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Variability in quality of white and green beans during in-pack sterilization

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Abstract

Non-uniformity in process quality was investigated during in-pack thermal sterilization of food products. This was accomplished through the combined application of the Monte Carlo procedure and a reliable mathematical method for process evaluation. Despite the large coefficients of variation found, the optimum quality process could be designed. The influence of the statistical variability of heating rate index on the retention of green beans' color was studied and an optimum temperature range was found between 125 and 135 °C. The variability in hardness of sterilized white beans, resulting from uncertainties of the combined effect of heating rate index and initial hardness of beans, was also evaluated by simulation. In this case, an optimum global temperature range between 120 and 135 °C was found, independently of the rotation, F_0 value and surface heat transfer coefficient assumed.

Keywords: Sterilization; Pre-packaged foods; Quality retention; Variability; Green beans; White beans

1. Introduction

Adequate evaluation of a process technology's impact on food safety and quality is essential for its viability and market acceptance (Smout, 1999). In the field of food sterilization, the minimum required thermal process should be designed to assure the desired microbial safety, and consequently produce minimal effects on product quality (Banga, Balsa-Canto, Moles, & Alonso, 2003; Lund, 1975). Both heating costs and product quality losses increase as the process time is lengthened (Banga et al., 2003; Clealand & Robertson, 1985).

Variations during thermal processing can arise naturally, even when operating the retort in a standard controlled manner. A sterilization process can be affected by a large number of factors, which are not known accurately (stochastic factors), and are related to: (i) variability in heat transferred to the food product (e.g. retort temperature, rotational speed, surface heat transfer coefficient), (ii) variability in product and container characteristics (e.g. composition of products, product homogeneity, product thermophysical properties, such as thermal diffusivity, initial product temperature, headspace volume, can fill weight), and (iii) variability in parameters of microbial or quality kinetics (k, E_a, D, z, initial spore load, initial quality). Uncertainty in any of these factors will result in an uncertainty in the delivered lethality, with consequent effects on the quality level (Clealand & Robertson, 1985; Hicks, 1961; Nicolai,

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Nomenclature

$(-a/b)$	color retention of green beans
adj.f_h	adjusted f_h value according to APNS method (min)
ANOVA	analysis of variance
c	level number for F_0 value
C/C_0	hardness retention
C_0	initial hardness value (kg/m^2)
C_f	final hardness value (kg/m^2)
CV	coefficient of variation (%)
d	level number for surface heat transfer coefficient
$D_{121.1\,°C}$	decimal reduction time at 121.1 °C (min)
e	level number for temperature
E_a	activation energy (kJ/mol)
F_0	sterilization value (min)
f_h	heating rate index (min)
h	surface heat transfer coefficient (W/(m^2 °C))
h_{fin}	finite surface heat transfer coefficient (W/(m^2 °C))
h_{inf}	infinite surface heat transfer coefficient (W/(m^2 °C))
j_h	heating lag factor (dimensionless)
j_{hB}	heating lag factor corrected according to Ball's 42% rule
$k_{110\,°C}$	degradation rate constant at 110 °C (min^{-1})
LSD	least significant difference
MSE	mean square error
n	sample size
s	standard deviation
T	holding temperature (°C)
t	studentized probability function
$\bar{x}$	average
z	temperature dependence of the decimal reduction time (°C)
α	level of significance

1994; Smout, 1999, Smout, Ávila, Van Loey, Hendrickx, & Silva, 2000a, 2000b; Varga, 1998).

Consequently, commercially sterilized food products are over processed to include additional safety margins that account for inherent variability in sterilization. This inherent variability cannot be avoided, however it is possible to estimate it, in order to develop adequate process assessment (Hicks, 1961; Nicolai, 1994; Varga, 1998). Hicks (1961) was one of the first authors who published work about the nature of uncertainties in canning processes. He discussed the uncertainties in lethality resulting from uncertainties in both heat penetration and bacteriological data. Powers, Pratt, Carmon, Somaatmadja, and Fortson (1962) reported coefficients of variation (CV) for the F_0 values of six products studied ranging from 16.3% to 57.4%, where the variance in heat penetration parameters was considered. Subsequently, many other authors (Hayakawa, De Massaguer, & Trout, 1988; Herndon, 1971; Jones, Pflug, & Blanchett, 1980; Lenz & Lund, 1977; Lund, 1978; Patino & Heil, 1985; Robertson & Miller, 1984; Smout et al., 2000a, 2000b) have studied the influence of variability of various parameters on process lethality.

