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Kinetics of Thermal-Induced Physical Quality Alterations in Chicken Meat Processing

Nadya Klaresza Audrey[1], Eko Hari Purnomo[2,✉], Nur Wulandari[1]

[1] Department of Food Science and Technology, Faculty of Agricultural Engineering and Technology, IPB University, INDONESIA.

[2] Head of the Department of Food Science and Technology, Faculty of Agricultural Engineering and Technology, IPB University, INDONESIA.

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Corresponding Author:
✉ h.purnomo@apps.ipb.ac.id
(Eko Hari Purnomo)

ABSTRACT

Thermal processing of food often leads to a reduction in quality, highlighting the need to optimize heating conditions based on the kinetics of quality changes. This study investigated the physical quality of chicken meat—including cooking loss, water-holding capacity, texture, and color—during heating in a water bath (75 and 95 °C) and a pressure cooker (110 °C) for defined durations and modeled the kinetics of these changes. Heat distribution tests confirmed uniform temperatures, as indicated by minimal differences between thermocouples and the cold spot, while heat penetration tests ensured thorough heating, with lag times of 18.25 ± 2.25, 16.13 ± 4.58, and 19.25 ± 4.77 minutes at 75, 95, and 110 °C, respectively. Changes in physical quality at constant temperatures followed first-order reaction kinetics, and the temperature effect was described using the Arrhenius equation. The Arrhenius model revealed that higher temperatures accelerated the rate of quality changes, resulting in increased cooking loss, shear force, L, and browning index, whereas water-holding capacity and cohesiveness decreased. Comparison of the D and Z values for physical quality parameters with those of* Clostridium botulinum *spores ($D_{121.1\,°C}$ = 0.22 min, Z = 10 °C) suggested that high-temperature, short-time treatments could minimize detrimental changes in chicken meat while effectively inactivating target microorganisms.*

1. INTRODUCTION

Household poultry consumption in Indonesia is predominantly dominated by broiler chickens, which have shown an average annual growth of 5.79% during 2002–2021 (Kemnaker, 2021). Broilers, as a specific breed, offer advantages such as uniform shape, size, and meat color. Additional benefits include low-fat content, affordability, ease and speed of cooking, and consistent availability due to their rapid growth and short harvesting periods (Chumngoen *et al*., 2018).

Broiler chicken meat quality is typically assessed on the breast portion, favored by consumers for its texture (Hidayat *et al*., 2015). With a protein content of 23%, pH of 5.96, water activity (a_w) of 0.96, and moisture content of 71.94% (Milicevic *et al*., 2015), chicken meat is highly perishable, particularly under fluctuating environmental conditions during transport, retail, and consumer handling. Annual losses of chicken meat are estimated at 3.7–4.2% (Buzby *et al*., 2009), highlighting the importance of preservation technologies such as thermal processing. Heating inactivates microorganisms, rendering the product microbiologically stable for long-term storage while maintaining quality (Tomasz, 2024). Consequently, a wide range of sterilized chicken products—nuggets, hotdogs, ham, sausages, meatballs, and ready-to-eat meals—have been commercialized in Indonesia.

Proper heating conditions not only ensure microbial safety and extended shelf life but also improve palatability (Katemala *et al*., 2023), flavor (Kavitha & Modi, 2007), and digestibility (Qi *et al*., 2018). Conversely, excessive heating adversely affects key physical quality attributes valued by consumers, including cooking loss, water-holding capacity, texture, and color (Wattanachant *et al*., 2005; Triyannanto *et al*., 2022). This issue is also relevant to processed chicken products and is frequently encountered in the food industry, motivating research on optimizing heating temperature and time to achieve sterilization while preserving quality.

Previous studies have examined the effects of heating on the physical quality of raw (Wattanachant *et al*., 2005; Chumngoen *et al*., 2018; Qi *et al*., 2018) and processed chicken meat (Hidayat *et al*., 2015; Li *et al*., 2023). Some investigations have applied kinetic approaches to quantify quality changes; for instance, Zhang *et al*. (2024) modeled physical quality changes in food using the Arrhenius equation and kinetic parameters *D* (decimal reduction time) and *Z* (temperature change required for a one-log reduction), though their study did not specifically address chicken meat. A comprehensive analysis of physical quality changes in raw chicken meat during heating, incorporating kinetic modeling, remains lacking.

Developed kinetic models can provide valuable insights for understanding, predicting, and controlling heat-induced food quality changes (Hindra & Baik, 2006). Determination of kinetic parameters such as *k*, *Ea*, *D*, and *Z* allows estimation of the rate of quality change under different heating conditions (Ling *et al*., 2015). This study aims to evaluate the effects of varying heating temperatures and durations on the physical quality of chicken meat, including cooking loss, water-holding capacity, texture, and color, and to analyze the collected data using kinetic models to determine the corresponding kinetic parameters.

2. MATERIALS AND METHODS

The research was conducted from December 2023 to March 2025 at the Laboratory of Food Science and Technology, Faculty of Agricultural Engineering and Technology, IPB University. The equipment utilized included a water bath (GFL 1008, Germany), a modified pressure cooker or presto pot with a temperature measuring device as illustrated in Figure 1 (Nagami, Indonesia), a 'kompor semawar', a vacuum sealer (Power Pack DZ400TN/B, Indonesia), a continuous sealer (DBF-1000G, China), a centrifuge (Hermle Z326K, Germany), a texture analyzer (TA1 Lloyd, USA) equipped with a Warner-Bratzler blade and a 35 mm probe, a chromameter (Chromameter Minolta CR-400, Japan), thermocouples (using K-type cable and sockets), a data logger (GRAPHTEC midi LOGGER GL840, Japan), a sample weight, a balance, a stopwatch, a knife, and a cutting board. The materials employed consisted of raw broiler chicken breast meat (boneless and skinless, 6-week-old, purchased from local vendors), tap water, LPG gas, retort pouches (13 cm × 10 cm; PET 8 μm/Al 7 μm/ONY 15 μm/CPP 75 μm), cable ties (3.6 cm × 30 cm), and red silicone adhesive.

This research methodology generally encompassed the characterization of heat distribution and heat penetration profiles; the profile of physical quality changes in chicken meat during heating; and the determination of kinetic parameters for physical quality changes in chicken meat, with data analyzed using Microsoft Excel 2016 software.

2.1. Characterization of Heat Distribution and Heat Penetration Profiles

Heat distribution tests were conducted on the water bath and pressure cooker to ensure uniform temperature profiles. The water bath was selected for its minimal temperature fluctuations. However, due to its maximum temperature limitations, a pressure cooker was incorporated, thereby extending the range of heating temperature treatments. The heat distribution testing phase followed the procedures of Kusnandar *et al*. (2023), Raits *et al*. (2021), and Saragih *et al*. (2021), with measurements initiated from the moment heat was applied to the water bath and pressure cooker until

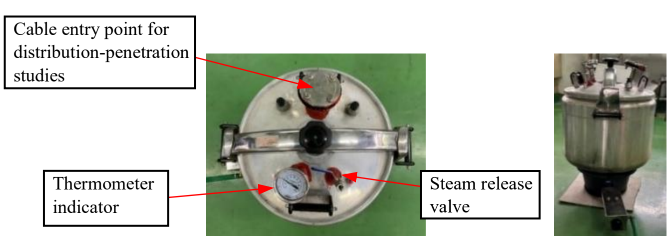

Figure 1. Modified pressure cooker (presto pot)

the end of the heating period. Thermocouples (TCs) and a data logger were employed to determine the come-up time (CUT) and the cold spot within the apparatus. CUT was defined as the point at which all TCs reached the target treatment temperature, while the cold spot was identified as the TC that was slowest to reach this temperature.

