Food Science of Animal Products

Research Article

Construction of a grading model based on the quality characteristics of different grades of chicken wooden breast

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Abstract: The deterioration of wooden breast myofibrillar protein (WBMP) increases with the increase in wooden breast grades. In order to quickly and conveniently classify wooden breast to prevent waste of raw materials and unsuitable processing. Different grades of wooden breasts that exhibited mild, moderate, and severe degrees were collected, and correlation analysis was employed for the quality and WBMP functional characteristic indicators. The indicators were further classified into two components according to the principal component analysis method. Based on the correlation and variation coefficients, two main indicators were selected to represent the quality level of wooden breasts (redness (a^*) and pH value (P)). The weights of the two indicators were 0.353 and 0.219 for a^* and P, respectively, using the weighted coefficient method. Therefore, a formula for calculating the comprehensive evaluation score (y) of different grades of wooden breast meat was obtained: $y = 0.353a^* + 0.219P$. Based on regression analysis, the fitting equation $y = 2.407\ 1x + 0.034\ 3$ ($R^2 = 0.988\ 3$) was obtained, for the comprehensive quality score (y) and sensory evaluation score (x) through regression analysis, with a fitting coefficient > 0.8. This equation can accurately predict sensory evaluation scores, effectively reflect the quality differences of different grades of wooden breasts, and accurately and rapidly grade wooden breasts.

Keywords: wooden breast; myofibrillar protein; grading model; principal component analysis; sensory evaluation

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1 Introduction

Wooden breast is one type of abnormal meat problem that is widespread and severe[1]. Officially reported in 2014 as a result of rapid growth and weight gain in white-feathered broilers[2], wooden breast presents as a hardened upper portion of the pectoralis major muscle, often accompanied by stripes and bleeding spots. In addition, the tail of the breast has ridged protrusions, accompanied with blood and viscous secretions[3]. This phenomenon critically affects the quality of muscles, resulting in changes in protein, water, fat contents, water-holding capacity (WHC), pH, and texture. These changes result in poor muscle protein function, which includes the decline of WHC and weakening of gel formation, hindering follow-up deep processing[4]. Wooden breasts also result in a decline in broiler processing performance, posing a significant challenge for broiler processors. The occurrence of wooden breasts in China is as high as 61.9%, with moderate-to-severe wooden breasts accounting for approximately 70.8% of the total incidence rate[5]. Consequently, severely damaged wooden breasts increase processing costs, reduce product grades, and increase scrap rates[4]. The problems associated with wooden breasts have become a challenge for downstream users supplying high-quality chicken products to the market.

The detection and grading of wooden breasts are typically completed on a segmentation production line, and screening for different grades (i.e., mild, moderate, and severe) of wooden breasts prepares them for the next step[6]. As shown in Figure 1, scoring and classifying wooden breasts are based on appearance and hardness. Normal (0 points) chicken breast meat is soft and elastic, without any hard features[7]. Mild (1 point) chicken wooden breast meat exhibits slight changes in the head and near the tail of the chicken breast, with a relatively hard head. Moderate (2 points) chicken wooden breast meat exhibits hard characteristics. However, springiness occurs from the middle to the tail[8]. Severe (3 points) chicken wooden breast meats include the overall appearance of hardness, accompanied by bleeding and infiltration. Mild wooden breasts do not significantly affect the quality of chicken breast meat and are the least common classification. However, moderate to severe wooden breast classifications seriously affect their deep processing and improved utilization, with moderate wooden breast meats representing the most common classification[9]. Though numerous methods and equipment applications for wooden breast are employed, the majority focuses on the detection of wooden breasts, which involves expensive and large instruments, and accurately identifying different grades remains a challenge. Consequently, significant limitations remain in the screening of different grades of wooden breasts[10].

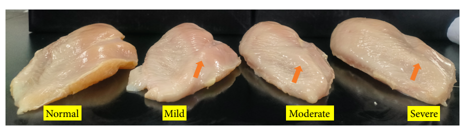

Figure 1 Display of different grades of wooden breast.

Herein, wooden breast meats and WBMPs were investigated, and the quality and functional characteristics of WBMPs of different grades (mild, moderate, and severe) were compared to determine the degree of deterioration. Primary indicators were screened to construct different wooden breast grading models for the rapid grading of wooden breast. After determining the quality characteristics of different grades of wooden breast tissue, and the functional characteristics of WBMPs, the representative indices were screened via principal component and correlation analyses. Furthermore, their weight factors were determined via the independent coefficient method. Grading models of different grades of wooden breast were established in coordination with sensory evaluation, and their feasibilities were verified using means of linear regression. This model construction method facilitates rapid detection and classification of wooden breast. This will help to improve the utilization of the wooden breast after grading and recover economic losses.

