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Kinetic modelling of texture and color changes during thermal treatment of chicken breast meat

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Abstract

Heat treatment is commonly applied as a primary method for ensuring the microbial safety of poultry meat and to enhance its palatability. Although texture and color of cooked chicken breast meat are important quality parameters for the consumers that need to be controlled during thermal processing, studies assessing the temperature-time-dependent quality changes during thermal treatment are lacking. This work aims to investigate the texture and color changes of chicken breast meat during thermal processing and to develop kinetic models that describe these changes. We studied the storage modulus changes of chicken breast meat as function of temperature. The storage modulus increases from 55 °C until levelling off in an equilibrium value above 80 °C, which was attributed to microstructure changes and described with a sigmoidal function. The changes in the texture (TPA) and color (CIE $L^*a^*b^*$) of chicken breast meat were measured as function of temperature and time. The texture and color parameters show a rise with heating time until reaching an equilibrium value, while the rate of change increased with temperature. Kinetic models that take the non-zero equilibrium into account were developed to describe the color (lightness) and texture (hardness, gumminess and chewiness) changes with heating time and temperature. The kinetic models provide a deeper insight into the mechanisms of texture and color changes during thermal treatment. They can be used to predict the texture and color development of chicken breast meat during thermal processing and, thus, help to optimize the process.

1. Introduction

The worldwide consumption of poultry meat has increased more than 30 % over the last 10 years (OECD, 2018). Particularly, chicken breast meat is popular among consumers due to its relative low price compared to other meat products (e.g., beef and pork meat) and its low fat and high protein content (Guerrero-Legarreta and Hui, 2010; Magdelaine et al., 2008).

To ensure the safe consumption of chicken meat it should be heated at least to an internal temperature of 72 °C (Fsis, 2000). The heating leads to changes in the microstructure, texture and appearance of the chicken breast meat and may affect the acceptance by the consumers (Lawrie and Ledward, 2006).

The convective roasting (using hot air) is the most common heating method for chicken meat in professional kitchens and the large scale food industry, but also contact frying/grilling or the cooking in hot water is often applied (Guerrero-Legarreta and Hui, 2010; Lawrie and Ledward, 2006). Different studies show that the heating methods have different impact on the texture and color of poultry meat. Barbanti and Pasquini (2005) reported that hot air roasting leads to tougher poultry meat samples compared to the steam cooked samples, whereas Zell et al. (2010) reported that there is no significant difference in the texture of samples prepared by ohmic-heating and convectional heating. In these studies, the poultry meat samples were heated to different core temperatures and the change in the quality correlated with these temperatures. However, conventional heating methods (e.g., roasting in convection oven) lead to temperature gradients inside the meat which results in a non-uniform texture and color development.

The heating of poultry meat above 55°C leads to denaturation of myoglobin protein which results in a whitening of the meat (Guidi and Castigliego, 2010). At higher temperatures Maillard reactions take place resulting in a browning of the surface and the formation of flavor components (Brunton et al., 2002). Heating also induces transversely shrinkage of the meat fibers leading to wider gabs between them, followed by longitudinal shrinkage of the fibers, solubilization of connective tissue, muscle protein aggregation and gel formation (Tornberg, 2005). This leads to changes in the microstructure (denser matrix with compact fiber arrangements) and, thus, to a toughening of the meat (Wattanachant et al., 2005). Additionally, the protein denaturation reduces the water holding capacity which results in water loss during the cooking process (Micklander et al., 2002).

If the main physical factors that influence the quality of chicken meat are known, the thermal processing can be optimized to achieve the best possible quality of the meat product for the consumer. In this manner, kinetic modelling can provide a deeper understanding of the changes that occur during thermal processing and help to control and optimize the food quality (Haefner, 2005). For different muscle foods and vegetables, researchers showed that the quality degradation during thermal treatment can be described by a general rate law. The quality changes mainly follow a zero, first or second order kinetic (Ling et al., 2015; Van Boekel, 2008). To describe the relationship between the temperature and the reaction rate constant the common Arrhenius model is mostly used (Goncalves et al., 2007; Goñi and Salvadori, 2011; Ko et al., 2007; Kong et al., 2007).

There have been no systematic studies of the thermal changes of chicken meat quality with time and related kinetic models. Therefore, the aim of this study is to investigate the changes of chicken meat quality (texture and color) with time and temperature in order to develop kinetic models that describe these changes. We here present the effect of temperature and time on the texture (texture profile analyses – TPA) and color of chicken breast meat, as well as the effect of the temperature on the rheological properties of chicken breast meat.

2. Kinetic modelling

The irreversible change of a quality attribute Q under isothermal condition can be described by the general rate law in the following form (Eq. (1)) (Levenspiel, 1999; Van Boekel, 1996):

$$\frac{\partial Q}{\partial t} = -kQ^n \qquad (1)$$

where k is the reaction rate constant ($\text{min}^{-1}\,[\text{Q}]^{1-n}$), Q the quality attribute at time t (min) and n the reaction order.

The temperature dependence of the reaction rate is mostly described by the Arrhenius equation (Eq. (2)):

$$k = k_0 \exp\left(-\frac{E_a}{R\,T}\right) \qquad (2)$$

where k_0 *is* the pre-exponential factor ($\text{min}^{-1}\,[\text{Q}]^{1-n}$), E_a is the activation energy (J/mol), R is the universal gas constant (8.314 J/(mol K)) and T is the temperature in °C.