Subsequently, heat penetration tests were performed to obtain the heat transfer profiles within the samples. This test was based on the methods described by Raits *et al*. (2021) and Saragih *et al*. (2021), with timing initiated either from the application of heat to the pressure cooker system or from the attainment of CUT in the water bath system until the end of the heating period. TCs and a data logger were used to determine the lag time. Lag time was defined as the point at which all sample TCs reached the treatment temperature. The schematic of TC placement is presented in Figure 2, with detailed testing conditions during both heat distribution and heat penetration tests provided in Table 1.

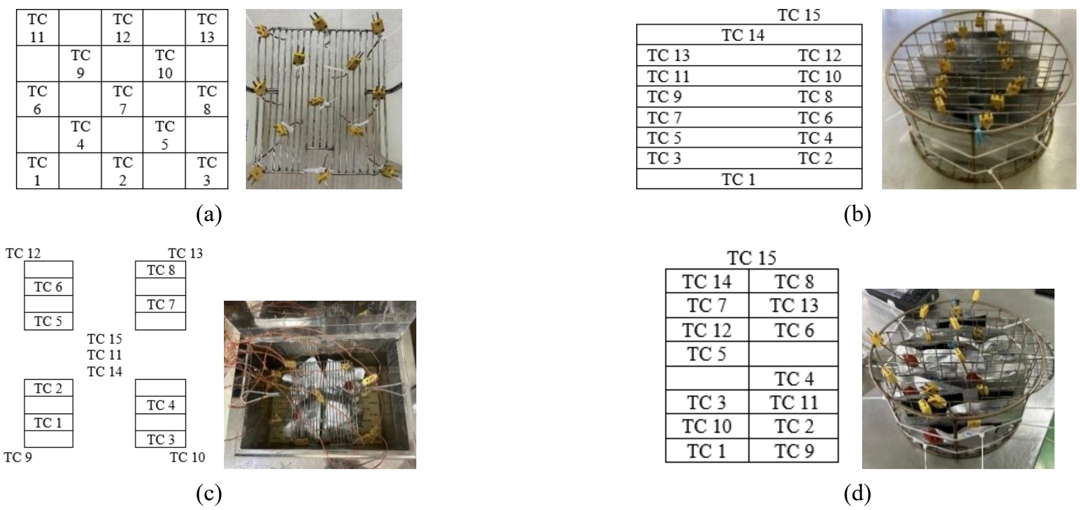

Figure 2. Schematic of thermocouple (TC) placement for heat distribution tests in (a) the water bath and (b) the pressure cooker; and for heat penetration tests in (c) the water bath and (d) the pressure cooker

Table 1. Testing conditions during heat distribution and heat penetration tests in the water bath and pressure cooker

Heating condition	Heat distribution test		Heat penetration test	
	Water bath	Pressure cooker	Water bath	Pressure cooker
Dummy weight (g)	10 ± 1		--	
Chicken meat sample weight (2 cm × 2 cm × 1 cm) (g)	--		7 ± 1	
Vacuum sealer settings	Vacuum application time 13 seconds; sealing time 3.5 seconds			
Continuous sealer settings	Conveyor speed 7 strips; temperature 170 °C			
Number of dummy/samples per heating	16			
Initial water temperature (°C)	27 ± 1	80 ± 1	27 ± 1	80 ± 1
Target/treatment temperature (°C)	75 ± 1; 95 ± 1	110 ± 1	75 ± 1; 95 ± 1	110 ± 1
Number of thermocouples per heating	13; TCs 1–13 outside packaging	15; TCs 1–14 outside packaging; TC 15 near thermometer sensor	15; TCs 1–8 inside packaging; TCs 9–14 outside packaging; TC 15 near thermometer sensor	

2.2. The Profile of Physical Quality Changes in Chicken Meat during Heating

2.2.1. Chicken Meat Preparation

Raw chicken breast meat sample was diced to dimensions of 2 cm × 2 cm ×1 cm along the muscle fiber axis. The sample was then placed into a retort pouch, subsequently sealed using a vacuum sealer and a continuous sealer with settings as specified in Table 1.

2.2.2. Application of Heat Treatment to Chicken Meat

Heat treatments were applied at three temperatures: 75, 95, and 110 °C. At a heating temperature of 75 °C, observations were conducted at 11 points (0, 90, 120, 150, 180, 210, 240, 360, 480, 540, 600 min); for the 95 °C heating temperature, 12 observation points were utilized (0, 30, 60, 90, 120, 150, 240, 360, 420, 480, 540, 600 min); and for the 110 °C heating temperature, observations were performed at 6 points (0, 40, 50, 60, 70, 80 min). The observation time intervals varied across these three temperatures to ensure the acquisition of significant changes in physical quality parameters. Following these heating periods, samples underwent cooling for 11 min for tests utilizing the water bath, while those subjected to the pressure cooker underwent a 14-min pre-cooling phase followed by a 9-min cooling phase. Each heat treatment involved 16 sample units.

2.2.3. Physical Quality Analysis of Chicken Meat

Raw chicken meat, serving as the 0-min observation control sample, was subjected to control analysis. Subsequently, heat-treated chicken meat samples underwent physical quality analysis in less than 24 h. Each parameter (cooking loss, water-holding capacity, shear force, cohesiveness, and color) was analyzed in quadruplicate.

Cooking loss analysis adhered to the method described by Patriani & Apsari (2022), involving the weighing of samples before and after the heating process, and calculation based on Equation 1.

$$Cooking\ loss\ (\%) = \frac{Weight\ of\ sample\ before\ heating - Weight\ of\ sample\ after\ heating}{Weight\ of\ sample\ before\ heating} \times 100 \quad (1)$$

Water-holding capacity was analyzed according to Laksono *et al.* (2019) using the centrifugation method. A 2 g sample was weighed as the initial sample weight before centrifugation. The sample was then wrapped in filter cloth, centrifuged (4,000 RPM, 15 min, 20 °C), subsequently weighed as the post-centrifugation sample weight, and calculated using Equation (2).

$$Water-holding\ capacity\ (\%) = (1 - \frac{Weight\ of\ sample\ after\ centrifugation}{Weight\ of\ sample\ before\ centrifugation}) \times 100 \quad (2)$$

Shear force texture analysis followed by Combes *et al*. (2004) utilizing a Texture Analyzer instrument. A Warner-Bratzler blade probe was employed to determine shear force by cutting the sample perpendicular to the fiber axis (1.7 mm/s), yielding the maximum force (kg_f). Cohesiveness texture analysis employing a different probe type, a 35 mm diameter cylindrical probe, (compressed twice at 5 mm/s, strains of 35 and 55% of initial height), determined cohesiveness based on the ratio of the area under the curve during the second compression (A_2) to the area under the curve during the first compression (A_1), calculated using Equation (3).

$$Cohesiveness = \frac{A_2}{A_1} \quad (3)$$

Color analysis referenced Taikerda & Leelawat (2023), leveraging the operating principle of a Chromameter instrument. The instrument's output data were processed into a browning index value, where $L*$ represents lightness; $a*$ represents green-red chromaticity; and $b*$ represents blue-yellow chromaticity, using Equation 4.

$$Browning\ index = \frac{100(x-0{,}31)}{0{,}172};\quad x = \frac{a^* + 1{,}75L^*}{5{,}645L^* + (a^* - 0{,}312b^*)} \quad (4)$$

2.3. The Determination of Kinetic Parameters for Physical Quality Changes in Chicken Meat

2.3.1. Determination of Reaction Order

Kinetics at constant temperature were described by zero-order and first-order kinetic equations, as shown in Equation (5) and Equation (6), respectively.

$$A = A_0 - kt \quad (5)$$

$$\ln A = \ln A_0 - kt \quad (6)$$

where A is the quality index at time t, with units determined by the quality index of the measurement object; A_0 is the initial quality index, with units similar to A; whereas k is the reaction rate constant in units of per second (s^{-1}).

