, and spores in foods. For example, microwave systems operating at 896 or 2,450 MHz are commercially used in Europe for production of a wide range of packaged foods, such as cakes, breads, pasta, and refrigerated ready-to-eat meals (Tang et al. 2002). In the USA, 915-MHz microwave systems have been used in the food industry since 1980. Recently, new 915-MHz microwave-assisted thermal processes received acceptance from the US Food and Drug Administration (FDA) for production of low acid shelf-stable foods (Knights 2013). Compared with the conventional convection, conduction, and radiation heating, the electro-heating is generated

volumetrically by converting the electrical energy to thermal one inside the food materials, which greatly reduces the heating time, and increases the heating rate so as to avoid the quality loss caused by slow overheating (Marra et al. 2009).

Proper design of conventional or novel thermal processes requires comprehensive understanding of thermal properties of foods and quantitative changes of target microorganisms, enzymes, or quality attributes in thermal processes (Stoforos 1995; Holdsworth and Simpson 2008; Simpson 2010). It is desirable to select optimal process conditions to control microorganisms and enzymes while minimizing food quality degradations. Kinetic studies on thermal inactivation of microorganisms and enzymes have been extensively reported and reviewed in the literature (FDA 2000; IFT 2003; Van Boekel 1996).

According to Haefner (2005), principles and applications of kinetic models developed for biological systems can provide valuable insights into understanding, predicting, and controlling the food quality changes that occur during the thermal processing. Comprehensive kinetic models on the thermodynamics and chemical kinetics at the molecular level may reveal the quality change mechanism. Fundamental kinetic parameters, such as activation energy, enthalpy, and entropy obtained from well-planned experiments, may be used to estimate the quality changes of foods in various thermal processes and ultimately lead to the optimal design of thermal processing conditions.

Numerous studies have been reported on different models for foods in thermal processing. Literature reviews are also available on estimation of kinetic parameters for non-isothermal conditions (Dolan 2003), thermal inactivation kinetics of microorganisms under conventional and emerging thermal treatments (Bermudez-Aguirre and Corradini 2012), enzyme inactivation in the thermal processing (Adams 1991), kinetics of quality changes in the food frying (Hindra and Baik 2006), and modeling of the temperature effect on the rate of chemical reactions and biological processes in foods (Barsa et al. 2012). No recent comprehensive review of progresses is, however, available on kinetics of quality changes during thermal inactivation of microorganisms and enzymes in foods.

This paper aims to provide a review of the literature on food quality changes during the thermal inactivation of microorganisms and enzymes. These include theories and experimental methods to obtain quality kinetic models, common reactions and special kinetic models in food processing, and recommendations for the future research to enhance practical applications of quality kinetic models. The quality parameters of interests in this paper include color, texture, and nutrient content. It is our intent to cover temperature and processing time ranges applicable to both lengthy conventional thermal processes and short-time microwave or RF processes.

Theoretical Basis and Experimental Methods of Food Quality Kinetics

Theoretical Background

Foods are generally complex biological systems. A number of reactions take place during thermal processing, either in series or in parallel, and competing. The final quality loss may be the results of many interacting and complex reactions rather than a single elementary step. An effective first-step kinetic modeling is to study simple food systems rather than real foods (Wedzicha et al. 1993). Chemical reaction kinetics can be applied to quantify individual attribute of an ideal food system in form of the general rate law (Van Boekel 1996; Steinfeld et al. 1998; FDA 2000):

$$\frac{dP}{dt} = \pm kP^n \tag{1}$$

where k is the rate constant (1/min), t the reaction time (min), and n the reaction order. In general, P represents a quantitative value for a quality attribute, enzymes activity, or population of microorganisms.

The core of kinetic studies on food quality changes in thermal processing is to quantify a quality attribute as a function of heating time at a certain temperature using temperature-dependant reaction rate constants after the order of reactions is decided. The order of kinetics is determined based on the goodness of fit of the observations to a preselected reaction order model. Kinetics of food quality changes generally follows zero-, first-, or second-order reactions as follows:

$$P = P_0 - kt \quad \text{for zero-order reactions } (n = 0) \tag{2}$$

$$P = P_0 e^{-kt} \quad \text{for first-order reactions } (n = 1) \tag{3}$$

$$\frac{1}{P} = kt + \frac{1}{P_0} \quad \text{for second-order reactions } (n = 2) \tag{4}$$

where P_0 is the initial value of the food quality attribute at t=0.

In thermal processing, D-value (min) is used for convenience and defined as the heating time in minutes to give 90 % or one-log change of food quality in a semi-log scale at a constant temperature. The D-value is directly related to the first-order reaction rate constant k by Eq. 5 (Anthon and Barrett 2002; Awuah et al. 2007; Van Boekel 2008):

$$D = \frac{2.303}{k} \tag{5}$$

To explore the temperature-dependent quality, the *Arrhenius* equation is the most common method to describe the temperature (T) effect on the reaction rate constant (k) as follows:

$$k = k_0 e^{-\frac{E_a}{RT}} \tag{6}$$

where k_0 is the rate constant, R is the ideal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). E_a is the activation energy (J/mol) and defined as the minimum energy needed to start a chemical reaction (sometimes called the energy barrier). A chemical reaction at a reasonable rate takes places when an appreciable number of molecules with energy equal to or greater than the activation energy. When temperature increases, the number of molecules increases with energy greater than the activation energy, thus improving the rate of reaction. Therefore, the activation energy is a parameter that indicates the sensitivity of the reaction rate to temperature. For greater activation energy, the rate of reaction is more sensitive to temperature changes and vice versa.

When conducting an analysis to estimate kinetic parameters for the Arrhenius relationship, it is recommended that the following alternative form can be used (Theodore et al. 1997; Peleg et al. 2012):

$$k = k_{\text{ref}} e^{-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{\text{ref}}}\right)} \tag{7}$$

where T_{ref} stands for a reference temperature (K) corresponding to the mean of the temperature range in consideration and k_{ref} is the reaction rate at the reference temperature.

The Q_{10}-value is another concept to describe the rate of quality changes with temperature. It is defined as follows (Lund 1977; Fu and Labuza 1993):

$$Q_{10} = \frac{k_{(T+10^{\circ}\text{C})}}{k_T} \tag{8}$$

where T is in degree Celsius (°C).

If the Arrhenius relationship holds, Q_{10}-value can be related to activation energy E_a by the following relationship (Buransompob et al. 2003):

$$\log Q_{10} = \frac{4.34 E_a}{RT(T + 10^{o}\text{C})} \tag{9}$$

The Q_{10}-value is commonly used to predict the storage period at lower temperatures based on the shelf life tests conducted at higher temperatures. Since dependent strongly on temperature, Q_{10}-value is applied in a small temperature range of 10 to 20 °C to avoid possible physical and chemical changes (Labuza 1984). The Q_{10} concept is successfully used to design the accelerated shelf life tests for thermally processed products, such as walnuts, almonds, powdered gabiroba pulp, fresh cut pineapple slices, and low acid foods (Breda et al. 2012; Gao et al. 2010; Riva and Torri 2009; Wang et al. 2006; Yoon et al. 2009).

