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**Prediction of thermal induced color changes of chicken breast meat during convective roasting:
A combined mechanistic and kinetic modelling approach**

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Abstract

Consumers first assess the quality of roasted chicken meat by its appearance. However, studies that evaluate the color changes during thermal processing are lacking. The aim of this work was, therefore, to develop a mathematical model that can predict the lightness (L^*) changes of chicken breast meat during convective roasting.

Chicken breast meat was roasted in a convection oven and the internal as well as surface lightness was measured at different time steps. The lightness of chicken meat increases in the beginning of the process, which shows a whitening due to myoglobin denaturation. When the surface temperature is rising above 88 °C, the lightness starts to decrease again as a result of browning reactions.

We developed a non-isothermal kinetic model that describes the browning (decrease of the lightness) of the surface as function of temperature, water activity and roasting time. The kinetic models for the whitening and browning were then coupled to the validated mechanistic model for chicken meat roasting. This enables the prediction of the internal as well as surface lightness development from the spatial temperature and water activity changes. The validation of the model showed a good agreement between model predictions and experimental values for different roasting conditions.

Overall, the developed model allows the prediction of the spatial lightness distributions with roasting time and advances our understanding of the mechanisms of heat induced color changes. Thus, the model can be applied to control and optimize the roasting of chicken meat to ensure the quality and safety for the consumer.

1. Introduction

The color and appearance of cooked chicken meat are the first quality parameters that are evaluated by the consumers, even before the actual consumption (Guerrero-Legarreta and Hui, 2010). Especially the color of the cooked meat provides information about the quality, flavor and safety of the product (Grunert et al., 2004; Pedreschi et al., 2006). Therefore, the color of cooked chicken breast meat is an important quality parameter in professional kitchens or the food industry that needs to be controlled thoroughly.

In the beginning of the cooking process, the color of chicken breast meat is changing from pink-red to an off-white color. This change is mainly caused by the heat induced denaturation of myoglobin to ferro- and ferrihemochromes, resulting in the color fading (King and Whyte, 2006). The denaturation of myoglobin takes place in the temperature range from 55 to 80 °C, while the rate and amount of denaturation is correlated mainly to the temperature and time of heating (Lawrie and Ledward, 2006; Martens et al., 1982; Rabeler and Feyissa, 2018a). Moreover, the denaturation of structural proteins, like myofibrillar proteins could result in an increased light scattering from the surface and an optical masking of the heme proteins. The protein denaturation leads to a reduction of the fiber diameter and larger gaps between the individual fibers. This allows for an increased light scattering and, consequently, the surface and inner regions of the meat product seems lighter (Hughes et al., 2014; Martens et al., 1982). However, especially at or close to the sample surface where the temperature is rising fast, this is mainly caused by myoglobin denaturation (Kondjoyan et al., 2014).

When the temperature is further increasing, the surface dries out due to water evaporation which leads to more greyish and darker colors. When the temperature is rising above 85 to 90 °C, caramelization as well as Maillard reactions take place (Kondjoyan et al., 2014; Nakamura et al., 2011). The latter, also

known as non-enzymatic browning is the reaction between reducing sugars and the amino groups of proteins, peptides and free amino acids. This results in the formation of the typical flavor and taste of roasted meat as well as the formation of the typical brown color (Shahidi et al., 2014). The formation of colored compounds (low molecular weight) as well as melanoidins (high molecular weight) during the Maillard reaction is mainly responsible for the browning. Furthermore, reactions in the early stages of the Maillard reaction could lead to the development of brown colors (Ames et al., 1993; Ledl and Schleicher, 1990; Namiki and Hayashi, 1981). When the surface temperature exceeds 150 °C carbonization reactions are taking place, which results in the formation of dark colors and a burned appearance (Matsuda et al., 2013).