Food quality changes are mostly reported to follow a zero, first or second order reaction. For isothermal conditions, integration of Eq. (1) gives: (Steinfeld et al., 1999; Van Boekel, 1996):

$$Q = Q_0 - k\,t \qquad n = 0 \qquad (3a)$$

$$\text{Q} = Q_0 * \exp(-k\,t) \qquad n = 1 \qquad (3b)$$

$$Q = \left(k\,t + \frac{1}{Q_0}\right)^{-1} \qquad n = 2 \qquad (3c)$$

where Q_0 refers to the initial quality value.

The common rate law in the form of Eq. (1) is not taking into account that most foods retain a constant measurable (non-zero) degree of quality (for example firmness and color) even after long heating times (Rizvi and Tong, 1997). To account for this non-zero equilibrium a modified rate law is used with the following forms:

Eq. (4a) when the non-zero equilibrium is smaller than the initial quality value (e.g. softening of the texture):

$$\frac{\partial Q}{\partial t} = -k\,(Q - Q_\infty)^n \qquad Q_0 \geq Q \geq Q_\infty \qquad (4a)$$

and Eq. (4b) when the non-zero equilibrium is larger than the initial quality value (e.g. toughening of the texture):

$$\frac{\partial Q}{\partial t} = k\,(Q_\infty - Q)^n \qquad Q_0 \leq Q \leq Q_\infty \qquad (4b)$$

where Q_∞ is the final non-zero equilibrium quality value after long heating times.

For isothermal conditions, integration of Eq. 4b for a first and n^{th} order leads to Eq. (5a) and Eq. (5b), respectively:

$$Q = Q_\infty - (Q_\infty - Q_0) * \exp(-\,k\,t) \qquad n = 1 \qquad (5a)$$

$$Q = Q_\infty - [kt(n-1) + (Q_\infty - Q_0)^{1-n}]^{\frac{1}{1-n}} \qquad n \neq 1 \qquad (5b)$$

For this study, Eq. (4b) is used to describe the quality changes (texture and color) of chicken breast meat. Therefore, only the integrated forms of this equation are shown here for clarity. For a first order reaction (Eq. (5a)) the same form as the fractional conversion model (proposed by Rizvi and Tong (1997) for food quality changes) is obtained. Instead of assuming the order of the reaction, it is, however, more appropriate to estimate the reaction order n together with the other kinetic parameters by solving and fitting the differential form of the kinetic model (Eq. (4a) or Eq. (4b)) to the experimental data set (see section 3.4).

3. Materials and methods

3.1. Raw material

Chilled (4 °C) chicken breast meat (without skin and bone) was obtained from a local supermarket (the same day as the experimental tests) and stored at 2 °C until preparation for the experiments.

3.2. Rheological measurement

For the rheological measurement the chicken meat was sliced along the fiber direction using an electrical meat slicer (AM 300, Minerva Omega group s.r.l., Italy) and circular samples with a height of 3 ± 0.5 mm and a diameter of 35 ± 1 mm were cut using a cork borer. The rheological characteristics of whole chicken breast meat were measured using a controlled stress rheometer (Haake Mars Rheometer, Type 006-0572; Thermo Fisher Scientific, USA) equipped with a 35 mm parallel plate attachment. Both plates were serrated to prevent any unwanted slipping and the rheometer was complemented with a temperature controller to precisely control (± 0.5 °C) and monitor the sample temperature. Dynamic rheological measurements were performed as described by Hashemi and Jafarpour (2016). One chicken disc sample was loaded between the plates and the sample sides covered with a thin layer of silicon oil to minimize the moisture evaporation with increasing temperature. The sample was held at 25°C (starting temperature) for 5 min to ensure equilibrium. Afterwards, the sample temperature was increased stepwise from 25 to 85 °C with steps of 5 °C and holding times of 3 min at every temperature step before measurements (recording the data). The holding time was chosen as no further changes in the storage modulus were found for longer holding times (> 3min). All dynamic oscillating analyses were performed with a gap of 3 mm between the plates, a constant stress of 6 Pa and a constant frequency of 1 Hz. The constant value for the stress was chosen within the linear viscoelastic region that was determined by performing stress sweeps (0.1 – 1000 Pa). Changes in the storage modulus G’ (elastic property), complex modulus G’’ (viscous property) and phase angle (ratio of loss modulus to storage modulus) were recorded directly by the rheometer software (Haake RheoWin 4).

3.3. Texture and color measurements

For the texture and the color measurements disked shaped chicken meat samples with heights of 6 ± 0.5 mm and diameters of 21 ± 1 mm and were prepared according to section 3.2. Thin samples were used to ensure a fast heating to the desired temperature and to achieve a uniform temperature within the chicken meat by reducing the time for internal heat transport. The samples were heated in a thermostatic water bath with circulating water (SW22, Julabo GmbH, Germany) at 5 different temperatures (50, 65, 75, 85 and 95 °C) with varying heating times (see Table 1). In order to control the sample temperature and moisture content, water as a heating medium was chosen, as it allows a fast heating of the samples and avoids water loss from the samples (the total moisture loss from the chicken meat was less than 6 %) (Thussu and Datta, 2012).