The z-value (°C) indicates the temperature increment to reduce D-value by 90 % or results in a one-log change, which presents sensitivity to temperature changes. For the first-order reaction, z-value can be calculated as a function of temperature below:

$$z = \frac{T_2 - T_1}{\log D_1 - \log D_2} \tag{10}$$

where D_1 and D_2 are the decimal reduction times at temperatures T_1 and T_2, respectively.

The interconversion of factors (E_a and z-values) from one concept to the other can, however, lead to discrepancies if experimental data are obtained outside the temperature limits. If the Arrhenius relationship holds, z-values can also be related to the activation energy E_a by the following relationship in a given temperature range $T_1 \sim T_2$ ($T_1 < T_2$) (Ramaswamy et al. 1989):

$$z = \frac{2.303 R T_1 T_2}{E_a} \tag{11))}$$

If the rate constant could be described well by both the Arrhenius equation and the z-value model, Eq. 11 can be written as follows (Saguy et al. 1978):

$$z = \frac{2.303 R T^2}{E_a} \tag{12}$$

where T stands for a temperature corresponding to the mean over the temperature range $T_1 \sim T_2$ in experiments.

The correlation between z-value and Q_{10} can also be proven as follows:

$$z = \frac{10}{\log Q_{10}} \tag{13}$$

Among D-value, z-value, E_a, k, Q_{10}, and T, each parameter can be easily converted by the two of known model parameters. It is worth noting that there are not only correlations but also distinctions between the Arrhenius equation and the z-value model. They are nearly the same within a certain temperature range, but z-value model gives a higher predicted k value than Arrhenius equation when using extrapolation data at high temperatures (Fujikawa and Itoh 1998; Jonsson et al. 1977; Saguy et al. 1978).

Experimental Determination of Kinetic Parameters

Although the most practical thermal processes are non-isothermal, kinetic models are developed under isothermal conditions, which can be easily integrated into accumulated effects under a given temperature-time history of a heating process to estimate the quality changes (Dolan 2003). It is recommendable that preliminary tests are conducted to select test conditions, in which adequate extent of quality changes could be observed over the maximum span of the time at any given temperature. This may ensure that the developed kinetic models cover desired range of quality changes. Precautionary measures should also be taken to reduce or eliminate the influence of the time that it would take for the sample to reach the set elevated temperatures (Chung et al. 2007).

Two experimental methods are widely used for kinetic studies, which include the direct and indirect heating. For the direct heating method, prepackaged samples are immersed directly into the heating media, such as water bath (<95 °C) or oil bath (>95 °C). This method works well as a confirmation for conventional heat treatments but is not suited for kinetic studies because the heat transfer starts from the surface and non-uniform temperatures between the food surface and the centre are usually observed in large-size samples. Due to taking long time for whole prepackaged samples to reach the target temperature, this method fails to provide isothermal conditions. The kinetic parameters obtained by this method can only be applied to the same heating conditions.

Indirect heating methods commonly use a small volume or thin product or samples so as to achieve an applicable isothermal condition. The instrumentation and device used for those tests include thermal death time (TDT) cans for vegetable (Van Loey et al. 1995), glass beakers for vegetable puree (Ahmed et al. 2002; Nisha et al. 2011), glass tubes for fruit extract or vegetable puree (Rudra et al. 2008; Suh et al. 2003), screw-cap test tubes for fruit juice (Dhuique-Mayer et al. 2007; Kechinski et al. 2010), Pyrex glass vials for fruit puree (Avila and Silva 1999), hermetically metal cells or tubes for fruit juice, vegetable extract and fruit tissue particles (Jimenez et al. 2010; Lemmens et al. 2011; Nayak et al. 2011; Verbeyst et al. 2010), and capillary tubes for fruit paste (Barreiro et al. 1997). The device employed depends on the type of product being tested and the purpose of research since some of these sample holders are only suitable for determining the thermal tolerance of quality properties at a certain condition. For instance, large glass tubes and beakers are fragile and not suited to hold samples for heating beyond 100 °C without losing water. In addition, capillary tubes are considered as the best method for characterizing thermal tolerance of quality properties in liquid samples, but they are not suitable for solid samples due to the difficulty of fitting samples in a narrow space.

Hermetically sealed test cells are suitable for thermal kinetic test of liquid, semi-solid, and solid foods beyond 100 °C. A custom-designed thermal kinetic test (TKT) cell developed at the Washington State University is shown in Fig. 1. This test cell, made from two pieces of aluminum alloy lids with a rubber o-ring on the top lid, can provide adequate strength and hermetic seal when a food sample is heated at temperatures up to 130 °C. A precalibrated type-T thermocouple is inserted through a rubber gland in the top lid to record the temperature-time history of the sample core using a data logger. Because of the high aspect ratios (diameter/height) and the high thermal conductivity (180 $Wm^{-1} K^{-1}$) of aluminum alloy, the come-up time (CUT: the time needed for the geometric center of a sample temperature to reach 0.5 °C less than the set temperature) of this test cell is small (e.g., less than 60 s), resulting in a close-to-ideal isothermal condition (Chung et al. 2008). Moreover, the aluminum alloy has a good corrosion resistance and machinability, so the test cell can be processed into different sizes used in kinetic studies for a variety of foods. For example, Nayak et al. (2011) use the TKT cells (∅ 20 mm×H 4.5 mm) to evaluate the thermal kinetic parameters of purified anthocyanins from purple potato over 100~150 °C and determine the antioxidant potencies of degradation products from the anthocyanins. Kong et al. (2008) used a TKT cell (∅ 30 mm×H 6 mm) to investigate the kinetics parameters of salmon fillets quality included cook loss, area shrinkage, and deteriorations of color and texture in the high temperature range of 100~131 °C.

To minimize the influence of slow heat transfer and obtain accurate determination of a quality's thermal tolerance, lag time (LT) and come-up time (CUT) for the target temperatures are main concerns in design of experiments and analyses of experimental data (Chung et al. 2007, 2008; Gondo et al. 1972; Jin et al. 2008). As a rule of thumb, if $P/P_0 \geq 25$ % when LT or CUT ends for first-order reactions (Beck and Arnold 1977), the heating time can be considered as zero at the end of LT or CUT (Dolan 2003).