Variations in quality retention from container to container, in a retort batch, can be so large that it might be difficult, or even impossible, to design an optimal process (Smout, Banadda, Van Loey, & Hendrickx, 2003). On this subject, only Smout et al. (2003) reported the non-uniformity in surface quality (color of green peas) during thermal processing. No other research studies on the effect of uncertainties on quality retention of foods have been reported yet.

Therefore, in this framework, the objective of this study was to investigate non-uniformity in quality retention during in-pack thermal processing of foods. A feasible statistical approach is proposed to assess process optimization design. Two case studies are presented: the influence of the heating rate index (f_h) variability on the retention of green beans' color, and the influence of the combined effect of heat penetration rate (f_h) and initial hardness variability on white beans final hardness retention.

2. Materials and methods

2.1. White beans

Dried white beans were obtained from a canning company and stored dry at 15 °C. Before processing, the white beans were soaked in distilled water at 15 °C for at least 16 h. The heat penetration trials were carried out in a pilot water cascading retort (Barriquand Steriflow retort. Paris, France). The beans were placed in 370 mL glass jars (84 mm height, 75 mm diameter, and 2.6 mm thickness) filled with distilled water and the retort operated in both static and end-over-end rotary modes. The heat penetration parameters, heating rate index (f_h value), lag factor (j_h value), and corrected lag factor according to Ball's 42% rule (j_{hB} value) were calculated using the Ball's (1923) formula method. Adjusted f_h and j_h values were estimated using a semi-empirical approach, the Apparent Position Numerical

Solution (APNS) method (Noronha, Hendrickx, Van Loey, & Tobback, 1995).

The kinetics of thermal softening of white beans were determined using cans of 71 mm diameter and 27 mm height, heated in a thermostated oil bath. The hardness of 100 g of heat-treated white beans were measured with an industrial Tenderometer unit (FMC, model 4011). The thermal softening kinetics were analyzed using a fractional conversion model (first order irreversible reaction) (Levenspiel, 1999).

The procedures applied, the parameters assumed and results obtained are described in detail in Ávila, Smout, Silva, and Hendrickx (1999).

Table 1 presents the values used to generate 300 random (normally distributed) adjusted f_h values and initial hardness (C_0) values, using Monte Carlo simulations.

2.2. Green beans

Broken green beans, produced in Belgium, were purchased frozen in a local supermarket and were all provided from the same lot number. The green beans were kept frozen until used in the experiments. Immediately before each experiment, the green beans were defrosted under warm tap water (20 °C) for 5 min, and then drained off during 2 min. Green beans' heat penetration rate was determined by similar procedures applied to white beans case study. In this case only the retort static mode of operation was used (Ávila, 2001; Ávila et al., 1999).

Values used in simulations are presented in Table 1.

2.3. Approach to assess process quality optimization

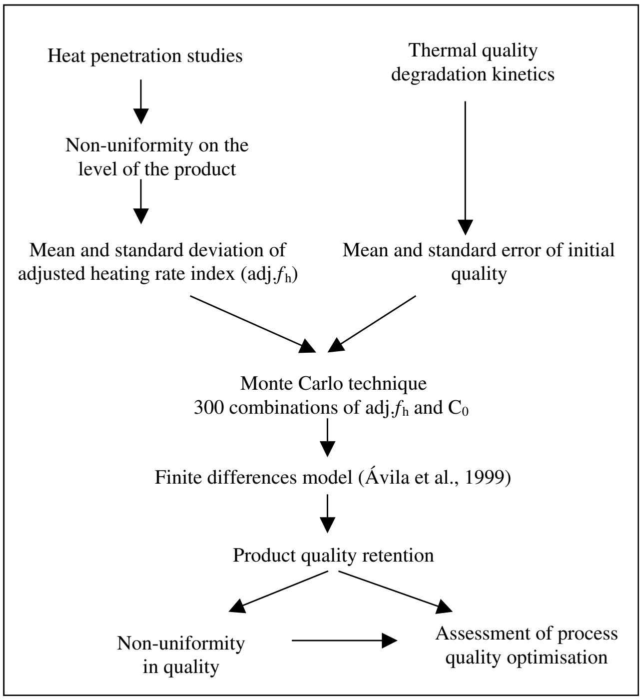

Fig. 1. Schematic representation of the approach used in the case study with white beans.