Table 1: Heating the chicken meat samples at different water bath temperatures and cooking times.

Water bath temperature [°C]	**Cooking times [s]**
50	200, 400, 600, 800, 1000, 1200
65	100, 200, 300, 400, 500, 600, 800, 1000
75	50, 100, 150, 200, 250, 300, 400, 600, 800
85	50, 100, 150, 200, 250, 300, 400
95	50, 100, 150, 200, 250, 300, 400

The water bath was filled with demineralized water and preheated for 30 minutes to achieve the desired temperatures and to ensure steady state conditions. The temperature of the water bath as well as the sample temperature was monitored during the heat treatment using thermocouples (type T). As the samples were thinly sliced, temperature equilibrium was reached for every time step. After heating the samples in the water bath, they were immediately placed in ice water for approximately 30 to 60 seconds to cool down the samples. Subsequently, excess moisture was removed with a filter paper. The samples were sealed in aluminum cups and stored for 2 hours at room temperature prior to further analysis.

3.3.1. Texture Profile Analysis

The texture of raw and cooked chicken breast meat was analyzed using a TA.XTplus (Stable Micro Systems, UK) texture analyzer with a 30 kg load cell. Double compression tests (TPA) were performed according to the procedure described by Bourne (2002) with a cylindrical probe of 50 mm diameter at room temperature. The probe contact area for all samples was 350 mm^2 and the samples were compressed to a final strain of 40 % with a test speed of 1 mm/s. The time interval between the first and the second stroke was 5 s. From the force-time plot of the double compression test the TPA parameters hardness, cohesiveness, springiness, gumminess and chewiness were calculated (Bourne, 2002).

3.3.2. Color measurements

The color of the chicken disc samples before and after cooking was measured using a hyper spectral imaging system (VidometerLab 2, Videometer A/S, Denmark) which allows measuring the color of the whole sample surface. The Videometer is widely used for imaging food samples, for example for assessing the quality of minced beef after a frying process (Daugaard et al., 2010). The device was calibrated radiometrically using a diffuse white as well as dark target and geometrical calibration was performed with a geometric target. The light setup of the device was then adjusted to chicken breast meat (Hansen, 1999).

The sample was placed in a petri dish under the camera and an image was taken. Afterwards, the image was processed using the software package MATLAB (R2017a, The Mathworks Inc., MA, USA) and the color of the raw and cooked chicken meat samples was obtained in the L*a*b* system. The $L*$ defines the color lightness of the product (varies from 0 for white to 100 for black), $a*$ indicates the color degree between red and green (a negative value indicates green color and a positive value indicates red color) and $b*$ specifies the color degree between yellow and blue (negative values indicate blue colors and positive values yellow colors). The total color difference ΔE is defined by Eq. (9):

$$\Delta E = \sqrt{(L - L_0)^2 + (a^* - a^*{}_0)^2 + (b^* - b^*{}_0)^2} \qquad (9)$$

with L_0 = 66.95 ± 1.62, a_0* = 5.05 ± 0.70 and b_0* = 18.95 ± 1.16 the lightness, redness and yellowness of the raw chicken meat, respectively.

3.4. Parameter estimation

MATLAB (R2017a, The Mathworks Inc., MA, USA) was used to solve the ordinary differential equations that describe the quality changes (Eq. (4a) and Eq. (4b)) and to estimate the kinetic parameters. The parameters were estimated using non-linear least squares (*lsqnonlin* solver in MATLAB) (minimization of the sum of squared differences between the predicted ($Q_{predicted}$) and measured ($Q_{experiment}$) quality changes) and the bootstrap method with 1000 bootstrap samples (Efron, 1979). A detailed description of the Bootstrap method can be found in Sin and Gernaey (2016).

3.5. Statistical analysis

The precision of the calculated parameters was assessed by confidence intervals at 95 %. Furthermore, the residuals randomness and normality was used to evaluate the quality of the regression. All experiments were repeated four times and the values from the rheological, texture and color measurements presented as mean values ± 95 % confidence intervals. Oneway ANOVA analyses and Tukey multiple range tests were performed to evaluate the influence of the heating time and temperature on the texture and on the color changes of chicken breast meat. Chi-square test was used to evaluate the goodness-of-fit. For all statistical analyses a significance level of P < 0.05 was used.

4. Results and discussion

4.1. Rheological changes

The changes of the storage modulus *G'* and the phase angle γ as function of the sample temperature were recorded as shown in Fig.1. In the range of 25 and 55 °C the storage modulus does not change with the temperature. However, from 60 to 80 °C, *G'* increases sharply with increasing sample temperature, and reaches a maximum plateau (around 92 kPa) above 80 °C. The phase angle (the ratio of loss modulus to storage modulus) decreases over the whole temperature range, while an accelerated decrease is observed for sample temperatures above 50 °C.

