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# Modelling the yield and texture of comminuted pork products using color and temperature. Effect of fat/lean ratio and starch

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Practices to control the processing of finely comminuted meat products are proposed. The objective was to test the practical value of both temperature and light reflection measurements made during emulsification as potential indicators of cooking losses and resulting gel texture in pork sausages emulsified within a wide range of temperatures and starch and fat levels. Prior to cooking, pork batters were chopped for different times to ensure final emulsion temperatures ranging from 5 to 50 °C. The effects of the fat/lean ratio (0.25 and 0.67) and starch addition (0.8 and 3.2% w:w) on temperature and optical reflection were also investigated. The chopping increased the temperature and decreased the light reflection of fresh meat emulsion. There was no relevant loss of emulsifying capacity at emulsion temperature below 30 °C and lightness values over 70 CIE units. The losses and textural parameters of cooked emulsions could be predicted by means of non-linear regression equations based on the temperature and color of the raw emulsion. The determination coefficients obtained ranged from 0.89 to 0.99. The prediction models needed to be fitted to each batter formulation, especially in the presence of reduced levels of gelation agents (meat protein and starch). Lightness was a better predictor than chromaticity, since it decreased constantly with chopping in the range of final emulsion temperatures studied (5–50 °C). This confirms previous studies that lightness could be used for monitoring emulsion stability in meat batters.


## 1. Introduction

The emulsification process is a critical operation in the manufacture of finely comminuted meat products such as hot dogs (frankfurters or wieners) and bologna. Emulsification strongly influences essential gel properties such as cooking loss and gel texture, among others. Obtaining a stable meat emulsion depends on many factors (see recent review by Álvarez et al., 2007), and involves decreasing the fat and meat particle sizes, extracting the natural emulsifying agents (mainly myosin) from the muscle, and coating fat globules with proteins before cooking. The chopping operation is a key factor in these three essential requirements (Allais, Viaud, Pierre, & Dufour, 2004), since fat particle size decreases during chopping, more protein is required to coat the fat particles to provide emulsion stability. In addition, the emulsion temperature increases with chopping, causing the surface tension of the fat particles and the emulsion viscosity to decrease, all of which increases the velocity of fat separation. Thus, emulsion over-heating might enhance local protein denaturation, decreasing the stabilizing capacity of proteins and inducing the coalescence of fat globules, which will result in greater cooking losses and softer gels (Allais et al., 2004; Álvarez et al., 2007; Barbut, 1998; Brown & Ledward, 1987; Thomas, Anjaneyulu, Gadekar, Pragati, & Kondaiah, 2007). As a result, maximum chopping temperatures between 12 and 18 °C are recommended for pork meat to prevent losses of the emulsifying capacity of meat proteins (Ambrosiadis & Wirth, 1984; Hedrick, Aberle, Forrest, Judge, & Merkel, 1994; Ladwig, Knipe, & Sebranek, 1989). However, meat products can be chopped within a wide margin of emulsification temperatures, since the thermal gelation of myofibrillar proteins mainly occurs at temperatures over 50 °C (Barbut, Gordon, & Smith, 1996).

Proper meat emulsification requires controlling chopping duration and speed as well as the emulsion temperature to prevent excessive water and fat separation, and the subsequent decrease in quality of the final products. Generally, the temperature reached during emulsification is an indicator of chopping intensity and/or duration, although Barbut (1998) indicated that temperature is not always the most accurate chopping endpoint predictor, especially in reduced fat meats. Barbut (1998) used a fibre optic probe to detect an early stage of meat emulsion breakdown, observing that lightness was correlated with cooking loss. Allais et al. (2004) suggested that it may be possible to predict the texture of frankfurters from the fresh emulsion fluorescence spectrum. They also observed changes in lightness and redness during chopping. Álvarez et al. (2007) found that lightness and other color coordinates

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were correlated with emulsion temperature, cooking loss and gel strength, and therefore showed promise as on-line indicators of the optimum chopping endpoint. In these preliminary studies, lightness increased in the early stages of the chopping process and started to decline just prior to the break point. This suggests that the beginning of a steady decrease in lightness would be an accurate indicator of an optimum level of emulsification, although little information was presented on these optical changes over a wide range of final temperatures.

Chopping is not the only factor that needs to be controlled to ensure emulsion stability. Lean, fat, water and starch levels are often modified during the manufacture of finely comminuted meat products to ensure emulsion stability and improve the final gel properties. An adequate proportion of functional protein is essential for both emulsion and gel stabilisation (Jiménez-Colmenero, Barreto, Mota, & Carballo, 1995). The effect of proteins on gel texture is influenced by several factors, such as protein concentration, pH, ionic strength and temperature, as they all affect protein functionality (Cofrades, Carballo, & Jiménez-Colmenero, 1997). The pH must be controlled to prevent possible meat quality deviations (e.g. acid, PSE and DFD meats), which can affect the emulsion properties of batters. Wismer-Pedersen (1987) reported that as the pH of meat nears the isoelectric point of myosin (pI = 5.4) the electrical net charge of myosin is minimized, resulting in a low water-binding capacity.