The final color of roasted chicken breast meat is still relying on the cook and a look approach, thus, it depends highly on the skills of the operator or chef. If it is possible to predict the color change during the heating, a better control of the process could be achieved. Kinetic models that describe the change of the color with roasting time can help to understand, predict and control the process to obtain a final high quality product (Haefner, 2005; Van Boekel, 2008).

Kinetic models were developed for the color change of beef (redness, a^*) and chicken breast meat (lightness, L^*) during isothermal heating in water baths (Goñi and Salvadori, 2011 and Rabeler and Feyissa, 2018a, respectively). However, in moist surroundings no browning reactions take place in the studied temperature range (40 to 100 °C). Thus, the kinetic models are not able to describe the browning at the surface of the meat product during a roasting process. Matsuda et al. (2013) investigated the change of the surface color of fish during grilling and developed kinetics model to describe the development as function of the measured surface temperature. However, the browning of the surface is not only a function of the temperature development but the change of the moisture content or water activity with time (Shahidi et al., 2014).

The accurate measurement of the surface temperature or moisture content is difficult or even not possible (Purlis and Salvadori, 2009; Zanoni et al., 1995). Mechanistic models, which are based on principle physical laws, are able to predict the complex change in temperature and moisture content of the product during heating. By combining kinetic models with models of heat and mass transfer (a combined modeling approach) the local quality change (for example texture) can be obtained (Kondjoyan et al., 2014; Rabeler and Feyissa, 2018b). For the baking of bread different researchers have shown that it is possible to predict the change of the surface color by combining kinetic models with mathematical models of heat and mass transfer (Purlis and Salvadori, 2009; Zanoni et al., 1995; Zhang and Datta, 2006).

However, for chicken breast meat no studies are available that describe the color changes during convective roasting. Therefore, the aim of this work is to develop a combined model which allows the prediction of the spatial lightness (L^*) changes as function of the local temperature and water activity development. Our hypothesis is that by combining kinetic models that describe the lightness changes, with the validated mechanistic model of chicken meat roasting it is possible to predict the lightness change as function of roasting time and process settings. Validation trials with an independent data set will then show the accuracy and reliability of the developed combined model.

2. Mathematical models

2.1. Kinetic model to describe the whitening of the chicken meat

The whitening of chicken breast meat during heating was described by Rabeler and Feyissa (2018a) with a modified rate law as function of sample temperature and heating time (Eq. (1)):

$$\frac{\partial L_{wh}^*}{\partial t} = k_{wh}(T) (L_{\infty}^* - L_{wh}^*)^n \quad (1)$$

with the lightness L^* at time t , the non-zero equilibrium value L_{∞}^* , the reaction order n and the reaction rate constant k ($\text{min}^{-1} [Q]^{1-n}$). The common Arrhenius equation was used to describe the temperature dependency of the reaction rate constant (for details see Rabeler and Feyissa (2018a)). The estimated values for the activation energy ($E_a = 101$ kJ/mol), pre-exponential factor ($k_0 = 2.65 \times 10^{15} \text{ min}^{-1}$), reaction order ($n = 1.1$) and non-zero equilibrium L^* value ($L_{\infty}^* = 87$) by Rabeler and Feyissa (2018a) were used in this study.

2.2. Kinetic model for the browning of chicken meat

The browning of the chicken meat depends on the surface temperatures and starts at temperatures greater than 85°C (Kondjoyan et al., 2014). During the roasting process the surface temperatures are not constant but it is increasing nearly continuously with final temperatures of up to 150°C . Consequently, the browning of the chicken meat surface is relying on the thermal history during heating.