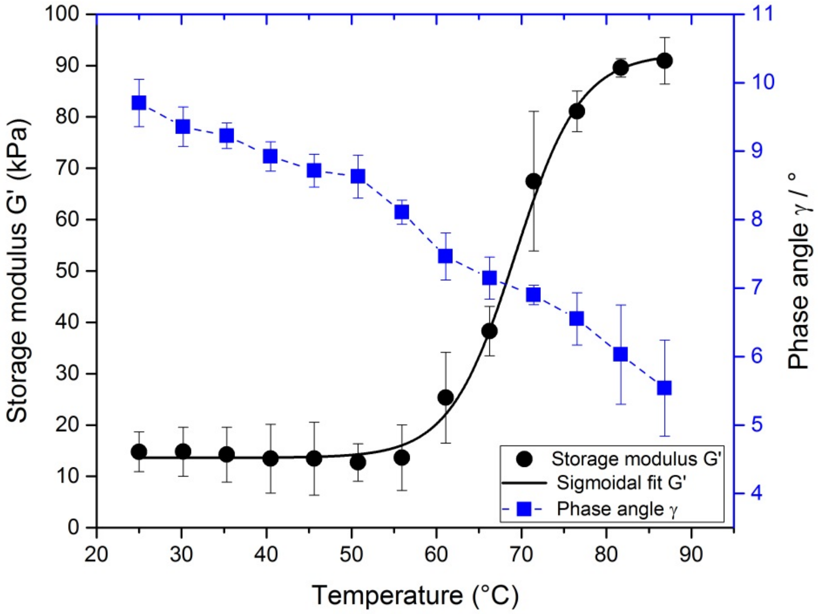

Fig. 1 Change of the storage modulus (kPa) and phase angle (degree) for chicken breast meat as function of sample temperature. Bars indicate the 95 % confidence intervals (n = 4).

Tornberg, (2005) observed a similar behavior of the storage modulus for whole beef meat with rising temperature. However, the storage modulus for beef meat increases earlier (around 50 °C) and also the maximum value is slightly lower (around 80 kPa) than for the chicken breast meat (92 ± 2 kPa). The different behavior of chicken breast meat compared to whole beef meat could be explained by an overall higher protein quality and quantity in chicken or broiler meat (16 % higher myofibrillar protein content) compared to beef meat (Montejano et al., 1984; Mudalal et al., 2014; Tornberg, 2005).

The storage modulus indicates the change in the meat microstructure due to protein denaturation that results in a toughening of the meat. Around a temperature of 62 °C myosin starts to denature, followed by collagen at 70 °C and actin at 82 °C (Bircan and Barringer, 2002). This leads to structural changes inside the meat by longitudinal and transversal shrinkage of meat fibers and solubilization of connective tissue. As a result, the meat becomes more compact and harder leading to the increase of the storage modulus with rising temperature (Tornberg, 2005).

The change of the storage modulus with temperature can be described as a sigmoidal curve (solid line, Fig. 1) with the following equation:

$$G' = G'_{max} + \frac{(G'_0 - G'_{max})}{1+\exp\left(\frac{T-\bar{T}}{\Delta T}\right)} \qquad (10)$$

where G'_{max} = 92 ± 2 kPa refers to the maximum storage modulus for chicken meat and G'_0 = 13.5 ± 1.3 kPa to the initial storage modulus. $\bar{T}$ = 69 ± 1°C and ΔT = 4 ± 0.6 °C are fitting parameters that were estimated using the bootstrap method (see section 3.4).

4.2. Texture changes

The TPA parameters hardness (*Ha*), gumminess (*Gu*) and chewiness (*Cw*) increase significantly (P < 0.01) with heating time (Fig. 2a-c). They all show a similar behavior with a steeper slope in the beginning, a gradually levelling-off with increasing heating time until the texture parameters reach a constant value (equilibrium). The rate (slope) of the texture change is influenced by the temperature, with steeper slopes at higher temperatures.

