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## Postharvest Hardness and Color Evolution of White Button Mushrooms (*Agaricus bisporus*).

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1 **Postharvest Hardness and Color Evolution of White Button Mushrooms (*Agaricus***  
2 ***bisporus*)**

3

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23 **Abstract:**

24 The quality evaluation of mushrooms was studied by storing fresh white button mushroom  
25 (*Agaricus bisporus*) for 6-8 days, at various controlled temperature conditions (3.5 -15°C)  
26 and measuring the instrumental textural hardness and color of the mushroom cap for different  
27 product batches. A non linear mixed effect weibull model was used to describe mushroom  
28 cap texture and color kinetics during storage considering the batch variability into account.  
29 Storage temperature was found to play a significant role in controlling texture and colour  
30 degradation. On lowering storage temperature i) the extent of the final browning extent in the  
31 mushroom after storage was reduced; and ii) the rate textural hardness losses was slowed  
32 down. A linear dependence of the final browning index with temperature was found. An  
33 Arrhenius type relationship was found to exist between the temperature of storage and  
34 storage time with respect to textural hardness. The average batch energy of activation was  
35 calculated to be  $207\pm 42$  kJ/mol in a temperature range of 3.5-20°C.

36 **Practical application**

37 This article evaluates how temperature abuse affects mushroom texture and colour, applying  
38 methods that allow for the consideration of the natural product variability that is inherent in  
39 mushrooms. Its result apply to mushroom producers, retail distribution and supermarkets for  
40 effective storage management.

41

42 **Introduction:**

43 Mushroom marketers often face difficulties in choosing a safe storage conditions on receiving  
44 different batches of mushrooms. Mushrooms may vary in their harvesting date and time,  
45 cultivated mushroom variety, harvest batches, storage conditions adopted and cold chain  
46 regime followed (Hertog and others 2007a; Aguirre and others 2008). Post-harvest,  
47 mushrooms immediately start to soften and begin to brown in color due to enzymatic  
48 breakdown of plant cells and loss of moisture through respiration (Burton and others 1987,  
49 Jolivet and others 1998, Brennan and others 2000; Zivanovic and others 2003; Zivanovic and  
50 others 2004; Lespinard and others 2009). This results in reduced product acceptability, as  
51 consumer's preference and demand is for white, unblemished and hard textured mushrooms.  
52 Additionally, bruising and storage at elevated temperatures enhances the degradation process  
53 and reduces mushroom shelf-life (Burton, 1986). Consequently, monitoring cold-chain  
54 storage conditions that will preserve the quality of mushrooms is both critical and challenging  
55 (Aguirre and others, 2009)

56 Quality control during postharvest requires precise methodologies to estimate the  
57 acceptability of fresh produce of varying batches, growers, cultivation practices and post  
58 harvest treatments. In an ideal situation, all products should arrive with the same  
59 homogeneity as if it was from an experimental station unit, however, food retailers face an  
60 input of produce arising from different growers, possibly harvested on different dates and  
61 locations and using very different cultural practices. Taken together, this has a significant  
62 effect on the homogeneity of the product and its' time to reach the limit of marketability  
63 (Hertog and others 2007b; Schouten and others 2004). Moreover, there is biological variation  
64 contributed by micro nutrients, growing conditions, etc. for each batch of produce. Different  
65 units of an individual batch may behave differently, even when stored under similar storage  
66 conditions (Brennan and others 2000; Hertog and others 2007a).

67 Modeling the quality kinetics of fresh products attempts to better understand the fate of  
68 quality during storage, taking not only the primary modeling variable (time) into account, but  
69 more importantly, the secondary variables that may be controlled during storage to optimally  
70 maintain the quality attributes of the product. Such information would be helpful to both  
71 producers and sellers in enabling them to optimize product storage conditions and in  
72 identifying the significant factors affecting product shelf-life. Modeling may also reveal the  
73 ways in which variability affects the quality during operating storage conditions, which may  
74 in turn be used to define limits beyond which the quality of product may be compromised  
75 within a certain tolerance (Lavelli and others 2006).

76 An assessment of fresh produce shelf-life requires proper understanding of the two  
77 phenomena affecting the process i) biological metabolism, and ii) underlying variability.  
78 Model building is employed to assess the shelf-life, normally based on experimental data that  
79 is generated through repetitive quality measurements, either by destructive or non-destructive  
80 methods carried out in real-situation or laboratory conditions. The repetitive measurements  
81 form a longitudinal data structure which is well correlated with the subject within a batch, but  
82 are independent of the intra batch variability (Lammertyn and others 2003). Least squares  
83 regression is commonly used to analyze the data by averaging repeated measurements.  
84 Although this statistical method is robust to build models within normal food experiments, it  
85 accumulates all the variation in one error term and does not allow for the estimation of the  
86 different possible sources of variation. While this is sufficient for use with many experiments,  
87 it may be more desirable to estimate other and different sources of variability. In particular,  
88 postharvest technology is a field where this approach might prove to be interesting from a  
89 number of different perspectives, such as; i) to be able to estimate the weight of different  
90 variability sources (within batch, between batches, between producers), which will help to  
91 make clearer purchasing decisions ii) to identify if variability can be reduced at any particular

