Food Science and Biotechnology (2023) 32:1057–1065
https://doi.org/10.1007/s10068-023-01247-8

RESEARCH ARTICLE

Heat penetration and quality analysis of retort processed vegetables for home meal replacement foods

Seung Su Yu[1] · **Han Soo Ahn**[1] · **Sung Hee Park**[1]

Received: 12 September 2022 / Revised: 24 November 2022 / Accepted: 4 January 2023 / Published online: 25 January 2023

Abstract
Heat penetration characteristics of different vegetable products were investigated during retort processing. A custom-developed variable temperature retort-sterilizer allowed us to test the following target retort-temperatures; 120, 130, 140, and 150 °C, combined with the following holding times: 1, 3, 5, 7 min. Radish showed the highest heating rate (9.56 ± 0.21 °C/min) among the tested vegetables, including radish, carrot, and potato. Textural qualities of retort-processed vegetables showed a close correlation with thermal dose. Hardness of potato was 3.07 ± 0.07 N after retort processing at 120 °C for 7 min, with a thermal dose of 127 ± 7 k °C s. Better hardness (3.72 ± 0.06 N) was obtained after retort processing at 150 °C for 3 min, with a thermal dose of 122 ± 6 k °C s. The data reported herein indicate that retort temperature should be appropriately controlled for different vegetable products based on their specific heat-penetration characteristics.

Keywords Retort · Temperature · Heat penetration · Vegetable · Texture

Introduction

Consumer demand for home meal-replacement (HMR) products has been continuously increasing over the past decade in association with several sociological factors, such as the increase in the number of single-person and double-income households (Choi and Kim, 2020). HMR foods are classified into frozen-stored, refrigerated, and shelf-stable products. Shelf-stable HMR products are convenient to store and consume. Retort treatment is essential to prevent microbial spoilage—and the resulting danger to human health—while producing shelf-stable HMR products.

In retort processing, a ready-meal package or a food packed in a metal container is heated with either saturated steam or hot water under a specific temperature (116–121.1 °C) for a certain time (Choi et al., 2013; Giraldo Gil et al., 2020). Although conventionally, retort-processed products have a proven track record for microbial safety, significant quality loss is unavoidable upon intense heating over a long time and subsequent thermal abuse (Park et al., 2014). Quality attributes of retort-processed food mainly depend on the characteristics of heat penetration of food products, based on their physicochemical and thermal properties. Specifically, textural quality of vegetable products easily deteriorates during retort processing, as intensive heat treatment results in the rupture of cell membranes and the loss of turgor pressure, leading to the loss of texture (Day et al., 2012; Greve et al., 1994a; 1994b). It has been proposed that rapid retort treatment might minimize quality degradation of food matrices by using fast temperature rising (Singh et al., 2015). However, in our best knowledge, there was no studies to evaluate the heat penetration characteristics of vegetable products during retort processing at different target temperatures and holding times.

This study investigated the effect of various target retort temperatures (120–150 °C) and holding times (1–7 min) for heat penetration characteristics of different vegetables (radish, carrot, potato). Subsequently, quality attributes of vegetable products were compared in consideration of heat penetration analysis to provide appropriate retort processing condition for shelf stable vegetable based HMR product.

✉ Sung Hee Park
sunghpark@seoultech.ac.kr

Seung Su Yu
tmdtn1016@seoultech.ac.kr

Han Soo Ahn
hansu1428@seoultech.ac.kr

[1] Department of Food Science and Technology, Seoul National University of Science and Technology, Seoul 01811, South Korea

Materials and methods

Sample preparation

Three different vegetables were selected; namely, radish, carrot, and potato, which are popularly used for the elaboration of HMR products in Korea. All tested vegetables were purchased at the same local market, where these vegetable were supplied by the same local farm, such that biological variation among raw samples was expected to be minimal. Vegetable samples of regular and uniform cylindrical shape and two sizes (small: 15 mm in diameter and 40 mm long, and large: 25 mm in diameter and 40 mm long) were obtained using a cork borer (Fisher scientific, Pittsburgh, PA, USA). K-Type thermocouples 0.51 mm in diameter (TFAL/CY-020, Omega engineering, Stamford, CT, USA) were inserted into the geometric center of the small and large samples of each vegetable for the heat penetration study. Circular hole (diameter: 10 mm) was made on the central position of retort pouch using pouch puncher (C-5.1, Ecklund-Harrison Technologies, Metairie, LA, USA) and then thermocouple was installed into geometric center of the small and large vegetable samples. Punctured hole of retort pouch (180×260 mm) was hermitically sealed with rubber gasket and thermocouple receptacle accessories (C-26 and C-27, Ecklund-Harrison Technologies, Metairie, LA, USA). Water (500 mL) was added as soup in the stew-type vegetable contained HMR product. For example, in the experiment with radish, the retort pouch contained one small radish sample with a thermocouple inserted in it, one large radish sample with a thermocouple inserted in it, six radishes for quality analysis and 500 mL of water.

Variable temperature retort sterilizer

The customized variable temperature retort sterilizer was equipped with a steam boiler (60 kW), a steam reheating unit, a sterilization chamber, a counter-pressure air compressor, a cooling water system, a pressure transducer, a pressure regulator, and a data acquisition system. The steam boiler generated saturated steam (100 °C) and was then reheated to generate high temperature steam (120–150 °C) under an equivalent pressure (101.3–400 kPa) calculated considering a steam table and vapor generation in the retort pouch. In turn, the counter-pressure air compressor controlled the pressure of the sterilization chamber to prevent rupture of the HMR pouch, while the K-type thermocouple and the pressure transducer measured the temperature and pressure data, which were recorded in the data acquisition system. Finally, after retort sterilization, the water pump injected the cooling water into the sterilization chamber for rapid cooling.