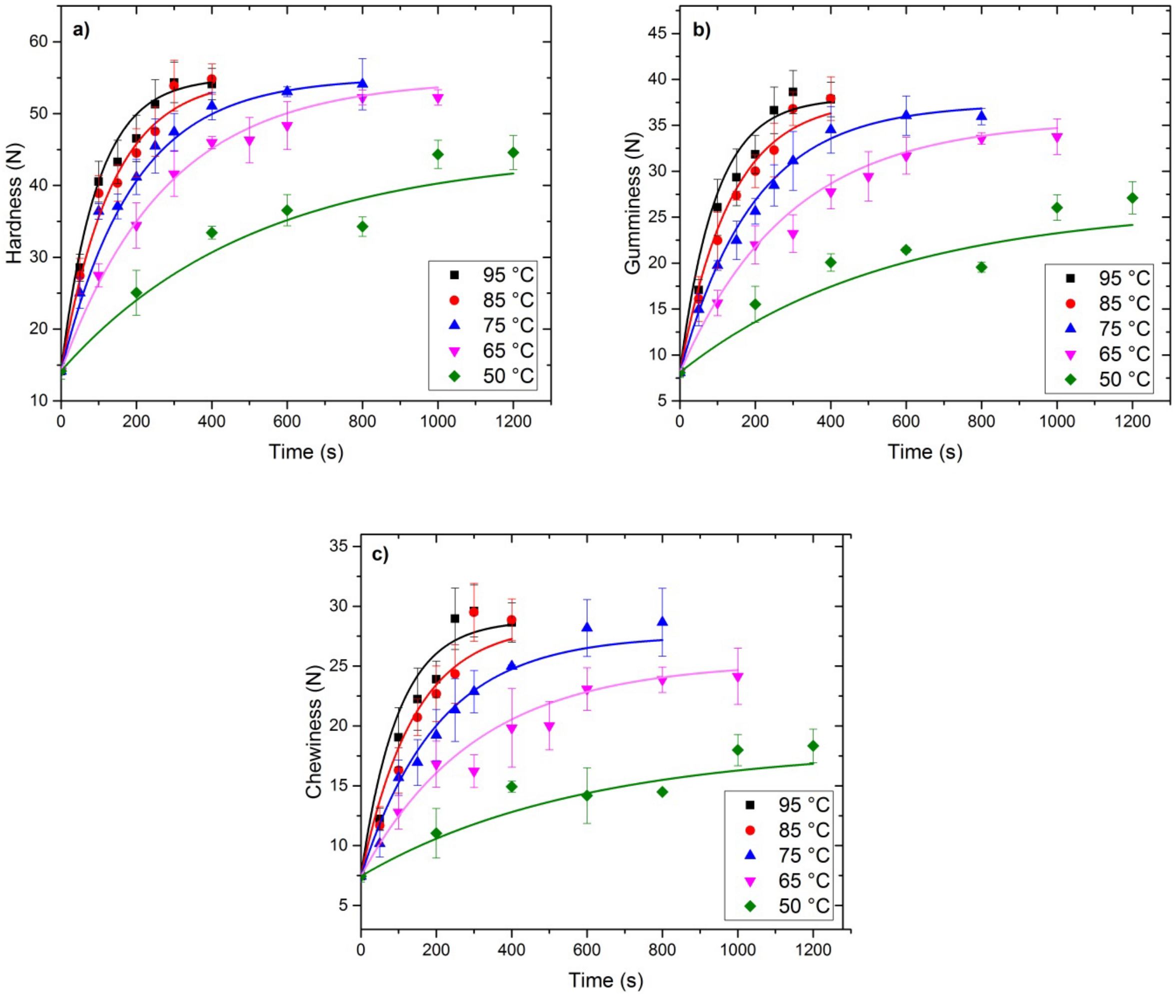

Fig. 2 Changes of the TPA parameters: a) hardness, b) gumminess and c) chewiness with heating time and sample temperature fitted with the modified rate law. Symbols with bars indicate the experimental mean values with the 95 % confidence intervals and the solid lines indicate the model fit (n = 4).

The changes of cohesiveness and springiness with temperature and time are summarized in Table 2. The cohesiveness shows an increase with time until reaching an equilibrium value, similar to hardness, gumminess and chewiness. The springiness shows a decrease in the beginning (50 – 200 s), after which it is also reaching an equilibrium value. However, no significant influence of the temperature on the springiness was found.

Table 2: Measured values of the TPA parameters cohesiveness and springiness of chicken breast meat with time and temperature.

	Cohesiveness					**Springiness**				
Time [s]	**Temperature [°C]**					**Temperature [°C]**				
	50	**65**	**75**	**85**	**95**	**50**	**65**	**75**	**85**	**95**
0	0.573 ± 0.038	0.573 ± 0.038	0.573 ± 0.038	0.573 ± 0.038	0.573 ± 0.038	91.98 ± 1.57	91.98 ± 1.57	91.98 ± 1.57	91.98 ± 1.57	91.98 ± 1.57
50	-	-	0.596 ± 0.028	0.589 ± 0.021	0.598 ± 0.001	-	-	68.38 ± 5.37	72.80 ± 2.78	71.60 ± 0.94
100	-	0.574 ± 0.015	0.543 ± 0.024	0.578 ± 0.038	0.644 ± 0.031	-	83.02 ± 1.55	79.32 ± 5.18	72.18 ± 3.59	73.08 ±3.73
150	-	-	0.606 ± 0.039	0.683 ±0.046	0.675 ± 0.031	-	-	75.30 ± 3.53	75.71 ± 4.98	75.08 ± 5.18
200	0.619 ± 0.013	0.599 ± 0.026	0.624 ± 0.011	0.676 ± 0.033	0.685 ± 0.038	70.72 ± 5.4	76.71 ± 3.02	74.91 ± 2.15	75.60 ± 5.64	75.24 ± 3.86
250	-	-	0.626 ± 0.001	0.681 ± 0.036	0.714 ± 0.031	-	-	84.46 ± 3.92	75.20 ± 5.50	78.65 ± 3.62
300	-	0.604 ± 0.060	0.642 ±0.0113	0.740 ± 0.048	0.712 ± 0.042	-	66.56 ± 5.57	70.21 ± 6.32	81.14 ± 2.50	76.65 ± 3.84
400	0.601 ± 0.038	0.623 ± 0.029	0.677 ± 0.021	0.692 ± 0.036	0.699 ± 0.035	74.45 ± 1.29	78.60 ± 0.74	82.52 ± 6.93	76.11 ± 3.00	71.71 ± 3.92
600	0.587 ± 0.027	0.655 ± 0.023	0.695 ± 0.037	-	-	66.08 ± 6.95	72.98 ± 2.00	79.44 ± 7.34	-	-
800	0.571 ± 0.007	0.652 ± 0.044	0.709 ± 0.013	-	-	74.07 ± 1.64	73.53 ± 3.98	76.62 ± 5.81	-	-
1000	0.588 ± 0.021	0.646 ± 0.036	-	-	-	68.96 ± 1.43	69.02 ± 5.27	-	-	-
1200	0.605 ± 0.015	-	-	-	-	78.59 ± 4.00	-	-	-	-