2 Material and methods

2.1 Materials

Different grades of wooden and normal chicken breast meats were collected from Zhucheng Foreign Trade Co., Ltd. (Zhucheng, China), with 1 000 pieces of chicken breast meat sourced from different production lines. The numbers of normal, mild, moderate, and severe grade samples were 300, 150, 400, and 150, respectively. Following the procedure by Cai et al.[11], wooden breasts were selected using visual testing and compression methods. White-feathered broilers were slaughtered and divided into three groups (mild, moderate, and severe) according to grade. Each chicken breast was trimmed into standardized blocks and stored in an environment at −80 ℃ for further experimentation. The control group consisted of normal chicken breasts. All the other chemicals were of analytical grade.

2.2 Determination of quality indicators of different grades of wooden breasts

2.2.1 Drip loss

Meat samples were collected and trimmed to the same weight specifications 24 h following the slaughter. Following precise weighing, meat samples were placed into an inflatable plastic bag. One end of the bag was tied using a thin wire and hung at 0–4 ℃ for 24 h. Water loss was calculated using Eq. (1).

$$\text{Drip loss (\%)} = \frac{m_1 - m_2}{m_1} \times 100 \tag{1}$$

Where m_1 and m_2 are the weights before and after hanging (g), respectively.

2.2.2 Cooking loss

Following accurate weighing, the meat sample was placed in a steaming bag and boiled in an 85 ℃ water bath until the center temperature reached 70 ℃. The meat sample was then dried with absorbent paper and weighed once the temperature decreased to 25 ℃. Cooking loss was calculated using Eq. (2).

$$\text{Cooking loss (\%)} = \frac{m_1 - m_2}{m_1} \times 100 \tag{2}$$

Where m_1 and m_2 are the weights before and after cooking (g), respectively.

2.2.3 Meat color

The color of the meat samples was immediately measured with the fresh side facing upwards using a portable colorimeter (CR-10 Plus, Konica Minolta Inc., Shanghai, China), and brightness (L^*), redness (a^*), and yellowness (b^*) were recorded.

2.2.4 pH

The pH was determined immediately after slaughter using a portable pH meter (temperature compensation was 25 ℃). Measurements were taken thrice, and the average value was calculated.

2.2.5 Shear force

Meat samples were wrapped in a steaming bag and placed in a water bath at 85 ℃ until the center temperature reached 70 ℃. The sample was then cooled to 25 ℃ and cut into 1 cm × 1 cm × 3 cm long strips to measure its shear force (kg) using a shear force meter.

2.2.6 Texture characteristics

Following steaming and boiling, the meat pieces remained at a central temperature of 70 ℃ for 20 min, then cooled to 25 ℃ and cut into 1 cm × 1 cm × 1 cm pieces. A texture analyzer and P50 probe were used for measurement. The measurement parameters included rate before testing (1.0 mm/s) and testing speed (0.5 mm/s). After testing, the speed, compression ratio, and initiating force were 1.0 mm/s, 50%, and 5 g, respectively.

2.2.7 Sensory evaluation

A professionally trained sensory evaluation group consisting of 12 individuals was selected based on sex. The room temperature remained at 25 ℃, and a comparison of the sensory evaluation standards are shown in Table 1. The evaluation items totaled 100 points and were based on the appearance and hardness of the chicken breast, with a score of 50 points each. Appearance primarily evaluates the color of the chicken breast, and the presence of bleeding spots or connective tissue stripes. Hardness primarily evaluates the ridge-like protrusions and tactile sensations, of which

Table 1 Sensory evaluation criteria for different grades of wooden breast.

Evaluation	Standard	Score
Appearance	Color is pink and shiny, without bleeding or connective tissue	34–50
	Color is average, dark, and yellowish, with a small amount of bleeding points and connective tissue	17–33
	Surface of chicken breast is accompanied by bleeding and infiltration	0–16
Hardness	Whole chicken breast is soft and elastic, without any hard features	34–50
	Slight changes in the head and near tail of the breast; head is relatively hard	17–33
	Whole chicken breast exhibits a hard characteristic, but there is springiness from the middle to the tail	0–16

both are important criteria for evaluating wooden breasts. Following the sensory evaluation, the scores were summarized, average and error values were calculated, and quality was analyzed.