92 storage condition and iii) to evaluate through a scenario analysis if making an hypothetical  
93 optimization in the cold chain, this optimisation will actually result in an appreciable  
94 improvement of the shelf life taking account of product variability. Mixed-effects models  
95 may be useful for those cases where one has to deal with within-subject, as well as between-  
96 subject variability, especially when having to deal with a biological commodity. A mixed  
97 effects model has two components i) fixed effect term, which deals with the trend  
98 components and ii) random effect term, which deals with subject specific intercepts and  
99 variance (Pinheiro and Bates, 2000). Moreover, it allows for the presence of missing data and  
100 can allow for time-varying or unbalanced designs with unequal numbers of subjects across  
101 experimental groups (Pinheiro and Bates 2000; Lammertyn and others 2003). Several studies  
102 have been undertaken to predict the quality kinetics of fresh produce using mixed effect  
103 models (Lammertyn and others 2003; Piagentini and others 2005; Latreille and others 2006;  
104 Schouten and others 2007; Aguirre et al. 2009). A mixed effect model that addresses a  
105 hierarchical level of variation has been employed by various researchers (Fonseca and others  
106 2002; Montanez and others 2002; Ketelaere and others 2006). Mushrooms are known to have  
107 a very short shelf- life and susceptible to browning and moisture loss due to the enzymatic  
108 activity and lack of cell wall. The quality deterioration is even faster at higher storage  
109 temperature conditions, due to enhanced metabolic activity. Therefore modeling the quality  
110 deterioration with respect to storage conditions provides ample opportunity for the mushroom  
111 growers and marketers to modify the storage and handling conditions in order to have higher  
112 shelf-life, thus reducing the economic loss. In this study, attempts were made to model  
113 product instrumental texture and color characteristics in order to predict mushroom shelf-life  
114 under different temperature storage conditions, taking batch variation into consideration,  
115 using a non-linear mixed effect model.

116

117 **2.0 Materials and methods:**

118 Closed cup *Agaricus Bisporus* button mushrooms (white, close, uniform, clear, fresh, L  
119 value=  $90 \pm 5$ ,  $a=0.3 \pm 0.8$ ,  $b=10 \pm 2$ ), sourced from the Ranairee mushroom farm (Macroom,  
120 Ireland) and commonly destined for retail supermarket sales, were delivered to the laboratory  
121 using a temperature monitored distribution chain ( $6 \pm 2^\circ\text{C}$ ,  $80 \pm 15\%$  RH) in 7 kg crates  
122 without any individual packaging. Bruised and damaged samples were discarded and samples  
123 for analysis were taken at random from each batch of crates. Half of the mushrooms from the  
124 same batch were stored in temperature controlled cold rooms at different temperatures (5, 10,  
125  $15 \pm 0.6^\circ\text{C}$ ) and the corresponding relative humidity was monitored ( $86 \pm 7\%$ ). The other half  
126 of the sample was kept in a domestic refrigerator that reproduced the ideal storage  
127 temperature during retail and distribution of  $3-4^\circ\text{C}$  ( $3.5 \pm 1.5^\circ\text{C}$ , RH  $92 \pm 5\%$ ) and served as  
128 the control sample to observe differences between ideal storage and the temperature used for  
129 each individual batch tested. The temperature range of  $3.5-15^\circ\text{C}$  was chosen considering the  
130 practical temperature distribution chain of mushrooms i.e. during post-harvest handling,  
131 transportation and storage. Texture and color measurement were performed after the  
132 mushrooms reached equilibrium temperature and every 24 hr thereafter, until the end of the  
133 storage experiment, which varied between 6-8 days, depending on storage temperature,  
134 taking random samples from the lot. A total of 14 batches of experiments were performed,  
135 covering a period of 1 year of production.

136

137 *2.1 Instrumental texture measurement:*

138 Texture measurement is a complex measurement, especially in a highly variable and  
139 anisotropic solid as mushrooms (McGarry and Burton 1994). Stored mushrooms were  
140 removed from storage and held at room temperature for 0.5 hr before performing textural  
141 assays. All such experiments were carried out using a texture profile analyser (Texture Expert



142 Exceed, Stable Microsystems, UK), with a 5 kg load cell following a modification of the  
143 method proposed by Gonzalez-Fandos and others (2000). The crosshead speed of the spindle  
144 for the pre-test, post-test and test speed were kept at 1 mm/min. Only the mushroom caps  
145 were used for texture hardness measurements. In order to obtain a sample with the same  
146 tissue orientation and dimensions, a cylindrical sample of 10 mm diameter was bored out  
147 from the mushroom cap using a steel borer and cut to 10 mm length using a sharp knife and  
148 was then compressed to 50% of the original height using a 35 mm aluminium cylindrical  
149 probe so as to achieve compression of the mushroom sample. Product hardness was the  
150 variable analyzed for each sample. Tests were performed on 5 replicate mushroom samples,  
151 from each storage condition, on each storage day, during the whole course of the trial period,  
152 accounting for over 700 measurements.

153

#### 154 *2.2 Color measurement:*

155 The color of the mushroom cap was measured using a Minolta Chroma Meter (Model CR-  
156 331, Minolta Camera Co., Osaka, Japan), using the Hunter Lab Color Scale. The color was  
157 measured at three equidistant points on each mushroom cap using an aperture diameter of  
158 4mm. Five mushrooms were randomly selected from each batch per day for the color  
159 measurement, accounting for over 2800 measurements of color. Mushroom color has been  
160 commonly measured using the L value of the Hunter scale (Brennan and others 2000; Jolivet,  
161 1998; Cliffe-Byrnes and O'Beirne 2007), however some studies have pointed to changes in  
162 other parameters of the hunter scale ( $a^*$  and  $b^*$ ) related to browning (Aguirre and others  
163 2008; Vizhanyo and Felföldi, 2000; Burton, 1998). In order to capture this variation in a  
164 single index that would be related to a turn towards brown colour, the Browning index (BI)  
165 was calculated using the following expression (Maskan 2001; Bozkurt and Bayram 2006):

166  $BI = 100 \times \left( \frac{X - 0.31}{0.17} \right)$ , where  $X = \frac{(a^* + 1.75L)}{(5.645L + a^* - 3.012b^*)}$ , L, a\*, b\* values represent the

167 lightness, redness and greenness of the sample.

168

### 169 **1.0 Mathematical modeling**

170 The mathematical model to predict mushroom shelf-life was carried out using the data  
171 generated from measurement of the textural hardness and color (as indicated by the browning  
172 index).