Kinetic data can be analyzed using one-step or two-step regression. The one-step method is to regress all data non-linearly to acquire E_a, k, and n simultaneously. But, the confidence intervals for the parameters E_a and k_0 would be narrow due to the increased number of degrees of freedom (Van Boekel 1996). The equation for the non-linear regression is obtained by combining Eqs. 1 and 6:

$$\frac{dP}{dt} = \pm k_0 P^n e^{-\frac{E_a}{RT}} \tag{14}$$

The two-step method is commonly used due to its mathematical simplicity and intuitive appeal when plotted. For the first-order of reaction, plotting $ln(P)$ against time t should result in a straight line, with a negative slope when the sum of residual squares is minimized, resulting in the interception

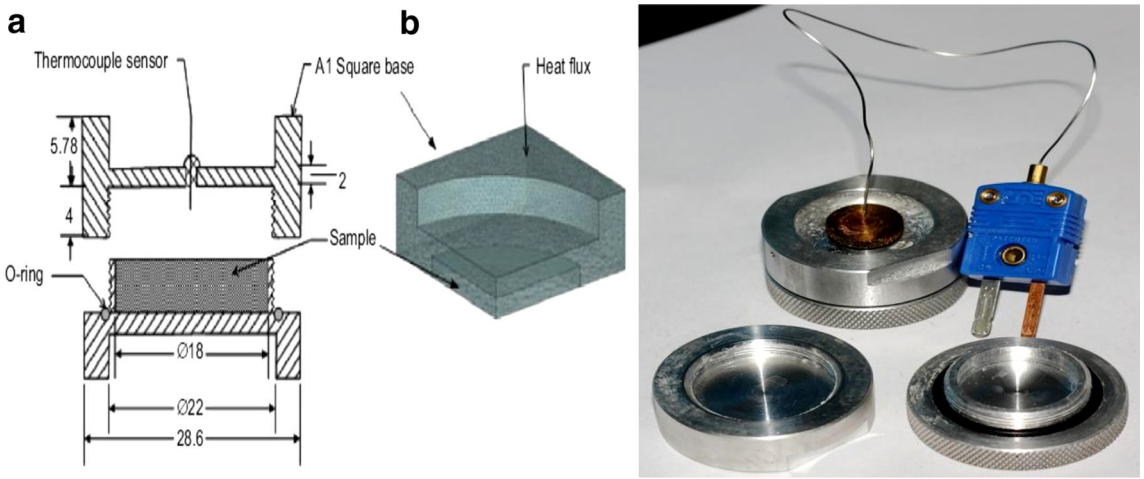

Fig. 1 Schematic diagram of WSU test cell (∅ 18×H 4 mm) (Chung et al. 2008)

of $ln(P_0)$ and the rate constant of k for each temperature. If plotting $ln(P)$ against time t is not a straight line, one may assume an nth-order reaction and plotting $(P^{1-n})/(1-n)$ against time t to obtain the best fitting model based on the largest average coefficient of determination (R^2) over the tested temperatures. Secondly, plotting $ln(k)$ against $1/T$ (K) may obtain E_a and $ln(k_0)$ from the slope and the y-intercept, respectively.

It is a very important task in kinetic analysis to determine the order of reactions. To be able to accurately estimate the order of the reaction from experimental data, Theodore et al. (1997) recommended that when selecting the largest heating time for a given temperature, the reaction should be allowed to carry far enough to distinguish the orders of reaction. As concluded by Lund (1977), it is necessary to have 2–3 log changes in the concentration or the physical property for meaningful determination of the reaction order, which is often expressed in integrals (0, 1, or 2) or simple fractional values (0.5 or 1.5) as related to simple mechanistic models (Swinbourne 1971).

Common Reactions and Kinetic Models in Food Processing

Important quality attributes in foods include appearance, flavor, texture, and nutrition (Bourne 2002). Changes in those attributes, such as color, bioactive compounds, and texture, due to thermal processing will be discussed in detail below.

Color

Color influences consumer's choice and preferences of foods (Pathare et al. 2013). The change in food color during a thermal process is influenced by various mechanisms, such as degradation of pigments, oxidation of ascorbic acid, enzymatic browning, and non-enzymatic browning. Colorimeters and spectrophotometers based on CIE LAB color space have been used extensively in the food industry for color measurement (Wu and Sun 2013). A summary of the kinetic parameters of color changes during thermal processing is listed in Table 1. Although the majority of the published work reports first-order or zero-order degradation reaction kinetics, it may not be always possible to use simple first- or zero-order kinetic models to describe color changes in foods during thermal processing, because these changes can not only be caused by the Maillard reaction, but also the thermal destruction of pigments (Skrede 1985). Barreiro et al. (1997) and Fante and Noreña (2012) described the thermal degradation kinetics of L in tomato paste and browning index in garlic, respectively, with the biphasic first-order model. Avila and Silva (1999) and Goncalves et al. (2007) reported the thermal degradation kinetics of a; total color difference (TCD) in peach puree; and L, a, b, and TCD in pumpkin, respectively, by applying the fractional conversion model. Goñi and Salvadori (2011) described the redness changes of beef during roasting using the fractional conversion first-order kinetics. Kong et al. (2007) and Brookmire et al. (2013) reported that the color changes of salmon fillets during thermal processing followed zero- and first-order kinetic models, respectively. Ovissipour et al. (2013) reported that the kinetic data of color changes on the whole mussel surface can not be collected in thermal pasteurization due to little color uniformity. The z-values and E_a values for various food color changes are summarized in Table 1.

Bioactive Compound

It is widely known that foods of plant origin are good sources of phytochemicals with biological activity and health-promoting functions. Although most of these compounds may be generally affected by temperature, thermal processing

Table 1 Published kinetic parameters for the thermal degradation of color of different products