To address this non-isothermal process and taking the temperature-time history into account, a non-isothermal kinetic was used to model the browning development at the top and bottom surface of the chicken breast meat during the roasting process. The browning reaction was assumed to follow a first order kinetic in the form of Eq. (2):

$$\frac{\partial L_b^*}{\partial t} = -k_b(T, a_w) L_b^* \quad (2)$$

The browning of the chicken meat surface relies not only on the temperature development but also the change in the water content or water activity at the surface (Eichner and Karel, 1972). Therefore, Purlis and Salvadori (2009) described for bread baking the reaction rate constant k_b as function of the temperature and water activity. This approach was adapted in this study (Eq. (3)):

$$k_b = \left(p_0 + \frac{p_1}{a_w(t)} \right) \exp \left(- \left(\frac{p_2 + \frac{p_3}{a_w(t)}}{T(t)} \right) \right) \quad (3)$$

with the water activity a_w , the temperature T (K) and the kinetic parameters p_0 , p_1 , p_2 and p_3 .

If the temperature-time history is neglected during the estimation of the kinetic parameters it is likely that the browning reaction, which is highly temperature dependent, has a larger error (Dolan, 2003).

However, the accurate measurement of the surface temperature or water activity during the roasting process is difficult or even not possible (Purlis and Salvadori, 2009). Therefore, we used in this study the validated mechanistic model of chicken breast meat roasting to obtain the change of the surface temperatures and water activities as function of the roasting time (see section 2.3).

The kinetic models for the whitening (see section 2.1) and for the browning of the chicken meat surface were combined with a Heaviside function f which is centered at the start of the browning temperature, T_b (see Eq. (4b)). The function is going from 1 to 0 and it is defined as the transition between the two kinetic models. This enables the estimation of the transition temperature for the surface browning and, additionally, both phenomena can be described with one equation (Eq. (4a)):

$$\frac{\partial L^*}{\partial t} = f \frac{\partial L_{wh}^*}{\partial t} + (1 - f) \frac{\partial L_b^*}{\partial t} = f k_{wh}(T) (L_{\infty}^* - L_{wh}^*)^n + (1 - f) k_b(T, a_w) L_b^* \quad (4a)$$

$$\text{Where } f \text{ is described as: } f = 1 - \frac{1}{1 + \exp(T - T_b)} \quad (4b)$$

2.3. Mechanistic model of chicken breast meat roasting

The validated mechanistic model of chicken breast meat roasting was used to obtain the development of the surface temperatures and water activities with roasting time. For a detailed description of the mechanistic model we refer the reader to Rabeler and Feyissa (2018b). The governing equation that is

describing the heat transfer by convection and conduction is given by Eq. (5). The liquid water transport inside the chicken breast meat by diffusion and convection is described with Eq. (6):

$$\text{Heat transfer:} \quad c_{p,cm} \rho_{cm} \frac{\partial T}{\partial t} = \nabla(k_{cm} \nabla T) - \rho_w c_{p,w} u_w \nabla T \quad (5)$$

$$\text{Mass transfer:} \quad \frac{\partial C}{\partial t} = \nabla(-D \nabla C + C u_w) \quad (6)$$

with $c_{p,i}$, ρ_i and k_i are the specific heat capacity, density and thermal conductivity, respectively, T is the temperature (K), C is the moisture content (kg of water/kg of sample), D is the moisture diffusion coefficient (m²/s), u_w is the fluid velocity (m/s) and t the time (s).

The thermal denaturation of proteins results in the shrinkage of the protein network as well as the reduction of the water holding capacity. Thus, a pressure gradient is induced inside the chicken breast meat. Darcy's law gives the relationship between this pressure gradient and the fluid velocity inside the chicken breast meat during the roasting process (Eq. (7)) (Rabeler and Feyissa, 2018b):

$$u_w = \frac{-\kappa}{\mu_w} \nabla p \quad (7)$$

with the swelling pressure $p = G'(C - C_{eq})$, the storage modulus G' (Pa), the water holding capacity C_{eq} , the permeability κ (m²), and the dynamic viscosity of the fluid μ_w (Pa s).