2.3.2. Arrhenius Modeling

Arrhenius modeling is a commonly employed approach to elucidate the effect of heating (Hindra & Baik, 2006), utilizing Equation (7).

$$\ln k = \ln k_0 - (\frac{Ea}{R} \times \frac{1}{T}) \tag{7}$$

Parameter k_0 represents the frequency factor; Ea denotes the activation energy, in J/mol; R is the ideal gas constant, in J/mol.K; and T is the absolute temperature, in K.

2.3.3. Determination of D and Z Kinetic Parameters

Beyond the Arrhenius approach, the kinetic parameters D and Z values offer another viable concept directly related to first-order kinetics (Ling *et al*., 2015; Purnomo *et al*., 2015). D and Z values are derived from plotting data on a semi-logarithmic curve, with the formulas adhering to Equation 8. Subsequently, Equation 9 is employed to map the D and Z values as kinetic parameters for physical quality changes, aligning with microbial inactivation kinetic parameters (Sitanggang *et al*., 2019).

$$D = \frac{t_2 - t_1}{lg_{Physical\ quality1} - lg_{Physical\ quality2}}\ ;\ Z = \frac{T_2 - T_1}{lg_{D1} - lg_{D2}} \tag{8}$$

$$D_T = D_{Ref} \times 10^{(\frac{T_{Ref} - T}{Z})} \tag{9}$$

Here, t_2 represents the second measurement time; t_1 is the first measurement time; T_2 denotes the second temperature; T_1 is the first temperature; D_T signifies D at a specific temperature; and D_{Ref} is the standard D value. The mapping of these parameters facilitates the identification of effective heating conditions that achieve microbial inactivation while simultaneously minimizing undesirable physical quality changes in chicken meat.

3. RESULTS AND DISCUSSION

3.1. Heat Distribution Profile of Apparatus and Heat Penetration in Chicken Meat

Valid kinetic data can only be obtained after conducting a heat distribution test of the apparatus to ensure uniform temperature within the heating equipment. Concurrently, penetration tests are also essential for understanding heat transfer within the product, along with associated quality changes occurring throughout the sample (Ahn *et al*., 2024).

The heat distribution test yielded CUT information (Saragih *et al*., 2021). The average CUT values for the water bath and pressure cooker at heating temperatures of 75, 95, and 110 °C were 42.00 ± 0.82, 65.38 ± 0.65, and 9.00 ± 0.00 minutes, respectively, with the temperature change profiles presented in Figure 3. For the water bath, the CUT at 95 °C was longer to achieve as the heating apparatus required greater effort to reach this temperature compared to 75 °C. However, heating at 110 °C with the pressure cooker resulted in the shortest CUT due to the distinct apparatus type and heating mechanism. According to Ahn *et al*. (2024), pressure cookers utilize high-pressure steam, which offers advantages such as an increased heat transfer rate and improved energy efficiency, ultimately reducing the CUT.

A heating apparatus is considered to have good or uniform heat distribution if the temperature difference among thermocouples placed at various points within the apparatus and its cold spot is not excessively large. Based on industry guidelines, this difference should ideally be less than -3.0 °F or -19.44 °C (one minute after CUT) and less than -1.0 °F or -18.33 °C (three minutes after CUT) (Ismail *et al*., 2013). Figure 3 visualizes the heat distribution curve, shows them to be nearby, indicating temperature uniformity. Under these conditions, the presence of a cold spot can be disregarded due to the uniform temperature throughout the heating apparatus (Ismail *et al*., 2013; Kusnandar *et al*., 2023). Therefore, it can be concluded that the water bath and pressure cooker utilized in this study possessed good heat distribution. The observed conditions in both the water bath and pressure cooker align with the findings of Indiani *et al*. (2019). This temperature uniformity is attributed to the relatively high thermal conductivity of water (its ability to conduct heat via conduction or direct molecular contact). Furthermore, the boiling process, which creates convective heat transfer phenomena (heat transfer through molecular movement), also induces turbulence that contributes to temperature homogenization, thereby rendering temperature differences within the heating apparatus insignificant.

Heat penetration tests were conducted to obtain lag time information (Raits *et al.*, 2021). In kinetic studies, a minimal lag time is generally preferred, as explained by Toledo (2007). This study yielded lag time values of 18.25 ± 2.25, 16.13 ± 4.58, and 19.25 ± 4.77 minutes at 75, 95, and 110 °C, respectively (Figure 4). The data indicate that the lag time for heating at 95 °C was lower compared to heating at 75 °C, using the same water bath. This can be explained by the primary driving force of heat transfer, namely the temperature gradient phenomenon. As the temperature difference between the heating apparatus and the product increases, the rate of heat transfer also increases, meaning the time required for heat transfer will decrease (Raits *et al.*, 2021). This aligns with Ahn *et al.* (2024), who investigated penetration time in processed meat at various temperatures. Through the evaluation of lag time, it can be confirmed that heat penetration into the product occurred thoroughly, ensuring uniform heating of the product (Kusnandar *et al.*, 2023).

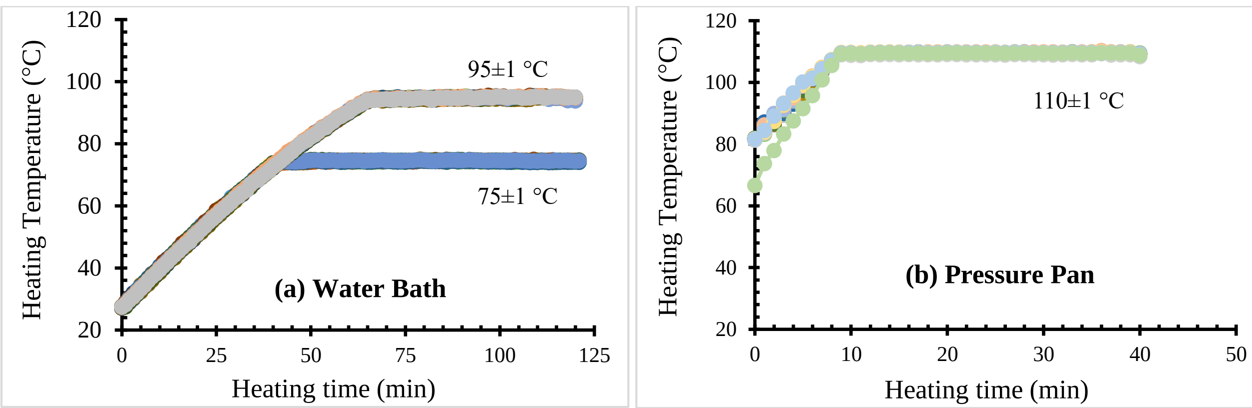

Figure 3. Measurement of heat distribution curves for (a) the water bath, and (b) the pressure cooker. [Different colored lines within each temperature legend indicate various thermocouple positions, as detailed in Figure 2 (a) and 2 (b)]