Product	Heating methods	Color parameter	Kinetic model	Kinetic parameters				Reference
				k (min^{-1})	E_a (kJ mol^{-1})	D (min)	z (°C)	
Tomato paste	Glass vials in water bath	L	Biphasic first order	$7.7\times10^{-3}{}_{T=85\ °C}$ (HLF)	48	–	–	Barreiro et al. (1997)
				$1.1\times10^{-3}{}_{T=85\ °C}$ (HRF)	24	–	–	
		a	First order	$9.4\times10^{-3}{}_{T=85\ °C}$	41	$245_{T=85\ °C}$	62.4[a]	
		b		$1.3\times10^{-3}{}_{T=85\ °C}$	86	$1{,}735_{T=85\ °C}$	29.8[a]	
		TCD	Zero order	$0.2_{T=85\ °C}$	43	–	–	
Peach puree	Glass vials in oil bath	L	First order	$2.9\times10^{-3}{}_{T=122.5\ °C}$	107	$794_{T=122.5\ °C}$	28.0[a]	Avila and Silva (1999)
		b		$4.0\times10^{-3}{}_{T=122.5\ °C}$	109	$576_{T=122.5\ °C}$	27.5[a]	
		a	Fractional first order	$0.0_{T=122.5\ °C}$	106	–	–	
		TCD		$8.5\times10^{-3}{}_{T=122.5\ °C}$	119	–	–	
Green asparagus	Water bath	a	First order	$6.4\times10^{-3}{}_{T=84\ °C}$ (Bud)	54	$350_{T=84\ °C}$	45.2[a]	Lau et al. (2000)
				$6.8\times10^{-3}{}_{T=84\ °C}$ (Butt)	55	$339_{T=84\ °C}$	44.4[a]	
Mulberry fruit extract	Test tube in water bath	BI	Zero order	$6.7\times10^{-4}{}_{T=90\ °C\ pH=2.0}$	31	–	–	Suh et al. (2003)
Orange juice	Ohmic heating	$a\times b$	First order	$0.6_{T=90\ °C}$	80	$4_{T=90\ °C}$	12.3	Vikram et al. (2005)
	Infrared heating			$0.6_{T=90\ °C}$	53	$4_{T=90\ °C}$	18.4	
Beef muscle	Water bath	a	Fractional first order	$1.2\times10^{-3}{}_{T=100\ °C}$	81	–	–	Goñi and Salvadori (2011)
Pink salmon (*Oncorhynchus gorbuscha*)	TKT cell in oil bath	L	Zero order	$1.2\times10^{-3}{}_{T=121\ °C}$	88	–	–	Kong et al. (2007)
		b		$3.8\times10^{-4}{}_{T=121\ °C}$	74	–	–	
		TCD		$3.1\times10^{-3}{}_{T=121\ °C}$	99	–	–	
Pumpkin (*Cucurbita maxima* L.)	Water bath	L	Fractional first order	$0.1_{T=85\ °C}$	120	–	–	Goncalves et al. (2007)
		a		$0.1_{T=85\ °C}$	118	–	–	
		b		$0.2_{T=85\ °C}$	111	–	–	
		TCD		$0.1_{T=85\ °C}$	99	–	–	
Pineapple puree	Glass flask in oil bath	L	First order	$2.1\times10^{-3}{}_{T=110\ °C}$	129	$1{,}097\ _{T=110\ °C}$	21.7[a]	Chutintrasri and Noomhorm (2007)
		b		$6.1\times10^{-3}{}_{T=110\ °C}$	109	$378_{T=110\ °C}$	25.7[a]	
		TCD	Zero order	$12.9\times10^{-3}{}_{T=110\ °C}$	94	–	–	
		BI*		$2.0\times10^{-3}{}_{T=110\ °C}$	109	–	–	
Cashew apples	Hermetically sealed test cell in oil bath	L	First order	$1.9\times10^{-2}{}_{T=140\ °C}$	98	$116_{T=140\ °C}$	33.0[a]	Lima et al. (2010)
Reconstituted blackberry juice	Hermetically sealed test cell in oil bath	BI	First order	$9.7\times10^{-2}{}_{T=140\ °C}$	107	$24_{T=140\ °C}$	30.5[a]	Jimenez et al. (2010)
Seedless guava (*Psidium guajava* L.)	Water bath	L	First order	$9.0\times10^{-2}\ _{T=85\ °C}$	123	$26_{T=85\ °C}$	20.0[a]	Ganjloo et al. (2011)
		a		$0.3\ _{T=85\ °C}$	88	$10_{T=85\ °C}$	27.7[a]	
		TCD	Zero order	$6.6\ _{T=85\ °C}$	113	–	–	
Garlic (*Allium sativum* L.)	Water bath	BI**	Biphasic first order	$1.9_{T=80\ °C}$(HLF)	67	–	–	Fante and Noreña (2012)
				$1.0\times10^{-2}{}_{T=80\ °C}$(HRF)	203	–	–	
Betacyanins from red beet	Pobel tube in water bath	TCD	First order	$3.2\times10^{-3}{}_{T=70\ °C}$	35	$727_{T=70\ °C}$	63.6[a]	Fernandez-Lopez et al. (2013)

HLF heat labile fraction; *HRF* heat resistance fraction; *BI* browning index, A_{510}/A_{420}; *BI** browning index, A_{420}; *BI*** $[100(X-0.31)]/0.172$, $X=(a+1.75L)/(5.645L+a-3.012b)$

[a] Value estimated by Eq. 11 or 12

remains the most commonly used technology for inactivating microorganisms and enzymes in food industry (Oms-Oliu et al. 2012). On the other hand, thermal treatments of industrial concerns had little adverse or even positive effects on these active compounds. Czerwonka et al. (2014) reported that the process of roasting and grilling had little effect on the vitamin B_{12} content in the final product as compared to the raw meat. It is also reported that availability of active compounds may increase after thermal treatments, and thus, the industrial process may enhance nutritional levels, such as increases β-carotene content in the heated ivy gourd and amaranth (Sungpuag et al. 1999), which could be interesting to develop thermal release kinetics of active compounds. However, heat processing under extreme conditions may cause chemical or physical changes and reduce the content or bioavailability of some bioactive compounds (Rawson et al. 2011). Table 2 presents kinetic data for health-related compounds and functions of foods in thermal processing. Similar to the color degradation, the first-order kinetic model is commonly used to study the kinetics of changes in these compounds. Some data fit well to the classical first-order models, but the second-order reaction model is well used for the decay of thiamin of salmon during high temperature thermal processes (Kong et al. 2007). Hadjal et al. (2013) also reported that a second-order model best fitted the thermal degradation curves of lutein of blood orange juice over a temperature range of 45–90 °C. Harbourne et al. (2008) investigated thermal degradation of blackcurrant anthocyanins in a model juice system over 4–140 °C. They suggested pseudo-first-order reaction kinetics for anthocyanin degradation. Zanoni et al. (2003) reported that the antioxidant activity of hydrophilic extract followed a pseudo-zero-order reaction during thermal sterilization. The biphasic first-order and fractional conversion models are also found to be suitable for thermal degradation of health-related compounds and functions (Hiwilepo-van Hal et al. 2012; Jaiswal et al. 2012; Vieira et al. 2000).

Texture

Texture can be characterized as a series of physical characteristics that arise from the composition and structure of the food, sensed by the feeling of mouth or some other parts of the body. It measures forces required for certain levels of deformation, disintegration, or flow of the food (Bourne 2002). Compression and puncture tests are the two most common methods to measure food texture properties. They are often conducted using a texture analyzer or an Instron testing machine (Chen and Opara 2013). Hardness, springness, and firmness have been most used in quantifying kinetics of texture thermal degradation, especially for firmness, which is best related to the thermal softening of food of plant origin (Jaiswal et al. 2012; Lau et al. 2000; Nisha et al. 2006). Limited information is available on texture kenitics for food of animal origin. Ovissipour et al. (2013) reported that the compression force of whole mussel during thermal pasteurization follows zero-order kinetic model. Kong et al. (2007) and Brookmire et al. (2013) reported that the shear force of salmon fillets during thermal processing follows first-order kinetic model. Other kinetic models, such as biphasic first-order model, fractional conversion model, and Weibull-log-logistic model, also fit well to the thermal degradation of texture (De Roeck et al. 2010; Ko et al. 2007; Vu et al. 2004; Yu et al. 2011). Table 3 summarizes kinetic modeling of texture changes of foods during thermal processing.