The heat and mass transfer at the boundaries of the chicken breast meat sample was described with Eq. (8) and Eq. (9), respectively (Rabeler and Feyissa, 2018b):

$$-k_{cm} \nabla T = h (T_{oven} - T_{surf}) \quad (8)$$

$$-D \nabla C + C u_w = \beta_{tot} (C_{surf} - C_{oven}) \quad (9)$$

where h is the heat transfer coefficient (W/(m² K)) (h_{top} at the top surface and h_{bot} at the bottom surface, see Table 1), T_{oven} and T_{surf} are the oven and surface temperature (K), respectively, β_{tot} is the total mass transfer coefficient (m/s), C_{surf} is the moisture content at the surface of the chicken meat sample (kg/kg)

and C_{oven} is the moisture content in the circulated ambient hot air. Table 1 summarizes the model input parameters.

3. Materials and Methods

3.1. Raw material and sample preparation

Chicken breast fillets without bones and skins were purchased at a local supermarket the same day as the experiments. The chicken breast fillets were cut into a rectangular shape with a length, width and height of 70, 40 and 20 mm, respectively. The average weight of the sample was $63 \text{ g} \pm 4$. The samples were stored at 2°C in sealed plastic bags until further usage.

3.2. Roasting experiments

The roasting trials were performed in a professional convection oven with dry hot air. The oven was preheated for 30 min before the experiments to ensure steady state conditions. In this study, oven temperatures of 200, 230 and 260°C were used. The temperature was regulated with the ovens thermostat and it was found to be stable around the setting temperature with $\pm 3^\circ\text{C}$ (Rabeler and Feyissa, 2018b). A single chicken meat sample was placed on the roasting tray which was then positioned centrally in the oven. The roasting times in this study were 1, 3, 5, 7, 10, 15 and 20 min. After the specific roasting times, the samples were immediately taken out of the oven, put into plastic bags and placed in ice water. Subsequently the color of the top surface and bottom surface of the sample was measured (see section 3.3).

3.3. Color measurements

For the color measurements a hyper spectral imaging system (VideometerLab 2, Videometer A/S, Denmark) was used. The device was calibrated with a diffuse white and diffuse black (radiometrical calibration) target as well as with a geometrical target (geometrical calibration) (Hansen, 1999). The colors of the chicken breast samples were evaluated after 1, 3, 5, 7, 10, 15 and 20 min of roasting (see section 3.2). First the color at the top and bottom surface of the roasted chicken meat sample was measured. One sample was placed underneath the camera and an image of the top surface was taken. Afterwards the sample was turned over and another image of the bottom surface was taken. For the internal color measurements, the sample was cut in half (perpendicular to the length axis) and an image was taken from the internal cut surface.

The images were then processed with MATLAB (R2017a, The Mathworks Inc., MA, USA) and the average surface colors of the chicken meat samples were obtained as L^* value (lightness), a^* value (green to red color) and b^* value (yellow to blue color) (Rabeler and Feyissa, 2018a).

3.4. Model solution and parameter estimation

The commercial finite element (FEM) software COMSOL Multiphysics® 5.3 was used to solve the partial differential equations (PDEs) for the transport phenomena (see section 2.3) and the ordinary differential equations (ODE) that describe the lightness changes of the chicken breast meat (see section 2.1 and 2.2). Mesh sensitivity analysis was conducted, to ensure the quality of the mesh. The mesh size was decreased in a sequence of simulations until the size had no effect on the solution of the model (Kumar and Dilber, 2006; Rabeler and Feyissa, 2018b).

The developed model was calibrated and validated by using experimental data for the change in the surface lightness of the chicken meat sample at different oven temperatures (see section 3.2 and 3.3).

The experimental data of the top surface color for an oven temperature of 230 °C was used to estimate the start temperature for browning, T_b (Eq. (4b)), and the kinetic parameters in Eq. (3). COMSOL was coupled with MATLAB (R2017a, The Mathworks Inc., MA, USA) by using the COMSOL LiveLink™. The parameter estimation was done by minimizing the sum of the squared differences between the experimental and the predicted lightness development at the top surface of the chicken meat sample (non-linear least squares, *lsqnonlin* solver in MATLAB) (Feyissa et al., 2011). The remaining measurements for the lightness developments at the top and bottom surface of the chicken meat sample were then used to validate the developed model.