The fat/lean ratio is another important factor for emulsion and gel stabilisation. Since fat is replaced by protein, then, gel strength increases (Allais et al., 2004; Bloukas & Paneras, 1993) and cooking losses become smaller (Mittal & Blaisdell, 1983). However, if fat is replaced by water while the amount of protein is held constant, gel strength decreases and cooking losses increase (Cofrades, Careche, Carballo, & Jiménez-Colmenero, 1997; Crehan, Hughes, Troy, & Buckley, 2000). As a result, starch is often used to stabilize meat emulsions manufactured with added water, since starch improves the water holding capacity of the emulsion, increasing both gel yield and strength (Hughes, Mullen, & Troy, 1998). Starch gelatinizes during thermal treatment, increasing emulsion viscosity and reducing fat globule mobility. On the other hand, more redness has been observed at low fat/lean ratios in fresh batters (Allais et al., 2004). Crehan et al. (2000) reported a decrease in lightness and an increase in redness as fat was replaced by water in frankfurters. Preliminary studies by Álvarez et al. (2007) found optical differences in emulsions with high and low breakdown tendencies (fat/lean × starch combinations), but did not investigate the separate effect of these two factors. Thus, further investigation into the separate effects of lean, fat and starch levels on the correlations between the optical reflection of meat emulsions, cooking losses and gel texture could be of interest.

The objective of this work was to establish the practical value of both temperature and optical reflection measured during emulsification as a potential indicator of cooking losses and texture in comminuted pork meat emulsified within wide ranges of temperature, starch and fat/lean levels.

## 2. Materials and methods

### 2.1. Experimental design

In controlled room temperature conditions, pork batters were emulsified using seven different chopping times (CT) to give a heating ramp ranging from 5 to 50 °C. A completely randomized factorial design was used to study the effects of formulation. Four different formulations (treatments) were made by combining two fat/lean ratios (FL) (0.25 and 0.67) and two added starch levels (AS) (0.8 and 3.2% w:w) were made, with three replicates per treatment. Samples of each emulsion were obtained from the bowl chopper during the chopping process at 2 min intervals, from CT = 3 min to CT = 15 min, stopping at each time for ~30 s to obtain the samples. Pork batters were stuffed, cooked and cooled. Five physical properties (temperature, optical reflection, pH, cooking losses and texture profile) were determined for each batter and sampling point. The temperature of the emulsions was measured in the mixture remaining in the bowl chopper, while optical reflection was measured in each sample immediately after sample extraction. The pH was measured after keeping the samples for 2 h at 4 °C. Finally, cooking losses and the texture profile were analysed on cooked samples.

### 2.2. Emulsion manufacturing

Pork lean and fat, potato starch, ice, salt and commercial Frankfurter additives were used as raw ingredients to manufacture the emulsion. The fresh pork lean and backfat were obtained from a local industrial slaughterhouse, trimming the meat manually to remove connective tissue. Both the lean meat and fat were cut into small pieces (200 g) using a knife and then packed under vacuum in individual plastic bags and frozen at −18 °C until use (typically within one month). All the ingredients were weight by balance (Sartorius BP 1200, Germany), as shown in Table 1. The mixture of additives was provided by a local purveyor (Juan Martínez Pérez S.L. Murcia, Spain) and consisted of spices, smoke aroma, monosodium glutamate, pentapotassium triphosphate, sodium polyphosphate, sodium erythorbate, sodium nitrite and carminic acid. The additive mixture was then mixed with the appropriate starch concentration and the final mixture was packed and stored at room temperature until use. The day before manufacturing, the raw meat mixtures were tempered overnight in a refrigerator at 4 °C until the frozen meat and fat were at −5 °C. The bowl chopper (Robot Coupe Chopper, R 5 V.V., France) was placed inside a cool room at 4 °C and the chopping operation was performed at 1500 rpm.

### 2.3. Temperature, color and pH measurements

Temperature (*T*), pH and CIELAB color were measured in fresh pork batters. Seven emulsion samples (50 g) were obtained every 2 min during the chopping process. The temperature was measured by inserting a probe model TM 65 (Digital thermometer, Crison Instruments, S.A. Barcelona, Spain) into the batters immediately after sampling. The color of the fresh emulsion samples was measured by a hand held tristimulus reflectance colorimeter (Chromameter II CR-200 Minolta Camera Co., Osaka, Japan), using a CIE standard 'C' illuminant, an observation angle of 0° and an 8 mm diameter measuring area, having previously calibrated the chromameter for light source index setting 'C'. The results were expressed as CIELAB units: $L^*$ (lightness); $a^*$ (redness); $b^*$ (yellowness); Chroma ($C^*$); and Hue angle (°Hue) (sexagesimal degrees); $C^* = (a^{*}2 + b^{*}2)^{1/2}$. $°\text{Hue} = \text{tg}^{-1}\ (b^*/a^*)$. The pH was mea-

**Table 1**
Formulation of the pork batters

| Formula | A | B | C | D |
|---|---|---|---|---|
| Fat/lean ratio | High | High | Low | Low |
| Added starch (%) | High | Low | High | Low |
| *Ingredients (g)* | | | | |
| Lean pork | 1200 | 1200 | 1600 | 1600 |
| Backfat | 800 | 800 | 400 | 400 |
| Ice | 300 | 300 | 300 | 300 |
| Potato starch | 80 | 20 | 80 | 20 |
| Frankfurter additive | 80 | 80 | 80 | 80 |
| Sodium chloride | 50 | 50 | 50 | 50 |

sured by homogenisation in water using a micropH 2001 pHmeter (Crison, Barcelona, Spain) equipped with a combined electrode Cat n° 52-22 (Ingold Electrodes, Inc. Wilmington, USA). Prior to pH measurement, the samples were held in a cool room until they reached 4 °C.