Retort treatment

Vegetable samples in the retort pouch were sterilized at four different target temperatures, i.e., 120, 130, 140, or 150 °C, for four different holding times, namely, 1, 3, 5, and 7 min. The K-type thermocouples measured the temperature changes of each small and large vegetable sample and water (i.e., soup). Rupture of the HMR pouches was prevented by maintaining the equivalent pressure of the retort chamber using the counter-pressure air compressor. After retort processing, HMR pouches were rapidly cooled down to room temperature (20 °C) using the water-spray cooling system.

Heat penetration study

Temperature come-up time (CUT) and heating rate

CUT was estimated as the time required for initial temperature (20 °C) of the vegetable samples to rise to target retort temperature. Heating rate (°C/min) was calculated using total temperature increase and CUT of retort as shown in Eq. (1).

$$\text{Heating rate } (^\circ\text{C/min}) = \frac{T_t - T_i}{\text{CUT}} \tag{1}$$

where T_i is initial temperature (°C), T_t is target temperature (°C). CUT is temperature come-up time to target temperature.

Thermal dose

Thermal dose (T_d, °C s) was adopted here to numerically estimate the extent of sample thermal exposure during retort processing, and was calculated using Eq. (2).

$$T_d = \int_{t_i}^{t_f} T dt = \frac{(T_0 + T_1) \cdot \Delta t}{2} + \frac{(T_1 + T_2) \cdot \Delta t}{2} + \frac{(T_2 + T_3) \cdot \Delta t}{2} + \cdots + \frac{(T_{n-1} + T_n) \cdot \Delta t}{2} \tag{2}$$

where T_d was estimated by the integration of temperature history (T) over processing time (s). This equation was numerically calculated using the trapezoidal numerical integration in the MATLAB software (Version 7.9.0.529, Mathworks Inc., MA, USA).

Analysis of thermophysical properties

The characteristics of heat penetration during thermal processing of foods are closely related to their thermophysical properties (Singh et al., 2015). Here, the following thermophysical properties of the tested vegetable were analyzed:

specific heat, thermal conductivity, thermal diffusivity and density. These Analyses were conducted at the Energy Research Center of Ajou University.

Analysis of quality attributes

Texture

The hardness of each vegetable sample was measured using the puncture force of a texture analyzer (TA-XT2i, Stable Micro Systems, Surrey, UK) equipped with a cylindrical probe (2 mm, p/2) to axially puncture each sample to a depth of 7 mm with a cross head speed of 5 mm/s. Maximum puncture force was determined for the hardness of the vegetable samples.

Color

The color of vegetable samples was measured using a handheld colorimeter (CR-10; Konica Minolta Sensing Inc., Sakai, Osaka, Japan). As there were 16 experimental treatment combinations (four levels of target temperature and four levels of holding time), only a representative color coordinate of each vegetable was selected for data expression. Thus, *L** (brightness), *a** (redness) and *b** (yellowness) was adopted for radish, carrot, and potato, respectively.

Statistical analysis

The significance of treatment effects was determined by analysis of variance (ANOVA) and Fisher's least significant difference test for multiple comparisons at a 95% confidence interval. All measurements were repeated three times. All statistical analyses were performed using the SAS software (version 9.1.3; SAS Institute, Cary, NC, USA).

Results and discussion

Heat penetration studies

Temperature profiles, temperature come-up time and heating rate

Temperature profiles of water and the tested vegetables (i.e., radish, carrot, and potato) during retort processing at target temperatures of 120, 130, 140, and 150 °C are shown in Fig. 1. In all tested pouches, water showed the fastest temperature increase by small and large samples, consistently with a previous study which reported that liquid products showed faster temperature increase than solid products (Singh et al., 2015).