3.5. Statistical analysis

Analysis of variance (one-way ANOVA without replication) and Tukey's honestly significant difference procedure was performed to assess the influence of the heating time and oven temperature on the lightness changes of the chicken breast meat during roasting. The significance level for the analysis was set to $P < 0.05$. The estimated parameters and measured values are presented as mean values $\pm$ confidence intervals at 95 %.

The standard root mean squared error (*RMSE*) was calculated with Eq. (10):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{\theta}_i - \theta_i)^2}{n}} \quad (10)$$

with $\hat{\theta}$ the predicted value, θ the measured value n is the total number of samples. The *RMSE* together with the randomness and normality of the residuals was used to evaluate the quality of the model predictions.

4. Results and discussion

4.1. Modelling the internal color changes

By combining the kinetic model for the chicken meat whitening (Eq. (1)) with the model of heat and mass transfer (section 2.3) it is possible to predict the internal lightness changes during the roasting process as a function of the local temperature change. The influence of the oven temperature on the internal lightness changes during roasting is shown in Fig. 1. A good agreement between the model predictions (solid lines) and the measured (symbols) lightness changes for all tested temperatures was found. The root mean squared errors (*RMSEs*) between predicted and experimental values are 0.825, 0.773 and 0.848 at 200, 230 and 260 °C, respectively.

The influence of the oven temperature on the internal lightness change was not significant ($P > 0.05$). An increase of the oven temperatures leads to a faster heat up of the sample surface (see Eq. (8)). However, the internal heat transfer from the surface towards the core is slow compared to the external heat transfer ($Bi = 1.1 > 0.1$), which also results in a decreased internal temperature rise (Rabeler and Feyissa, 2018b). Since the internal whitening of the chicken meat is a function of the temperature development with time (see Eq. (1)), it is reasonable that the oven temperature has no significant influence on the internal lightness changes.

Moreover, a visual comparison between the simulated and measured color change with roasting time for an oven temperature of 230 °C is shown in Fig. 2. First, the surface of the chicken meat which is in contact with the surrounding hot air and roasting plate (only bottom) is getting white. This whitening is caused by the heat induced denaturation of heme-proteins and the change in structural proteins (Hughes et al., 2014; King and Whyte, 2006). The whitening is faster from the bottom of the sample compared to the top surface. This is due to a higher heat transfer from the roasting plate to the meat that leads to a

faster temperature increase at the bottom surface (Rabeler and Feyissa, 2018b). The heat is then transferred inside the chicken meat by convection and conduction which results in the internal whitening of the meat.

After around 7 minutes of roasting the internal of the chicken breast meat became white ($L_{int}^* = 85.9 \pm 1$) nearly reaching the equilibrium L^* value ($L_{\infty}^* = 87$) (see also Figure 2). The absence of any pink inside the chicken meat is still used in kitchens to assess the doneness of the meat (cook and a look approach). Chicken meat should be heated to an internal temperature of at least 72 °C to ensure the safety of the product for the consumer. However, after 7 min of roasting at an oven temperature of 230 °C, the core temperature of the chicken meat reaches only 59 °C (Rabeler and Feyissa, 2018b). Thus, the chicken meat is not safe for the consumer, yet, even though it is already completely white. This shows the advantage of the developed model to ensure the safety of the roasted chicken meat for the consumer independently of the operator or chef.