### 2.4. Cooking losses

Pork batter aliquots of 50 g were collected at each chopping time, as described above, and stuffed into 100 mL plastic screw tap test tubes, prior to heating in a water bath (Mainca S.L., Spain). Controlled temperature and time conditions (30 min at 75°C) were used to ensure an internal temperature of 68–70 °C. After this thermal treatment, the cooked emulsions were pre-cooled in a cold water bath and finally refrigerated for 24 h at 4°C. Cooking losses (CL) were determined by mass balance (% w:w), after each tube was emptied into a sieve and drained. CL was calculated in duplicate from the amount of exudate (e.g., jelly and fat) separated from the emulsion during the thermal treatment and the initial weight of the sample before cooking as follows:

$$\mathrm{CL}\ (\%) = \frac{\text{Liquid loss (g)}}{\text{Weight sample (g)}} \times 100$$

### 2.5. Texture profile analysis

The texture profile analysis (TPA) was made in cooked emulsions by means of two cycle compression test, as described by Bourne (1978), using a texture analyzer (Brookfield CNS Farnell, Borehamwood, Hertfordshire, England) equipped with a load cell of 25 kg, a 10 N sensor and Texture Pro V. 2.1 software. Prior to the analysis, the tubes containing meat batters were placed in a thermosted water bath (Digiterm 100 Selecta, Barcelona, Spain) until an internal temperature of 20 °C was reached. The target temperature of the samples was verified using a portable T200 thermometer. Cylindrical samples (2.2 ± 0.1 cm diameter × 2 ± 0.1 cm height) were compressed with a 2 cm diameter cylindrical probe and texture profile measurements were performed at 20 °C. Two consecutive cycles of 50% compression, using a cross-head constant speed of 5 cm $\mathrm{min}^{-1}$, of 0.05 N were performed, making five measurements per sample. Five primary textural parameters were obtained from the recorded force–time curves: Hardness (N), the maximum force required to compress the sample; Cohesiveness (dimensionless), the extent to which sample could be deformed prior to rupture ($A2/A1$), where $A1$ and $A2$ were the total energy required for the first and second compression, respectively; Gumminess (N), the force needed to disintegrate a semi-solid food to a state ready for swallowing (hardness × cohesiveness); Springiness (mm), the ability of the sample to recover its original form after the deforming force was removed; and Chewiness (N mm), the work needed to chew a solid sample to a state ready for swallowing (springiness × gumminess).

### 2.6. Statistical analysis

Data were analysed using Statistix for Windows 2.0 program (Analytical Software, USA). An analysis of variance was used to investigate the sources of variation of the dependent variables (i.e., TP, CL, $T$, pH and color parameters). The main effects evaluated in the ANOVA were CT, FL ratio and AS level as well as their interactions. The least-squares means (LSM) and significance of treatments were calculated using type IV sum of squares. The Scheffe Means Test was used to compare the LSM, which were considered to be statistically different when $P < 0.05$. Pearson correlation coefficients between the different dependent variables were determined. For CL and texture parameter predictions, exponential, power and polynomial non-linear regression models were tested to obtain the maximum $R^2$ coefficients.

## 3. Results and discussion

The effects of the main factors (i.e., chopping time, fat/lean ratio and starch addition level) on the physical properties of fresh ($T$, color and pH) and cooked (CL and TP) emulsion were determined by ANOVA. The $F$ statistics for emulsion and gel dependent variables are shown in Table 2. Least-square means are presented in Tables 3 and 4.

### 3.1. Effect of chopping and raw material composition on emulsion temperature

As shown in Table 2, $T$ was affected by chopping time, fat/lean ratio and starch addition levels. $T$ increased significantly ($P < 0.001$) during the chopping operation (Table 3). This represented

**Table 2**
Analysis of variance and $F$-statistics for emulsion and gel dependent variables

| | Variation source | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CT | | FL | | AS | | CT × FL | | CT × AS | | FL × AS | | CT × FL × SP | |
| | DF | $F$ | DF | $F$ | DF | $F$ | DF | $F$ | DF | $F$ | DF | $F$ | DF | $F$ |
| *Emulsion* | | | | | | | | | | | | | | |
| Temperature | 6 | 783.4*** | 1 | 84.4*** | 1 | 13.8*** | 6 | 1.8 | 6 | 1.1 | 1 | 9.7** | 6 | 0.9 |
| $L^*$ | 6 | 228.4*** | 1 | 107.3*** | 1 | 10.1** | 6 | 3.7** | 6 | 1.0 | 1 | 31.0*** | 6 | 1.3 |
| $a^*$ | 6 | 152.2*** | 1 | 98.9*** | 1 | 6.3* | 6 | 13.3*** | 6 | 2.3* | 1 | 0.9 | 6 | 2.6* |
| $b^*$ | 6 | 6.4*** | 1 | 19.1*** | 1 | 2.3 | 6 | 2.2* | 6 | 1.3 | 1 | 3.1 | 6 | 1.6 |
| $C^*$ | 6 | 114.5*** | 1 | 119.1*** | 1 | 19.9*** | 6 | 11.5*** | 6 | 2.0 | 1 | 0.3 | 6 | 4.5*** |
| °Hue | 6 | 113.0*** | 1 | 39.1*** | 1 | 0.0 | 6 | 9.1*** | 6 | 1.5 | 1 | 4.6* | 6 | 0.7 |
| pH | 6 | 0.9 | 1 | 1.9 | 1 | 0.1 | 6 | 0.0 | 6 | 0.0 | 1 | 36.9*** | 6 | 0.0 |
| *Gel* | | | | | | | | | | | | | | |
| Cooking loss | 6 | 153.8*** | 1 | 19.3*** | 1 | 18.4*** | 6 | 2.1 | 6 | 1.2 | 1 | 47.3*** | 6 | 3.2** |
| Hardness | 6 | 61.1*** | 1 | 18.8*** | 1 | 13.5*** | 6 | 7.9*** | 6 | 4.6*** | 1 | 30.9*** | 6 | 1.9 |
| Gumminess | 6 | 121.9*** | 1 | 29.0*** | 1 | 13.4*** | 6 | 9.3*** | 6 | 3.1** | 1 | 16.5*** | 6 | 1.6 |
| Springiness | 6 | 26.6*** | 1 | 17.9*** | 1 | 6.2* | 6 | 2.0 | 6 | 1.5 | 1 | 16.9*** | 6 | 2.0 |
| Cohesiveness | 6 | 121.0*** | 1 | 20.5*** | 1 | 0.4 | 6 | 5.3*** | 6 | 0.4 | 1 | 0.0 | 6 | 1.0 |
| Chewiness | 6 | 131.9*** | 1 | 32.0*** | 1 | 16.2*** | 6 | 9.9*** | 6 | 4.1*** | 1 | 22.7*** | 6 | 1.8 |

