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Kinetics of carrot texture degradation under pasteurization conditions

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ABSTRACT

Texture degradation of carrot dices in different solutions (distilled water, 0.1% and 1.4% $CaCl_2$ solutions) under temperatures ranging from 80 to 110 °C was investigated. The effects of preheating (60 °C for 20 min) before high temperature treatment on carrot texture were studied and kinetic parameters were estimated. Preheating enhanced the texture of the final products, and the improvement in texture became more apparent when $CaCl_2$ was added. High temperature increased the texture degradation rate. The isotonic solution of carrot tissue was evaluated to avoid possible ion leakage of carrot tissue during heating, but no significant differences were found between the texture of carrots immersed in isotonic solution and distilled water after thermal treatments. The texture degradation of preheated carrot dices under the investigated pasteurization conditions follows a 2nd order reaction. Kinetic results obtained were used to recommend processing conditions for carrot products that could control food pathogens and inactivate enzymes.

1. Introduction

Carrots are one of the most commonly consumed vegetables in the United States, with one-fourth of all carrots consumed in processed form, largely canned and frozen (Lucier and Lin, 2007). In processed vegetables, texture is a primary marketable characteristic for the customer. The texture of processed products is mainly controlled by the chemical composition, physical structure and amount of cell wall and middle lamella (Bourne, 1989). The various mechanisms of texture loss during heating of vegetables include breakdown of cellular membranes, and cell wall degradation and disassembly resulting from enzymatic and non-enzymatic transformations in pectin structure and composition (Anthon et al., 2005; Greve et al., 1994a,b; Sila et al., 2008). Pectinmethylesterase (PME) and polygalacturonase (PG) are the two principle enzymes related to the enzymatic degradation of cell wall pectin. PME catalyzes the de-esterification of pectins, creating binding sites for divalent cations (primarily Ca^{2+}, naturally present in the tissue or added during processing) on the polygalacturonic acid backbone of the pectin to form cross-links between pectin chains which improves the texture. Pectin may undergo non-enzymatic degradation through β-elimination, a chemical reaction that takes place at higher pH levels (>4.5) and at temperatures higher than 80 °C (Keijbets and Pilnik, 1974; Sila et al., 2008).

Texture degradation of carrots during thermal processing has previously been investigated in several studies. Huang and Bourne (1983) and Bourne (1989) observed a rapid initial softening followed by a much slower rate of softening during the retort process of diced carrots. The authors proposed that carrot texture degradation consisted of two simultaneous first order reactions at different reaction rates during the thermal softening process. Rizvi and Tong (1997) re-determined the kinetic parameters using the fractional conversion technique based on the published data supporting two substrate mechanisms of tissue softening. They suggested fractional conversion as an alternate technique which was more accurate and reliable to describe the overall trends for texture degradation of vegetables. Vu et al. (2004) investigated the kinetic degradation of sliced carrots in distilled and demineralized water in a temperature range from 80 to 110 °C, and estimated the kinetic parameters using a fractional conversion model. Later, Smout et al. (2005) studied the thermal texture degradation of carrot cylinders in a 0.5% $CaCl_2$ solution using different preheating conditions followed by treatments at two heating temperatures (90 and 100 °C) and also applied a fractional conversion model. In the current study, the concepts of "equilibrium texture" and the fraction of texture changes were used to evaluate the kinetic data of texture degradation of diced carrots. Kinetic models with different reaction order were evaluated and the best-fit one was selected to estimate the related kinetic parameters.

When heating cut vegetables in aqueous solutions, differences in osmotic pressures within and outside the cells may result in ion leakage of the higher salt concentration within the cell leading

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to loss of cell integrity, which may influence mechanical properties (e.g. texture) (De EscaladaPla et al., 2006; Gonzalez et al., 2010). Thus, an isotonic solution may be helpful in reducing the additional stress that a hypotonic bathing solution places on the already perturbed vegetable membranes. Gonzalez et al. (2010) found that isotonic solutions help maintain membrane integrity in fresh onion tissues, and reported that the onion cell membranes ruptured between 50 and 60 °C. However, no published literature reported the rupture temperature of carrot cell membranes, nor the impact of osmotic solutions on carrot texture. In the current study, the isotonic concentration of carrot tissue was determined and the effects of immersing carrot slices in the isotonic solution on the texture of the tissue at elevated temperatures were studied.