173 Model building was performed using the following procedure:

174 **1.** An ANOVA analysis of the quality parameters clearly showed that they were all affected  
175 by temperature and storage time ( $p < 0.05$ ). The primary modeling of the data was then  
176 performed using suitable mathematical models for individual temperatures and batch  
177 experiments. After a graphical, the first order model, the biexponential model, the logistic  
178 model and the weibull model were used as candidate models to describe the kinetics of  
179 texture and browning. The most appropriate model which gave maximum determination  
180 coefficient  $R^2$ , a low standard error, lower Akaike's Information Criterion (AIC) and  
181 Bayesian Information Criterion (BIC) was chosen. The AIC and BIC are model  
182 discrimination criteria used for selection nonlinear models, which consider the goodness  
183 of fit of the model and the number of parameters employed. The smaller the value of the  
184 AIC and BIC the better a model performs (Pinheiro and Bates, 2000).

185 **2.** The secondary modeling of the data considered two components: i) dependence of the  
186 texture and browning primary model parameters was described following the equations  
187 proposed in section 3.3 below ii) batch variation would be expected to follow the  
188 hypothesis of Hertog and others (2007a) that each individual product and batch has  
189 perturbation at the initial state at which it is processed. Extra random effects were

190 introduced following this and its addition tested using a log-likelihood ratio test. A  
191 likelihood-ratio test is a statistical test for making a decision between two models where  
192 the hypothesis is based on the value of the log-likelihood ratio of the two models  
193 following a chi-square distribution (Bates and Watts, 1988). The log-likelihood ratio test  
194 is a conservative test that will check for statistical significance of adding further nested  
195 random effects to a model (Pineiro and Bates, 2000). The test requires that the two  
196 models must be nested, this is, that if one of the models can be transformed into the other  
197 by fixing one parameter.

198 **3.** Finally prediction plots using the Best Linear Unbiased Prediction (BLUP), which depict  
199 the model prediction of each individual experiment considering the random effects  
200 assigned to it in the model (Pineiro and Bates, 2000), were made to confirm the  
201 suitability of the candidate models.

202 **4.** An iterative procedure was used to find the best candidate secondary model that could  
203 describe, with a minimum set of parameters, that data that resulted from the  
204 experimentation.

### 205 *3.1 Modeling texture*

206 The best candidate primary model to describe the texture and browning kinetics, in a similar  
207 way as with Kong and others (2007).

208 The textural hardness of the mushrooms was described by the weibull model as follows:

$$209 \quad H = B_H + (A_H - B_H)e^{-e^{lk_H} \times t^{\beta_H}} \quad (2)$$

210 Where,  $H$  is the textural hardness of the mushroom cap,  $A_H$ , and  $B_H$  are the initial and final  
211 hardness of mushroom cap during storage,  $t$  is the time of storage (day),  $lk_H$  is the natural  
212 logarithm of the rate constant of the reaction and  $\beta_H$  is the dimensionless shape parameter.

213 The shape parameter accounts for upward concavity of the curve ( $\beta_H < 1$ ), a linear curve ( $\beta_H$   
214 = 1) as in case of first order kinetics, and downward concavity ( $\beta_H > 1$ ) (Pineiro and Bates,

215 2000).

### 216 3.2 Modeling color

217 The browning index of the mushroom caps was analyzed using a modified weibull model, to  
218 force the rate constant parameter to be positive:

$$219 \quad BI = A_{BI} + (B_{BI} - A_{BI})e^{-e^{lk_{BI}} \times t^{\beta_{BI}}} \quad (3)$$

220 Where,  $BI$  is the browning index,  $A_{BI}$  is the upper asymptotic value of the weibull curve,  $B_{BI}$ ,  
221 is the initial value of the browning index,  $t$  is the time of storage in days,  $lk_{BI}$  is the log rate  
222 constant of the reaction, and  $\beta_{BI}$  is the shape factor for browning index.

223

### 224 3.3 Temperature dependence

225 The temperature dependence of the rate constant was modeled following an Arrhenius  
226 relationship

$$227 \quad k = k_{ref} e^{-\frac{E_a}{R} \left( \frac{1}{T} - \frac{1}{T_r} \right)} \quad (4)$$

228 Where  $k_{ref}$  is the rate constant at the reference temperature  $T_{ref}$  (5°C),  $E_a$  is the energy of  
229 activation of the process and  $R$  is the universal gas constant (8.314 kJ Mol<sup>-1</sup> K<sup>-1</sup>). In this way  
230  $k_{ref}$  and  $E_a$  are easy to interpret parameters and allow for comparison of the temperature  
231 dependence of this process with other quality factors (chemical or not).

232 The temperature dependence of the  $A$ ,  $B$  and  $\beta$  parameter followed a polynomial relation:

$$233 \quad y = a + b \times T + c \times T^2 \quad (5)$$

234 Where  $y$  is the parameter  $A$ ,  $B$  or  $\beta$  and  $a$  and  $b$  and  $c$  are the intercept, linear and quadratic  
235 dependence of the parameter with temperature, respectively. Parameters statistically non-  
236 significant ( $p > 0.05$ ) were dropped from the model building.

### 237 3.5 Statistical analysis

238 On the basis of the primary models generated, the secondary models were developed by

239 including the random effect terms that addressed batch and individual variance effects on  
240 quality evolution. The non-linear mixed modeling was performed using the nlme library  
241 (Pinheiro and Bates, 2000) from the R 2.9.1 software (R Development Core Team 2007), for  
242 textural hardness and browning index.