DF: Degree of freedom; $F$: ANOVA $F$-statistic. CT: Chopping time; FL: Fat/lean ratio; AS: Added starch level.
Level of significance: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$. $N = 84$.

**Table 3**
Effects of chopping time, fat/lean ratio and added starch level on LSM temperature, color and pH measured in fresh meat emulsions[1]

| | $T$ | $L^*$ | $a^*$ | $b^*$ | $C^*$ | °Hue | pH |
|---|---|---|---|---|---|---|---|
| *Chopping time (min)* | | | | | | | |
| 3 | 5.2[f] | 72.9[a] | 10.3[a] | 11.2[a] | 15.2[a] | 47.3[c] | 5.9 |
| 5 | 16.4[e] | 72.1[b] | 9.6[b] | 11.2[a] | 14.8[a] | 49.5[b] | 5.9 |
| 7 | 27.4[d] | 70.8[c] | 8.4[c] | 11.1[ab] | 13.9[b] | 53.0[a] | 5.9 |
| 9 | 36.3[c] | 69.6[d] | 7.6[d] | 10.6[ab] | 13.3[c] | 54.8[a] | 6.0 |
| 11 | 43.4[b] | 68.2[e] | 7.8[d] | 10.7[ab] | 13.2[c] | 53.9[a] | 6.0 |
| 13 | 47.5[a] | 67.5[ef] | 7.8[d] | 10.7[ab] | 13.2[c] | 53.7[a] | 6.0 |
| 15 | 49.9[a] | 66.9[f] | 7.8[d] | 10.5[b] | 13.1[c] | 53.2[a] | 6.0 |
| *Fat/lean ratio (dimensionless)*[2] | | | | | | | |
| 0.25 | 30.2[b] | 69.1[b] | 8.8[a] | 11.1[a] | 14.1[a] | 51.6[b] | 5.9[b] |
| 0.66 | 34.4[a] | 70.3[a] | 8.2[b] | 10.6[b] | 13.5[b] | 52.8[a] | 6.0[a] |
| *Added starch percentage (%)*[3] | | | | | | | |
| 0.8 | 31.4[a] | 69.9[a] | 8.4[a] | 10.8 | 13.7[a] | 52.2 | 6.0 |
| 3.2 | 33.1[b] | 69.5[b] | 8.6[b] | 10.9 | 13.9[b] | 52.2 | 6.0 |

[1] LSM with different superscripts were different for $P < 0.05$. $N = 84$.
[2] Average ratio for all chopping times.
[3] Average percentage for all chopping times.

a marked degree of over-heating with respect to previous studies made on frankfurters (Allais et al., 2004; Álvarez et al., 2007; Barbut, 1998; Boles, Mikkelsen, & Swan, 1998; Thomas et al., 2007), where maximum emulsion temperatures of between 15 °C and 24 °C were reached. As mentioned, our experiment was designed to obtain additional information to complement previous studies on the interaction between temperature and the color measurements obtained from the beginning of the chopping operation to the initiation of fat melting and protein gelation phenomena caused by heating (i.e., in over-chopping conditions). The combined use of a blade speed of 1500 rpm, a room temperature of 4 °C and a bowl chopper without a cooling system, where heat losses would mainly have occurred through the steel bowl, allowed us to control the emulsion over-heating ramp. In addition, our results indicated that, during chopping, $T$ LSM values were significantly ($P < 0.001$) higher (4.2 °C; Table 3) in fatter emulsions (0.67) than in leaner emulsions (0.25). Similarly, when 3.2% starch was added, $T$ LSM values were 1.7 C° ($P < 0.001$) higher than when 0.8% starch was added (Table 3). The addition of both fat and starch may have decreased the thermal conductivity and diffusivity of the comminuted meat, so that the internal heat generated by chopping was kept for longer (Lewis, 1993; Willix, Lovatt, & Amos, 1998; Zhang, Lyng, & Brunton, 2007).