It is known that blanching vegetables at low-temperatures (generally 50–70 °C) prior to high-temperature processing may improve the texture of the final products (Anthon and Barrett, 2006; Bartolome and Hoff, 1972; Vu et al., 2004; Wu and Chang, 1990). Preheating at these conditions activates pectin methylesterase (PME), resulting in extensive pectin de-esterification. This increases the chances for formation of ionically cross-linked pectin complexes and reduces the β-elimination reaction. Vu et al. (2004) reported that preheating carrots in distilled and demineralized water at 50–70 °C for 20–40 min prior to high temperature heating could slow texture degradation, increase the final value of hardness and lower the activation energy of texture degradation. In the current study, one preheating condition (60 °C for 20 min) was selected. According to published literature, preheating carrots at 60 °C for 20 min prior to high heat treatment should enhance the vegetable texture (Stanley et al., 1995; Vu et al., 2004). The preheating step also mimics the microwave processing in our further study for pre-packaged carrot dices, where we always preheat the samples to a certain temperature before microwave heating (Tang et al., 2008). Since calcium salt is a commonly used firming agent, the effects of calcium on carrot texture were also investigated in this study. The calcium solution concentration used was chosen based on the FDA regulation for canned carrot products (0.036% Ca in the final products), which is far lower than that used in the published literature (Rastogi et al., 2008; Smout et al., 2005).

In addition to investigating the kinetics of texture degradation of carrot dices in solutions with different calcium levels, the goal of microbial/enzyme inactivation vs. texture retention of carrots during thermal processing predicted by the degradation models was also discussed. This study provides useful information for determining thermal processing parameters for pre-packaged diced carrots, and for predicting quality changes related to texture during processing.

2. Materials and methods

2.1. Sample preparation

Fresh carrots (Bolthouse Farms, Inc., Bakersfield, CA) purchased from a local grocery store were diced into 12.7 × 12.7 × 6 mm pieces. In order to prepare consistent samples, carrots with similar length and diameter were selected (the portion between 4 and 6 cm from the root tip and 4 and 8 cm from the stem), only those dices that contained a core (xylem) size of 4–7 mm diameter and 6 mm height were used in the study. A specially designed cylindrical aluminum test cell with a net inner space of 50 mm in diameter and 8 mm in depth was used to hold meaningful sample sizes for texture analyses while minimizing the come-up time during heating. Eight carrot dices (6.5 ± 0.2 g) were placed in the test cell, then 6 mL solution was added and the test cell was sealed. An o-ring fitting placed in the groove between the base and lid was used to provide a hermetic seal.

2.2. Determination of isotonic concentration of carrot tissue

The concentration of isotonic solution was determined according to the method of Saltveit (2002). Briefly, fresh cut carrot dices were rinsed twice in distilled water for about 1 min each time, blotted dry, and 20 randomly selected pieces were transferred to each tared Petri-dish. The Petri-dishes were placed into a plastic tub lined with wet paper towels and held overnight (ca. 18 h) at room temperature. Twenty-five mL of mannitol solution (0–0.4 M) was added to each dish and shaken at 60 cycles/min for a time period of either 20, 60, 120 or 240 min, and then the solutions were vacuum aspirated off. The weight gain or loss by the carrot pieces bathed in the mannitol solutions was recorded. The concentration of mannitol where there was no net weight gain or loss of the carrot pieces after the initial weight gain was taken to be the isotonic concentration of the carrot tissue. Experiments were done in triplicates.

2.3. Thermal treatment

Carrot dices immersed in different solutions in each test cell were heated in a thermostated oil bath (Model HAAKE DC 30, Thermo Electron Corp., Waltham, MA, USA) at 80, 90, 100 and 110 °C for different time intervals. The temperatures were selected based on the heat-sensitivity of carrot texture and pasteurization conditions. Four solutions were investigated in this study:

(1) Double distilled water.
(2) Isotonic mannitol solution.
(3) 0.1% $CaCl_2$ solution (equivalent to containing 0.035% calcium).
(4) 1.4% $CaCl_2$ solution (equivalent to containing 0.5% calcium).

For the two calcium levels, the former was chosen according to the FDA regulation which allows addition of "up to 0.036% calcium to canned carrots" while the latter was within the range of the most commonly used calcium concentrations (0.5–2.0% $CaCl_2$) added to vegetable products in published reports (Rastogi et al., 2008; Smout et al., 2005). Since the diffusion of calcium into carrot tissues before heating may affect their texture, the time that was sufficient for sample preparation which resulted in little texture change was pre-determined as the equilibration time to keep the consistency of the initial carrot texture. According to our preliminary tests, all samples in the test cells were equilibrated in solutions for 10 min before heating.

To evaluate the effects of preheating on carrot texture, test cells containing carrot dices with different solutions were preheated in a thermostated water bath (Model HAAKE DC 30, Thermo Electron Corp., Waltham, MA, USA) at 60 °C for 20 min, then immediately transferred to an oil bath (Model HAAKE DL 30, Thermo Electron Corp., Waltham, MA, USA) and followed by a high heat treatment with preset temperatures ranging from 80 to 110 °C. After heating, samples were cooled in ice water for 2 min, drained, equilibrated to room temperature and texture analysis was conducted. Unless otherwise stated, the zero-time samples were the samples at the end of the come-up time for the high heat.