The approach used in this work is schematically illustrated in Fig. 1 for the white beans case study. Smout et al. (2000b), also using the Monte Carlo technique, developed a similar approach to evaluate the non-uniformity in lethality delivered to the food product, resulting from the combined effect of the variability of product heating characteristics and retort temperature. In the present study, the non-uniformity in quality (texture) retention of sterilized white beans was investigated by combining the non-uniformity on the level of the product (heat penetration data) with uncertainties on the initial hardness (C_0) of the beans. The mean and standard deviation of the adjusted heating rate index (adj.f_h) were combined with the mean and standard error of the initial quality, through Monte Carlo simulations. Three hundred random combinations of adjusted f_h values and C_0 were generated, assuming normal distribution of both factors. The number of simulations (300) was chosen to assure

Table 1
Values used in the simulations for white and green beans case studies (Ávila, 2001; Ávila et al., 1999)

	White beans	Green beans
Kinetic parameters	$E_a = 120$ kJ/mol $k_{110\ °C} = 0.066\ min^{-1}$ $C_f = 26.0\ kg/m^2$ $\bar{x}_{C_0} = 211.8\ kg/m^2$ $s_{C_0} = 7.1E3\ kg/m^2$	z-value = 38.9 °C $D_{121.1\ °C} = 21$ min Hayakawa and Timbers (1977)
F_0 values	3 min 5 min	3 min 5 min
Heat penetration data (adjusted f_h value)	0 rpm: $\bar{x}_{adj.f_h} = 9.06$ min, $s_{adj.f_h} = 0.75$ min 10 rpm: $\bar{x}_{adj.f_h} = 6.51$ min, $s_{adj.f_h} = 0.69$ min	$\bar{x}_{adj.f_h} = 7.87$ min $s_{adj.f_h} = 0.37$ min
Surface heat transfer coefficient (h)	$h_{fin} = 408\ W/(m^2\ K)$ h_{inf}	$h_{fin} = 408\ W/(m^2\ K)$ h_{inf}
Heating medium holding temperature range	100–160 °C	100–160 °C

results with a low error ($\varepsilon < 0.05$) (Hahn & Shapiro, 1994).

For each run generated, volume average quality retention was calculated using a finite differences model (Ávila et al., 1999) for different holding temperatures (100–160 °C), considering finite (408 W/(m^2 K)) and infinite surface heat transfer coefficient, for F_0 values of 3 and 5 min at static mode or 10 rpm retort processes (Ávila et al., 1999). Industrial retorts can only operate at a maximum of 135 °C, however, it was necessary to perform simulations until 160 °C in order to better visualize the optimum quality retention.

In the case of green beans, the finite differences model calculates color retention ($-a/b$) of green beans as a function of process temperature. In this case, a more simplified approach was utilized, since the kinetic parameters for color degradation were taken from the literature (first order model: z-value = 38.9 °C, $D_{\text{tref}=121.1\,°\text{C}} = 21$ min: Hayakawa & Timbers, 1977) and, therefore, no variability at this level was taken into account.

2.4. Statistical analysis

A three-factor fixed effects (F_0 value, h value and temperature) Analysis of Variance (ANOVA) was performed for each case study, using Statistica (2001), at a 5% level of significance. Multiple pairwise comparisons of treatment means were performed, using a 95% confidence interval based on least significant difference (LSD). The LSD was calculated using the following formula (Neter, Kutner, Nachtsheim, & Wasserman, 1996):

$$\text{LSD} = t_{[(1-\alpha/2),(cde(n-1))]} \times \sqrt{\frac{\text{MSE}}{n}} \qquad (1)$$

where t is the studentized probability function; α the level of significance (which is 0.05); c the level number for F_0 value (which is 2); d the level number for surface heat transfer coefficient (which is 2), e the level number for temperature (which is 13); n is the sample size (which is 300) and MSE is the mean square error.