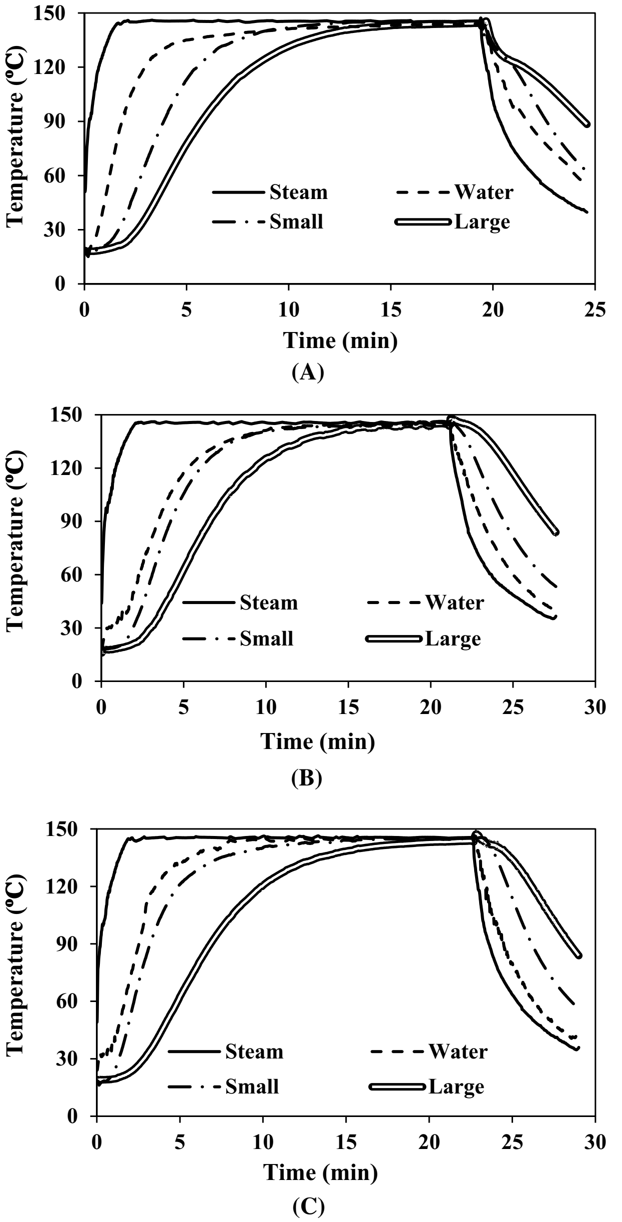

Fig. 1 Temperature histories of (**a**) radish, (**b**) carrot and (**c**) potato during retort processing at different target retort temperatures

In the retort pouch, heat is transferred into a liquid product from steam and then it is delivered to a solid product. Liquids have higher volume than solids; thus, liquids have a greater surface area for heat transfer. This explains the earlier temperature rise of water than those of the tested vegetable, among which, radish showed the shortest temperature come-up time followed by carrot and potato. Specifically, large samples of radish, carrot and potato showed the temperature come-up time of 12.55 ± 0.28, 14.04 ± 0.27, and 15.23 ± 0.10 min at a target temperature of 140 °C, respectively, corresponding to heating rates of 9.56 ± 0.21, 8.55 ± 0.16 and 7.88 ± 0.05 °C/min, respectively. In thermal processing, the rate of heat transfer mainly depends on the thermophysical properties of the food, such as specific heat, thermal conductivity, and density (Barbosa-Cánovas et al., 2014; Verheyen et al., 2021). Particularly, the specific heat of radish, carrot and potato are 3.81, 3.49 and 3.42 J/g·K at 25 °C, respectively. Although potato shows the lowest specific heat, here it showed the lowest heating rate during retort processing at 140 °C, likely due to potato starch gelatinization at high temperature during retort processing. As gelatinization enthalpy of starch ranges from 0.807 to 1.591 J/g during the heating process (Coral et al., 2009; Jo and Park, 2019), starch gelatinization actually absorbs heat from potato, rather than causing a temperature increase. In turn, carrot has a slightly lower specific heat (Δ0.32 J/g K) than radish; however, radish showed a faster temperature increment than carrot. The specific heat of vegetables depends on the moisture content; thus, when vegetable products lose moisture, their specific heat decreases (Fakayode and Ojoawo, 2019). Radish, carrot and potato moisture contents are 93.64 ± 0.71, 88.08 ± 1.00, and 79.15 ± 1.25%, respectively (Table 1). We propose that the high specific heat of radish decreased with moisture loss during retort processing, whereby, it eventually showed the highest heating rate among the three tested vegetable products. Therefore, thermophysical properties, including, moisture content, density, specific heat, thermal conductivity and thermal diffusivity, should be carefully considered while estimating heat penetration for vegetable products (Table 2).

Thermal dose (°C s)

The thermal doses of vegetable samples for the different target-retort temperatures tested for different holding times are shown in Table 3. As sample volume has a significant influence on temperature increase and the resulting thermal dose, small and large samples were compared. The results of this comparative analysis showed that small vegetables had higher thermal dose than large samples, and that the

Table 1 Thermal properties of different vegetables during various target retort temperatures

	Radish	Carrot	Potato
Moisture content (%)	93.64 ± 0.71^{a}	88.08 ± 1.00^{b}	79.15 ± 1.25^{c}
Density (g/cm^{3})	0.97 ± 0.07^{b}	1.03 ± 0.01^{ab}	1.11 ± 0.06^{a}
Thermal conductivity (W/(m K))	0.65 ± 0.04^{a}	0.64 ± 0.07^{a}	0.57 ± 0.05^{a}
Thermal diffusivity (m^{2}/s)	0.17 ± 0.01^{a}	0.18 ± 0.02^{a}	0.15 ± 0.01^{a}
Specific heat (J/g K)	3.81 ± 0.16^{a}	3.49 ± 0.24^{ab}	3.42 ± 0.08^{b}

Table 2 Temperature come-up time (min) and heating rate (°C/min) of different vegetables during various target retort temperatures

	Size	Target temperature (°C)	Sample		
			Radish	Carrot	Potato
Temperature come-up time (min)	Small	120	7.42 ± 0.21^{e}	8.53 ± 0.24^{d}	9.21 ± 0.12^{c}
		130	8.34 ± 0.17^{d}	9.56 ± 0.32^{c}	10.31 ± 0.33^{b}
		140	9.25 ± 0.12^{c}	10.26 ± 0.21^{b}	10.50 ± 0.17^{b}
		150	10.62 ± 0.27^{b}	11.37 ± 0.17^{a}	11.61 ± 0.20^{a}
	Large	120	12.29 ± 0.24^{f}	13.05 ± 0.26^{e}	14.24 ± 0.25^{cd}
		130	12.40 ± 0.13^{f}	13.29 ± 0.22^{e}	14.43 ± 0.13^{c}
		140	12.55 ± 0.28^{f}	14.04 ± 0.27^{d}	15.23 ± 0.10^{b}
		150	13.12 ± 0.18^{e}	15.37 ± 0.17^{b}	16.55 ± 0.33^{a}
Heating rate (°C/min)	Small	120	13.48 ± 0.38^{A}	11.73 ± 0.33^{D}	10.86 ± 0.14^{FG}
		130	13.19 ± 0.27^{AB}	11.52 ± 0.39^{DE}	10.67 ± 0.34^{G}
		140	12.97 ± 0.18^{B}	11.70 ± 0.25^{D}	11.43 ± 0.19^{DE}
		150	12.25 ± 0.31^{C}	11.44 ± 0.17^{DE}	11.20 ± 0.19^{EF}
	Large	120	8.14 ± 0.16^{F}	7.66 ± 0.15^{HI}	7.03 ± 0.12^{J}
		130	8.87 ± 0.09^{C}	8.28 ± 0.14^{EF}	7.63 ± 0.07^{I}
		140	9.56 ± 0.21^{B}	8.55 ± 0.16^{D}	7.88 ± 0.05^{G}
		150	9.91 ± 0.13^{A}	8.46 ± 0.10^{DE}	7.86 ± 0.16^{GH}