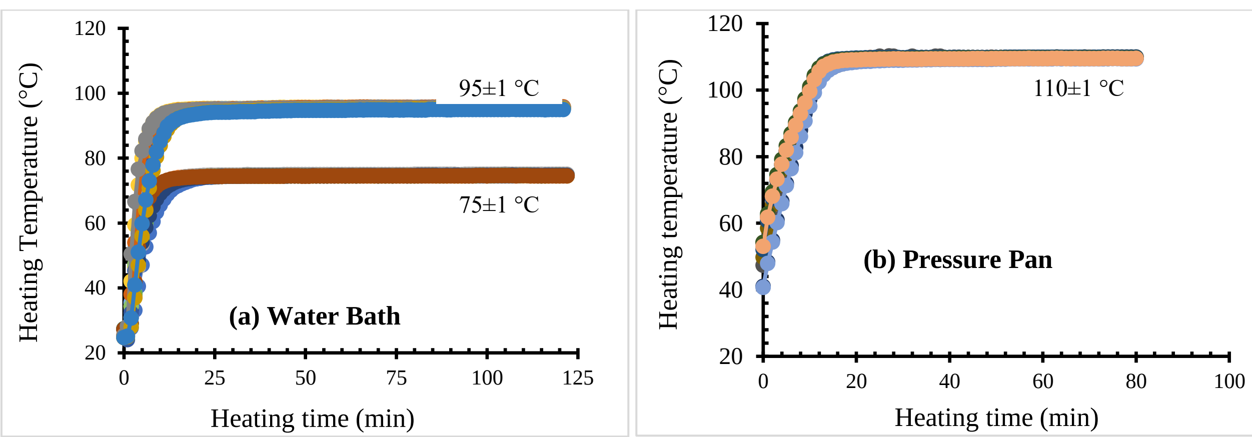

Figure 4. Measurement of heat penetration curves for (a) the water bath, and (b) the pressure cooker. [Different colored lines within each temperature legend indicate various thermocouple positions, as detailed in Figure 2 (c) and 2 (d)]

3.2. The Profile of Physical Quality Changes in Chicken Meat during Heating

This study confirms that heating significantly impacts the physical quality of chicken meat (Katemala *et al.*, 2023). The results, presented in Figure 5, indicate that cooking loss, shear force, *L**, and browning index values increased, while water-holding capacity and cohesiveness decreased after chicken meat was subjected to thermal processing. Prolonged heating durations tend to stabilize the physical quality parameters of the chicken meat towards constant values.

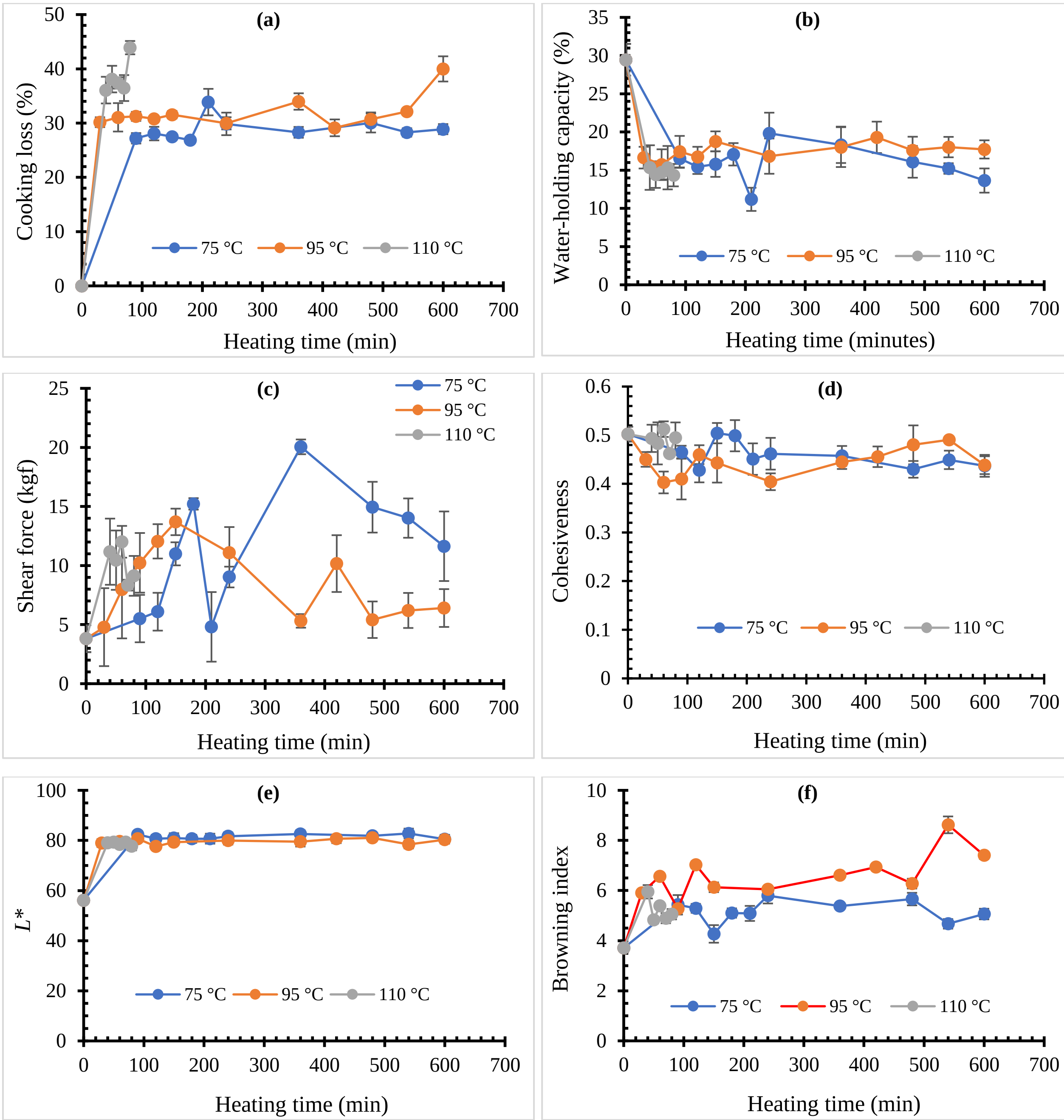

Figure 5. Profile of physical quality changes in chicken meat after heating for parameters (a) cooking loss, (b) water-holding capacity, (c) shear force, (d) cohesiveness, (e) L^*, and (f) browning index

Heating raw meat is a common practice in food processing; however, this treatment frequently leads to a reduction in quality. Such quality alterations, including physical properties like cooking loss, water-holding capacity, texture, and color, are primarily influenced by protein, as the main constituent, along with other substances such as water. Heating induces protein denaturation, a key mechanism underlying these quality changes. Protein denaturation causes non-uniform shrinking of muscle cells in all directions, leading to muscle fibers becoming shorter, thicker, and more densely packed. This shrinkage drives water movement from the intramyofibrillar space to the myofibrillar gaps and ultimately to the meat surface, initiating the phenomenon of cooking loss (CL) (Mehmood *et al*., 2019). CL is defined as the loss of fluid from meat due to heating, comprising water, myofibrillar and sarcoplasmic proteins, collagen, lipids, salts, polyphosphates, aroma compounds, and other soluble components. This loss can escalate with increasing temperature and heating time, potentially resulting in a leaching effect of highly soluble components (Gerber *et al*., 2009). The observed increase in CL values, presented in Figure 5(a), aligns with the findings of Qi *et al*. (2018). This denaturation process also leads to a loss of biological specificity in proteins, directly contributing to a decrease in WHC (water-holding capacity) (Mehmood *et al*., 2019). WHC indicates the amount of water bound by the meat structure, with 50% of water bound by myofibrillar proteins, 3% by sarcoplasmic proteins, and 47% by non-protein components (Kudryashov & Kudryashova, 2023). The observed increase in water release after heating signifies a reduction in WHC, as depicted in Figure 5(b), consistent with the research by Katemala *et al*. (2023).