243

## 244 **4.0 Results and discussion**

### 245 *4.1 Textural hardness*

246 The textural hardness kinetics of button mushrooms stored at different temperatures is shown  
247 (Figure 1). It was evident that the while cap hardness could be maintained with storage at  
248 3.5°C, higher temperatures produced a decline in textural hardness that was more pronounced  
249 with the increase in storage temperature. If storage temperature was changed to 10 °C, after 4  
250 days the mushrooms would have a texture different ( $p<0.05$ ) from the control at 3.5 °C and if  
251 changed at 15°C after the 2<sup>nd</sup> day of storage.

252 The estimated fixed and random effect parameters of the final model are outlined in table 1  
253 with 95% confidence intervals, all parameters being significant ( $p<0.05$ ). Initial models were  
254 built considering within-lot and within-batch variability similar to Mohapatra and others  
255 2008. When performing individual fits in each batch, it was observed that the standard  
256 deviation of the estimated power terms was very low compared to the average ( $2.2\pm 0.2$ ). In  
257 this way, the random effect associated to the  $\beta$  term was removed from the model.

258 As indicated in Figure 1, the kinetics, and therefore the rate constant, of texture decay was  
259 found to be dependent on the storage temperature. In order to study this, an Arrhenius plot  
260 with the random effects associated to the  $k$  parameter of a model without temperature  
261 dependence was built (see Figure 2) which confirmed this dependence. From the slope of the  
262 linear regression of Figure 2, energy of activation of  $190\pm 40$  kJ/mol could be estimated. This  
263 value was used as an initial estimate for the one-step estimation of the model parameters.

264 The activation energies at the 95% confidence level and the estimates of the initial and final  
265 values of hardness and the power term for the final model are shown (Table 1). The  
266 activation energy for the loss of mushroom hardness ( $207\pm 42 \text{ kJmol}^{-1}$ ) value was well within  
267 the range of other quality characteristics for other reported forms of stored vegetables  
268 (Giannakourou and Taoukis 2003; Piagentini and others 2005). The estimated power term  
269 ( $2.2 > 1$ ) suggested that the kinetics had a downward concavity feature that made texture  
270 kinetics depart from conventional first order kinetics. The best fitted values for mushroom  
271 textural hardness when stored under different temperature-time for different batches of  
272 mushrooms are shown (Figure 3). It can be seen that the model describes the kinetics and the  
273 differences between abuse storage temperature and control. Despite the natural variability,  
274 mushrooms abused suffer a decrease in hardness that is apportioned to the temperature abuse  
275 and that the model built in the present study is able to reproduce.

276

277 The random effect terms in Table 1 suggest that the final value of the mushroom hardness at  
278 the end of storage ( $\sigma_{BH}$ ) did not vary much among batches, compared to the variation in  
279 initial textural hardness ( $\sigma_{A-BH}$ ), which is 5 times higher. The structure of the best model fit  
280 and the estimated parameters point to the interesting hypothesis that as a result of storage, the  
281 variation between batches of mushrooms will decrease. The variation of the reaction rate  
282 constant between batches showed a coefficient of variation of over the 30%, (Table 1). This  
283 is characteristic of the high variability associated to fresh produce for retail in general and in  
284 particular of mushrooms (Aguirre and others 2009)

285

#### 286 *4.2 Browning index*

287 The kinetics of the average browning index for different temperatures of storage is shown in  
288 (Figure 4). From a graphical inspection similar conclusions can be drawn as with the texture

289 in respect to the effect of temperature abuse during the storage of mushrooms can be  
290 concluded, with time and temperature having a significant effect ( $p < 0.05$ ). Since the loss of  
291 hardness and browning of mushrooms are governed by enzymatic activities, low temperature  
292 storage would inactivate the enzymes thus slowing down the metabolic activities and other  
293 biochemical process. Storage at 5°C after 5 days produces a browning index different from  
294 control conditions and after 4 days at 10°C. From comparing Figure 1 and Figure 4 variation  
295 in color of mushrooms seems to be less pronounced than that of texture. This is in agreement  
296 with previous results found for enzymatic activity responsible of browning (Mohapatra and  
297 others 2008).

298

299 The best fit model to the data is presented in Figure 5. There was an increasing trend in the  
300 browning index with respect to storage days and storage temperature. The pattern does not  
301 seem to follow first order kinetics, although many researchers have proposed a logistic  
302 function, or a zero order function, to describe this color change in fruits and vegetables  
303 during storage (Giannakourou and Taoukis 2002; Lukasse and Polderdijk 2003; Muskovics  
304 and others 2006; Hertog and others 2007b). In this study, a steady increase in the color  
305 pattern was evident as storage time progressed. When the mushrooms were initially  
306 received/purchased, their color was predominantly white, but as the storage days progressed  
307 the discoloration on the cap intensified due to both enzymatic reactions (Jolivet and others  
308 1998; Mohapatra and others 2008). The enzymes responsible for browning react with the  
309 substrate and the evolution of brown pigmentation occurs. When there is no more substrate  
310 available over a longer storage time, the enzymatic reaction slows down and the formation of  
311 browning pigments stops (Jolivet and others 1998). As no decline or reversal in browning  
312 pigments occurs once formed, the weibull model is most suitable in describing browning  
313 index kinetics or color kinetics in mushrooms. There was a difference in the kinetics of