### 3.2. Effect of chopping and raw material composition on emulsion color

Emulsion color was affected by both chopping time and formulation as well as by their interaction (Table 2). Considerable changes in light reflection were observed as the emulsification process progressed (Table 3). LSM values for $L^*$ fell from 73 (3 min) to 67 (15 min), $a^*$ fell from 10.3 to 7.8, at the same times, $b^*$ fell slightly from 11.2 to 10.5, $C^*$ fell from 15.2 to 13.1, while the LSM for °Hue increased from 47.3 to 53 (CIE Units). Although these results are consistent with previous studies (Allais et al., 2004; Álvarez et al., 2007; Barbut, 1998; Boles et al., 1998), the early increase of $L^*$ described by these authors was not observed. Rather, $L^*$ decreased steadily during chopping. According to Barbut (1998) and Álvarez et al. (2007), the maximum $L^*$ value corresponds to the maximum degree of meat emulsion stability (i.e., minimum cooking losses) during chopping. This suggests that, under the processing conditions used in our study, rapid emulsification might be taking place, maximum emulsion stability probably being achieved even before the first sample was obtained at CT = 3 min. The decrease in $a^*$ and $C^*$ LSM values during chopping differed slightly from the $L^*$ values. While $L^*$ fell steadily and significantly ($P < 0.001$) throughout the chopping process, even in over-chopping conditions, the main decrease ($P < 0.001$) in $a^*$ and $C^*$ LSM occurred during the early stages of chopping (3–9 min).

Color changes in meat batters during chopping have been attributed to a combination of physical–chemical phenomena, probably associated with fat particle size variations, the presence of air bubbles and/or protein–fat interactions (Álvarez et al., 2007). According to Palombo, Van Room, Prins, Koolmes, and Krol (1994), both the reduction in fat particle size and the presence of air bubbles entrapped in the meat emulsion may act as light scattering agents. On the other hand, local denaturation and myoglobin oxidation during chopping may also contribute to emulsion decoloration (Carlez, Veciana-Nogues, & Cheftel, 1995; Ginar & Denoyer, 1982). Indeed, it is difficult to establish the exact mechanisms involved in color changes during the chopping process. Early changes in color, especially in redness, might be related with the haem pigment degradation, while the subsequent decrease in $L^*$ values observed as chopping progressed might be explained by the residual denaturation of muscle proteins caused by local overheating, since protein denaturation reduces the water holding capacity of meat, increasing exudation and light reflection. Fat melting also could change the color of batters at over-chopping, since melted fat has a yellow tone compared with solid fat. This

**Table 4**
Effects of chopping time, fat/lean ratio and added starch level on weight losses and texture profile of cooked meat emulsions[1]

| | CL (%) | Hard (N) | Cohesive (No units) | Gummy (N) | Springy (mm) | Chewy (N mm) |
|---|---|---|---|---|---|---|
| *Chopping time (min)* | | | | | | |
| 3 | 0.23[e] | 36.2[b] | 0.67[a] | 24.5[ab] | 8.5[a] | 205.3[b] |
| 5 | 0.22[e] | 39.7[ab] | 0.66[a] | 26.3[ab] | 8.6[a] | 226.2[ab] |
| 7 | 0.46[de] | 44.7[a] | 0.63[a] | 28.4[a] | 8.6[a] | 244.1[a] |
| 9 | 1.14[d] | 41.8[a] | 0.57[b] | 23.8[b] | 8.5[a] | 202.2[b] |
| 11 | 2.69[c] | 29.9[c] | 0.45[c] | 13.8[c] | 8.1[b] | 114.2[c] |
| 13 | 3.79[b] | 27.4[c] | 0.40[c] | 11.1[c] | 8.0[b] | 90.2[c] |
| 15 | 4.57[a] | 25.1[c] | 0.40[c] | 10.0[c] | 7.9[b] | 79.2[c] |
| *Fat/lean ratio (dimensionless)*[2] | | | | | | |
| 0.25 | 1.63[b] | 36.3[a] | 0.56[a] | 21.0[a] | 8.4[a] | 177.3[a] |
| 0.67 | 2.11[a] | 33.7[b] | 0.52[b] | 18.4[b] | 8.2[b] | 154.5[b] |
| *Added starch percentage (%)*[3] | | | | | | |
| 0.8 | 2.11[b] | 33.5[b] | 0.54 | 18.6[b] | 8.3[b] | 155.8[b] |
| 3.2 | 1.64[a] | 36.5[a] | 0.54 | 20.8[a] | 8.4[a] | 176.0[a] |

[1] LSM with different superscripts were different for $P < 0.05$. $N = 84$.
[2] Average ratio for all chopping times.
[3] Average percentage for all chopping times.

would have been possible in the experimental conditions tested, since the melting point of pig backfat, depending of the diet, could be around 40 °C (Suzuki, Shibata, Kadowaki, Abe, & Toyoshima, 2003). However, no differences in $L^*$, $a^*$ or $b^*$ coordinates was observed at $T$ 40–50 °C compared to 30–40 °C.

As mentioned, the fat/lean ratio affected $L^*$, $a^*$ and $C^*$ more than $b^*$ and °Hue (Table 2). The mean values for $L^*$ and °Hue increased significantly ($P < 0.001$) with the higher fat/lean ratio, while the opposite effect ($P < 0.001$) was observed for $a^*$, $b^*$ and $C^*$. According to Allais et al. (2004), high-fat emulsions show greater light reflection and less redness, despite the use of liquid carmine (a red colorant). The whitening effect of fat globule reduction during chopping together with the increase of myoglobin denaturation and oxidation might have contributed to the redness decrease observed with increasing levels of fat. However, the addition of starch had the opposite effect to fat on color. With increasing levels of added starch a significant increase in the LSM for $L^*$ ($P < 0.01$), $a^*$ ($P < 0.05$) and $C^*$ ($P < 0.001$) was observed, although, no significant effect ($P > 0.05$) on $b^*$ and °Hue was found. The high-starch emulsions reflected more light and showed increased redness compared with low-starch emulsions, perhaps because of a reduction in the quantity of liquid in the meat emulsion surface since starch improves the water-binding capacity, thus reducing exudation. According to Hale and Querry (1973), water absorption for red light is much higher that for blue light, which suggests that an increase in surface water could decrease meat emulsion redness. As can be observed in Table 2, the effect of starch addition on color was less pronounced than the effects produced by changes in the fat/lean ratio.