2.4. Texture measurement

The firmness of treated carrot dices was determined using a TA.XT2 Texture analyzer (Stable Micro Systems Ltd., Godalming, UK) fitted with a 25 mm diameter aluminum cylinder probe following the methods described by Lemmens et al. (2009). The samples were compressed to 70% strain at a cross head speed of 1 mm/s. For each test, one piece of sample was placed under the probe. The peak force of the first compression cycle of the sample was marked

the maximum force and recorded as the indicator of firmness. At least 6 replicates were measured for each treatment condition. Statistical analysis (Student's *t*-test) was performed using Matlab 7.0 (MathWorks Inc., Natick, MA, USA), and the significance level α was set as 0.05.

2.5. Kinetic analysis

A general form of the reaction equation is expressed as:

$$-\frac{dC}{dt} = kC^n \tag{1}$$

where C is a quality index or concentration of a chemical compound, t is the reaction time, k is the rate constant and n is the order of reaction.

Following the integration of both sides of Eq. (1), it becomes:

$$\text{For } n = 1, \quad kt = -\ln\frac{c}{c_0} \tag{2}$$

$$\text{For } n \neq 1, \quad kt = \left(\frac{1}{n-1}\right)\left(\frac{1}{C^{n-1}} - \frac{1}{C_0^{n-1}}\right) \tag{3}$$

The texture property is presented as the fraction of texture change C, which provides an accurate way to know the extent of quality change at any time t and can be expressed as:

$$C = \frac{F_t - F_\infty}{F_0 - F_\infty} \tag{4}$$

where F_0 is the initial firmness at time 0; F_t is the firmness at time t; F_∞ is the firmness at equilibrium or the nonzero maximum retainable firmness after prolonged heating (Rizvi and Tong, 1997). In the current study, the F_∞ value was obtained by measuring the texture of carrot after 24 h heating at 80 and 90 °C, 12 h heating at 100 and 110 °C, that the firmness was no longer changed with respect to time (within the standard deviation) (Rizvi and Tong, 1997).

A graph of t against $\frac{1}{C^{n-1}}$ ($n \neq 1$) or ln C ($n = 1$) was plotted and linear regression was performed. The best-fitted reaction order was determined by comparing the coefficient of determination (r^2) for all the treated temperatures. The rate constant (k) of samples at each temperature was determined accordingly.

The temperature dependence of the reaction rate constant can by represented by the Arrhenius equation:

$$\ln k = \ln A - \frac{E_a}{RT} \tag{5}$$

where A is a pre-exponential factor, E_a is activation energy (J/mol), R is the universal gas constant (8.314 J/K mol), and T is the temperature (K). Thus, by plotting ln k against $1/T$ should result in a straight line, and the activation energy (E_a) can be calculated by the slope of the line ($E_a = 8.314 \times$ Slope).

3. Results and discussion

3.1. Determination of the isotonic solution for the carrot tissue and its effect on carrot texture

Apparent weight gain of carrot dices was observed after the first 20 min in all mannitol solutions, from 0.0 to 0.4 M (Fig. 1A). After 60 min, carrot dices in the 0.3–0.4 M solutions began to lose weight; the higher the mannitol concentration, the more the weight loss. For those in 0.0–0.1 M solutions, the carrot dices kept gaining weight for up to 4 h. Only in the 0.2 M solution, carrot dices did not have any weight change after the initial weight gain. The initial weight gain was due to the rapid ion diffusion of carrot tissue when it was immersed in the aqueous solution, until the rate of ion leakage reached a relatively constant point where there was neither weight gain nor loss. A better understanding of the isotonic concentration of carrot tissue can be seen in Fig. 1B, the weight change with regard to solution concentration. For the 0.2 M solution, the weight gain of carrot dices maintained 10% when compared to the fresh samples for up to 4 h without any change. Therefore the concentration of the solution was considered to be isotonic with respect to the carrot tissue. Saltveit (2002) also found the concentration of isotonic mannitol solution for mature green tomato tissue to be 0.2 M.

The texture of carrot dices heated in isotonic solution under temperatures ranging from 80 to 110 °C up to 2 h was compared with those heated in double distilled water (Fig. 2). At each temperature, no significant difference was found in the texture between samples immersed in isotonic solution and distilled water at the corresponding heating time. It is likely that carrot cell membranes were completely ruptured at the test temperatures (80–110 °C) in the thermal treatments. Gonzalez et al. (2010) observed complete loss of membrane integrity of onion cells at 60 °C and above.