4.2. Modelling the surface color development

The visual inspection of the roasted chicken meat sample top surfaces shows that two stages of color change can be distinguished (Fig. 3). In the beginning of the roasting process (0 to around 3 min) the surface becomes white mainly due to the thermal denaturation of heme proteins (hemoglobin and myoglobin) and to some degree due to the denaturation of structural proteins (Guidi and Castigliego, 2010; Rabeler and Feyissa, 2018a). Afterwards, the surface of the chicken meat dries out due to the evaporation of water, which leads to a first decrease of the lightness (see for example at 230 °C, 5 min) (Nakamura et al., 2011). When the surface temperature is further rising a browning of the surface can be seen (for example after 5 min at 260 °C, Fig. 3). This can be correlated to non-enzymatic browning reactions (mainly Maillard and caramelization reactions) that take place when the surface temperature

is increasing above 85 to 90 °C (Kondjoyan et al., 2014; Martins et al., 2001). Finally, when the surface temperature is rising above 150 °C, carbonization reactions take place, which are resulting in a further darkening and even burning of the sample (see for example after 20 min at 260 °C, Fig. 3) (Nakamura et al., 2011).

4.2.1. Model calibration

For the roasting of chicken breast meat at an oven temperature (T_{oven}) of 230 °C, the two stages of color change (whitening and browning) can be distinguished by following the development of the top surface lightness (L^*_{top}) with roasting time (symbols in Fig. 4). First, the lightness is increasing showing the whitening of the meat surface, followed by a decrease of the L^*_{top} value, which can be associated with the darkening of the sample surface. A similar trend was also reported for the infrared heating (grilling) of fish (Matsuda et al., 2013; Nakamura et al., 2011) or microwave cooking of beef meat (Kondjoyan et al., 2014). We found that the roasting time has a significant influence ($P < 0.01$) on the lightness of the chicken meat surface.

The coupled model for the transport phenomena and lightness changes of chicken breast meat during roasting was calibrated by fitting the experimental data ($L^*_{exp, 230\text{ °C}}$) to the corresponding model predictions (see section 2.4). Consequently, the kinetic parameters in Eq. (3) (p_0, p_1, p_2 and p_3) and the start temperature for browning in Eq. (4b), T_b , were estimated.

The parameter estimation showed, that the lightness starts to decrease at surface temperatures around $T_b = 88 \pm 2\text{ °C}$ (see Eq. (4b)), which corresponds to the start of the surface browning. The identified temperature is in the same range as reported for beef meat (85 °C) or fish products (95 °C) (Kondjoyan et al., 2014 and Matsuda et al., 2013, respectively). The temperature T_b distinguishes between the two mechanisms of whitening (lightness decrease) and browning (lightness increase) (see section 2.2). As it

was identified by the parameter estimation, a better insight into the mechanisms of the chicken meat surface browning during heating is obtained. The kinetic parameters p_0 , p_1 , p_2 and p_3 in Eq. (3) were estimated to be $6.369 \times 10^6 \pm 1.309 \times 10^5$, $1.2943 \times 10^6 \pm 1.488 \times 10^5$, $6.477 \times 10^3 \pm 711.4$ and 929.68 ± 62.49 , respectively. The comparison between the predicted and experimental L^*_{top} values shows that the calibrated model is able to predict the development of the top surface lightness during the roasting at 230 °C (filled circles in Fig. 5). The root mean squared error (*RMSE*) between model predictions and experimental values was estimated to be 1.31.

The developed model was then validated against the measured lightness developments for oven temperatures of 200 and 260 °C as well as the lightness developments at the bottom surface of the chicken meat sample (see section 4.2.2).

4.2.2. Validation of the developed model

The validation of the developed model was done by comparing the predicted and measured lightness development at the top and bottom surface of the chicken meat samples for oven temperatures of 200 and 260 °C. A good agreement between the predicted (solid lines) and measured (symbols) lightness changes at the top surface was found for all tested oven temperatures (Fig. 6a). The root mean squared error (*RMSE*) between the predicted and experimental values is 1.61 and 1.8 at 200 and 260 °C, respectively. Additionally, the simulated lightness development at the bottom surface of the chicken meat samples agrees well with the measured values for all oven temperatures (Fig. 6b) with *RMSE* values of 2.29, 1.09 and 1.61 for 200, 230 and 260 °C, respectively. The comparison between the predicted and experimental L^* values for the top (filled symbols) and bottom (unfilled symbols) surfaces is shown in Fig. 5. The results show that the developed model is able to accurately predict the change in surface lightness during the roasting of chicken breast meat.