### *3.3. Effect of chopping and raw material composition on emulsion pH*

The pH remained stable around ~6 during the emulsification process. No significant ($P > 0.05$) changes in emulsion pH (measured at constant reference temperature, 4 °C) were caused by chopping time, the fat/lean ratio or starch level, although a significant ($P < 0.001$) increase in pH was caused by the interaction of fat/lean and starch (Table 2). Thomas et al. (2007) reported stable pH values in buffalo meat nuggets (cooked) manufactured at different comminution temperatures.

### *3.4. Effect of chopping and raw material composition on cooking losses*

Cooking losses were affected by chopping time, the fat/lean ratio and the level of starch addition, as well as by their interaction. The $F$-statistics (Table 2) showed that chopping time had a pronounced effect on CL, which increased CL from 0.2% at 3 min to 4.6% at 15 min in the cooked batter (Table 4). CL remained stable ($P > 0.05$) for the first 5 min of chopping, but showed a significant increase ($P < 0.001$) after 7 min. Other authors (Allais et al., 2004; Barbut, 1998; Thomas et al., 2007), have observed that the overheating caused by long chopping times is correlated with higher CL. The fat/lean ratio and starch addition level had opposite effects on CL. Both, a reduction in the fat/lean ratio and an increase in starch level led to a significant ($P < 0.001$) decrease in CL from 2.1% to 1.6%. Allais et al. (2004) found no significant effect of the fat/lean ratio on the processing yield of frankfurters, although CL increased as the fat/lean increased. Our results were not unexpected since the addition of fat with no proportional increase in lean meat reduces the emulsifying protein around the fat globules, resulting in less stable meat emulsions. Hughes et al. (1998) reported lower CL in meat emulsions containing added tapioca starch, since hydrated starch gelatinizes during cooking, resulting in higher emulsion viscosity, lower fat globule mobility and more water-binding.

### *3.5. Effect of chopping and raw material composition on texture profile*

The texture profile was affected by chopping time, the fat/lean ratio and starch addition level, as well as by their interaction (Table 2). The gradual emulsification of batters resulted in an increase of the gel strength of cooked emulsions up to ~7 min of chopping. Then, an appreciable ($P < 0.001$) decrease in the hardness, cohesiveness, gumminess, springiness and chewiness was observed after 7–9 min of chopping (Table 3). This decrease in gel consistency after 7–9 min of chopping may have been due to improper fat emulsification as fat size decreases (i.e., the globule surface to volume ratio increased) and/or to the local denaturation of meat emulsifying proteins (Barbut, 1998). It is difficult to say which factor is more influential, although it seems that this loss of firmness should be mainly due to the loss of the emulsifying capacity of meat at over-chopping conditions, since the machine used provides sufficient mechanical energy input to obtain a stable meat emulsion at 3 min. A subsequent fat globule reduction (even fat melting) by chopping could have affected emulsion stability if there are insufficient functional emulsifying agents in the system.

Whatever the reason, this lack of consistency was typically accompanied by a significant increase of CL. An increase in the fat/lean ratio also decreased gel strength, leading to lower hardness, cohesiveness, gumminess, springiness and chewiness, all of which was to be expected. Increasing fat level without a proportional increase in lean meat could lead to the relative lack of emulsifying agents, which would increase cooking losses and decrease gel consistency, especially in the case of over-chopping. This effect was reported by Álvarez et al. (2007), although, Allais et al. (2004) reported greater adhesiveness in frankfurters as the fat/lean ratio was increased, while hardness and cohesiveness were not affected. The addition of starch had the opposite effects compared to fat/lean ratio. Increasing the starch level increased hardness, gumminess, springiness and chewiness. However, no significant effect was observed on cohesiveness. Hughes et al. (1998) found higher gel strength in frankfurters manufactured with added starch. Starch improves the formation of stronger heat-induced structures as the starch granules embedded in the protein gel matrix swell. This could increase water-binding capacity of the gel matrix, which would result in a firmer, more compact structure after cooking (Chen, Lee, & Crapo, 1993; Jiménez-Colmenero et al., 1995). According Table 2 the effect of the fat/lean ratio on textural attributes was more evident than the effect of starch level.