314 browning index at higher temperatures. The estimates of both fixed and random parameters  
315 are listed (Table 2). The final candidate model indicates that when storage temperatures are  
316 very low, there will be no change in the BI with time, however, as temperature increases the  
317 final value of the BI at long storage times will be higher. From the structure of the model it  
318 can be inferred that no significant increase of browning index would be found theoretically at  
319 0°C (through extrapolation). Therefore the best policy would be to employ the lowest  
320 refrigeration temperature possible, where the least color variation would be found. This  
321 points to the need of ensuring cold chains in mushrooms that ensure the lowest level of  
322 browning by maintaining the lowest temperature (Aguirre and others 2009). In terms of  
323 slowing down browning as no significant dependence of the rate constant ( $k_{BI}$ ) or the shape  
324 parameter ( $\beta_H$ ) with temperature browning kinetics will proceed in the same way  
325 independently of the temperature. This seems to be in disagreement with previous results  
326 found for frozen mushrooms (Giannakourou and Taoukis, 2002). This is possibly due to the  
327 biological processes associated to fresh products where possibly an enzyme expression  
328 process is taking place due to the natural senescence of the mushroom (Mohapatra, 2008),  
329 instead of the slower temperature controlled processes in frozen foods. However the  
330 significant temperature effect found in the parameter  $B_{BI-A_{BI}}$  indicates that the higher the  
331 temperature the higher the final browning stage of the mushrooms will be. Previous studies  
332 (Mohapatra and others 2008) have pointed to an earlier over expression of browning related  
333 enzymes associated with temperature abuse, which would be in agreement with this result.  
334 While the initial stages of browning might be controlled by the integrity of the mushroom  
335 tissues, the integrated effect of an earlier induction of high activity of browning enzymes by  
336 temperature abuse would create higher color formation over time. The random effect  
337 components of the models represent the effect that the product variability have on the  
338 uncertainty of both quality index. As such, the  $B_{BI-A_{BI}}$  associated to browning is the



339 parameter with a bigger variability (70% CV at 3.5°C) followed by the initial value of the BI  
340  $A_{BI}$  (30%), whereas for the texture the  $k_H$  is the parameter most affected by product  
341 variability (30% CV). This means that the biggest uncertainty resides in controlling the final  
342 browning stage of the mushrooms, and then the rate of hardness losses will present the  
343 biggest variability. Because of this under the present temperature range, the optimization of  
344 texture through temperature control might appear more manageable than the control of  
345 browning. However, the policy for controlling browning is clear despite of variability, the  
346 lower the temperature the lower the extent of the browning.

347

## 348 **5.0 Conclusion**

349 This study has demonstrated the ability to predict the quality of fresh mushrooms stored  
350 under isothermal conditions, using models that take into account not only the instrumental  
351 error as a source of variance, but also components of variability arising from product  
352 variability. The temperature dependence of these qualities gives further insight into the ability  
353 to choose proper time-temperature management during storage. Storage under low  
354 temperature would delay the biological decay process associated to texture and would extend  
355 the shelf-life of the product. In the same way, lower temperature will produce lower levels of  
356 browning. The models built can be useful in predicting the quality attributes of fresh  
357 mushrooms under a temperature range of 3.5-15°C, which is adopted by most conventional  
358 distribution chains and more specifically, during the commercial storage of mushrooms.  
359 Browning seems to be the quality index most influenced by product variability, especially in  
360 the final value at long storage times. However a strategy of minimising storage temperature  
361 warrants a minimum browning appearance.

362

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367

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467 **List of abbreviations**

468	$\sigma$	Standard deviation
469	$\sigma_{A-BH}$	Variation in the hardness value at the initial stage, N
470	$\sigma_{ABI}$	Variation in the browning index value at the final stage
471	$\sigma_{ABI-ABI}$	Variation in the browning index value at the final stage
472	$\sigma_{BH}$	Variation in the hardness value at the final stage, N
473	$\beta_{BI}$	Dimensionless Shape factor for browning index.
474	$\beta_H$	Dimensionless shape parameter for hardness
475	$\sigma_{lkBI}$	Variation in the log rate constant of the weibull curve for browning index
476	$\sigma_{lkH}$	Variation in the log rate constant of the weibull curve for hardness
477	a,b,c	Constants of polynomial equation
478	$A_{BI}$	Upper asymptotic value of the weibull curve
479	$A_H$	Initial hardness of mushroom cap, N
480	AIC	Akaike's Information Criterion
481	$B_{BI}$	Initial value of the browning index
482	$B_H$	Final hardness of mushroom cap, N
483	BI	Browning Index
484	BIC	Bayesian Information Criterion
485	<b>BLUP</b>	<b>Best linear unbiased prediction</b>
486	CV	Coefficient of Variation
487	$E_a$	Activation Energy of the process, $\text{kJmol}^{-1}$
488	H	Textural hardness, N
489	$k$	Rate constant for weibull distribution
490	$k_{\text{ref}}$	Rate constant at the reference temperature
491	$lk_{BI}$	Log rate constant of the browning reaction

492	$lk_H$	The rate constant of texture decay at the reference temperature
493	p	Probability
494	R	Universal gas constant, 8.314 kJ Mol <sup>-1</sup> K <sup>-1</sup>
495	R <sup>2</sup>	Coefficient of determination
496	REML	Restricted maximum likelihood
497	$t$	Storage duration (day)
498	T <sub>ref</sub>	Reference temperature (278K)
499		



500 **List of Figures**

501

502 Figure 1 Average textural hardness kinetics of mushrooms at different storage temperatures □  
503 15°C, ▽10°C, + 5°C, o 3.5°C (control). Error bars represent 95% confidence intervals  
504 based on the t-distribution for each time/temperature combination.

505

506 Figure 2 Arrhenius plot of the individually fitted  $\kappa$  parameter for each batch studied.

507

508 Figure 3 Typical textural hardness kinetics of mushrooms batches at different storage  
509 temperatures with their respective control and best linear unbiased predictors  
510 (BLUP) of the model described in Table 1 (a) ◇ 15°C (observed), -  
511 15°C(BLUP),(b)o 10°C (observed), - 10°C (BLUP), (c) □ 5°C (observed), - 5°C  
512 (BLUP), Δ 3.5°C(observed), --- 3.5°C (BLUP)

513

514 Figure 4 Average **Browning Index kinetics** of mushrooms at different storage temperatures □  
515 15°C, ▽10°C, + 5°C, o 3.5°C (control). Error bars represent 95% Gaussian confidence  
516 intervals based on the t-distribution for each time/temperature combination.