3. Results and discussion

3.1. White beans

The non-uniformity in hardness of white beans was simulated taking into consideration the combined variability in the heating rate index and initial texture (Table 1). Analyzing Table 2, for the static retort mode of operation and considering the experimental range of retort temperatures (100–135 °C), the coefficients of variation ($\text{CV} = s/\bar{x} \times 100$) for simulated hardness retention, of the combined effect, range from 1.7% to 14.6%. This means that the simulated uncertainties in the heating rate index and initial hardness have large effects on the final average texture variability, at high temperatures. It can be observed from Table 2 that CV values increase with increasing temperature. At high temperatures, processing times are considerably smaller and slight changes in heat transferred to the product can cause large variations in the final quality retention (e.g. at T = 135 °C, for f_h = 11.17 min, C/C_0 = 22.1%; while for f_h = 7.79 min, C/C_0 = 16%). On the other hand, at low temperatures of 100–115 °C the processing times are so large, that the temperature gradient inside the product becomes homogeneous and, therefore, the variations in terms of final average quality retention become very small.

Comparing both finite and infinite h values, the coefficients of variation are lower for finite h values (Table 2). Assuming an infinite h value, means to consider no surface resistance to heat transfer (e.g. product packed in a metallic container and steam as heating medium). Consequently, the sterilization value is achieved faster than for a finite h. In addition, a larger temperature gradient can be found inside the container, because the product surface becomes subjected to higher tempera-

Table 2
Coefficients of variation (CV) for simulated hardness retention of white beans at different holding temperatures, F_0 values of 3 and 5 min, finite and infinite surface heat transfer coefficients (h) and static retort mode of operation

T (°C)	CV (%) (h_inf, F_0 = 3 min)	CV (%) (h_fin, F_0 = 3 min)	CV (%) (h_inf, F_0 = 5 min)	CV (%) (h_fin, F_0 = 5 min)
100	0.0	0.0	0.0	0.0
105	0.0	0.0	0.0	0.0
110	1.7	1.7	0.0	0.0
115	5.5	4.5	2.5	2.6
120	8.4	6.7	5.6	5.1
125	11.1	8.8	8.2	6.8
130	13.3	10.8	10.8	8.8
135	14.6	11.9	11.5	9.7
140	15.7	13.2	12.2	10.8
145	15.9	13.9	12.8	11.2
150	15.1	14.6	13.3	11.6
155	14.9	14.5	12.8	12.0
160	14.4	15.0	13.1	12.4

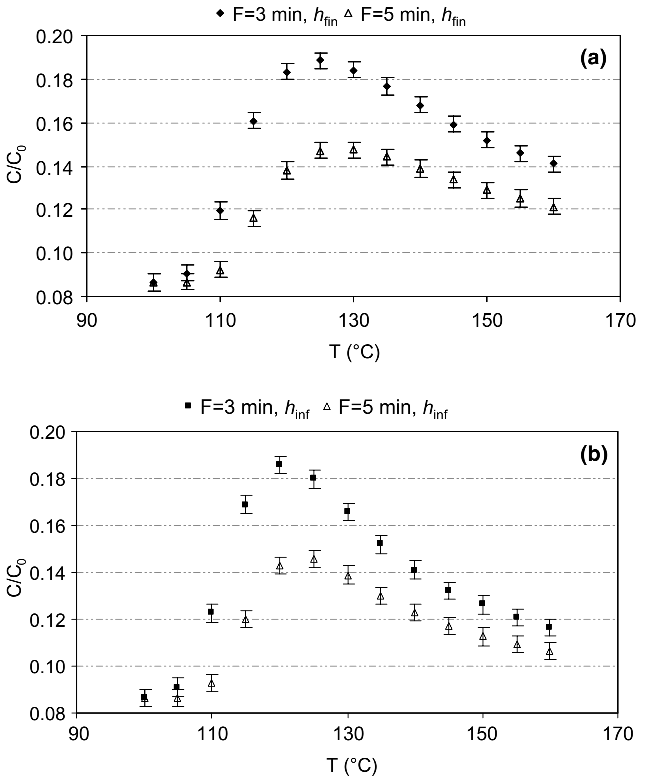

Fig. 2. Simulated non-uniformity in texture retention of white beans, for (a) finite and (b) infinite surface heat transfer coefficient, considering an F_0 value of 3 and 5 min and static retort mode of operation.