### *3.6. Correlation between the physical properties of batters*

ANOVA gave good correlations between the physical properties measured prior ($T$ and color) and after (CL and texture) cooking. The Pearson's correlation coefficients and $P$-values for $T$, color, CL and textural attributes were calculated (Table 5). $T$ and color coordinates were strongly correlated ($P < 0.001$) with CL and textural attributes. The best correlation coefficients were observed between cohesiveness, CL and $T$ ($R = -0.80$ and 0.77, respectively) and with

**Table 5**
Pearson's correlations between emulsion and gel measurements

| | CL | Hard | Cohesive | Gummy | Springy | Chewy |
|---|---|---|---|---|---|---|
| $T$ | $0.77^{***}$ | $-0.45^{***}$ | $-0.80^{***}$ | $-0.67^{***}$ | $-0.54^{***}$ | $-0.66^{***}$ |
| $L^*$ | $-0.68^{***}$ | $0.44^{***}$ | $0.72^{***}$ | $0.62^{***}$ | $0.42^{***}$ | $0.61^{***}$ |
| $a^*$ | $-0.53^{***}$ | $0.19^{**}$ | $0.58^{***}$ | $0.40^{***}$ | $0.37^{***}$ | $0.41^{***}$ |
| $b^*$ | $-0.29^{***}$ | $0.22^{***}$ | $0.40^{***}$ | $0.35^{***}$ | $0.21^{**}$ | $0.35^{***}$ |
| $C^*$ | $-0.57^{***}$ | $0.30^{***}$ | $0.62^{***}$ | $0.49^{***}$ | $0.43^{***}$ | $0.50^{***}$ |
| °Hue | $0.43^{***}$ | $-0.07$ | $-0.47^{***}$ | $-0.27^{***}$ | $-0.27^{***}$ | $-0.27^{***}$ |

Level of significance: $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$.

$L^*$ ($R$ = 0.72 and −0.68, respectively). Higher temperatures resulted in greater CL and softer gels (Barbut, 1998; Hedrick et al., 1994). A negative correlation between gel strength and chopping time was reported by Barbut (1998) and Álvarez et al. (2007). In agreement with Álvarez et al. (2007), $L^*$ gave better $R$ coefficients with both CL and TP than for the coordinates, $a^*$, $b^*$, $C^*$ and $H^*$. On the other hand, and as expected, $T$ was strongly correlated with $L^*$ ($R$ = −0.82; $P < 0.001$). Changes in both $T$ and $L^*$ during emulsification were clearly associated with changes in CL and gel strength, which underlines the potential use of $T$ and $L^*$ for monitoring gel yield and texture during the manufacture of comminuted meat products.

### 3.7. Cooking loss and texture prediction by temperature–lightness parameters

The abilities of $T$ and $L^*$ as predictors of CL and texture parameters when using different formulations was evaluated. Non-linear regressions for CL and cohesiveness vs. $T$ and $L^*$ are shown in Figs. 1 and 2 and Tables 6, 7. The best $R^2$ coefficients were obtained using the following exponential, power and polynomial equations, respectively:

$$V = \beta_1 e^{\beta_2 T}, \quad (1)$$

$$V = \beta_0 + \beta_1 L^{*\beta_2}, \quad (2)$$

$$V = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 P^3, \quad (3)$$

**Table 6**
Predictive models for cooking loss vs. temperature/lightness

| | Formulation (FL; AS) | | Regression equation for CL | $R^2$ |
|---|---|---|---|---|
| ▲ | 0.25 | 0.8% | $0.0582\ e^{0.0840T}$ | 0.89 |
| X | 0.25 | 3.2% | $0.1041\ e^{0.0704T}$ | 0.91 |
| ♦ | 0.67 | 0.8% | $0.1612\ e^{0.0699T}$ | 0.95 |
| ■ | 0.67 | 3.2% | $0.0633\ e^{0.0758T}$ | 0.95 |
| ▲ | 0.25 | 0.8% | $2 \times 10^{69}\ L^{*-37.659}$ | 0.90 |
| x | 0.25 | 3.2% | $2 \times 10^{65}\ L^{*-35.585}$ | 0.99 |
| ♦ | 0.67 | 0.8% | $4 \times 10^{72}\ L^{*-39.193}$ | 0.99 |
| ■ | 0.67 | 3.2% | $1 \times 10^{81}\ L^{*-43.894}$ | 0.98 |

FL: Fat/lean ratio; AS: Added starch level; CL: Cooking losses.

where $V$ was the dependent variable (CL or cohesiveness), $\beta_0$ to $\beta_3$ were regression coefficients and the predictor, $P$, in Eq. 3 represented either $L^*$ or $T$. $L^*$ gave slightly better $R^2$ coefficients than $T$ for both CL and cohesiveness predictions. The $R^2$ coefficients ranged from 0.89 to 0.99. Preliminary studies by Álvarez et al. (2007) proposed four different predictive functions for CL in frankfurters, based on combinations of dependent ($L^*$ and $a^*$) and independent (chopping time, lean–fat–starch level) variables. Álvarez et al. (2007) reported $R^2$ coefficients between 0.42 and 0.69. Our study proposes a simple prediction model for CL and cohesiveness using only one dependent variable, where the effect of chopping treatment on the subsequent quality of sausages can be followed simply by using an optical or/and temperature sensor.