2.3 Determination of functional characteristics of myofibrillar proteins in different grades of wooden breasts

2.3.1 Extraction of WBMPs

The fascia and connective tissues were then removed from the chicken breasts[12]. The muscles were ground and homogenized at 10 000 × *g* for 30 s in 4 times the volume of four-buffer system (100 mmol/L KCl, 2 mmol/L $MgCl_2$, 1 mmol/L EGTA, and 10 mmol/L K_2HPO_4; pH 7.0).

2.3.2 Solubility

The samples were diluted to 2 mg/mL with 5 mmol/L sodium phosphate (5 mmol/L EDTA, pH 7.0) and centrifuged at 10 000 × *g* for 15 min (4 ℃). Solubility was expressed as the ratio of the protein content in the clear liquid to the total protein content[13].

2.3.3 Emulsion activity index (EAI) and emulsion stability index (ESI)

EAI and ESI were measured using previously reported methods[14]. The WBMP sample was dissolved in phosphate buffer solution (0.1 mol/L) to a mass concentration of 1 mg/mL protein. The WBMP emulsion (50 μL) was added to 5 mL of 1 g/L sodium dodecyl sulfate solution. The absorbance at 500 nm was measured initially (A_0) and then at 10 min (A_{10}) after emulsion formation. The EAI and ESI values were calculated using Eqs. (3) and (4), respectively.

$$\text{EAI (m}^2\text{/g)} = \frac{2 \times 2.303}{\rho \times (1-\varphi) \times 10} \times A_0 \times n \tag{3}$$

$$\text{ESI (\%)} = \frac{A_{10}}{A_0} \times 100 \tag{4}$$

Where ρ is the sample concentration (mg/mL) before emulsification, φ is the oil volume fraction (*V*/*V*) of the protein solution (0.1), and *n* is the dilution ratio (100).

2.3.4 Texture of WBMP gels

The method described by Wang et al.[15] was used with slight modifications. WBMPs were diluted to 60 mg/mL in a phosphate buffer (0.6 mol/L KCl and 0.01 mol/L KH_2PO_4, pH 6.0). Subsequently, the treated WBMPs were placed in a water bath and heated from 20 to 80 ℃ at a rate of 1 ℃/min, followed by incubation at 80 ℃ for 30 min. A texture analyzer (Texan 200, Lamy Inc., France) device was used to measure the gel texture[16]. The texture probe was P0.5, and the measurement parameters were set as follows: strain of 50%, trigger force of 5 g, and pre-test, test, and post-test speeds of 0.2, 0.8, and 0.8 mm/s, respectively.

2.3.5 WHC of gel

The method described by Wang et al.[17] with slight modifications. The sample (10 g) was placed in a centrifuge tube and centrifuged at a speed of 10 000 × *g* for 15 min to dry the water. Following weighing, the WHC of the WBMP gel was calculated based on the centrifugation method using Eq. (5).

$$\text{WHC (\%)} = \frac{m_2 - m}{m_1 - m} \times 100 \tag{5}$$

Where m_2 is the total weight (g) of the centrifuge tube and WBMP gel after centrifugation; m_1 is the total weight (g) of the centrifuge tube and WBMP gel (dry water) before centrifugation; and *m* is the weight (g) of the centrifuge tube.

2.3.6 Construction of a hierarchical model

First, different levels of wooden breast quality and WBMP functional characteristic indicators were collected for analyses of the correlation and coefficient of variation. The indicators were further classified via the principal component analysis method. The target principal components were determined based on the component contribution rate, and the primary indicators representing the wooden breast quality were selected based on the correlation and coefficient of variation. The weights of the target components were determined using the weighted coefficient method, and a formula was determined for the comprehensive evaluation score for the quality of different grades of wooden breasts. Finally, regression analysis and model validation were conducted using the sensory evaluation data to obtain the fitting formula. When the fitting coefficient was > 0.8, the sensory evaluation score could be accurately predicted, which enabled the construction of a grading model for the different grades of wooden breasts.

2.4 Statistical analysis

One-Way Analysis of Variance was used to determine statistical differences. Multiple comparisons were performed according to Duncan's multiple range test using SPSS 19.0 software. All values were expressed as the mean ± standard deviation, with a significant difference of $P < 0.05$. Correlation, principal component, and linear regression analyses were performed using the SPSS software. In addition, Origin 2018 software was used for the drawing.