3.2. Effects of preheating and calcium treatment on carrot texture

The effect of preheating on carrot texture was investigated by heating at 60 °C for 20 min before subjecting the samples to high temperatures ranging from 80 to 110 °C in distilled water or calcium solutions (0.1% and 1.4%). As shown in Fig. 3, preheating carrot dices at 60 °C for 20 min changed their initial texture very little, with texture expressed by maximum force at 260 ± 22 N in distilled water compared to those fresh ones at 274 ± 23 N. However, the preheating step retarded the texture degradation of carrots in

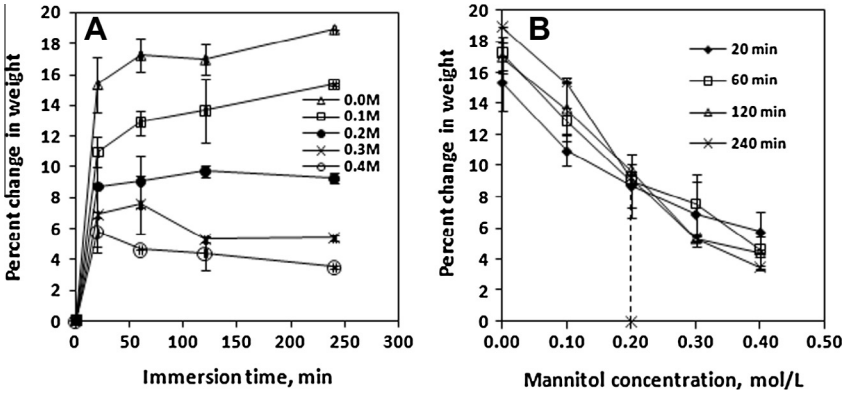

Fig. 1. Percent change in weight of excised carrot pericarp discs in 25 mL of aqueous solution at different mannitol concentrations. The percent change in weight is related to (A) time in solution, or (B) solution concentration. Data are the means ± SD ($n \geqslant 3$).

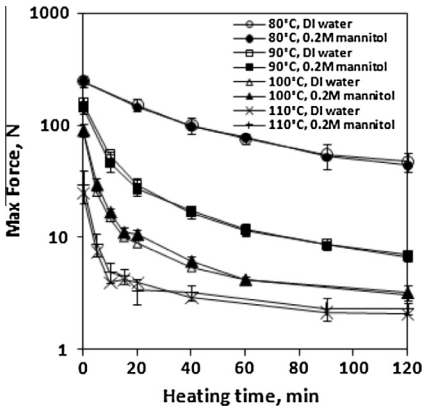

Fig. 2. Thermal degradation of texture of carrot dices in isotonic solution or distilled water at different temperatures. Data are the means ± SD ($n \geqslant 6$).

each solution at the subsequently high temperature; and the higher calcium concentration, the greater the decrease in degradation rate. The most possible reason is that PME activity greatly increased at the mild preheating temperature, resulting in the increase of demethylation of pectins and the number of calcium-binding sites. This allows increased calcium cross-linking of the pectin chains and improved texture. A more apparent texture improvement due to preheating was observed in samples at 90, 100 and 110 °C. But regardless of pre-treatment, at 110 °C carrots lost most of their texture during the first 5–10 min. Nearly 80% loss in firmness took place within the come-up time (5 min) in those immersed in DI water or 0.1% calcium solution, and around 70% texture loss in firmness occurred within 10 min heating in those immersed in 1.4% calcium solution. Anthon et al. (2005) also observed the texture of diced tomatoes was reduced to about 1/3 of the original level after 1 min at 100 °C with very little additional change over the next 4 min.