$^{a–f}$Means (± Standard deviation) with a different letter within the same size (small or large) of all the tested vegetables are significantly different for come-up time ($P < 0.05$)

$^{A–J}$Means (± Standard deviation) with a different letter within the same size (small or large) of all the tested vegetables are significantly different for heating rate ($P < 0.05$)

Table 3 Thermal dose (k °C s) of different vegetables during various target retort temperatures

Sample	Size	Target temperature (°C)	Holding time (min)			
			1	3	5	7
Radish	Small	120	$75\pm1^{\mathrm{g}}$	$91\pm1^{\mathrm{f}}$	$105\pm1^{\mathrm{g}}$	$120\pm1^{\mathrm{h}}$
		130	$87\pm2^{\mathrm{ef}}$	$103\pm2^{\mathrm{e}}$	$119\pm1^{\mathrm{ef}}$	$135\pm2^{\mathrm{fg}}$
		140	$88\pm2^{\mathrm{def}}$	$105\pm2^{\mathrm{cde}}$	$122\pm2^{\mathrm{de}}$	$140\pm2^{\mathrm{ef}}$
		150	$95\pm8^{\mathrm{cde}}$	$113\pm8^{\mathrm{c}}$	$132\pm7^{\mathrm{c}}$	$150\pm8^{\mathrm{d}}$
	Large	120	$60\pm1^{\mathrm{H}}$	$75\pm1^{\mathrm{G}}$	$90\pm1^{\mathrm{F}}$	$105\pm1^{\mathrm{G}}$
		130	$71\pm3^{\mathrm{FG}}$	$86\pm3^{\mathrm{EF}}$	$103\pm3^{\mathrm{E}}$	$119\pm3^{\mathrm{F}}$
		140	$74\pm3^{\mathrm{EF}}$	$91\pm3^{\mathrm{DE}}$	$108\pm3^{\mathrm{DE}}$	$125\pm3^{\mathrm{EF}}$
		150	$78\pm4^{\mathrm{DEF}}$	$96\pm4^{\mathrm{D}}$	$114\pm4^{\mathrm{D}}$	$133\pm4^{\mathrm{D}}$
Carrot	Small	120	$81\pm3^{\mathrm{fg}}$	$96\pm3^{\mathrm{ef}}$	$110\pm3^{\mathrm{fg}}$	$125\pm3^{\mathrm{gh}}$
		130	$87\pm5^{\mathrm{def}}$	$104\pm5^{\mathrm{de}}$	$120\pm5^{\mathrm{e}}$	$136\pm5^{\mathrm{f}}$
		140	$95\pm4^{\mathrm{cde}}$	$113\pm4^{\mathrm{cd}}$	$130\pm4^{\mathrm{cd}}$	$147\pm4^{\mathrm{de}}$
		150	$114\pm7^{\mathrm{b}}$	$133\pm7^{\mathrm{b}}$	$151\pm8^{\mathrm{b}}$	$170\pm9^{\mathrm{b}}$
	Large	120	$65\pm3^{\mathrm{GH}}$	$80\pm3^{\mathrm{FG}}$	$95\pm3^{\mathrm{F}}$	$110\pm3^{\mathrm{G}}$
		130	$72\pm4^{\mathrm{FG}}$	$88\pm4^{\mathrm{E}}$	$104\pm4^{\mathrm{E}}$	$120\pm4^{\mathrm{F}}$
		140	$80\pm2^{\mathrm{DE}}$	$97\pm2^{\mathrm{D}}$	$115\pm2^{\mathrm{D}}$	$132\pm2^{\mathrm{DE}}$
		150	$95\pm6^{\mathrm{B}}$	$114\pm7^{\mathrm{B}}$	$132\pm7^{\mathrm{B}}$	$150\pm7^{\mathrm{B}}$
Potato	Small	120	$98\pm8^{\mathrm{c}}$	$112\pm7^{\mathrm{cd}}$	$127\pm7^{\mathrm{cde}}$	$142\pm7^{\mathrm{def}}$
		130	$96\pm3^{\mathrm{cd}}$	$114\pm5^{\mathrm{c}}$	$127\pm2^{\mathrm{cde}}$	$144\pm3^{\mathrm{def}}$
		140	$108\pm7^{\mathrm{b}}$	$126\pm7^{\mathrm{b}}$	$143\pm7^{\mathrm{b}}$	$160\pm7^{\mathrm{c}}$
		150	$130\pm9^{\mathrm{a}}$	$149\pm9^{\mathrm{a}}$	$167\pm9^{\mathrm{a}}$	$186\pm9^{\mathrm{a}}$
	Large	120	$83\pm8^{\mathrm{CD}}$	$97\pm7^{\mathrm{D}}$	$112\pm7^{\mathrm{D}}$	$127\pm7^{\mathrm{DE}}$
		130	$82\pm1^{\mathrm{D}}$	$98\pm2^{\mathrm{D}}$	$113\pm1^{\mathrm{D}}$	$129\pm0^{\mathrm{DE}}$
		140	$90\pm3^{\mathrm{BC}}$	$107\pm3^{\mathrm{C}}$	$124\pm3^{\mathrm{C}}$	$141\pm3^{\mathrm{C}}$
		150	$103\pm6^{\mathrm{A}}$	$122\pm6^{\mathrm{A}}$	$140\pm6^{\mathrm{A}}$	$158\pm6^{\mathrm{A}}$