3 Results and discussion

3.1 Changes in physical and chemical properties and functional characteristics

3.1.1 Changes in drip loss, cooking loss, shear force, and pH

WHC and tenderness are important indicators for determining the quality of meat products, and consumers often select meat products with excellent WHC and tenderness[18]. Among the indicators of WHC, dripping and cooking losses can reflect the degrees of WHC and juiciness of fresh and ripe meat products. Table 2 reveals that the indicators of water loss, cooking loss, shear force, and pH of wooden breast are significantly higher than those of normal breast meats ($P < 0.05$). Furthermore, as the degree of wooden breasts increases (i.e., mild < moderate < severe), the WHC of chicken breast meat significantly decreases. For example, the dripping and cooking losses in severe wooden breast meats significantly increased from (1.68 ± 0.06)% and (25.22 ± 1.12)% (normal breast meat data) to (3.41 ± 0.02)% and (35.11 ± 2.25)% ($P < 0.05$), respectively. These results indicate that the higher the degree of wooden breast, the lesser the WHC of the muscle fibers, causing a dry appearance and hard texture of the meat. Therefore, the increases in dripping and cooking losses reveal the poor WHC of the wooden breast meats. The decreases in WHC may be caused by lipid peroxidation, resulting in the uncoupling of skeletal muscle sarcoplasmic reticulum calcium pumps, thus inactivating the pumps. This phenomenon can lead to an increase in calcium ion concentration

Table 2 Drip loss, cooking loss, shearing force, and pH of different grades of wooden breasts ($n = 70$).

Classification	Drip loss (%)	Cooking loss (%)	Shearing force (kg)	pH
Normal	1.68 ± 0.06^d	25.22 ± 1.12^d	14.33 ± 1.01^d	5.89 ± 0.22^d
Mild	2.11 ± 0.22^c	27.47 ± 1.09^c	16.33 ± 1.01^c	6.09 ± 0.31^c
Moderate	2.45 ± 0.86^b	30.35 ± 1.11^b	18.71 ± 1.01^b	6.28 ± 0.45^b
Severe	3.41 ± 0.02^a	35.11 ± 2.25^a	20.74 ± 2.01^a	7.13 ± 0.51^a

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

and the production of free radicals, which disrupts the integrity of muscle cell membranes, resulting in a decrease in muscle system hydraulic capacity. Furthermore, changes in the structure of muscle fibers result in the transfer of water inside the muscle fibers to outside the myofibril network, aggravating water loss[19]. The shearing force results confirm this phenomenon. The shearing force of normal chicken breast meats was (14.33 ± 1.01) kg; However, for severe wooden breast meats, the shear force increased to (20.74 ± 2.01) kg, indicating a significant decrease in the tenderness of wooden breast meats. Tenderness is an important indicator of meat palatability. Compared with that of normal chicken breast meats, moderate or severe wooden breast meats exhibited a shearing force above (18.71 ± 1.01) kg, which has critically impacted consumer choice in purchasing chicken breast meats[20]. Furthermore, the moderate wooden breast category comprises a higher incidence among the different grades of wooden breasts, leading to increased economic losses. Additionally, the pH of the wooden breasts exhibited a continuous upward trend. Compared to that of normal chicken breast meats (5.89 ± 0.22), the pH of severe wooden breast meat significantly increased to 7.13 ± 0.51 ($P < 0.05$), resulting in a slightly alkaline meat product. Downregulation of gluconeogenesis and glycolysis pathways may cause an increase in the endpoint pH. Therefore, a higher pH indicates that the wooden breast meat has been exposed to oxidative stress for long periods, thus affecting muscle glycogen fermentation. After slaughter, changes in muscle pH are primarily caused by muscle glycogen hydrolysis, and the endpoint pH depends on muscle glycogen content. Studies have determined that wooden breast muscles undergo oxidative stress[21]. Under long-term stress conditions[20], the body consumes a certain amount of inositose to maintain life. In addition, the gluconeogenesis and glycolysis pathways in wooden breast muscles are downregulated[20], which may cause the endpoint pH to increase.