Special Kinetic Models

A majority of kinetic models used for food quality changes during thermal processing employ simple and traditional zero- or first- and second-order kinetics. But, Hiwilepo-van Hal et al. (2012) reported that a simple first-order model was inadequate to describe the thermal degradation of vitamin C in some tropical fruit because of the occurrence of biphasic behaviors. Similar observations are about of the biphasic behaviors in the texture degradation during thermal processing (Ko et al. 2007). Several alternative models have been proposed to improve description of thermal degradations. Those models include the biphasic first-order kinetic model and Weibull-log-logistic model, which will also be discussed in detail below.

The biphasic model is proposed by Liing and Lund (1978) to describe the inactivation thermal kinetics of an enzyme system formed by heat labile and resistant fractions, both with first-order inactivation kinetics as follows:

$$P = P_{01}e^{-k_1 t} + P_{02}e^{-k_2 t} \tag{15}$$

where indexes 1 and 2 are indicative quality properties for heat labile and resistant fractions, respectively. When plotting the logarithm of the quality property against time, a dual mechanism first-order kinetic model reveals a linear relationship with a steep slope for heat labile fractions followed by another linear function with a shallow slope for heat-resistant fractions. The rate constant and activation energy are calculated separately for each mechanism. For example, Barreiro et al. (1997) suggested that several reactions leading to the color changes of foods can take place simultaneously. Those reactions can be parallel or sequential; their contributions to the overall color changes vary, depending on the quality attributes in questions.

Instead of using an absolute measurement value to indicate quality changes, the concept of fractional conversion is commonly used in chemical engineering. It measures the extent of a reaction as an indication of quality change (Hill 1977; Levenspiel 1999). When using the

Table 2 Published kinetic parameters for the thermal degradation of health-related compounds and functions of different products

Nutrient	Product	Heating methods	Kinetic model	Kinetic parameters				Reference
				k (min^{-1})	E_a (kJ mol^{-1})	D (min)	z (°C)	
Vitamin C	Cupuacu nectar	TDT tubes in water bath	Fractional first order	$3.2\times10^{-2}{}_{T=80\ °C}$ (AA)	74	–	–	Vieira et al. (2000)
			First order	$1.3\times10^{-2}{}_{T=80\ °C}$ (DHAA)	65	$177_{T=80\ °C}$	36.7[a]	
	Orange juice	Ohmic heating	First order	$1.6\times10^{-1}{}_{T=90\ °C}$	47	$15_{T=90\ °C}$	20.7	Vikram et al. (2005)
		Microwave heating		$5.0\times10^{-2}{}_{T=100\ °C}$	65	$46_{T=100\ °C}$	19.2	
		Water bath		$1.8\times10^{-1}{}_{T=90\ °C}$	40	$13_{T=100\ °C}$	24.4	
	Citrus juice	Sealed Pyrex tubes in oil bath	First order	$1.9\times10^{-3}{}_{T=80\ °C}$	36	$1{,}212_{T=80\ °C}$	64.0	Dhuique-Mayer et al. (2007)
	Guava pulp	Capped steel tubes in heating block	Biphasic first order	$1.2\times10^{-1}{}_{T=100\ °C}$[b]	58	–	–	Hiwilepo-van Hal et al. (2012)
				$5.3\times10^{-5}{}_{T=100\ °C}$[c]	190	–	–	
Thiamin	Pink salmon (*Oncorhync husgorbuscha*)	TKT cell in oil bath	Second-order	$0.1_{T=121\ °C}$	105	–	–	Kong et al. (2007)
			Weibull	b(121 °C)=32.6 min^{-n}	k=0.078($°C^{-1}$)	Tc (°C)=165	–	
Folic acid	Folic acid dissolving in sodium borate (0.05 M, pH 9.22)	Sealed Pyrex tubes in water bath	First order	$1.0\times10^{-3}{}_{T=120\ °C}$	52	$2{,}214_{T=120\ °C}$	–	Nguyen et al. (2003)
Carotenoids	Citrus juice	Sealed Pyrex tubes in oil bath	First order	$5.3\times10^{-3}{}_{T=90\ °C}$ β-carotene	110	$435_{T=90\ °C}$	22.9[a]	Dhuique-Mayer et al. (2007)
	Blood orange juice		Second order	$3.0\times10^{-3}{}_{T=67.5\ °C}$ lutein	65	–	–	Hadjal et al. (2013)
Anthocyanin	Blackcurrant juices	Capped Pyrex tubes in water bath	Pseudo-first order	$3.5\times10^{-4}{}_{T=60\ °C}$	73	–	–	Harbourne et al. (2008)
	Raspberries	Test tubes in oil bath	First order	$2.06\times10^{-2}{}_{T=110\ °C}$ cyanidin 3-sophoroside	75	$112_{T=110\ °C}$	37.4	Verbeyst et al. (2011)
	Reconstituted blackberry juice	Hermetically sealed test cell in oil baths		$5.4\times10^{-2}{}_{T=120\ °C}$	92	$43_{T=120\ °C}$	–	Jimenez et al. (2010)
				$1.2_{T=160\ °C}$	44	$2_{T=160\ °C}$	–	
	Purple potato	TKT cell in oil bath		$7.1\times10^{-2}{}_{T=120\ °C}$	73	$32_{T=120\ °C}$	47.9	Nayak et al. (2011)
Total phenolic	Cabbage (*Brassica oleracea capitata*)	Water bath	Fractional first order	$4.2\times10^{-1}{}_{T=90\ °C}$	12	–	–	Jaiswal et al. (2012)
Total flavonoid				$3.5\times10^{-1}{}_{T=90\ °C}$	9	–	–	
	Tomato puree	Batch-sterilization plant	Pseudo-zero order	$1.9\times10^{-2}{}_{T=95\ °C}$	149	–	–	Zanoni et al. (2003)
Antioxidant activity	Mulberry fruit extract	Test tubes in water bath	Zero order	$2.2\times10^{-2}{}_{T=90\ °C\ pH=2.0}$	82	–	–	Suh et al. (2003)
				$0.38_{T=90\ °C\ pH=4.0}$	41	–	–	
	Cabbage (*Brassica oleracea capitata*)	Water bath	Fractional first order	$3.5\times10^{-1}{}_{T=90\ °C}$ (DPPH)	22	–	–	Jaiswal et al. (2012)
				$3.0\times10^{-1}{}_{T=90\ °C}$ (FRAP)	9	–	–	