$^{\mathrm{a-g}}$Means (± Standard deviation) with a different letter within the same holding time of all the tested small vegetables (radish, carrot, potato) are significantly different ($P<0.05$)

$^{\mathrm{A-H}}$Means (± Standard deviation) with a different letter within the same holding time of all the tested large vegetables (radish, carrot, potato) are significantly different ($P<0.05$)

temperature of small products reached the target retort temperatures earlier and, consequently, were exposed to target sterilization temperatures for longer holding times. For example, in retort processing for 1 min at 140 °C, the thermal dose of small carrot samples (95 k °C s) was larger than that for large samples (80 k °C s).

As for quality attributes, a lower thermal dose minimizes the thermal abuse of vegetable products during the sterilization process (Park et al., 2014). With respect to large carrot samples, the thermal dose for retort treatment for 1 min at 140 °C was 80 k °C s, the same as that for retort treatment for 3 min at 120 °C, implying that a rapid treatment at higher retort temperature would result in lesser thermal abuse of foods, compared to a longer treatment at a lower retort temperature. Thermal dose should show a high correlation with quality attributes; thus, the relation between them was analyzed in more detail in connection with two quality attributes, namely, texture and color.

Quality analysis

Texture

Textural hardness was compared among the three tested vegetables after different target temperatures of retort processing (Table 4). Hardness of all tested vegetables decreased with increasing temperature and holding time. Textural degradation of thermally-treated vegetables is reportedly due to several effects, including, breakdown of cellular membranes, rupture of the cell wall and enzymatic and non-enzymatic transformations leading to disassembly of pectin structure (Anthon et al., 2005; Greve et al., 1994a; 1994b; Peng et al., 2014; Sila et al., 2008). Overall, the effect of holding time was more significant at lower target temperature. For example, in large carrot samples, hardness was 1.41 ± 0.06 and 0.96 ± 0.15 at 120 °C for 1 and 7 min, respectively, decreasing by 32% during the longer holding time. In contrast, at 140 °C, carrot hardness

Table 4 Hardness (N) of different vegetables during various target retort temperatures

	Size	Target temperature (°C)	Holding time (min)			
			1	3	5	7
Radish	Small	Control	2.27 ± 0.76^{a}			
		120	0.83 ± 0.04^{bc}	0.78 ± 0.16^{bcd}	0.63 ± 0.13^{def}	0.46 ± 0.05^{gh}
		130	0.79 ± 0.04^{bc}	0.73 ± 0.02^{bcde}	0.60 ± 0.04^{efgh}	0.62 ± 0.08^{ef}
		140	0.63 ± 0.04^{ef}	0.62 ± 0.02^{efg}	0.51 ± 0.04^{fgh}	0.46 ± 0.03^{h}
		150	0.84 ± 0.09^{bc}	0.75 ± 0.17^{bcde}	0.85 ± 0.13^{b}	0.70 ± 0.10^{cde}
	Large	Control	2.88 ± 0.19^{a}			
		120	1.72 ± 0.21^{b}	1.49 ± 0.16^{c}	1.15 ± 0.23^{d}	0.87 ± 0.13^{ef}
		130	0.69 ± 0.07^{fghi}	0.61 ± 0.05^{ghi}	0.57 ± 0.05^{hi}	0.55 ± 0.05^{i}
		140	0.92 ± 0.06^{e}	0.88 ± 0.13^{ef}	0.79 ± 0.15^{efg}	0.51 ± 0.03^{i}
		150	0.75 ± 0.10^{efgh}	0.67 ± 0.09^{ghi}	0.64 ± 0.12^{ghi}	0.58 ± 0.04^{hi}
Carrot	Small	Control	4.34 ± 0.30^{a}			
		120	1.18 ± 0.13^{d}	1.17 ± 0.14^{d}	0.85 ± 0.13^{fg}	0.82 ± 0.10^{fg}
		130	1.43 ± 0.20^{bc}	1.12 ± 0.02^{de}	0.86 ± 0.13^{fg}	0.70 ± 0.09^{g}
		140	1.51 ± 0.06^{b}	1.23 ± 0.08^{cd}	0.95 ± 0.08^{ef}	0.73 ± 0.08^{g}
		150	1.11 ± 0.09^{de}	1.10 ± 0.05^{de}	0.86 ± 0.09^{fg}	0.75 ± 0.06^{fg}
	Large	Control	5.16 ± 0.06^{a}			
		120	1.41 ± 0.06^{b}	1.17 ± 0.08^{c}	0.89 ± 0.06^{fg}	0.96 ± 0.15^{def}
		130	1.17 ± 0.02^{c}	0.82 ± 0.06^{gh}	0.79 ± 0.08^{gh}	0.80 ± 0.15^{gh}
		140	1.02 ± 0.03^{d}	0.88 ± 0.04^{fg}	0.90 ± 0.03^{efg}	0.88 ± 0.04^{fg}
		150	1.02 ± 0.09^{de}	0.89 ± 0.05^{fg}	0.80 ± 0.04^{gh}	0.72 ± 0.03^{h}
Potato	Small	Control	5.76 ± 0.19^{a}			
		120	3.48 ± 0.25^{d}	3.24 ± 0.10^{ef}	3.10 ± 0.04^{fg}	2.99 ± 0.02^{g}
		130	3.91 ± 0.09^{b}	3.87 ± 0.16^{bc}	3.81 ± 0.06^{bc}	3.75 ± 0.03^{bc}
		140	3.77 ± 0.10^{bc}	3.71 ± 0.06^{c}	3.72 ± 0.03^{c}	3.34 ± 0.05^{de}
		150	3.02 ± 0.11^{g}	2.95 ± 0.08^{g}	2.68 ± 0.07^{h}	2.50 ± 0.06^{i}
	Large	Control	6.03 ± 0.03^{a}			
		120	3.78 ± 0.06^{de}	3.51 ± 0.10^{f}	3.14 ± 0.15^{g}	3.07 ± 0.07^{g}
		130	4.04 ± 0.20^{c}	4.00 ± 0.13^{c}	3.97 ± 0.08^{c}	3.95 ± 0.12^{cd}
		140	4.26 ± 0.06^{b}	4.10 ± 0.08^{bc}	4.07 ± 0.12^{c}	3.61 ± 0.04^{ef}
		150	3.73 ± 0.16^{e}	3.72 ± 0.06^{e}	2.83 ± 0.12^{h}	2.70 ± 0.06^{h}