tures than the center and, consequently, a larger gradient in product quality retention can also be found.

An ANOVA was performed on all data for 0 rpm, showing significant main effects and their two-way and three-way interactions. Least significant differences between treatment means were subsequently computed at a 5% significance level. Fig. 2 shows the optimum texture profile of the beans and LSDs, for finite (a) and infinite (b) surface heat transfer coefficients, and F_0 values of 3 and 5 min. In this case, the LSD found (see Eq. (1)) was 0.0037, which affects mainly the optimum range of quality retention. Observing Fig. 2 for a finite h value (a) and an F_0 value of 3 min there are no significant differences between temperatures of 120 and 135 °C, which means that if the product is processed at any of these temperatures, its final average quality in terms of texture will be similar. For an F_0 value of 5 min, no significant differences were found in the average texture of the beans processed above 120 °C. Comparing both F_0 values, all retentions are lower for an F_0 value of 5 min and the CV 's found were also lower (Table 2 and Fig. 2). To obtain a larger target F_0 value, for the same holding temperature, it is necessary to process the product for longer times and, consequently, the quality retention will be lower at the end.

When an infinite surface heat transfer coefficient is considered in the calculations, a similar optimum temperature range for both F_0 values can be observed (Fig. 2(b)). For an F_0 value of 3 min, the optimum process temperature is between 120 and 125 °C, while for an F_0 value of 5 min between 120 and 130 °C.

The same reasoning can be made considering the rotation mode of operation (10 rpm). The results of uncertainties of the combined effect of C_0 and adj.f_h on the final texture retention of white beans are shown in Table 3. A larger variability was found, as the CV values range from 0% to 15.7%, considering also the experimental range of temperatures for retorts. However, despite this larger variability observed, the thermal process of white beans can still be optimized and optimum temperature ranges found were exactly the same (see Fig. 3(a) and (b) for a finite and infinite surface heat transfer coefficient, respectively). In this case, the LSD (see Eq. (1)) calculated was 0.0043. Considering a finite h, for an F_0 value of 3 min, no significant differences were found on quality retention for the temperature range of 120–135 °C. For an F_0 value of 5 min, no significant differences were found for a process temperature above 120 °C. Considering an infinite surface heat

Table 3
Coefficients of variation (CV) for simulated hardness retention of white beans at different holding temperatures, F_0 values of 3 and 5 min, finite and infinite surface heat transfer coefficients (h) and rotation (10 rpm) retort mode of operation

T (°C)	CV (%) (h_{inf}, F_0 = 3 min)	CV (%) (h_{fin}, F_0 = 3 min)	CV (%) (h_{inf}, F_0 = 5 min)	CV (%) (h_{fin}, F_0 = 5 min)
100	0.0	0.0	0.0	0.0
105	0.0	0.0	0.0	0.0
110	2.3	1.6	0.0	0.0
115	4.8	4.5	3.1	2.4
120	7.9	6.2	6.8	5.2
125	11.0	8.2	10.1	7.7
130	13.5	9.7	12.6	9.3
135	15.7	11.4	15.1	11.2
140	17.4	12.5	16.4	12.4
145	18.2	13.8	16.8	13.6
150	18.8	14.4	17.8	14.1
155	19.1	15.3	17.5	14.7
160	19.0	16.0	17.3	15.3