AA ascorbic acid; *DHAA* dehydroascorbic acid; *FRAP* ferric reducing ability power; *DPPH* 2,2-diphenyl-1-picrylhydrazyl free radical scavenging capacity

[a] Value estimated by Eq. 11 or 12

[b] Heat labile fraction of texture

[c] Heat resistance fraction of texture

fractional conversion model, the quality index, f, is defined as (Rizvi and Tong 1997):

$$f = \frac{P_0 - P_t}{P_0 - P_\infty} \tag{16}$$

where P_0 is the initial quality property of the food, P_t is the quality property after a certain treated time t, and P_∞ is the final quality property at the non-zero equilibrium value. For a first-order reaction, substituting the index f into Eq. 3 and taking natural log yields the following:

$$\ln(1-f) = \ln\frac{P_t - P_\infty}{P_0 - P_\infty} = -kt \tag{17}$$

However, the P_∞ for an irreversible reaction would be zero when the reaction is completed, and the quality property as a function of time can be simplified as follows:

$$\ln(1-f) = \ln\frac{P_t}{P_0} = -kt \tag{18}$$

P_∞ may be only approximated to zero for some quality indices, such as the concentration of bioactive compounds, antioxidant capacity, and color of foods after high temperature treatments. But for texture, P_∞ may also have non-zero characteristic values after thermal processing. For example, while most vegetables and fruits are significantly softened after prolonged heating, they retain small but some measurable firmness (Peng et al. 2014). It may be one of the main reasons why the texture degradation under prolonged heating is better characterized by the fractional conversion model than the biphasic model. Rizvi and Tong (1997) suggested that the first-order kinetic model used for some published texture degradation studies might be acceptable while a relatively short heating time was applied before softening.

The Weibull model is developed initially to describe the failure of a given system subjected to stress conditions over time. The cumulative form of the Weibull distribution function (Van Boekel 2002) can be described mathematically as follows:

$$\ln\frac{P}{P_0} = -b(T)t^{n(T)} \tag{19}$$

where $b(T)$ and $n(T)$ are temperature-dependent coefficients. $n(T)$ is the "shape factor," and the reciprocal of $b(T)$ is the "location factor." When $n<1$, the isothermal semi-logarithmic curve has an upper concavity, and when $n>1$, the curve shows a downward concavity. The log-linear or first-order kinetics is, in fact, a case when $n=1$; therefore, the Weibull model offers great flexibility for biological systems (Corradini and Peleg 2006).

$b(T)$ can be described by the log-logistic model, which has been proposed as an alternative temperature-dependent model for the Weibull model when the data do not follow the fixed-order kinetics. The log-logistic model could also be used to describe food systems (Barsa et al. 2012; Bermudez-Aguirre and Corradini 2012) and written in the following form:

$$b(T) = \log e^{\{1+\exp[c(T-T_c)]\}} \tag{20}$$

where c is a constant and T_c refers to the temperature range where $b(T)$ starts to rise.

Fractional conversion technique can also be employed in Weibull models to improve the model accuracy, which can be written as follows:

$$\ln(1-f) = \ln\frac{P_t - P_\infty}{P_0 - P_\infty} = -b(T)t \tag{21}$$

Weibull distribution function describes well the non-linear microorganism inactivation after non-thermal processing (Peleg and Cole 1998). It has recently been used to describe enzymatic and chemical degradation kinetics. For example, Corradini and Peleg (2004, 2006) reported that the Weibull model was useful for describing the thermal degradation of heat labile vitamins and pigments. Kong et al. (2007) demonstrated that the Weibull-log-logistic model was effective in quantifying the isothermal decay of thiamin in salmon fillets. Yu et al. (2011) used the Weibull-log-logistic model as a preferred model for litchi texture as compared to the first-order Arrhenius model.

Each quality attribute may react differently to various temperature ranges. If any attribute becomes unacceptable to the consumer, the treated food loses its market value. All quality attributes of food must be considered in developing quality kinetic curves. For example, stem color, fruit appearance and firmness, total solid soluble content, and titratable acidity are the major quality attributes that must be factored into the quality kinetic curve when developing a treatment for fresh vegetables (Lau et al. 2000). Sugar caramelization, starch gelatinization, and protein denaturation are changed during bread baking (Earle and Earle 2003), suggesting that the possible reactions in parallel should be taken into account in thermal processing.

Applications of Kinetic Data

The important value of kinetic models is to predict quality changes and optimize thermal processes. For the prediction purpose, we can use Eqs. 7 and 8 to estimate the rate constant of quality changes at different temperatures. When combining the Arrhenius relationship with the zero- or first-order kinetic model, one may obtain the

Table 3 Published kinetic parameters for the thermal degradation of texture of different products