Sembor & Tinangon (2022) state that CL and WHC correlate with juiciness, a complex attribute. Juiciness correlates negatively with CL but positively with WHC. Juiciness can be interpreted as the meat's succulence, representing the amount of fluid released upon mastication, a combination of water extracted from the meat and salivary secretions (Park *et al*., 2020). In the meat industry, retaining water within the meat is crucial for enhancing product yield and ensuring optimal juiciness, given that uncontrolled meat heating can lead to dryness due to protein denaturation.

Protein denaturation due to heating influences CL and WHC, which subsequently correlate with meat texture. High CL and low WHC tend to result in high objective hardness (Mehmood *et al*., 2019; Park *et al*., 2020). Instruments capable of objectively simulating mastication include the Texture Analyzer, employing a Warner-Bratzler blade probe to obtain shear force values and a 35 mm cylindrical probe to measure cohesiveness (Park *et al*., 2020). The observed increase in shear force after heating (Figure 5(c)) parallels the findings of Wattanachant *et al*. (2005). It is explained that heating causes protein denaturation, which promotes a denser meat structure and more tightly packed fibers, leading to increased meat hardness. The impact of protein denaturation also creates inter-myofibrillar spaces due to uneven compaction, hindering the meat structure's ability to maintain its integrity. This directly affects cohesiveness, defined as the degree of product deformation before cracking, crumbling, or breaking. The observed trend of decreasing cohesiveness values after heating, as shown in Figure 5(d), aligns with the results of Yang *et al*. (2022). Practically, when meat shear force increases but cohesiveness decreases, the meat will feel tougher to cut but brittle or easily crumbled during chewing or handling, tending to disintegrate rather than retaining its solid structure.

The L^* notation in the Chromameter analysis indicates lightness. The L^* value contributes most significantly to the absolute color change in a product. Heating leads to an increase in L^* values, as depicted in Figure 5(e). This phenomenon of increased lightness is attributed to enhanced light reflection, associated with structural changes undergone by the meat due to heating, such as protein denaturation, decreased water-holding capacity, and sarcolemma damage. These alterations create gaps between meat fibers, which then reflect more light, consistent with the findings of Moya *et al*. (2021). Specifically, the color parameter that determines the acceptance of thermally processed meat products is the browning index (Chumngoen *et al*., 2018). The increase in the browning index after heating is triggered by lipid oxidation. Lipid oxidation produces compounds, such as aldehydes from the degradation of unsaturated fatty acids. These compounds can interact with proteins or meat pigments, forming dark-colored pigment complexes that lead to an increase in the browning index of meat after heating (Tan *et al*., 2025). The research data show an increase in the browning index (Figure 5(f)) is consistent with the study by Wattanachant *et al*. (2005).

3.3. Kinetic Parameters of Physical Quality Changes in Chicken Meat

The accuracy of kinetic parameter values is highly dependent on the congruence between the applied kinetic model and the available experimental data (Ling *et al*., 2015). In this study, experimental data exhibiting significant changes were utilized, consistent with the fundamental principles of kinetic modeling outlined by Toledo (2007).

During the heating process, food quality changes commonly follow either zero-order or first-order kinetic equations. The selection of the appropriate order is determined by comparing R^2 values (coefficient of determination), with a higher R^2 indicating superior predictive capability of the model (Zhang *et al*., 2024). It is important to note that, in the kinetics of physical food quality, R^2 values are often not exceptionally high, as also observed by Kong *et al*. (2007) and Zhang *et al*. (2024). To facilitate comparative discussion regarding kinetic modeling, a first-order approach was employed in this study, with the data visualized in Figure 6. The results of this modeling were subsequently analyzed using the Arrhenius equation, summarized in Table 2.

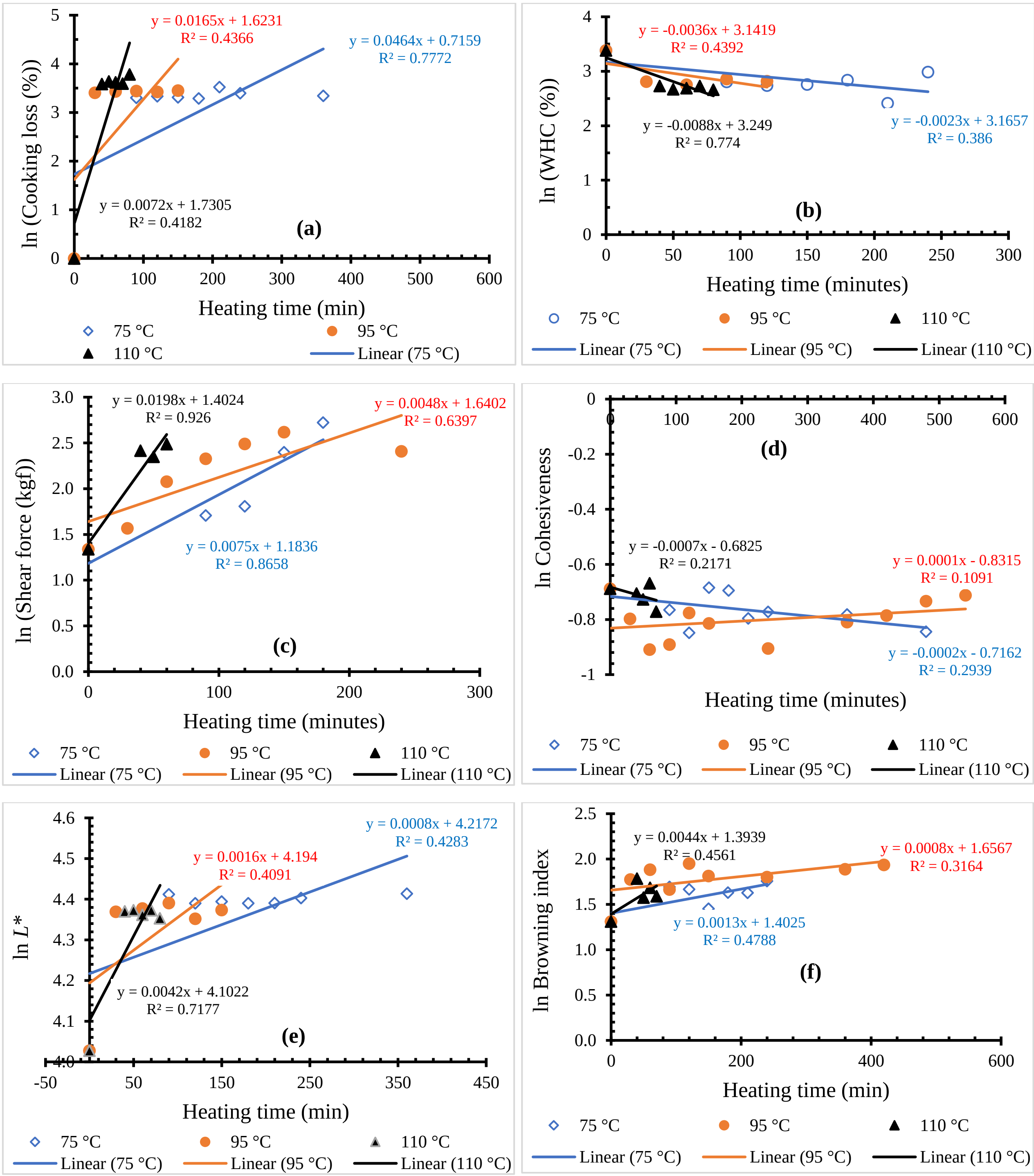

Figure 6. First-order kinetic equations for (a) cooking loss, (b) water-holding capacity, (c) shear force, (d) cohesiveness, (e) L^*, and (f) browning index