$^{a-i}$Means (±Standard deviation) with a different letter within the each size (small or large) for respective vegetables (radish, carrot, or potato) are significantly different ($P<0.05$)

Control control vegetables were cooked at 100 °C for 20 min

was 1.02 ± 0.03 and 0.88 ± 0.04 at 1 and 7 min, respectively, in which case, hardness reduction over the longer holding time was 14%. Previous researchers reported that retort-processed carrots showed a rapid initial softening followed by a much lower softening rate, in which case, carrot texture degradation consisted of two simultaneous first-order reactions at different reaction rates during thermal softening (Bourne, 1989; Huang and Bourne, 1983; Peng et al., 2014). It is reasonable to discuss hardness results in relation with thermal dose, as the texture of vegetables is mainly influenced by thermal exposure. Hardness of large carrot samples was 0.89 ± 0.10 N at 120 °C for 5 min, and the corresponding thermal dose was 95 ± 3 k °C s. When retort temperature increased to 140 °C and was held at that point for 3 min, hardness and thermal dose of large carrot samples were 0.88 ± 0.04 N and 97 ± 2 k °C s, respectively. Similar thermal dose (95-97 k °C s) and hardness (0.88–0.89 N) were observed upon retort processing at 120 °C for 5 min and at 140 °C for 3 min. In the retort-treated large potato samples, hardness and thermal dose were 3.07 ± 0.07 N and 127 ± 7 k °C s at 120 °C for 7 min, respectively. Increasing retort temperature to 150 °C for 3 min increased the textural hardness of large potato samples to 3.72 ± 0.06 N, while slightly reducing the thermal dose to 122 ± 6 k °C s. These findings suggested that a shorter treatment time at a higher retort temperature produces similar changes in harness and thermal dose to those resulting from a longer treatment time at a lower retort temperature.

Color

Table 5 shows the representative color values of the tested vegetables. L^*, a^*, and b^* values were selected for radish, carrot, and potato as representative color values, respectively. L^* values of retort-treated radish samples decreased as a function of increasing temperature and holding time. These findings are consistent with a report by Liu et al. (2021), according to which, thermal treatment at temperatures over 80 °C significantly reduced the whiteness of radish.

Large, fresh carrot samples showed a mean a^* value of 26.90 ± 2.31 which decreased to a minimum mean value of 14.77 ± 0.58 upon retort processing at 150 °C for 7 min. Similarly, several previous studies reported reduced a^* values in thermally-treated carrots and their subsequent darkening due to loss of heat-sensitive carotenes (Leadley et al., 2008; Patras et al., 2008; Rawson et al., 2010; Sulaeman et al., 2001). Color is an important quality index influencing consumer acceptance of processed carrots (Kreutzmann et al., 2007; Rawson et al., 2010). This study showed that retort treatment at temperatures higher than 140 °C is not beneficial for color attributes of carrot.

Retort processing of potato samples caused tissue browning when target temperature and holding time increased. Browning of potato may be estimated by increasing a^* values after thermal processing (Gökmen and Senyuva, 2006; Kou et al., 2019). For example, in large potato samples, a^* values increased from 3.53 ± 0.32 to 6.70 ± 0.36 when temperature increased from 120 °C to 150 °C and a 1-min

Table 5 External color (L^*, a^*) of different vegetables during various target retort temperatures