Product	Heating methods	Texture parameter	Kinetic model	Kinetic parameters				Reference
				k (min^{-1})	E_a (kJ mol^{-1})	D (min)	z (°C)	
Green asparagus	Water baths	Shear stress	First order	$1.6\times10^{-2}{}_{T=84\ °C}$ (butt)	25	143	99.6[a]	Lau et al. (2000)
				$2.3\times10^{-2}{}_{T=84\ °C}$ (middle)	25	100	99.6[a]	
				$2.7\times10^{-2}{}_{T=84\ °C}$ (bud)	24	85	104.0[a]	
Carrots (*Daucus carota* L.)	Water bath (≤95 °C) and oil bath (≥95 °C)	Hardness	Fractional first order	$1.5\times10^{-1}{}_{T=95\ °C}$ (without preheating)	118	–	–	Vu et al. (2004)
				$7.0\times10^{-2}{}_{T=100\ °C}$ (preheating 60 °C 30 min)	99	–	–	
Potato cubes (*Solanum tuberosum* L.)	Water bath	The force resisting the probe	First order	$8.9\times10^{-2}{}_{T=90\ °C}$	9	$26_{T=90\ °C}$	256.0[a]	Nisha et al. (2006)
Green gram (*Vigna radiate* L.)				$3.3\times10^{-2}{}_{T=90\ °C}$	7	$70_{T=90\ °C}$	338.0[a]	
Pink salmon	TKT cell in oil bath	Shear force	First order	$1.9\times10^{-2}{}_{T=111\ °C}$ (rapid tenderization)	100	$121_{T=111\ °C}$	28.1[a]	Kong et al. (2007)
				$2.3\times10^{-3}{}_{T=121\ °C}$ (slow toughening)	76	$1{,}001_{T=121\ °C}$	39.1[a]	
Whole blue mussel	TKT cell in oil bath	Compression force	Zero order	$2.6\times10^{-2}{}_{T=90\ °C}$	65	–	–	Ovissipour et al. (2013)
Pumpkin (*Cucurbita maxima* L.)	Water bath	Firmness	Fractional first order	$3.9\times10^{-1}{}_{T=85\ °C}$	72	–	–	Goncalves et al. (2007)
		Energy		$1.8\times10^{-1}{}_{T=85\ °C}$	102	–	–	
Winter mushrooms (*Flammulina velutipes*)	Water bath	Hardness	Biphasic first order	$2.7\times10^{-1}{}_{T=100\ °C\ Cap}{}^{b}$	15	$9_{T=100\ °C\ Cap}{}^{b}$	0.1	Ko et al. (2007)
				$1.4\times10^{-2}{}_{T=100\ °C\ Cap}{}^{c}$	10	$165_{T=100\ °C\ Cap}{}^{c}$	0.2	
		Springiness		$1.5\times10^{-1}{}_{T=100\ °C\ Cap}{}^{b}$	8	$15_{T=100\ °C\ Cap}{}^{b}$	4.3	
				$7.7_{T=100\ °C\ Cap}{}^{c}$	16	$0_{T=100\ °C\ Cap}{}^{c}$	0.0	
		Fracturability		$2.9\times10^{-1}{}_{T=100\ °C\ Stipes}{}^{b}$	18	$8_{T=100\ °C\ Stipes}{}^{b}$	0.1	
				$7.4\times10^{-2}{}_{T=100\ °C\ Stipes}{}^{c}$	22	$31_{T=100\ °C\ Stipes}{}^{c}$	83.3	
Carrot (*Daucus carota var.* Nerac)	Stainless steel tubes in oil bath	Hardness	Fractional first order	$3.0\times10^{-1}{}_{T=100\ °C}$	152	–	–	De Roeck et al. (2010)
Litchi	Water bath	Firmness	First order	$5.4\times10^{-3}{}_{T=90\ °C}$	59	–	R^2=0.920	Yu et al. (2011)
			Fractional first order	$1.5\times10^{-2}{}_{T=90\ °C}$	80	–	R^2=0.996	
			Weibull-log-logistic	$b(90\ °C)=2.7\times10^{-2}\ min^{-n}$	k=0.26 ($°C^{-1}$)	Tc(°C)=105	R^2=0.999	
			Fractional Weibull	$b(90\ °C)=8.7\times10^{-3}\ min^{-n}$	k=0.19 ($°C^{-1}$)	Tc(°C)=113	R^2=0.999	
Cabbage (*Brassica oleracea capitata*)	Water bath	Firmness	First order	$9\times10^{-2}{}_{T=90\ °C}$	34	$26_{T=90\ °C}$	74.6[a]	Jaiswal et al. (2012)

[a] Value estimated by Eq. 11 or 12

[b] Heat labile fraction of texture

[c] Heat resistance fraction of texture

equations that directly relate quality properties to heating time at various temperatures:

$$\text{Zero order under isotherm conditions}: P = P_0 - tk_0e^{-Ea/RT} \tag{22}$$

$$\text{Zero order under transient conditions}: P = P_0 - \int_0^t k_0e^{-Ea/RT(t)}dt \tag{23}$$

$$\text{First order under isotherm conditions}: \ln\frac{P}{P_0} = -tk_0e^{-Ea/RT} \tag{24}$$

$$\text{First order under transient conditions}: \ln\frac{P}{P_0} = -\int_0^t k_0e^{-Ea/RT(t)}dt \tag{25}$$

The activation energy is 63–126, 209–418, and 8–63 kJ/mole for a food quality loss, microbial inactivation, and enzymatic reactions or oxidation reactions, respectively (Nelson 2010). If we assume that the activation energy for food quality loss and microbial inactivation is 90 and 300 kJ/mole, respectively, for a temperature increase of 20 °C to 121 °C (394.12 K), the change in reaction rates is estimated as follows using the Arrhenius relationship (Eq. 7):

$$\text{Quality loss}: \quad k_{141^oC} = k_{121^oC}\, e^{\frac{90\times1{,}000}{8.314\times394.12\times414.12}(141-121)} = 3.77 \times k_{121^oC} \tag{26}$$

$$\text{Microbial inactivation}: k_{141^oC} = k_{121^oC}\, e^{\frac{300\times1{,}000}{8.314\times394.12\times414.12}(141-121)} = 83.2 \times k_{121^oC} \tag{27}$$

Thus, for 20 °C increase from 121 °C, the rate of quality loss increases by 3.77 times, while the rate for microbial inactivation increases 83.2 times. When a thermal process is designed at 141 °C to deliver the same lethality to microorganism at 121 °C, the holding time can be reduced by a factor of 83.2, and the quality loss can be reduced by a factor of 83.2/3.77=22.1 during holding periods. Figure 2 illustrates this difference in temperature sensitivity between microbial control and quality loss and demonstrates the advantage of high-temperature short-time heating (HTST) or ultra-high-temperature treatment (UHT).

Total quality loss and microbial or enzyme inactivation are dependent on the cumulative thermal exposure during the course of the non-isothermal treatment. From the z-value and the time-temperature data recorded from the samples during heating, the cumulated lethal time model can be established, and then, the sterilizing value (F_0, min) and cook values (C, min) are calculated below (Hansen et al. 2004; Wang et al. 2003).

$$F_0 = \int_0^t 10^{\left[\frac{T-T_{ref}}{z_M}\right]}dt \tag{28}$$

where T_{ref} is a reference temperature and commonly used at 121.1 °C. F_0 indicates the cumulative thermal effect on microbial reduction in a thermal process. A z-value of 10 °C is used for *Clostridium botulinum* spores. F_0 for commercial sterilization of canned foods ranges from 2 to 15 min, but most commercial processes are designed for a F_0 of less or equal to 6 min (Stumbo 1973; FDA 2000).

$$C = \int_0^t 10^{\left[\frac{T-T_{ref}}{z_Q}\right]}dt \tag{29}$$

where z_Q and T_{ref} represent the z-value and reference temperature, respectively, for the most heat labile components. Generally, the reference cook value is characterized by z_Q= 33.1 °C and T_{ref}=100 °C. The cook value, C_{100}, relates the quality loss during a high-temperature thermal process to an equivalent cooking process at 100 °C (Lund 1977).

From the temperature-time history (heat penetration profile), one can calculate heating time required to obtain a target pasteurization unit (PU). Figure 3 illustrates a typical temperature-time history for RF heated meat products compared to the temperature-time profile for a steam-cooked sample heated at 80 °C. When the similar lethality to microorganism is achieved both by steam (PU=3389) and RF (PU=3393) heating, a significant reduction in cooking time (110 vs. 30 min) and quality loss (C_{100}=6.445 vs. 1.582) could be achieved using steam heating compared with RF heating (Zhang et al. 2004). The similar results on F_0 *and* C_{100} have been reported in RF-treated macaroni and cheese (Wang et al.