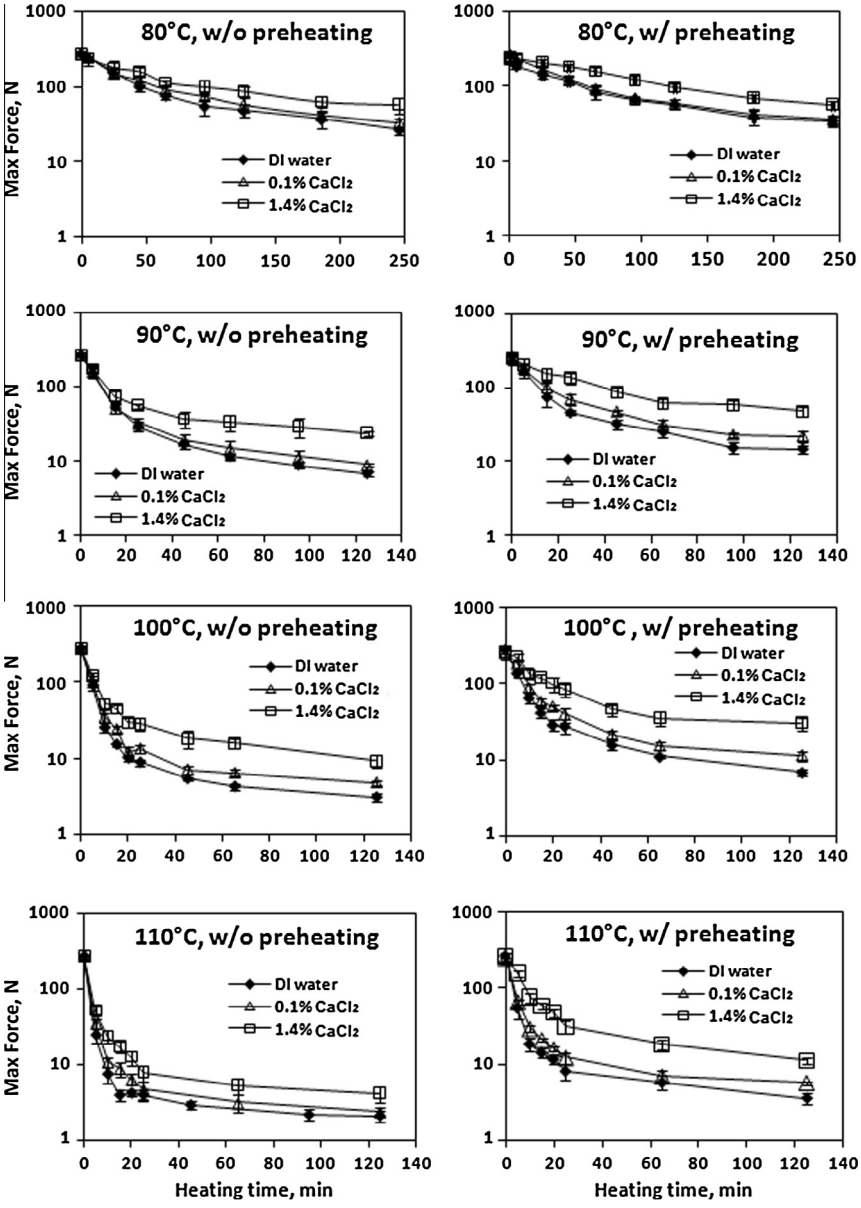

Fig. 3. Effect of preheating (60 °C for 20 min) on the thermal texture degradation of carrots at different temperatures. For samples without preheating, time-zero equals raw materials before heating; for preheated samples, time-zero represents the time preheated samples were beginning to be subjected to high temperature heat. Data are the means ± SD ($n \geqslant 6$).

Table 1
Coefficients of determination (r^2) from kinetic order (n) models for carrot texture degradation at four temperatures.

Temp (°C)	Solution	r^2 for different kinetic orders (n) with preheating treatment		
		1	1.5	2
80	DI water	0.921	0.979	0.989
	0.1% $CaCl_2$	0.928	0.985	0.990
	1.4% $CaCl_2$	0.997	0.971	0.939
90	DI water	0.846	0.955	0.975
	0.1% $CaCl_2$	0.887	0.961	0.977
	1.4% $CaCl_2$	0.918	0.961	0.981
100	DI water	0.784	0.975	0.990
	0.1% $CaCl_2$	0.787	0.938	0.980
	1.4% $CaCl_2$	0.800	0.887	0.936
110	DI water	0.513	0.930	0.979
	0.1% $CaCl_2$	0.669	0.922	0.992
	1.4% $CaCl_2$	0.809	0.970	0.992

The reaction order was determined to select the texture degradation model with the best fit. According to the maximum force–time curve of carrot texture which is clearly non-linear, the reaction order n in Eq. (1) was set to 1, 1.5 and 2, and the coefficients of determination (r^2) were obtained according to the methods described previously and listed in Table 1. One can observe that at 80 °C, the kinetic model of the three reaction orders all work well for carrots immersed in each solution, but the 1st order reaction did not fit well at high temperatures. Considering each temperature and immersion solution, the 2nd order reaction had the highest r^2 values in all cases, thus it is the best fitting model for the degradation of carrot texture. The plot of $1/C$ vs. time of preheated carrots at different temperature (Fig. 4) shows a well-fitting linear regression of the model when $n = 2$ and demonstrates that the degradation of carrot texture followed a 2nd order reaction. This indicates complex chemical reaction mechanisms that resulted in the texture changes of carrots during heating, which could have been affected by many factors such as the amount of cell wall and middle lamella, physical structures, and enzymes. The 2nd order reaction model of this study is different from those obtained by Smout et al. (2005) and Vu et al., 2004, 2006 who used a modified 1st order reaction model to analyze carrot texture degradation. However, in those studies, they did not assess the suitability of other reaction orders. In addition, they did not experimentally determine F_∞ values but rather estimated those values through regression analyses.