314 We found that the oven temperature has a significant influence ($P < 0.05$) on the lightness development
 315 at the top surface of the chicken meat sample (Fig. 6a). An increase of the oven temperature from 200
 316 to 260 °C results in a faster heat up of the sample surface (see Eq. (8)). Subsequently, the heme proteins
 317 denature faster which leads to the faster whitening of the sample surface (Lawrie and Ledward, 2006;
 318 Martens et al., 1982). Moreover, the transition temperature between whitening and browning ($88\text{ °C} \pm$
 319 2 , see section 4.2.1) is reached earlier due to the more rapidly heat up. Consequently, an earlier
 320 browning of the surface with increasing oven temperature was found. This earlier decrease of the L^*_{top}
 321 value also results in darker sample surfaces at all time steps (Fig. 6a).
 322 The temperature at the bottom of the chicken meat sample (in contact with the roasting plate) is
 323 increasing faster compared to the top surface due to a higher heat transfer coefficient (conduction)
 324 which is also resulting in a higher moisture evaporation rate (Rabeler and Feyissa, 2018b). Thus, the
 325 reaction rate constants for the whitening ($(k_w(T))$ and browning ($k_b(T, a_w)$) period (Eq. 4) are higher for
 326 the bottom compared to the top surface. This is clearly illustrated in Figure 7. Accordingly, the lightness
 327 at the bottom is changing faster compared to the top surface (Fig. 6b and 6a, respectively).
 328 Overall, the results show that the developed model is able to accurately predict the change in the
 329 lightness development at the top and bottom surface. The surface lightness is a function of the
 330 temperature and moisture content development during roasting. Thus, by adjusting the oven settings it
 331 is possible to directly impact the change of the surface lightness. The developed model can be used to
 332 control the color change during the roasting process. Furthermore, the acquired knowledge in
 333 combination with the developed model can be used to optimize the process of chicken meat roasting to
 334 obtain a high quality product for the consumer.

5. Conclusion

In this study, we have focused on the development of a mathematical model to predict the internal as well as surface lightness (L^*) development of chicken breast meat during convective roasting. First a non-isothermal kinetic model was developed to describe the browning of the chicken breast meat surface during roasting as function of the temperature and water activity changes. By combining the kinetic model for browning with the before developed kinetic for the whitening of chicken breast meat the temperature at which browning reactions at the chicken meat surface start was estimated. Thus, a better insight into the mechanisms behind the browning of chicken meat during roasting was achieved. Furthermore, the combination of the two kinetic models enables the prediction of both processes (whitening and browning) with one equation.

The kinetic models were then coupled with the mechanistic model of chicken breast meat roasting which allows the prediction of the internal as well as surface lightness development as function of the local temperature and water activity changes. The validation of the developed model shows that both the internal as well as surface lightness development can be predicted. Furthermore, the influence of changing oven temperatures on the internal and external lightness development was obtained. We found that the oven temperature has a significant influence on the top surface lightness development (L^*_{top}). However, no significant influence of the oven temperature on the bottom (L^*_{bot}) and internal lightness (L^*_{int}) changes was found.

Overall, the developed model is able to predict the lightness changes inside and on the surface of chicken breast meat during convective roasting from the local temperature and water activity changes for different process conditions. Thus, the model can be applied to control the lightness development of the chicken breast meat during convective roasting and at the same time ensure the safety of the final

357 product. Furthermore, the roasting process can be optimized to obtain the product with the highest
 358 quality for the consumer.