Sample	Size	Target temperature (°C)	Holding time (min)			
			1	3	5	7
Radish (L^* value)	Small	Control	34.77 ± 0.76^{bc}			
		120	42.43 ± 1.25^{a}	41.90 ± 0.75^{a}	41.63 ± 1.29^{a}	35.87 ± 1.10^{b}
		130	35.90 ± 0.36^{b}	33.93 ± 0.40^{c}	30.23 ± 0.55^{e}	31.73 ± 0.31^{d}
		140	30.93 ± 0.99^{de}	30.20 ± 1.25^{e}	27.87 ± 0.46^{f}	28.53 ± 0.67^{f}
		150	30.00 ± 0.46^{e}	25.37 ± 0.40^{g}	23.37 ± 1.26^{h}	23.07 ± 0.78^{h}
	Large	Control	37.67 ± 0.67^{a}			
		120	36.17 ± 0.91^{b}	35.70 ± 0.89^{b}	32.50 ± 1.47^{cd}	32.53 ± 1.40^{cd}
		130	36.57 ± 0.86^{ab}	32.17 ± 0.68^{d}	33.73 ± 1.02^{c}	26.53 ± 0.42^{f}
		140	28.50 ± 1.13^{e}	26.93 ± 1.32^{f}	26.33 ± 0.90^{fg}	26.40 ± 0.46^{f}
		150	25.80 ± 0.36^{fg}	24.93 ± 0.45^{g}	22.40 ± 0.17^{h}	19.27 ± 0.29^{i}
Carrot (a^* value)	Small	Control	24.07 ± 1.27^{a}			
		120	22.40 ± 2.07^{b}	20.17 ± 0.25^{c}	14.23 ± 0.60^{gh}	13.63 ± 1.17^{h}
		130	16.37 ± 0.29^{ef}	17.67 ± 1.12^{de}	17.53 ± 0.55^{de}	18.67 ± 0.31^{d}
		140	17.93 ± 1.21^{d}	17.37 ± 0.40^{de}	15.23 ± 0.55^{fg}	14.43 ± 0.87^{gh}
		150	18.47 ± 0.47^{d}	18.37 ± 0.67^{d}	14.53 ± 0.21^{gh}	13.70 ± 0.98^{h}
	Large	Control	26.90 ± 2.31^{a}			
		120	20.80 ± 1.40^{ef}	20.57 ± 0.45^{f}	20.13 ± 0.64^{fg}	21.07 ± 1.03^{ef}
		130	25.17 ± 0.35^{abc}	24.83 ± 0.87^{bc}	24.03 ± 1.32^{cd}	19.53 ± 2.04^{fgh}
		140	25.93 ± 0.87^{ab}	22.57 ± 0.40^{de}	18.27 ± 1.42^{gh}	17.80 ± 0.40^{hi}
		150	16.10 ± 0.75^{ij}	15.37 ± 0.55^{j}	15.27 ± 0.76^{j}	14.77 ± 0.58^{j}
Potato (a^* value)	Small	Control	3.57 ± 1.02^{gh}			
		120	3.03 ± 0.47^{h}	4.00 ± 0.62^{efg}	3.90 ± 0.40^{fg}	4.17 ± 0.06^{efg}
		130	4.37 ± 0.06^{ef}	4.20 ± 0.26^{efg}	4.63 ± 0.06^{de}	5.07 ± 0.35^{cd}
		140	5.43 ± 0.35^{c}	5.63 ± 0.21^{c}	5.60 ± 0.30^{c}	7.57 ± 0.32^{a}
		150	6.30 ± 0.40^{b}	6.50 ± 0.26^{b}	6.87 ± 0.25^{b}	7.57 ± 0.21^{a}
	Large	Control	3.00 ± 0.35^{i}			
		120	3.53 ± 0.32^{hi}	3.77 ± 0.15^{gh}	3.80 ± 0.30^{fgh}	4.07 ± 0.81^{fgh}
		130	4.10 ± 0.20^{fgh}	4.10 ± 0.17^{fgh}	4.30 ± 0.17^{efg}	4.47 ± 0.31^{ef}
		140	4.93 ± 0.12^{e}	5.70 ± 0.10^{de}	6.33 ± 0.61^{cd}	7.17 ± 0.51^{ab}
		150	6.70 ± 0.36^{bc}	7.40 ± 0.36^{a}	7.83 ± 0.84^{a}	7.63 ± 0.35^{a}

$^{a-j}$Means (± Standard deviation) with a different letter within the same size (small or large) of respective samples (radish, carrot, or potato) are significantly different ($P < 0.05$)

control: control vegetables were cooked at 100 °C for 20 min holding time was used for treatment. Furthermore, when target temperature increased to 140 °C, a^* values were 4.93 ± 0.12 and 7.17 ± 0.15 at 1 and 7 min holding time, respectively. Thermally-treated potatoes showed increasing brown color formation with increasing severity of heat treatment, i.e., higher retort processing temperature (Kou et al., 2019). The formation of a brown color in thermally-treated potato is due to the accumulation of polymeric compounds such as melanoidins (Kwak and Lim, 2004; Rawson et al., 2010). However, a retort temperature of 150 °C resulted in sharp discoloration of potatoes. In the scope of this study, recommended retort condition is 140 °C & 1 min for all the tested vegetables (radish, carrot, potato) for both microbial safety and quality attributes. Therefore, the recommended temperature for thermal processing should be specific for each different vegetable product.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10068-023-01247-8.

Acknowledgements This work was supported by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through High Value-added Food Technology Development Program, funded by Ministry of Agriculture, Food and Rural Affairs (MAFRA) (321042-03).