The estimated relative final values of the texture parameter (F_∞/F_0) are shown in Fig. 5. The F_∞/F_0 values decreased with increasing temperature, from 0.037 ± 0.006 to 0.008 ± 0.002 for samples immersed in distilled water and from 0.129 ± 0.025 to 0.023 ± 0.004 for those immersed in 1.4% $CaCl_2$ solution, due to decreasing F_∞ values with increasing temperature. The carrots immersed in 1.4% $CaCl_2$ solution had the highest F_∞/F_0 while samples in distilled water exhibited the lowest values at each corresponding temperature. This can be explained by the fact that the F_∞ value increased with increasing calcium concentration due to the firming effects of calcium. Smout et al. (2005) also reported a general decreasing trend of the final texture values of carrot discs with higher temperature processing in distilled and demineralized water.

The reaction rate constant (k) of carrot texture degradation behaved in the opposite way, as illustrated in Fig. 6. As the temperature increased, the degradation rate constant increased from 0.035 min^{-1} to 1.453 min^{-1} for samples immersed in distilled water, and from 0.018 min^{-1} to 0.360 min^{-1} for those immersed in 1.4% $CaCl_2$ solution. The degradation rate constant started to increase sharply when the temperature was higher than 90 °C for samples without added calcium, while for samples with added calcium, this sharp increase occurs when the temperature exceeded 100 °C. It is likely that higher temperature facilitated the breakdown of the pectins, which resulted in texture softening. However,

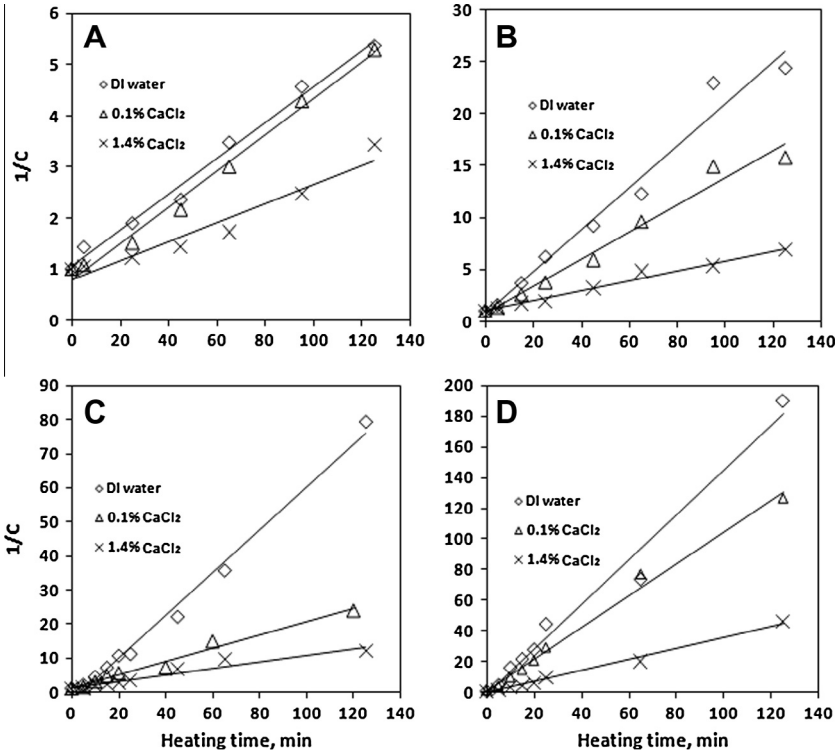

Fig. 4. Plot of 1/C vs. time at different temperatures ($n = 2$). A: 80 °C; B: 90 °C; C: 100 °C; D: 110 °C; all the samples were preheated at 60 °C for 20 min. The line is the regression to the 2nd order model.

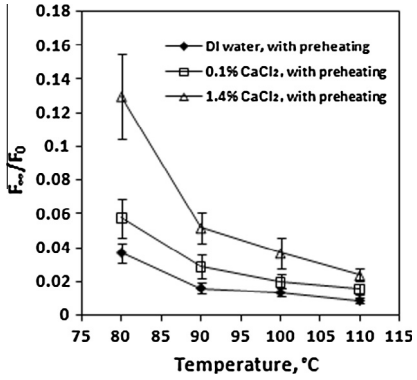

Fig. 5. The final texture value (F_∞/F_0) of pretreated carrot dices as a function of temperature in different solutions. Data are the means ± SD ($n \geqslant 6$).