The Arrhenius equation yields kinetic parameters in the form of the reaction rate constant (k) and activation energy (Ea) required for a particular change to occur (Hindra & Baik, 2006). The values of k and Ea for each physical quality parameter are presented in Table 2.c Based on Equation 7, a diagram illustrating the relationship between ln k and T^{-1} was generated, as shown in Figure 7. Subsequently, Ea values can be derived from the slope of the linear regression. The

Table 2. Arrhenius kinetic constants for first-order physical quality parameters of chicken meat during heating

Physical quality parameter	**Temperature (°C)**	***k*** **(menit^{-1})**	**R^2**	***Ea*** **(kJ/mol)**	**R^2**
Cooking loss	75	0.0072	0.4182	57.89	0.9706
	95	0.0165	0.4366		
	110	0.0464	0.7772		
Water-holding capacity	75	0.0023	0.3860	41.10	0.9135
	95	0.0036	0.4392		
	110	0.0088	0.7740		
Shear force	75	0.0075	0.8658	26.69	0.3425
	95	0.0048	0.6397		
	110	0.0198	0.9260		
Cohesiveness	75	0.0002	0.2939	33.98	0.2996
	95	0.0001	0.1091		
	110	0.0007	0.2171		
*L**	75	0.0008	0.4283	51.34	0.9592
	95	0.0016	0.4091		
	110	0.0042	0.7177		
Browning index	75	0.0013	0.4788	33.82	0.3742
	95	0.0008	0.3164		
	110	0.0044	0.4561		

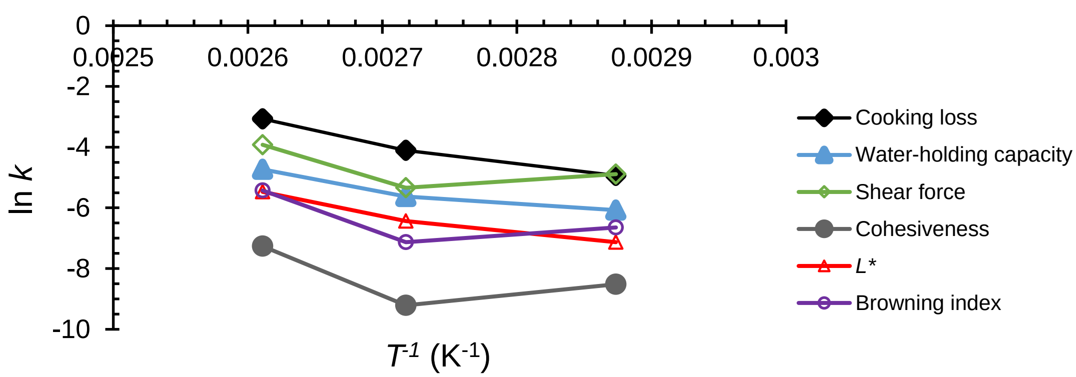

Figure 7. Arrhenius plots (*Ea*) for physical quality parameters of chicken meat during thermal processing

resulting *Ea* values were 57.89 kJ/mol for cooking loss; 41.10 kJ/mol for water-holding capacity; 26.69 kJ/mol for shear force; 33.98 kJ/mol for cohesiveness; 51.34 kJ/mol for *L**; and 33.82 kJ/mol for the browning index. Kinetic parameters are inherently specific; thus, the data obtained from this study differ from previous research findings, such as the *Ea* value for cooking loss, which is higher than that reported by Kong *et al*. (2007). Conversely, the *Ea* values for shear force and *L** are lower compared to the findings of Kong *et al*. (2007) and Zhang *et al*. (2024). These discrepancies are attributable to experimental factors, including variations in the samples used, heating methods, and analytical techniques. Figure 7 illustrates the physical quality changes across various temperatures, indicating a decline. This suggests that higher heating temperatures (smaller T^{-1} values) lead to a faster rate of quality change (higher ln *k* values) (Zhang *et al*., 2024). Based on the physical quality change profiles during heating, it was also observed that the rate of change for cooking loss, shear force, *L**, and browning index generally exhibited an increasing trend, while water-holding capacity and cohesiveness tended to decrease due to heating.

In addition to *k* and *Ea* values, *D* values (the time required for a one-log reduction in quality at a specific temperature) and *Z* values (the temperature change required to alter the *D* value by one log cycle) can also be utilized (Zhang *et al*., 2024). The *D* and *Z* values for physical quality changes can subsequently be mapped alongside the kinetic parameters of target microbial inactivation during heating. *Clostridium botulinum* spores are a primary inactivation target in thermal processes, as other thermophilic spores can be controlled by ensuring product storage below 30 °C. This target microbe possesses a $D_{121.1\ °C}$ value of 0.22 minutes (requiring 0.22 minutes to reduce 90% or 1 log of the population) and a Z value of 10 °C. Utilizing Equation 9, the kinetic parameters for *C. botulinum* and the physical quality changes of chicken meat during heating are presented in Table 3, with the results of their mapping illustrated in Figure 8.

Table 3. *D* and *Z* kinetic parameters of *Clostridium botulinum* and chicken meat physical quality

***T* (°C)**	***D* (min)**						
	Clostridium botulinum	**Cooking loss**	**Water-holding capacity**	**Shear force**	**Cohesiveness**	***L****	**Browning index**
75	8962.37	322.58	1000.00	303.03	10000.00	3333.33	1666.67
95	89.62	111.85	474.24	185.13	5675.45	1210.26	928.64
110	2.83	50.54	271.02	127.93	3711.08	566.08	598.89
121.1	0.22	28.08	179.13	97.32	2710.00	322.61	432.89
Z (°C)	10.00	43.48	61.73	93.46	81.30	45.45	78.74

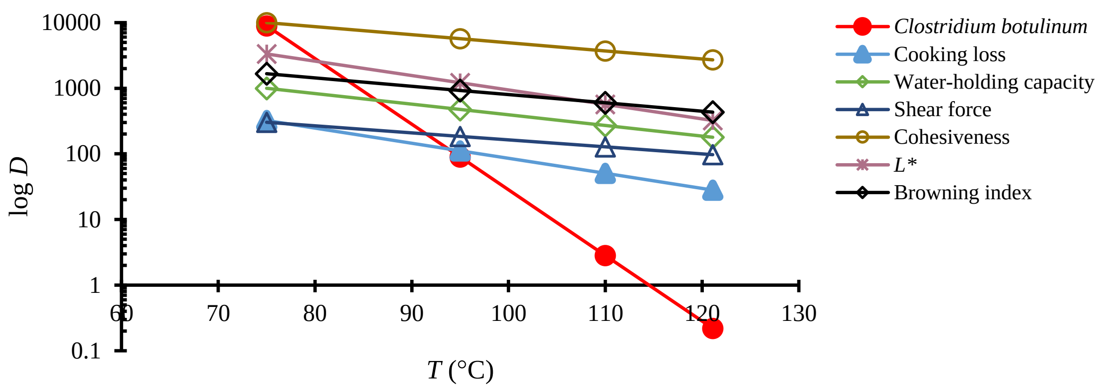

Figure 8. Mapping of *Z* kinetic parameters for *Clostridium botulinum* and *Z* values for physical quality changes in chicken meat