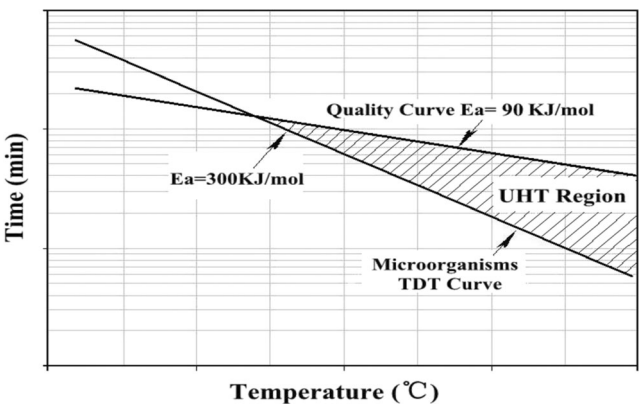

Fig. 2 The ultra-high-temperature treatment (UHT) region characterized by temperature-time combinations

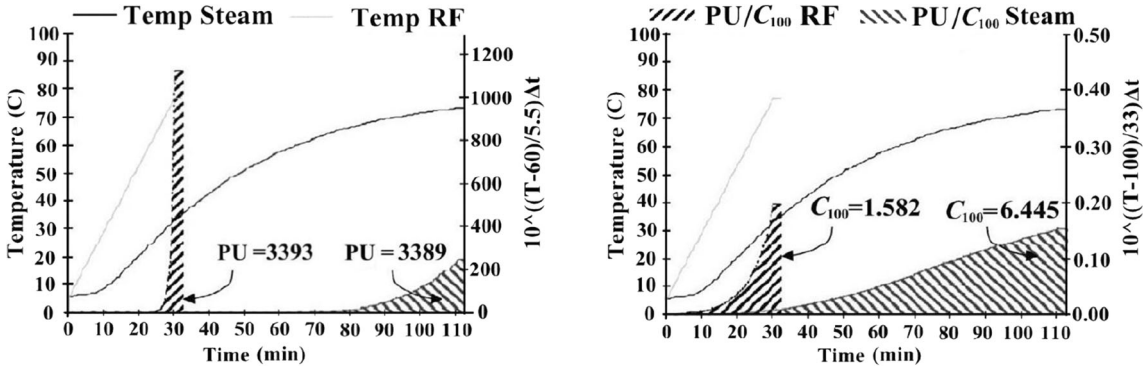

Fig. 3 Temperature-time, cook value ($C_{100}=\sum 10^{((T-100/33)\Delta t)}$), and pasteurization unit value ($PU=\sum 10^{((T-60/5.5)\Delta t)}$) profile for RF and steam-cooked meat products (Zhang et al. 2004)

2003). Microwave-processed beef demonstrates that the cook value C_{100} gained in the MW process is about 60 % of that gained in the retort process when achieving the same F_0= 8 min (Tang et al. 2008).

Suggestions for Future Research

Applications of Real Food in Kinetic Studies

Model foods are widely used for quality loss kinetic studies since they are uniform, reliable, and easy to collect. The simplified or pure components in model foods may help to obtain clear reaction results under special experimental conditions. But, real foods are different from model foods, since they contain complicated components, resulting in complicated physical and chemical reactions during thermal processing. The kinetic models developed based on model foods could not be directly used to design thermal processing protocols in industry applications. Especially, using novel heating technology, such as microwave or RF treatments, direct applications or guidance based on the model food kinetics would result in underestimated quality losses. Further research is needed to make model foods more reliable and representative and to develop the quantitative relationship for quality loss kinetics between model foods and real ones.

General Kinetic Model Establishment for Quality Loss

Food quality loss kinetics is usually determined with a single attribute of the food quality or selected representative quality indicators. However, consumers judge food quality by the appearance, texture, and flavor. In addition, the Maillard browning, thermal degradation of vitamins, and thermal denaturation of proteins are common food chemical reactions and follow some complicated kinetics in different food systems. These special kinetic models are inconvenient to guide thermal processing developments. Therefore, kinetic models of general food qualities should be developed within a narrow temperature range and over a limited time period specific to process conditions in question.

Applications of Food Quality Kinetics in Non-Isothermal Conditions

Food quality kinetics is commonly developed using data collected under isothermal conditions. In industrial heat treatment of foods, however, an actual process that includes heating, holding, and cooling is non-isothermal. The general solution is to calculate the accumulated microorganism inactivation and quality loss over the entire process time. For special kinetic models, such as the complex biphasic models, fractional conversion models, and Weibull distribution models, further research is needed to quantify the quality changes with these complex models and to guide the development of optimal thermal processes.

Exploring Pretreatments to Expand the Operational Treatment Region

The optimal operational treatment region is very limited for many heat-sensitive foods. Pretreatments can be used before or during the formal thermal processing to reduce the heat sensitivity and the reaction rate of the quality deterioration or improve the enzyme reaction rate. For example, microwave or RF treatments could be applied as preheating for blanching to enhance the food quality tolerance to heat. Some mild heat treatments at low temperatures could also be used as pretreatment to increase the food adaptation to heat, such as preheating carrots in calcium solutions to reduce texture degradation in canning processes. Future extensive research would be required for exploring different pretreatment steps to improve the food quality.

Applications of Non-linear Scientific Theories in Food Quality Modeling

Since food processing, quality control, and component analysis are usually identified as non-linear and non-steady state systems, traditional kinetic models may no longer be applicable to the actual situations. Artificial neural network (ANN) and fuzzy logic (fuzzy Logic) methods would be applied in quality kinetic studies for process optimization, control, and prediction. Applications of the above method are very limited in food science fields, and the non-linear modeling may be able to provide more reliable predictions and control means for complex food quality changes during thermal processing.

Conclusions

This review has shown that the step functional temperature profile is required for food samples to achieve the isothermal conditions in conducting TKTs. Significant progresses have been made in developing quality loss kinetic models, from commonly used zero- and first-order reaction models to sophisticated biphasic and Weibull ones. This study also demonstrates that using the kinetic models to estimate process sterilizing value and cook value based on the measured temperature-time history of the heated food leads to the conclusions that HTST processes are able to reduce food quality degradation while achieving food safety. But, physical and chemical reactions for the complex chemical compositions of foods during thermal processing are complicated. Future researches should be focused on applying kinetic models to real foods and non-isothermal conditions, optimizing food quality modeling using non-linear scientific theories, establishing general kinetic model for quality loss, and exploring pretreatments to increase the operational treatment region.

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