359 Nomenclature

a_w	water activity
C	mass concentration (kg/kg)
C_{eq}	Water holding capacity (kg/kg)
c_p	specific heat capacity (J/(kg K))
D	diffusion coefficient (m ² /s)
f	Heaviside function
G'	Storage modulus (Pa)
h	heat transfer coefficient (W/(m ² K))
k	reaction rate constant (1/min)
k_{cm}	thermal conductivity chicken meat (W/(m K))
L^*	lightness
p	swelling pressure (Pa)
T	temperature (K)
t	time (min)
u	velocity (m/s)
$RMSE$	Root mean squared error
Greek symbols	
β	mass transfer coefficient (m/s)
ρ	Density (kg/m ³)
μ	Viscosity (Pa s)
Subscripts	
b	browning
bot	bottom
cm	chicken meat

int	internal
surf	surface
w	water
wh	whitening
∞	equilibrium

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441 **Table 1: Model input parameters (Rabeler and Feyissa, 2018b)**

Parameter	Symbol	Value	Unit	Source
Density				
chicken meat	ρ_{cm}	1050	kg/m ³	Calculated from (Choi and Okos, 1986)
water	ρ_w	998	kg/m ³	
Diffusion coefficient	D	3 x 10 ⁻¹⁰	m ² /s	(Ngadi et al., 2006)
Permeability	κ	3 x 10 ⁻¹⁷	m ²	(Datta, 2006)
Viscosity water	μ_w	0.988 x 10 ⁻³	Pa s	(Rabeler and Feyissa, 2018b)
Initial composition				
Water	y_{w0}	0.76	kg/kg	(Rabeler and Feyissa, 2018b)
Protein	y_{p0}	0.22	kg/kg	(Barbanti and Pasquini, 2005)
Fat	y_{f0}	0.01	kg/kg	(Barbanti and Pasquini, 2005)
Ash	y_{a0}	0.01	kg/kg	(Barbanti and Pasquini, 2005)
Initial meat temperature	T_0	6	°C	(Rabeler and Feyissa, 2018b)
Initial moisture concentration	C_0	0.76	kg/kg	(Rabeler and Feyissa, 2018b)
Water vapor concentration in ambient air	C_{air}	0.05	kg/kg	(Rabeler and Feyissa, 2018b)
Heat transfer coefficient	h_{top} h_{bot}	44 59	W/(m ² K) W/(m ² K)	(Rabeler and Feyissa, 2018b)

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Figure captions

Figure 1: Comparison between the predicted (solid lines) and measured (symbols) lightness development inside the chicken meat sample during roasting at 200 (blue), 230 (black) and 260 °C (red). Bars indicate the standard deviation ($n = 3$).

Figure 2: Visual comparison between the experimental (left side) and predicted (right side) color development inside the chicken meat sample during roasting at 230 °C.

Figure 3: Color development at the top surface of chicken breast samples roasted at 200, 230 and 260 °C for different roasting times (1, 3, 5, 7, 10, 15, 20 min).

Figure 4: Measured (symbols) and simulated (solid line) lightness development of the chicken meat top surface (L^*_{top}) with roasting time for an oven temperature of 230 °C. Bars indicate the standard deviation ($n = 3$).

Figure 5: Comparison between the predicted and experimental lightness values. Filled and unfilled symbols show the top and bottom surface data points, respectively.

Figure 6: Measured (symbols) and predicted (solid lines) lightness development at the a) top and b) bottom surface of the chicken breast sample with roasting time. Bars indicate the standard deviation ($n = 2$).

Figure 7: Predicted development of the reaction rate constants $k_{w, Top Surface}$, $k_{w, Bottom Surface}$, $k_{b, Top Surface}$ and $k_{b, Bottom Surface}$ with roasting time ($T_{oven} = 230$ °C).

Highlights

- A non-isothermal kinetic model for the lightness changes of chicken meat was developed
- The surface browning is described as function of temperature, water activity and time
- The kinetic model was coupled with the mechanistic model of chicken meat roasting
- This allowed the prediction of the spatial lightness changes during convective roasting
- Model predictions and experimental measured lightness changes agree well

1 min

3 min

5 min

7 min

10 min

b)