Table 3 indicates that the *Z* values for all physical quality parameters are greater than the *Z* value for *C. botulinum* microbes. Although specific values may vary between studies, the relatively large *Z* values obtained for the physical quality parameters of meat in this research are consistent with the findings of Zhang *et al*. (2024). The small *Z* value for *C. botulinum* microbes suggests that the microbial *D* value is more sensitive to temperature changes compared to the physical quality changes of chicken meat. The visualization in Figure 8 further reinforces that higher applied heating temperatures lead to smaller *D* values for both physical quality and target microbes. Nevertheless, the *D* values for physical quality consistently remain larger than those for target microbes at every temperature. Therefore, high-temperature heating is recommended as it creates conditions for a shorter processing time to inactivate microbes. This shorter duration, even at high temperatures, effectively minimizes changes in physical quality. This acceleration of microbial inactivation at higher temperatures, coupled with its minimal impact on quality changes, aligns with existing literature (Awuah *et al*., 2007; Diao *et al*., 2014; Purnomo *et al*., 2015). For instance, at 100 °C, a 1-log microbial inactivation requires approximately 20 min, with the 6th physical quality change occurring in less than 1-log. Conversely, at 80 °C, 1-log microbial inactivation requires approximately 2,000 min, with physical quality changes potentially exceeding 1-log.

4. CONCLUSION

Heating chicken meat at 75 and 95 °C in a water bath and at 110 °C in a pressure cooker resulted in uniform heat distribution. Heat penetration across all observation points was consistent for each temperature, as indicated by lag times of 18.25±2.25, 16.13±4.58, and 19.25±4.77 min at 75, 95, and 110 °C, respectively. Thermal treatment significantly affected the physical quality of chicken meat. Cooking loss, shear force, *L**, and browning index increased with heating, whereas water-holding capacity and cohesiveness decreased. First-order kinetic modeling using the Arrhenius equation revealed that higher temperatures accelerated the rate of physical quality changes. Kinetic parameters, including *D* and *Z* values, were successfully determined for these quality changes. Comparison with *Clostridium botulinum* spore inactivation ($D_{121.1\,°C} = 0.22$ min, $Z = 10$ °C) indicated that high-temperature, short-time treatments have the potential to minimize adverse physical quality changes while effectively inactivating target microorganisms.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
NKA	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓
EHP	✓	✓	✓	✓	✓			✓		✓	✓	✓		
NW	✓	✓	✓	✓	✓			✓		✓	✓	✓		

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

REFERENCES

Ahn, H.S., Yu, S.S., Kim, C.Y., Kim, Y.W., Yoon, Y., Lee, H., & Park, S.H. (2024). Heat penetration and quality attributes of superheated steam sterilization (SHS) home meal replacement (HMR) meat products stew. *LWT - Food Science and Technology*, ***191***, 115621. https://doi.org/10.1016/j.lwt.2023.115621

Awuah, G.B., Ramaswamy, H.S., & Economides, A. (2007). Thermal processing and quality: Principles and overview. *Chemical Engineering and Processing - Process Intensification*, ***46***(6), 584–602. https://doi.org/10.1016/j.cep.2006.08.004.

Buzby, J.C., Wells, H.F., Axtman, B., & Mickey, J. (2009). *Supermarket Loss Estimates For Fresh Fruit, Vegetables, Meat, Poultry, and Seafood and Their Use in the ERS Loss - Adjusted Food Availability Data* (*Economic Information Bulletin No. 44*). U.S. Department of Agriculture, Economic Research Service. https://doi.org/10.22004/AG.ECON.58313

Chumngoen, W., Chen, C.-F., & Tan, F.-J. (2017). Effects of moist- and dry-heat cooking on the meat quality, microstructure and sensory characteristics of native chicken meat. *Animal Science Journal*, ***89***(1), 193–201. https://doi.org/10.1111/asj.12864

Combes, S., Lepetit, J., Darche, B., & Lebas, F. (2004). Effect of cooking temperature and cooking time on Warner–Bratzler tenderness measurement and collagen content in rabbit meat. *Meat Science*, ***66***(1), 91–96. https://doi.org/10.1016/S0309-1740(03)00019-6

Diao, M.M., André, S., & Membré, J.-M. (2014). Meta-analysis of D-values of proteolytic *Clostridium botulinum* and its surrogate strain *Clostridium sporogenes* PA 3679. *International Journal of Food Microbiology*, ***174***, 23–30. https://doi.org/10.1016/j.ijfoodmicro.2013.12.029

Gerber, N., Scheeder, M.R.L., & Wenk, C. (2009). The influence of cooking and fat trimming on the actual nutrient intake from meat. *Meat Science*, ***81***(1), 148–154. https://doi.org/10.1016/j.meatsci.2008.07.012

Hidayat, C., Sumiati, & Iskandar, S. (2015). Persentase bobot karkas dan potongan komersial ayam Sentul-G3 yang diberi ransum mengandung dedak tinggi dengan suplementasi fitase dan ZnO. *Jurnal Ilmu Pertanian Indonesia*, ***20***(2), 131–136. https://doi.org/10.18343/jipi.20.2.131

Hindra, F., & Baik, O.-D. (2006). Kinetics of quality changes during food frying. *Critical Reviews in Food Science and Nutrition*, ***46***(3), 239–258. https://doi.org/10.1080/10408690590957124

Indiani, F., Titisari, D., & Lamidi, L. (2019). Waterbath design equipped with temperature distribution monitor, temperature and timer control parameters. *Journal of Electronics, Electromedical Engineering, and Medical Informatics*, ***1***(1), 1–6. https://doi.org/10.35882/jeeemi.v1i1.3

Ismail, I.M., Fahmy, A., Azab, A., Abadir, M., & Fateen, S.-E. (2013). Optimizing the sterilization process of canned food using temperature distribution studies. *IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS)*, ***6***(4), 26–33. https://doi.org/10.9790/2380-0642633

Katemala, S., Molee, A., Thumanu, K., & Yongsawatdigul, J. (2023). Heating temperatures affect meat quality and vibrational spectroscopic properties of slow- and fast-growing chickens. *Poultry Science*, ***102***(8), 102754. https://doi.org/10.1016/j.psj.2023.102754

Kavitha, S., & Modi, V.K. (2007). Effect of water activity and temperature on degradation of 5′-inosine monophosphate in a meat model system. *LWT - Food Science and Technology*, *40*(7), 1280–1286. https://doi.org/10.1016/j.lwt.2006.07.014

Kemnaker (Kementerian Ketenagakerjaan Republik Indonesia). (2021). *Keputusan Menteri Ketenagakerjaan Nomor 103 Tahun 2021 tentang Penetapan Standar Kompetensi Kerja Nasional Indonesia Kategori Industri Pengolahan Golongan Pokok Industri Makanan Bidang Industri Pengolahan dan Pengawetan Produk Daging (Sub Bidang Non Produksi).* Kementerian Ketenagakerjaan Republik Indonesia.