Under thermal treatment the meat proteins denature stepwise with different mechanisms for each temperature interval. In the temperature range from 40 to 50 °C, collagen fibers partially denature and straighten, leading to a first toughening of the meat (Lewis and Purslow, 1989). Further temperature increase leads to denaturation and shrinkage of myofibrillar proteins as well as dehydration and shrinkage of actomyosin, resulting in a supplementary toughening of the meat (Christensen et al., 2000; Tornberg, 2005). The rate of the protein denaturation increases with increasing temperature of the sample, resulting in a faster toughening of the meat at higher temperatures (Bailey and Light, 1989).

Wattanachant et al. (2005) investigated the change of the chicken meat microstructure at different core temperatures. They showed that the microstructure of chicken meat became denser with more compact fiber arrangements at increasing internal temperature. However, no further toughening of the texture above 80 °C was observed. Furthermore, the storage modulus of chicken breast meat, *G'*, is reaching an equilibrium value for temperatures above 80 °C (see Fig. 1, section 4.1), indicating no further changes in the microstructure due to protein denaturation. These observations could explain why there is no significant difference between the slope as well as the equilibrium values of hardness ($P > 0.05$), gumminess ($P > 0.05$) and chewiness ($P > 0.05$) for sample temperatures of 85 to 95 °C.

For the TPA parameters hardness, gumminess and chewiness (Fig. 2a-c) a small plateau is visible before reaching the equilibrium value especially at 50 and 65 °C. Feyissa et al. (2013) showed that the microstructure of meat is changing dramatically during the cooking. Protein denaturation leads to pore formation, decrease in the water holding capacity (WHC) and water migration into the spaces between the muscle fibers. For chicken breast meat, Van der Sman (2013) showed that the WHC is a function of temperature. The unbound water could work as a plasticizer leading to the small plateau before further denaturation results in the further toughening of the meat until the equilibrium is reached (Hughes et al., 2014).

Eq. (4b) (Q_∞ is larger than the initial value Q_0) was used to model the changes in the TPA parameters hardness, gumminess and chewiness with temperature and time. The Arrhenius equation (Eq. (2)) is used to describe the temperature dependence of the rate constant k. By solving and fitting Eq. (4b) to the experimental data set the equilibrium values Q_∞, the activation energies E_a, the pre-exponential factors k_0 and the reaction orders n were estimated (see section 3.4).

The obtained individual equilibrium values for hardness (Ha_∞), gumminess (Gu_∞) and chewiness (Cw_∞) vary with temperature (see Fig. 2a-c) and are described by Eq. (11a-c):

Hardness $$\mathrm{Ha}_\infty(\mathrm{T}) = Q_{max} + \frac{Q_0 - Q_{max}}{1 + \exp\left(\frac{T-\bar{T}}{\Delta T}\right)} \tag{11a}$$

Gumminess $$\mathrm{Gu}_\infty(\mathrm{T}) = Q_{max} + \frac{Q_0 - Q_{max}}{1 + \exp\left(\frac{T-\bar{T}}{\Delta T}\right)} \tag{11b}$$

Chewiness $$\mathrm{Cw}_\infty(\mathrm{T}) = Q_{max} + \frac{Q_0 - Q_{max}}{1 + \exp\left(\frac{T-\bar{T}}{\Delta T}\right)} \tag{11c}$$

where Q_{max}, $\bar{T}$ and ΔT are fitting parameters. The corresponding parameters are presented in Table 3. The changes of the equilibrium values with temperature show a similar behavior as the change of the storage modulus with temperature (see Fig. 1). This indicates that the degree of structural changes due to protein denaturation is responsible for the change in the equilibrium value with temperature.

Table 3: Estimated parameters for Eq. (7a-c) to describe the equilibrium of hardness, gumminess and chewiness of chicken meat as a function of temperature.

	Q_{max} [N]	Q_0 [N]	$\bar{T}$ [°C]	ΔT [°C]
Hardness Ha_∞	55.2 ± 3.5	14 ± 1.4	45 ± 1.5	4 ± 1.1
Gumminess Gu_∞	38.6 ± 2.2	7 ± 1.1	47 ± 2.1	8 ± 1.4
Chewiness Cw_∞	28.5 ± 1.7	6.9 ± 1.5	50 ± 2.9	10 ± 2.1

The results for the estimated activation energies E_a, pre-exponential factors k_0 and reaction orders n are summarized in Table 4 with the corresponding 95 % confidence intervals. As shown in Fig. 2a-c the developed kinetic models (solid lines) can describe the changes in hardness, gumminess and chewiness with time and temperature ($X^2_{hardness} = 4.05$, $X^2_{gumminess} = 3.15$, $X^2_{chewiness} = 39.67$, $P > 0.05$).