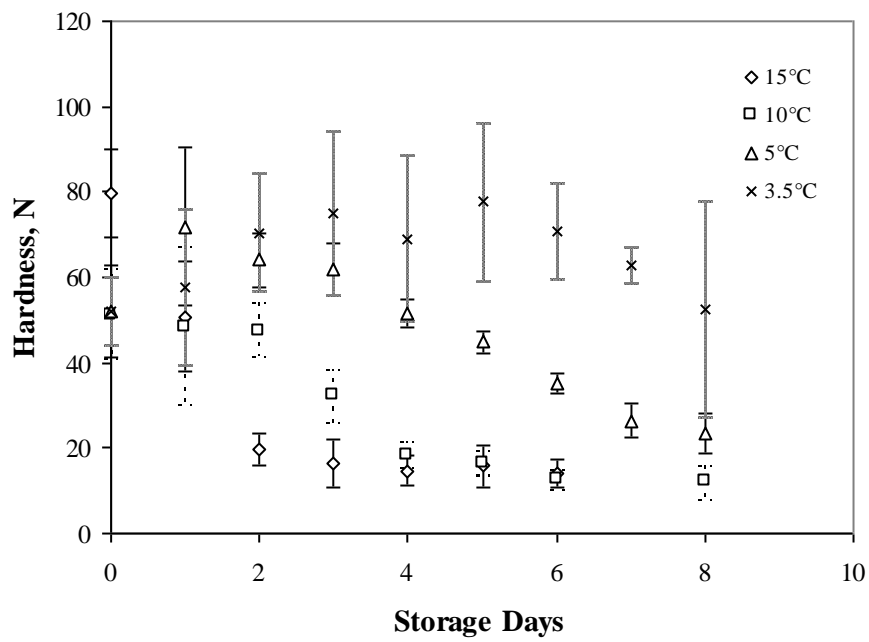
517

518 Figure 5 Typical browning index kinetics of mushrooms at different storage temperatures  
519 fitted to weibull model (a) ◇ 15°C (observed), - 15°C(predicted),(b)o 10°C (observed),  
520 - 10°C (predicted), (c) □ 5°C (observed), - 5°C (predicted), Δ 3.5°C(observed), ---  
521 3.5°C (predicted). It can be seen that mushroom storage temperature has an effect on  
522 the average browning kinetics and how inherent mushroom variability influences the  
523 whole process.

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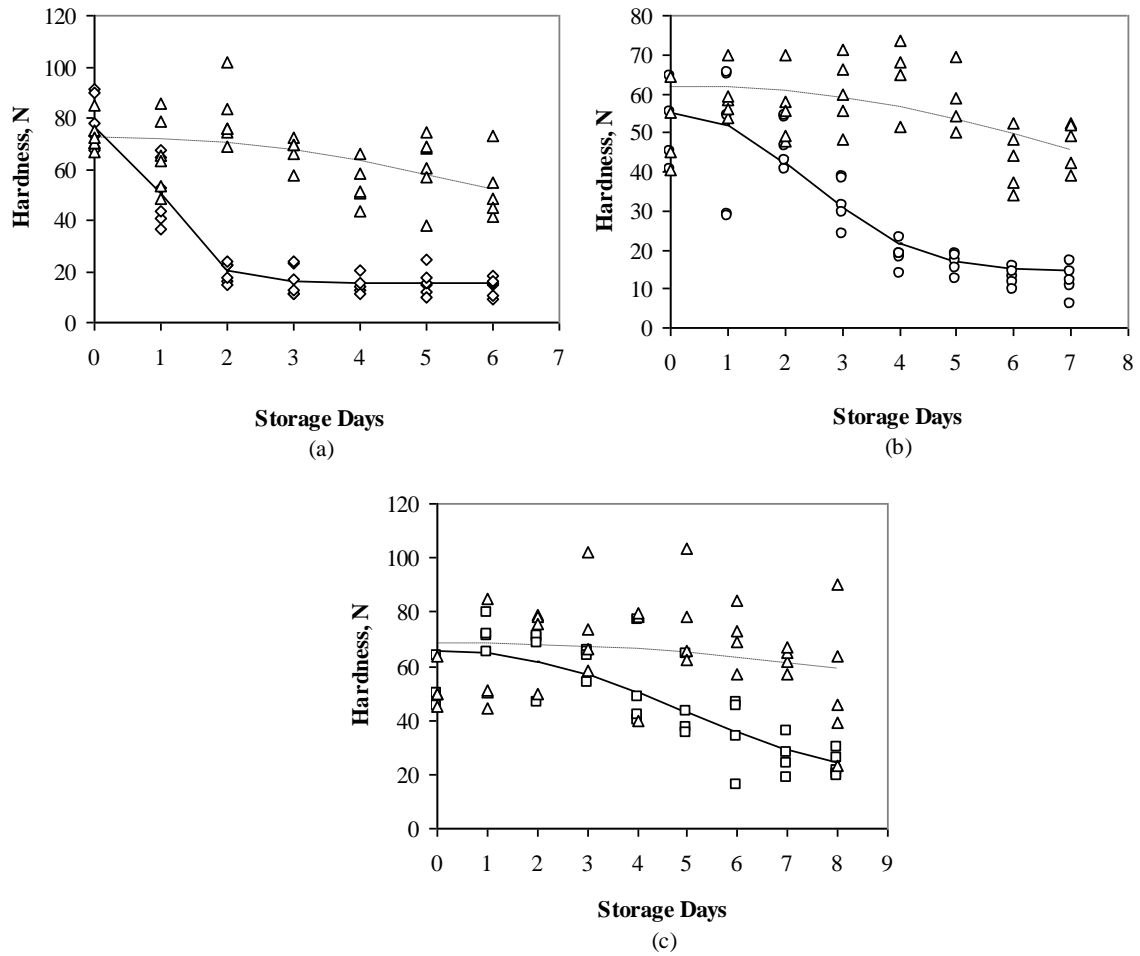