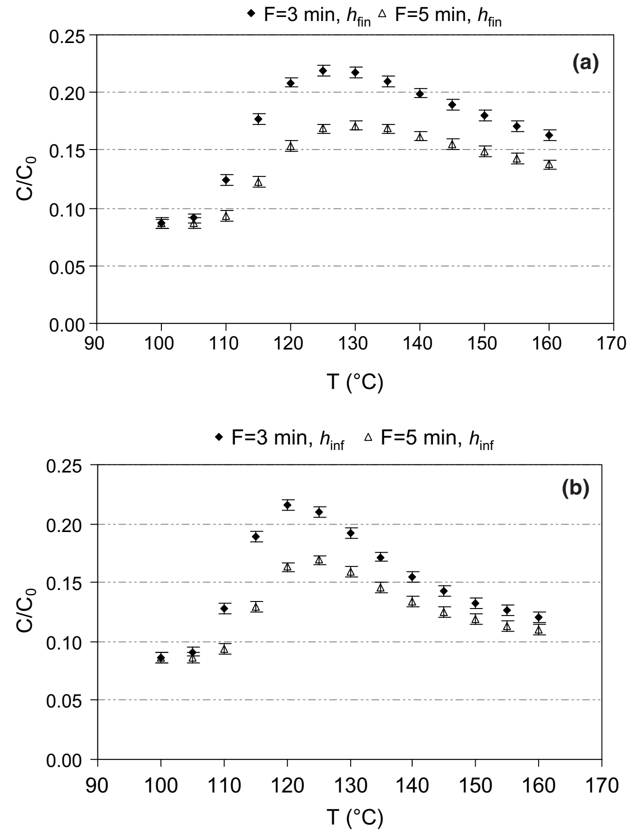

Fig. 3. Simulated non-uniformity in texture retention of white beans, for (a) finite and (b) infinite surface heat transfer coefficient and F_0 values of 3 min and 5 min, considering rotation (10 rpm) retort mode of operation.

transfer coefficient and an F_0 value of 3 min, the optimum temperature was between 120 and 125 °C, while for an F_0 value of 5 min between 120 and 130 °C. Therefore, for each h value assumed, the optimum temperature range is the same for both static or rotary retort modes of operation. Another important observation is the lower quality retention found for the static retort mode of operation, when comparing with the rotary retort mode. For the rotary mode, the heat is transferred much faster to the product, and consequently a lower time is needed to reach the same F_0 value. Therefore, the final product quality retention is increased.

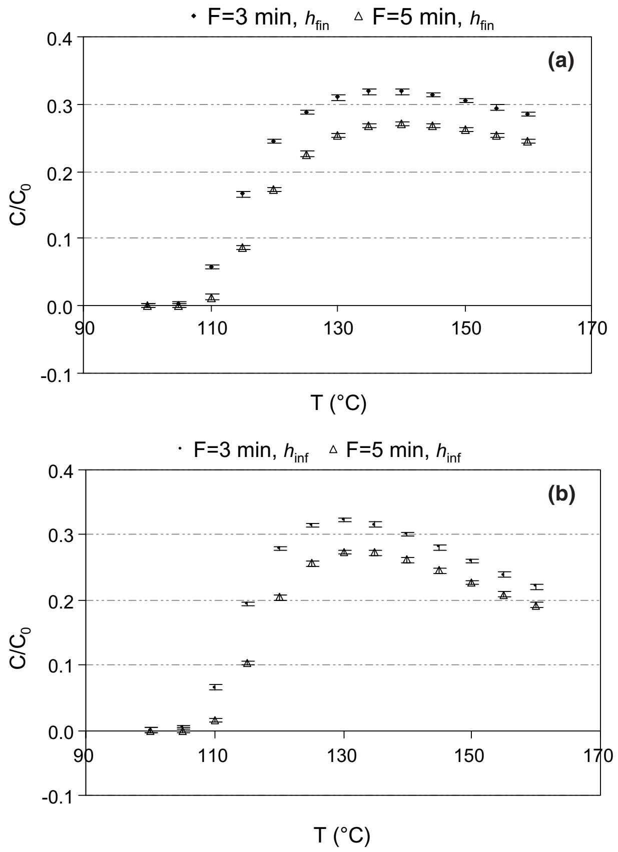

Fig. 4. Simulated non-uniformity in color retention of green beans for (a) finite and (b) infinite surface heat transfer coefficient, considering F_0 values of 3 and 5 min and static retort mode of operation.