Funding Funding was provided by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) (Grant Number 321042-03).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Anthon GE, Blot L, Barrett DM. Improved firmness in calcified diced tomatoes by temperature activation of pectin methylesterase. Journal of Food Science. 70: C342–C347 (2005)

Barbosa-Cánovas GV, Medina-Meza I, Candoğan K, Bermúdez-Aguirre D. Advanced retorting, microwave assisted thermal sterilization (MATS), and pressure assisted thermal sterilization (PATS) to process meat products. Meat Science. 98: 420–434 (2014)

Bourne MC. Applications of chemical kinetic theory to the rate of thermal softening of vegetable tissue. In: Jen, J.J. (Ed.), Quality Factors of Fruits and Vegetables, ACS Symp. Ser. 405. American Chemical Society, Washington, USA pp. 98–110 (1989)

Choi E, Kim BH. A comparison of the fat, sugar, and sodium contents in ready-to-heat type home meal replacements and restaurant foods in Korea. Journal of Food Composition and Analysis. 92: 103524 (2020)

Choi SH, Cheigh CI, Chung MS. Optimization of processing conditions for the sterilization of retorted short-ribpatties using the response surface methodology. Meat Science. 94: 95–104 (2013)

Coral DF, Pineda-Gómez P, Rosales-Rivera1 A, Rodriguez-Garcia ME. Determination of the gelatinization temperature of starch presented in maize flours. Journal of Physics: Conference Series. 167: 012057 (2009)

Day L, Xu M, Øiseth SK, Mawson R. Improved mechanical properties of retorted carrots by ultrasonic pre-treatments. Ultrasonics Sonochemistry. 19: 427–434 (2012)

Fakayode OA, Ojoawo OO. Moisture dependent thermal properties of selected vegetables in Akwa Ibom State, Nigeria. Research in Agricultural Engineering. 65: 56–62 (2019)

Giraldo Gil A, González OAO, Sepúlveda LFC, Torres PNA. Venting stage experimental study of food sterilization process in a vertical retort using temperature distribution tests and energy balances. Case Studies in Thermal Engineering. 22: 100736 (2020)

Jo YJ, Park SH. Evaluation of energy efficacy and texture of ohmically cooked noodles. Journal of Food Engineering. 248: 71–79 (2019)

Gökmen V, Şenyuva HZ. Study of colour and acrylamide formation in coffee, wheat flour and potato chips during heating. Food Chemistry. 99: 238–243 (2006)

Greve LC, McArdle RN, Gohlke JR, Labavitch JM. Impact of heating on carrot firmness. Changes in cell wall components. Journal of Agricultural and Food Chemistry. 42: 2900–2906 (1994a)

Greve LC, Shackel KA, Ahmadi H, McArdle RN, Gohlke JR, Labavitch JM. Impact of heating on carrot firmness: contribution of cellular turgor. Journal of Agricultural and Food Chemistry. 42: 2896–2899 (1994b)

Huang YT, Bourne MC. Kinetics of thermal softening of vegetables. Journal of Texture Studies 14: 1–9 (1983)

Leadley C, Tucker G, Fryer P. A comparative study of high pressure sterilization and conventional thermal sterilisation: quality effects in green beans. Innovative Food Science and Emerging Technologies. 9: 70–79 (2008)

Park SH, Balasubramaniam VM, Sastry SK. Quality of shelf-stable low-acid vegetables processed using pressure-ohmic-thermal sterilization. LWT—Food Science and Technology. 57: 243–252 (2014)

Patras A, Tiwari BK, Brunton NP, Butler F. Modelling the effect of different sterilisation treatments on antioxidant activity and colour of carrot slices during storage. Food Chemistry. 114: 484–491 (2008)

Peng J, Tang J, Barrett DM, Sablani SS, Powers JR. Kinetics of carrot texture degradation under pasteurization conditions. Journal of Food Engineering. 122: 84–91 (2014)

Rawson A, Koidis A, Patras A, Tuohy MG, Brunton NP. Modelling the effect of water immersion thermal processing on polyacetylene levels and instrumental colour of carrot disks. Food Chemistry. 121: 62–68 (2010)

Sila DN, Duvetter T, Roeck AD, Verlent I, Smout C, Moates GK, Hills BP, Waldron KK, Hendrickx M, Loey AV. Texture changes of processed fruits and vegetables: potential use of high-pressure processing. Trends in Food Science & Technology. 19: 309–319 (2008)

Kou X, Lia R, Zhang L, Ramaswamy H, Wang S. Effect of heating rates on thermal destruction kinetics of *Escherichia coli* ATCC25922 in mashed potato and the associated changes in product color. Food Control. 97: 39–49 (2019)

Kreutzmann S, Christensen LP, Edelenbos M. Investigation of bitterness in carrots (*Daucus carota* L.) based on quantitative chemical and sensory analyses. LWT—Food Science and Technology. 41: 193–205 (2007)

Kwak EJ, Lim SI. The effect of sugar, amino acid, metal ion, and NaCl on model Maillard reaction under pH control. Amino Acids. 27: 85–90 (2004)

Li X, Liu SQ. Effect of pH, xylose content and heating temperature on colour and flavour compound formation of enzymatically hydrolysed pork trimmings. LWT—Food Science and Technology. 150: 112017 (2021)

Singh AP, Singh A, Ramaswamy HS. Modification of a static steam retort for evaluating heat transfer under reciprocation agitation thermal processing. Journal of Food Engineering. 153: 63–72 (2015)

Sulaeman A, Keeler L, Giraud DW, Taylor SL, Wehling RL, Driskell JA. Carotenoid content and physicochemical and sensory characteristics of carrot chips deep-fried in different oils at several temperatures. Journal of Food Science. 66: 1257–1264 (2001)

Verheyen D, Altind O, Skipnese D, Erdogdud F, Skårae T, Van Impe JF. Thermal inactivation of Listeria monocytogenes in the Shaka agitated reciprocal retort: Influence of food matrix rheology and fat content. Food and Bioproducts Processing. 125: 22–36 (2021)