527

528 Figure 1 Typical textural hardness kinetics of mushrooms at different storage temperatures  $\diamond$

529 15°C,  $\circ$  10°C,  $\Delta$  5°C,  $\times$  3.5°C (control)

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533 Figure 2 Typical textural hardness kinetics of mushrooms at different storage

534 temperatures fitted to weibull model (a)  $\diamond$  15°C (observed), - 15°C(predicted),(b)o

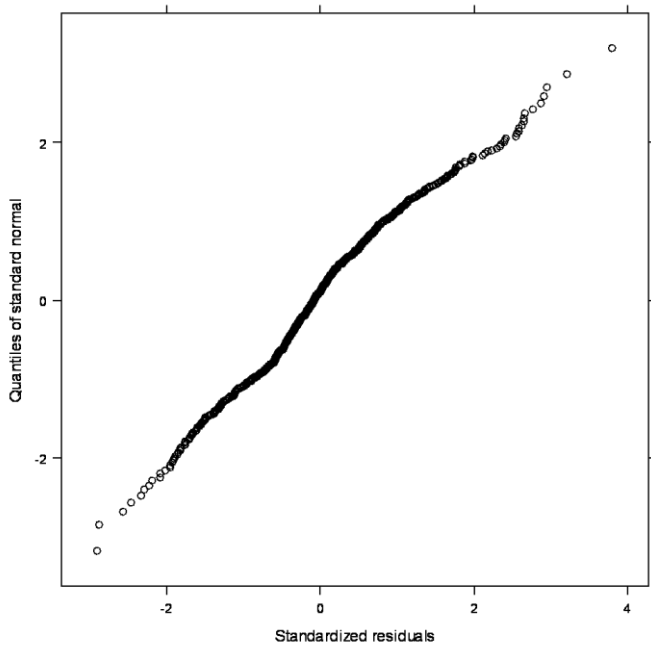
535 10°C (observed), - 10°C (predicted), (c)  $\square$  5°C (observed), - 5°C (predicted),  $\Delta$

536 3.5°C(observed), --- 3.5°C (predicted)

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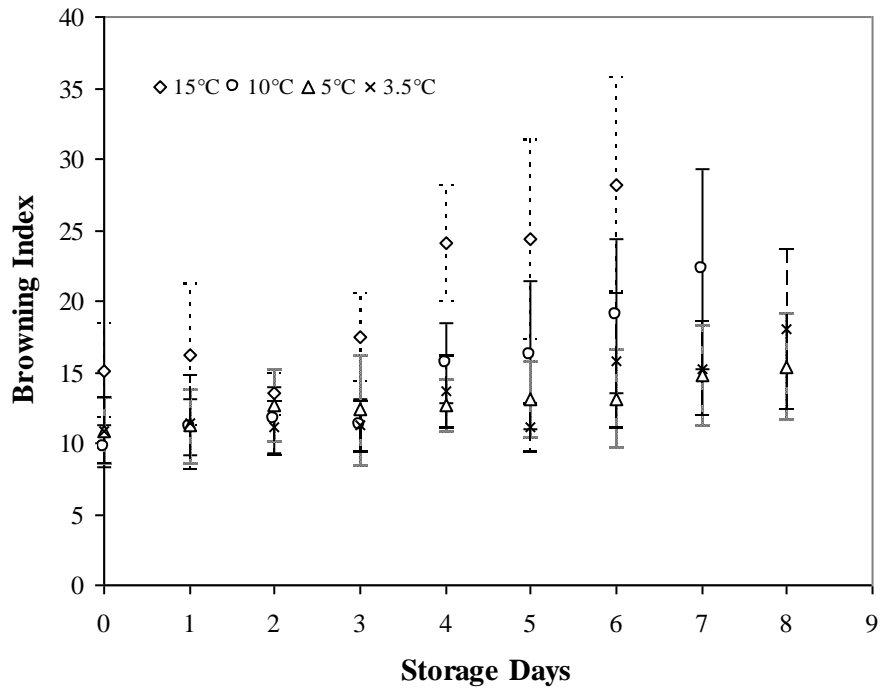
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541 Figure 3 Normal distribution plot for the proposed weibull model fitted to the textural  
542 hardness data of mushrooms stored under controlled conditions of temperature considering  
543 the batch variability