Table 4: Obtained kinetic parameters for the change of the TPA parameters (hardness, gumminess and chewiness) of chicken meat with time and temperature.

Texture index	n	E_a (kJ/mol)	k_0 (min^{-1} $[Q]^{1-n}$) x 10^{-3}	X^2
Hardness (N)	1.12 ± 0.11	39.3 ± 2.7	196 ± 8.3	4.05
Gumminess (N)	0.98 ± 0.06	35.9 ± 2.2	64 ± 4.1	3.15
Chewiness (N)	1.01 ± 0.09	44.6 ± 3.5	773 ± 29	39.67

The obtained activation energies E_a for hardness, gumminess and chewiness are 39.3 ± 2.7, 35.9 ± 2.2 and 44.6 ± 3.5 kJ/mol, respectively. The values are in the same range as reported by other authors for textural changes of different foods (10 - 100 kJ/mol) (Ling et al., 2015): for example mussels (65 kJ/mol) (Ovissipour et al., 2013), pumpkin (72 kJ/mol) (Goncalves et al., 2007) or mushrooms (15 kJ/kg) (Ko et al., 2007).

4.3. Color changes

Fig. 3a-d show the changes of chicken meat color (CIE L^*, a^*, b^*) with heating time. During thermal treatment in a moist surrounding chicken breast meat becomes white, leading to significant changes in the color values compared to the raw chicken meat color. For temperatures of 75 to 95 °C the values of lightness L^* and total color difference ΔE (Eq. (1)) rise rapidly until levelling off and reaching an equilibrium value of 87 ± 0.72 and 21 ± 0.67 , respectively (Fig. 3a and 3b). However, for 85 and 95 °C no significant difference ($P < 0.01$)) was found between the slopes of the curves. For temperatures of 65 and 50 °C the slope of the curve decreases significantly ($P < 0.01$). For 65 °C the same equilibrium value is reached as for 95, 85 and 75 °C, while for 50 °C the equilibrium value for the lightness L^* and total color change ΔE is at 82 ± 0.63 and 15 ± 0.57, respectively (Fig. 3a and 3b).