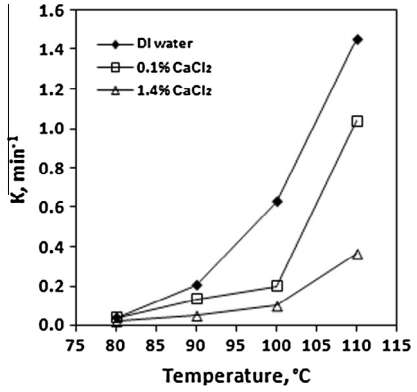

Fig. 6. Reaction rate k of preheated carrot dices as a function of temperature in different solutions.

increasing temperature could increase the calcium diffusion into the carrot tissue which might have a firming effect on texture. The degradation rate constant of samples at each temperature ranged in the following order: lowest for those immersed in 1.4% $CaCl_2$ solution, followed by 0.1% $CaCl_2$ solution, and lastly the highest ones were in distilled water. This increase of the degradation rate constant among samples in the three solutions was more evident at high temperatures than at low temperatures. At 110 °C, the degradation rate constant of carrots in 1.4% $CaCl_2$ is 1.453 min^{-1}, almost 4 times smaller than those in distilled water, and 3 times smaller than those in 0.1% $CaCl_2$ solution. The reason again is due to the firming effects of calcium, which positively correlates to the calcium concentration within a certain level depending on the free calcium-binding sites in the carrot pectin chains, and therefore reduces the degradation of carrot texture.

The Arrhenius equation accurately described the temperature dependence of the reaction rate constants, and can be used to correlate the reaction rate constant in food systems over typical temperature ranges associated with preservation processes and storage of food products. The Arrhenius plot ($\ln k$ vs. $1/T$, the reciprocal absolute temperature) of carrot texture degradation is given in Fig. 7. The activation energy (E_a), which represents the least amount of energy needed for a chemical reaction to take place, was calculated by the Arrhenius plot based on Eq. (5). The calculated E_a was 138.9 kJ/mol for carrots immersed in distilled water, 118.3 kJ/mol for samples in 0.1% $CaCl_2$ solution and 108.0 kJ/mol for samples in 1.4% $CaCl_2$ solution. Vu et al. (2004) reported activation energies for texture degradation of carrots in distilled and demineralized water of 117.56 kJ/mol using the conversion fraction model, while Paulus and Saguy (1980) obtained E_a values of 92–117 kJ/mol for three different carrot varieties during thermal softening.

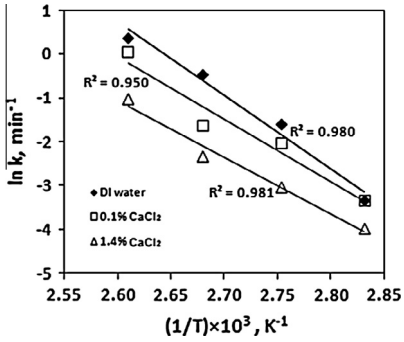

Fig. 7. Arrhenius plot of texture degradation rates of carrots immersed in different solutions with pretreatment.

3.3. Quality versus microbial/enzyme inactivation

Kinetic models for quality degradation are required to predict quality changes for different processes targeted to achieve an equivalent level of microbial safety, thus helping optimizing process conditions. For pasteurization of diced carrot products, target bacterium and processing requirements are decided based on product storage temperature and desired shelf-life. For mild pasteurization of low-acid foods to provide a shelf life of 10 days maximum at 5 °C, traditionally a 6 log or 6 D reduction of *Listeria monocytogenes* (*L. monocytogenes*) is recommended; while for a longer shelf life (up to 6 weeks at 5 °C), a 6 log reduction of non-proteolytic *Clostridium botulinum* (NP *C. botulinum*) type E spores is required (ECFF, 2006; Vervoort et al., 2012).

In addition to pathogen inactivation, pasteurization also aims to inactivate enzymes that cause quality loss during storage. For carrots, polygalacturonase (PG) is the most heat resistant texture-related enzyme which is involved in the degradation of pectins and results in texture loss (Anthon and Barrett, 2002). Anthon and Barrett (2002) reported an E_a-value of PG in carrot juice as 411 kJ/mol and a reaction rate (k) of 0.0087 s^{-1} at 80 °C.

Gaze et al. (1989) determined the heat resistance of two strains of *L. monocytogenes* in carrots and obtained a z-value of 6.70–7.04 °C; later they studied the thermal resistance of NP *C. botulinum* type E spores in carrot from 75 to 90 °C and reported a z-value of 9.84 °C (Gaze and Brown, 1990).

The processing times to achieve 4 and 6 log reductions of NP *C. botulinum* type E spores and *L. monocytogenes* in carrots and 90% inactivation of PG under different processing temperatures were calculated based on the thermal kinetic data obtained from the publications mentioned above, and are presented in Fig. 8. For the quality of carrots, texture is selected as the parameter and the quality retention in this study focuses on carrot dices immersed in 0.1% $CaCl_2$ solution. The times needed to achieve 20%, 50% and 80% texture loss under each temperature were calculated from the kinetic texture degradation model obtained previously and are illustrated in Fig. 8. Since the texture of carrots degraded very quickly at 110 °C (nearly 80% texture loss during the come-up time), the temperature of 110 °C was not considered as a processing temperature for pasteurization and was not included in Fig. 8.