3.2. Green beans

The simulated variability on color retention ($-a/b$) of green beans is presented in Fig. 4, for (a) finite and (b) infinite surface heat transfer coefficients and F_0 values

Table 4
Coefficients of variation (CV) for simulated color ($-a/b$) retention of green beans at different holding temperatures, F_0 values of 3 and 5 min, finite and infinite surface heat transfer coefficients (h) and static retort mode of operation

T (°C)	CV (%) (h_{inf}, F_0 = 3 min)	CV (%) (h_{fin}, F_0 = 3 min)	CV (%) (h_{inf}, F_0 = 5 min)	CV (%) (h_{fin}, F_0 = 5 min)
105	2.6	1.4	0.0	0.0
110	1.7	1.7	2.0	1.7
115	2.3	2.1	2.3	2.3
120	2.8	2.5	3.1	2.8
125	3.3	2.8	3.6	3.1
130	3.8	3.0	4.2	3.5
135	4.3	3.3	4.8	3.7
140	5.0	3.6	5.5	4.1
145	5.6	3.8	6.3	4.5
150	6.4	4.2	7.1	4.7
155	7.2	4.4	7.9	5.1
160	7.9	4.7	8.7	5.5

of 3 and 5 min. The overall CV values range from 0% to 4.8% (Table 4) considering again only the experimental operational retort temperatures, which means that the variability in the final color retention is lower than for the case of texture loss of white beans.

LSDs performed at a 5% significance level (value equal to 0.0033), show no significant differences for color retention in the temperature range 130–150 °C, for an F_0 value of 3 min and finite h value (Fig. 4a). For an F_0 value of 5 min, no significant differences were found when using temperatures higher than 135 °C (Fig. 4a). Therefore, for a finite h value the optimum process temperature to give the maximum color retention for green beans is around 130 to 135 °C. These temperatures are also near the maximum limit permitted by an industrial retort. Considering an infinite h value (Fig. 4b), no significant differences were found from 125 to 135 °C. At this range, maximum color retention for green beans was obtained considering an F_0 value of 3 or 5 min. As was expected, lower color retentions were obtained for the F_0 value of 5 min.

4. Conclusions

In the case studies presented, with green and white beans, optimum sterilization conditions in terms of final quality retention were found by simulation. Taking into account the statistical analysis performed, important conclusions can be taken about the possibility of process optimization. In the case of white beans, for static and rotation retort modes of operation, uncertainties in the heating rate index and initial hardness have large effects on the final average texture variability, at high temperatures. The optimum range of quality retention was mainly affected. However, it is still possible to obtain lower hardness losses for process temperatures between 120 °C and 135 °C. In the case of green beans, the uncertainties in the heating rate index did not affect so largely the final color retention. The optimum process temperature ranged from 125 to 135 °C. Therefore, it is possible to design the optimum process for both case studies. This means that, particularly for these case studies, if the product is processed at the temperatures pointed out previously, maximum hardness values for white beans and color retentions of green beans will be experimentally obtained. However, the process temperature should be chosen taking into account the F_0 value and the material used to pack the product (glass or metal), as this influences the surface heat transfer coefficient value.

Therefore, the approach applied is a valuable tool to get an idea of the non-uniformity in process quality retention. Consequently, the existence of an optimum process, in terms of maximizing quality, is possible to be assessed. With this knowledge, decisions can be taken, whether to reduce quality degradation and costs or, if it is not possible at all to optimize quality retention, to minimize only costs.

As in any simulation study, the objective is to try to mimic reality as much as possible, but unfortunately some assumptions had to be made. In the present study the assumptions performed in the calculations should be kept in mind: variations in initial hardness value of white beans were assumed to be normally distributed; the finite differences model used to calculate quality retentions, although already proved to be a reliable program (Ávila et al., 1999), was developed for homogeneous and conduction heating foods; other sources of uncertainties could have been taken into account (see Section 1). An important aspect, in designing a process, is to combine all the possible sources of uncertainty to get the correct idea of the overall effects on the final quality variability.

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