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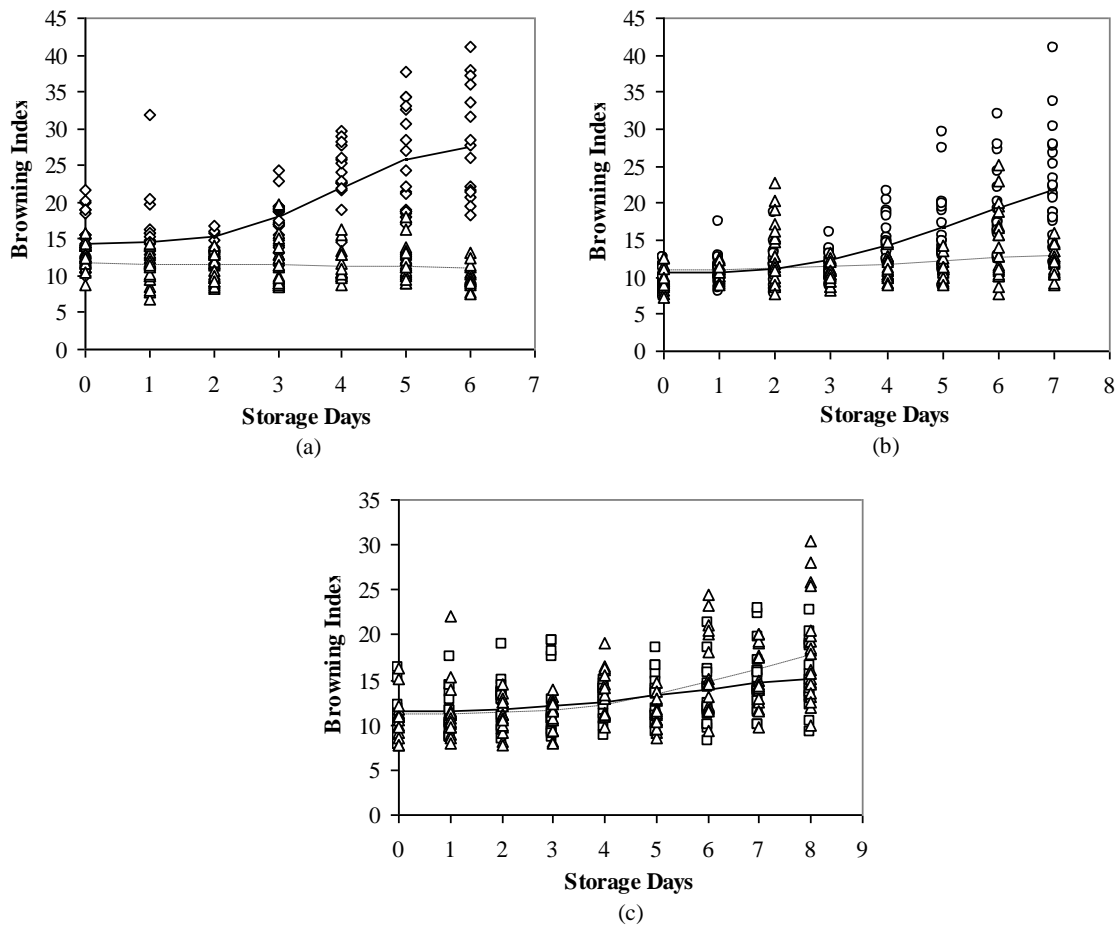


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548 Figure 4 Typical browning index kinetics of mushrooms at different storage temperatures ◇

549 15°C, ○ 10°C, △ 5°C, × 3.5°C (control)

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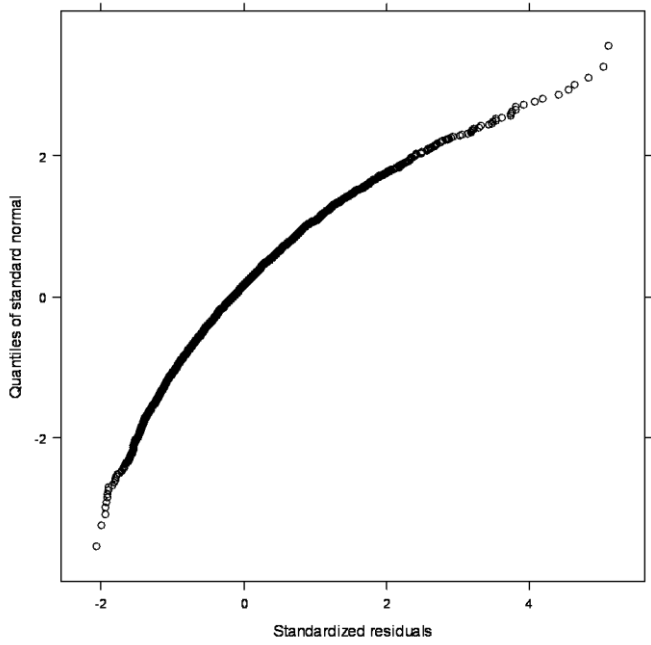
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Figure 5 Typical browning index kinetics of mushrooms at different storage temperatures fitted to weibull model (a)  $\diamond$  15°C (observed), - 15°C(predicted),(b) o 10°C (observed), - 10°C (predicted), (c)  $\square$  5°C (observed), - 5°C (predicted),  $\Delta$  3.5°C(observed), --- 3.5°C (predicted)

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563 Figure 6 Normal distribution plot for the proposed weibull model fitted to the browning index

564 of mushrooms stored under controlled conditions of temperature considering the batch

565 variability

566

567 Table 1 Parameter estimates of the Weibull model for predicting the textural hardness of  
 568 mushroom

**Fixed Parameters**

Parameter	Low 95% CI	Estimate	Up95%CI
<i>A</i>	13.241	15.726	18.211
<i>A-B</i>	-55.322	-49.876	-44.429
<i>n</i>	1.840	2.234	2.628
$\tau$ ( <i>Intercept</i> )	-1.443	-0.263	0.917
$\tau$ [ <i>1/Temperature</i> ]	-179252.8	-127525.4	-75798.1

**Random parameters**

Parameter	Low 95% CI	Estimate	Up95%CI
$\sigma$ ( <i>A</i> )	0.444	1.913	8.252
$\sigma$ ( <i>A-B</i> )	6.945	10.250	15.126
$\sigma$ ( $\tau$ [ <i>Intercept</i> ])	0.830	1.207	1.755

569 \* shows the direct temperature effect on the rate constant of the hardness

570

571



572 Table 2 Parameter estimates of the Weibull model for predicting the browning index of  
 573 mushroom

**Fixed Parameters**

Parameter	Low 95% CI	Estimate	Up95%CI
<i>Asymp</i>	17.542	21.470	25.397
<i>Initial</i>	11.462	12.184	12.905
<i>Iτ</i>	1.307	1.540	1.772
$\beta$	2.212	3.005	3.799

**Random parameters**

Parameter	Low 95% CI	Estimate	Up95%CI
$\sigma(Asymp)$	5.588	8.135	11.842
$\sigma(Initial)$	1.082	1.540	2.192
$\sigma(I\tau)$	0.250	0.392	0.615
$\beta$	0.668	0.936	1.312

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