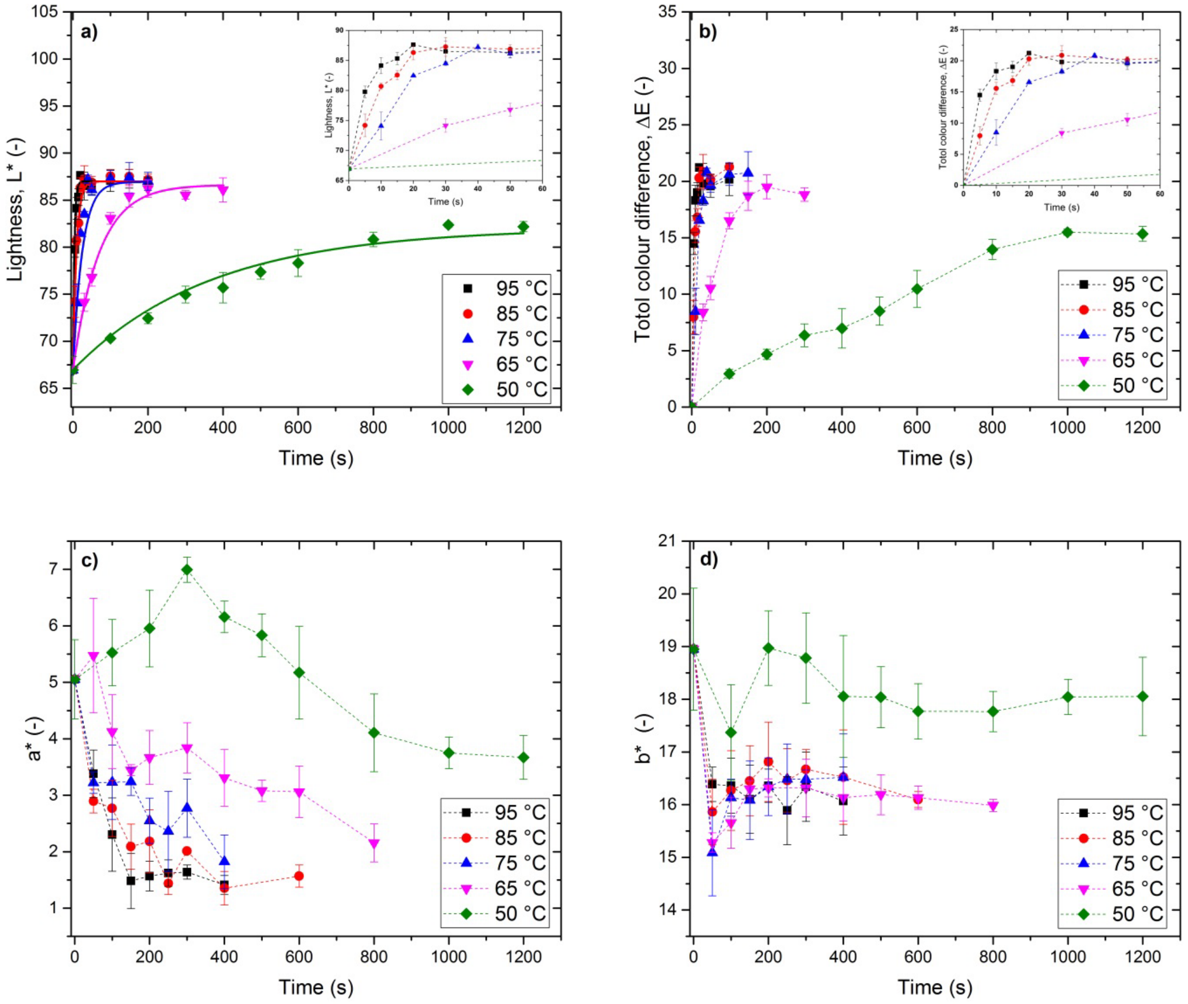

Fig. 3 Changes of the chicken meat color with heating time and sample temperature: a) lightness (L*), b) total color difference (ΔE), c) redness (a*) and d) yellowness (b*). Symbols with bars indicate the experimental mean values with the 95 % confidence intervals (n = 4). The solid line in a) shows the model fit.

For temperatures of 65 to 95 °C, the a^* and b^* values decrease with time until reaching an equilibrium, while the slopes of the curves increase with rising temperature. At 50 °C the a^* value first increases before it is decreasing and levelling off to an equilibrium value (Fig. 3c). The b^* value is first slightly decreasing at 50 °C until reaching an equilibrium which is just marginally beneath the b^* value for the raw sample (Fig. 3d).

During the heating heme proteins (hemoglobin and myoglobin) denature resulting in the whitening of the muscle. Hemoglobin and myoglobin are relatively heat stable and completely denature at temperatures around 65 to 80 °C while the rate and degree of denaturation increases with temperature (Lawrie and Ledward, 2006; Martens et al., 1982). For temperatures below the denaturation temperature of myoglobin (< 65 °C) the color change cannot be explained just by heme protein denaturation. However, structural changes, initiated from the denaturation of myofibrillar proteins and other structural proteins, could lead to a higher light scattering and optical masking of heme-proteins causing a lighter product (Hughes et al., 2014; Martens et al., 1982).

The changes in the lightness $L*$ of chicken breast meat for the tested temperature (50-95 °C) and time range (50 – 1200 s) were modeled using Eq. (4b) (Q_∞ is larger than the initial value Q_0). The Arrhenius equation (Eq. (2)) is used to describe the temperature dependence of the rate constant. By solving and fitting Eq. (4b) to the experimental data set, the activation energy E_a, the pre-exponential factor k_0 as well as the reaction order n were estimated (see section 3.4). The estimated value for the activation energy, pre-exponential factor k_0 and reaction order n are 101.59 ± 7.83 kJ/mol, $2.65 \times 10^{15} \pm 1.97 \times 10^{14}$ min^{-1} and 1.1 ± 0.06, respectively. The developed kinetic model (solid lines in Fig. 3a) can describe the change in lightness with time and temperature ($X^2_{lightness} = 1.29$, $P > 0.05$).

The obtained E_a value for the change in the lightness $L*$ (101.59 ± 7.83 kJ/mol) is within the same range reported for the color changes of different muscle foods and vegetables (80 to 120 kJ/mol) (Ling et al., 2015): salmon (88 kJ/mol) (Kong et al., 2007), beef (81 kJ/mol) (Goñi and Salvadori, 2011) or pumpkin (120 kJ/mol) (Goncalves et al., 2007).

Conclusion

In this study, we developed kinetic models that describe the texture and color changes of chicken breast meat as function of temperature and heating time. The TPA parameters hardness, gumminess and chewiness as well as the color parameter lightness increase with heating time until reaching an equilibrium value. The rate of the texture and color changes increases with temperature due to a faster protein denaturation. The color and texture changes were fitted to a modified rate law that takes the non-zero equilibrium into account. The resulting kinetic models well describe the measured quality changes. Moreover, the change in the storage modulus of chicken breast meat with temperature was evaluated and the development was well described with a sigmoidal function. The storage modulus increases sharply between 60 and 80 °C due to heat-induced protein denaturation which leads to changes in the microstructure of the chicken meat.

Overall, the developed kinetic models and rheological properties provide a deeper understanding of the mechanism of the quality changes during the thermal processing of chicken breast meat. These can be coupled to physical based models (such as heat and mass transfer) enabling the prediction of quality changes during thermal processing. This means that the spatial quality attributes can be predicted from the local temperature development with time, thus, helping to optimize the process settings for thermal treatments of foods to obtain the optimal quality for the consumer.

Nomenclature

t	time (min)
Q	quality attribute
T	temperature (°C)
f	quality index (-)
n	reaction order
k	reaction rate constant (min^{-1} [Q]$^{1-n}$)
k_0	pre-exponential factor (min^{-1} [Q]$^{1-n}$)
E_a	activation energy (J/mol)
R	gas constant (8.314 J/mol K)
L^*, a^*, b^*	color dimensions (-)
ΔE	the total color difference (-)
G'	storage modulus (Pa)
Ha	hardness (N)
Gu,	gumminess (N)
Cw	chewiness (N)

Subscripts

0	initial value
∞	equilibrium value

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