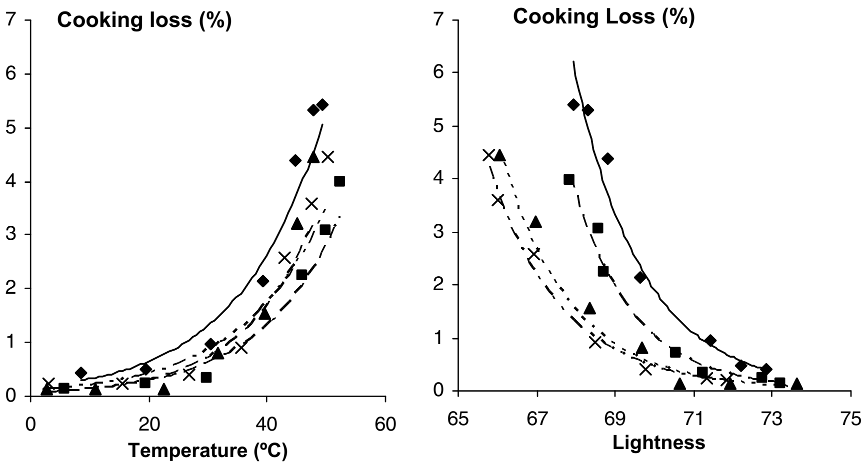


**Fig. 1.** Predictive models for cooking loss vs. temperature/lightness.

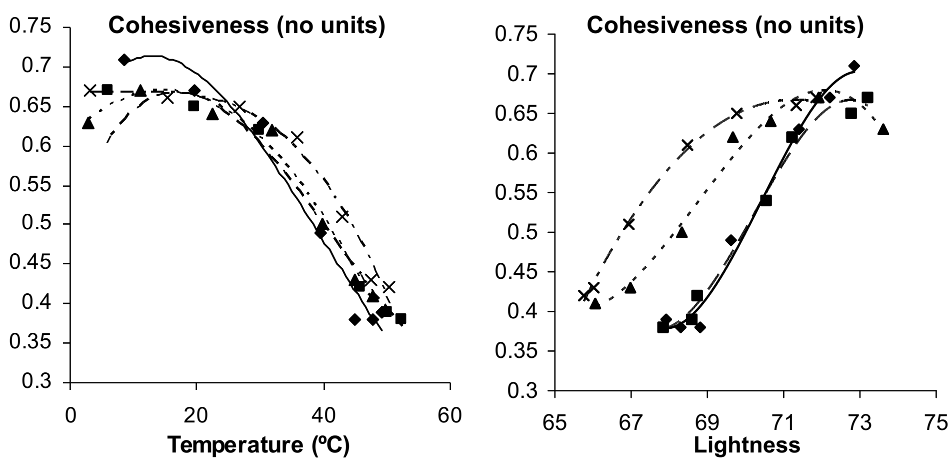


**Fig. 2.** Predictive models for cohesiveness vs. temperature/lightness.

**Table 7**
Predictive models for cohesiveness vs. temperature/lightness

| | Formulation | | Regression equation for cohesiveness | $R^2$ |
|---|---|---|---|---|
| ▲ | 0.25 | 0.8% | $6 \times 10^{-7}\ T^3 - 3 \times 10^{-4}\ T^2 + 0.0084\ T + 0.6092$ | 0.98 |
| X | 0.25 | 3.2% | $-4 \times 10^{-6}\ T^3 + 9 \times 10^{-5}\ T^2 - 7\ 10^{-4}\ T + 0.6690$ | 0.98 |
| ♦ | 0.67 | 0.8% | $6 \times 10^{-6}\ T^3 - 7 \times 10^{-4}\ T^2 + 0.154\ T + 0.6206$ | 0.97 |
| ■ | 0.67 | 3.2% | $6 \times 10^{-6}\ T^3 - 8 \times 10^{-4}\ T^2 + 0.0207\ T + 0.5078$ | 0.90 |
| ▲ | 0.25 | 0.8% | $-0.0019\ L^{*3} + 0.3995\ L^{*2} - 27.404\ L^{*} + 625.73$ | 0.99 |
| x | 0.25 | 3.2% | $0.0001\ L^{*3} - 0.0388\ L^{*2} + 3.303\ L^{*} - 90.585$ | 0.99 |
| ♦ | 0.67 | 0.8% | $-0.0050\ L^{*3} + 1.0548\ L^{*2} - 74.196\ L^{*} + 1738$ | 0.99 |
| ■ | 0.67 | 3.2% | $-0.0044\ L^{*3} + 0.9320\ L^{*2} - 65.352\ L^{*} + 1526$ | 0.99 |

In agreement with the above mentioned ANOVA, the fat/lean ratio and starch levels modified the predictive equations. The most pronounced slopes were found for a 0.67 fat/lean ratio × 0.8% added starch, the formulation with the least emulsifying capacity. This confirms that $T$ and $L^*$ variations during emulsification corresponded to greater changes in CL and gel texture when high-fat and low-starch formulations were used. As expected, high emulsion temperatures affected further gelation, since the slopes were more pronounced at temperatures above 30 °C and above 70 $L^*$ CIE units, i.e., at long chopping times (>7 min). These results agree with others (Álvarez et al., 2007; Barbut, 1998; Thomas et al., 2007) and suggest that $L^*$ could also be a useful parameter for monitoring thermal gelation in frankfurters. Future studies should be performed to clarify this possibility.

## 4. Conclusions

The chopping process increased the temperature and decreased light reflection in pork batters. Under the experimental conditions studied, no relevant loss of emulsifying capacity occurred at emulsion temperatures below 30 °C and lightness values over 70 CIE units. However, over-chopping and subsequent over-heating negatively affected further gelation, increasing cooking losses and diminishing gel strength. Both cooking losses and the textural attributes of cooked emulsions were strongly correlated with temperature and optical reflection measured in the raw meat emulsions. Thus, cooking losses, cohesiveness and other textural attributes could be predicted before cooking by using non-linear regression equations. Temperature–optical reflection predictive equations must be fitted to the formulation used for emulsion manufacturing, since the formulation modified both cooking losses and gel strength, especially with reduced levels of gelling agents (meat protein and starch). Lightness was a better predictor than the chromatic coordinates in the range of emulsion temperatures studied (5–50 °C). This suggests that lightness could be used to monitor both emulsion stability and thermal gelation in meat batters. Thus, on-line optical sensor technology could assist during manufacturing to minimize quality losses in finely comminuted meat products.

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