Kong, F., Tang, J., Rasco, B., & Crapo, C. (2007). Kinetics of salmon quality changes during thermal processing. *Journal of Food Engineering*, ***83***(4), 510–520. https://doi.org/10.1016/j.jfoodeng.2007.04.002

Kudryashov, L.S., & Kudryashova, O.A. (2023). Water-holding and water-holding capacity of meat and methods of its determination. *Teoriya i Praktika Pererabotki Myasa* [*Theory and Practice of Meat Processing*], ***8***(1), 62–70. https://doi.org/10.21323/2414-438X-2023-8-1-62-70

Kusnandar, F., Dafiq, H.H., Rahayu, W.P., & Irmawan, D. (2023). Evaluasi kecukupan panas dan pengembangan proses alternatif dalam sterilisasi komersial jamur kancing dalam kaleng. *Jurnal Mutu Pangan*, ***10***(2), 100–109. https://doi.org/10.29244/jmpi.2023.10.2.100

Laksono, U.T., Suprihatin, S., Nurhayati, T., & Romli, M. (2019). Enhancement of textural quality from Daggertooth Pike Conger fish surimi with sodium tripolyphosphate and transglutaminase activator. *Jurnal Pengolahan Hasil Perikanan Indonesia*, ***22***(2), 273–282. https://doi.org/10.17844/jphpi.v22i2.27373

Li, Y., Liang, S., Ye, G., Zhang, M., Feng, S., Wang, Z., Zhang, Q., & Sun, C. (2023). Effects of different sterilization methods on sensory quality and lipid oxidation of Dezhou braised chicken. *Food Science and Technology (Campinas)*, ***43***, e119222. https://doi.org/10.1590/fst.119222

Ling, B., Tang, J., Kong, F., Mitcham, E.J., & Wang, S. (2015). Kinetics of food quality changes during thermal processing: A review. *Food and Bioprocess Technology,* ***8***(2), 343–358. https://doi.org/10.1007/s11947-014-1398-3

Mehmood, W., Qian, S., Zhang, C., & Li, X. (2019). Biophysical properties and volumetric changes in breast meat of broilers and yellow-feathered chicken as affected by cooking process. *International Journal of Food Properties,* ***22***(1), 1935–1951. https://doi.org/10.1080/10942912.2019.1696361

Milicevic, D., Trbovic, D., Petrovic, Z., Jakovac-Strajn, B., Nastasijevic, I., & Koricanac, V. (2015). Physicochemical and functional properties of chicken meat. *Procedia Food Science,* ***5***, 191–194. https://doi.org/10.1016/j.profoo.2015.09.054

Moya, J., Lorente-Bailo, S., Ferrer-Mairal, A., Martínez, M.A., Calvo, B., Grasa, J., & Salvador, M.L. (2021). Color changes in beef meat during pan cooking: Kinetics, modeling and application to predict turn over time. *European Food Research and Technology,* ***247***, 2751–2764. https://doi.org/10.1007/s00217-021-03787-1

Park, C.H., Lee, B., Oh, E., Kim, Y.S., & Choi, Y.M. (2020). Combined effects of sous-vide cooking conditions on meat and sensory quality characteristics of chicken breast meat. *Poultry Science,* ***99***(6), 3286–3291. https://doi.org/10.1016/j.psj.2020.03.004

Patriani, P., & Apsari, N.L. (2022). *Peningkatan Mutu Daging Menggunakan Rempah*. CV. Anugerah Pangeran Jaya Press, Medan.

Purnomo, E.H., Giriwono, P.E., Indrasti, D., Firlieyanti, A.S., & Kinasih, A.G. (2015). Parameter kinetika inaktivasi termal dan isolasi Staphylococcus aureus pada minuman dari gel cincau hijau dan rosela. *Jurnal Teknologi dan Industri Pangan,* ***26***(1), 124–131. https://doi.org/10.6066/jtip.2015.26.1.124

Qi, J., Li, X., Zhang, W., Wang, H., Zhou, G., & Xu, X. (2018). Influence of stewing time on the texture, ultrastructure and in vitro digestibility of meat from the yellow-feathered chicken breed. *Animal Science Journal,* ***89***(2), 474–482. https://doi.org/10.1111/asj.12929

Raits, E., Pinte, L., Kirse-Ozolina, A., & Muizniece-Brasava, S. (2021). A case study: Temperature distribution and heat penetration in steam-air retort, using glass jars and retort pouches. *Rural Sustainability Research,* ***46***(341), 90–96. https://doi.org/10.2478/plua-2021-0020

Saragih, D.S., Adawiyah, D.R., & Rungkat, F.Z. (2021). Sterilisasi komersial cassava chunk pada kemasan hermetis standing pouch dan perubahan sifat fisikokimianya. *Jurnal Ilmu Pertanian Indonesia*, ***26***(2), 184–195. https://doi.org/10.18343/jipi.26.2.184

Sembor, S., & Tinangon, R.M. (2022). *Industri Pengolahan Daging*. CV. Patra Media Grafindo, Bandung.

Sitanggang, A.B., Hunaefi, D., Adawiyah, D.R., Purnomo, E.H., Syamsir, E., Kusnandar, F., Wulandari, N., & Hariyadi, P. (2019). *Landasan Teknik Pangan*. IPB Press, Bogor.

Taikerda, T., & Leelawat, B. (2023). Effect of young jackfruit, wheat gluten, and soy protein isolate on physicochemical properties of chicken meat analogs. *Kasetsart Journal: Agriculture and Natural Resources*, ***57***(2), 201–210. https://doi.org/10.34044/j.anres.2023.57.2.01

Tan, H., Huang, Q., Yu, J., Lu, Y., Wei, L., Shi, L., Yu, W., & Qiao, Y. (2025). Analysis of factors affecting the browning of crayfish hepatopancreas after high-temperature sterilization. *LWT - Food Science and Technology*, ***223***, 117792. https://doi.org/10.1016/j.lwt.2025.117792

Toledo, R.T. (2007). *Fundamentals of Food Process Engineering* (3rd ed.). Springer Science+Business Media, LLC.

Tomasz, K. (2024). Thermal processing: A key method in food preservation. *African Journal of Food Science and Technology*, ***15***(12), 1–2.

Triyannanto, E., Febrisiantosa, A., Kusumaningrum, A., Amri, A.F., Fauziah, S., Sulistyono, E.P., Dewandaru, B.M., & Nurhikmat, A. (2022). The quality characteristics of ready-to-eat empal gentong affected by meat pre-cooking. *Food Science of Animal Resources*, ***42***(4), 557–565. https://doi.org/10.5851/kosfa.2021.e70

Wattanachant, S., Benjakul, S., & Ledward, D.A. (2005). Effect of heat treatment on changes in texture, structure and properties of Thai indigenous chicken muscle. *Food Chemistry*, ***93***(2), 337–348. https://doi.org/10.1016/j.foodchem.2004.09.032

Yang, X., Li, Y., Wang, P., Luan, D., Sun, J., Huang, M., Wang, B., & Zheng, Y. (2022). Quality changes of duck meat during thermal sterilization processing caused by microwave, stepwise retort, and general retort heating. *Frontiers in Nutrition*, ***9***, 1016942. https://doi.org/10.3389/fnut.2022.1016942

Zhang, M., Yang, Y., Zhang, H., Li, C., He, L., & Deng, L. (2024). Changes in food quality and characterization under thermal accumulation conditions during Chinese cooking. *Food Science & Nutrition*, ***12***(3), 2081–2092. https://doi.org/10.1002/fsn3.3908