Appropriate processing conditions may be chosen based on the data in Fig. 8 using a graphic approach as suggested by Holdsworth and Simpson (2008). That is, process conditions for carrots can be selected above the dashed lines in Fig. 8 to ensure adequate reduction of target bacteria (NP CB type E spores or LM) or 90% of inactivation of PG, but below the solid lines to avoid a chosen level of carrot texture degradation. It is clear from Fig. 8A that very short

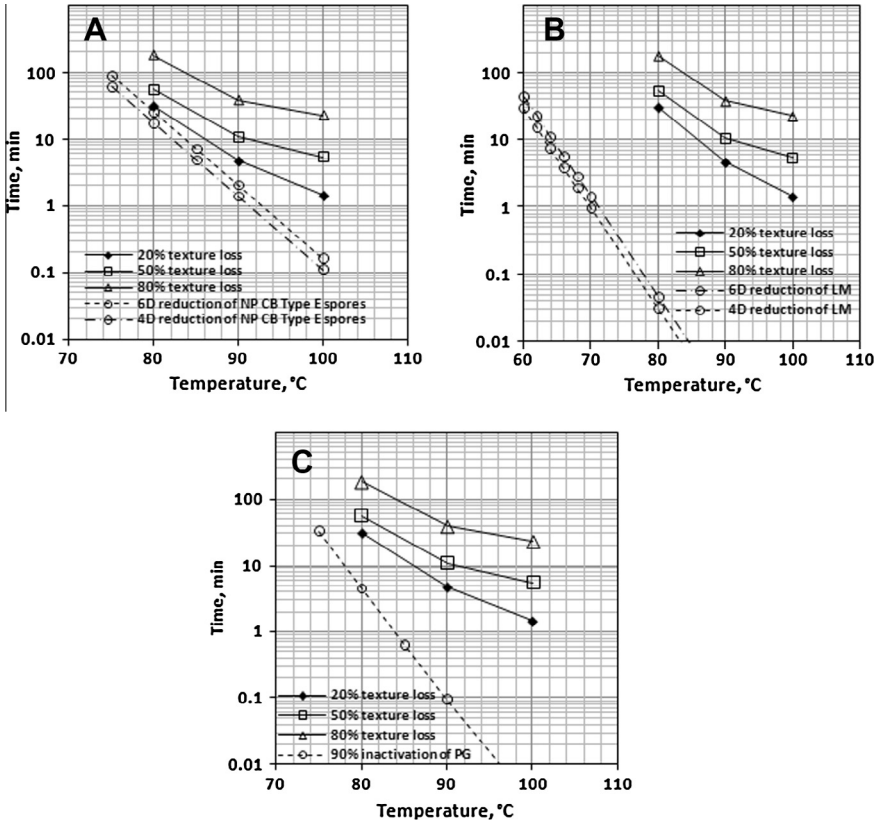

Fig. 8. TDT curves of target bacteria, enzymes vs. carrot texture. A: Non-proteolytic *C. botulinum* type E spores; B: *L. monocytogenes*; C: Polygalacturonase enzyme. Data for NP CB type E spores are from Gaze and Brown (1990), LM are from Gaze et al. (1989) and PG are from Anthon and Barrett (2002). The dash lines represent either 4D (6D) reduction on microbial load, or 90% inactivation of enzyme activity.

process times (e.g., 2–10 min at 90 °C or 0.2–5 min at 100 °C) should be used to achieve 6 log reduction in NP C. *botulinum* type E spores while still retaining 50% of the original texture in diced carrots. For control of LM, up to 20 min can be used at 80 °C to retain 80% texture while achieving over 90% of PG inactivation (Fig. 8B and C). More curves for other quality parameters could be added to this figure to give a comprehensive quality retention-microbial/enzyme inactivation chart to facilitate the selection of appropriate process conditions.

4. Conclusions

Thermal degradation of carrot texture with pretreatments (preheating and calcium addition) under investigated pasteurization conditions follows a 2nd order reaction. Data presented in this paper also show that carrot dices immersed in isotonic solution during preheating treatment (60 °C for 20 min) followed by high temperature heating did not help maintain their texture, compared to those immersed in distilled water. The obtained kinetic model of carrot texture was used to draw the temperature–time plots for texture retention of carrots during thermal processing, along with its microbial/enzyme inactivation curves. These provide a useful graphic approach for selecting appropriate processing conditions for pasteurization processes of carrot products, and also for predicting texture retention of thermally processed carrots.

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