3.1.2 Changes in color

Typically, color intuitively reflects the freshness and quality of meat products. Table 3 shows that the L^* of wooden breast meats was significantly lower than that of the normal breast meats ($P < 0.05$). The L^* of normal breast meat was 62.35 ± 1.17, while the L^* of both mild and moderate wooden breast meats significantly decreased to 58.15 ± 1.28 and 55.78 ± 1.11 ($P < 0.05$), respectively. The L^* of severe wooden breast meats was 39.14 ± 1.04, indicating an overall darker meat color. The wooden breast meats were significantly darker than the normal breast meats, and the decrease in a^* and b^* values indicated a yellowish meat that lacked the traditional pink color of chicken breast meats. Considering moderate wooden breast meats, the a^* and b^* values were 0.87 ± 0.07 and 5.47 ± 0.58, respectively, which were significantly different from the a^* (1.22 ± 0.15) and b^* (7.98 ± 0.16) values of normal breast meats. Furthermore, the a^* value for severe wooden breast meats was significantly lower than that of normal breast meat. Considering meat color, little differences were noted between mild wooden breast and normal breast meats, which are typically unnoticed by consumers. However, moderate to severe wooden breast meats cannot be sold fresh. Consequently, the relationship between the changes in meat color and the properties of meat proteins were examined. Oxidation causes protein browning and may be a possible cause of wooden breast formation. An exudate appears when the degree of the wooden breast is high, which increases natural light reflection, resulting in a pale color of the wooden breast and decrease in meat acceptability by consumers.

Table 3 Color values of different grades of wooden breasts ($n = 40$).

Classification	L^*	a^*	b^*
Normal	62.35 ± 1.17^a	1.22 ± 0.15^a	7.98 ± 0.16^a
Mild	58.15 ± 1.28^b	1.03 ± 0.06^b	6.33 ± 0.22^b
Moderate	55.78 ± 1.11^c	0.87 ± 0.07^c	5.47 ± 0.58^c
Severe	39.14 ± 1.04^d	0.51 ± 0.14^d	4.10 ± 0.18^d

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

3.1.3 Changes in texture characteristics

Textural characteristics reflect the tenderness and palatability of meat products. The hardness, springiness, cohesion and chewiness of mild wooden breast samples differ slightly from the textural characteristics of normal breast meat (Table 4). The hardness and chewiness of severe wooden breast meat were higher than those of normal breast meat, indicating that the degree of wooden breast enhances muscle hardening and thickening of the muscle fibers. Furthermore, the springiness of severe wooden breast meats were significantly lower than those of normal breast meats, possibly due

Table 4 Texture characteristics of different grades of wooden breasts ($n = 20$).

Classification	Hardness (g)	Springiness	Cohesion	Chewiness
Normal	5 818.66 ± 20.15^d	0.48 ± 0.03^a	0.35 ± 0.01^a	773.15 ± 41.70^d
Mild	6 015.85 ± 84.44^c	0.40 ± 0.02^b	0.35 ± 0.01^a	800.14 ± 70.94^c
Moderate	6 550.87 ± 16.76^b	0.32 ± 0.01^c	0.34 ± 0.01^a	825.23 ± 31.29^b
Severe	7 125.66 ± 45.39^a	0.25 ± 0.07^d	0.33 ± 0.02^a	914.36 ± 50.52^a

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

to the reduction in muscle fiber strength and tightness between muscle fibers. These phenomena are caused by the degeneration and atrophy of muscle fibers, consistent with histological changes. Textural characteristics, such as hardness and springiness, affect the acceptability of meat products by consumers. Therefore, as the degree of wooden breast increased, a series of changes occurred in the muscle fibers of chicken breast meats. Though the fibers become thicker, the fiber spacing increases, which results in a less compact meat product that has lost some of the traditional muscle fiber characteristics, ultimately leading to a significant decrease in the taste quality of chicken breast meats.

3.1.4 Changes in gel properties

Table 5 shows that the gel quality of WBMPs decreases with the increase of wooden breast degree. The hardness, springiness, and cohesion of normal breast myofibrillar protein (NBMP) gel are (85.62 ± 2.11) g, 0.67 ± 0.13, and 0.78 ± 0.11, respectively, while the indexes of mild WBMP begin to decrease to (67.20 ± 4.42) g, 0.55 ± 0.12, and 0.54 ± 0.02, respectively. Subsequently, the quality of gel decreases. The texture indexes of the moderate WBMP gel were (55.23 ± 6.72) g, 0.45 ± 0.11, and 0.35 ± 0.04, respectively, which indicates that the gel loosened and softened. Therefore, the quality of the gel formed by moderate WBMPs significantly decreased. The gel formed by WBMP has poor WHC, as shown from the gel WHC and strength data. Therefore, WBMP exhibits a poor protein interaction in the process of forming gel due to the reduction of its gel performance and cannot form disulfide bonds. The weakening of the binding ability between myosin also leads to the difficulty in forming gel networks. Furthermore, the WHC is significantly affected[22]. As the cross-linking of the gel network weakens, water molecules cannot be trapped, resulting in water loss[23]. The gel dries and exhibits cracks with many macropores, ultimately resulting in the poor quality of the WBMP gel[24].

3.1.5 Changes in solubility and emulsification performance

Protein solubility is an important functional property because proteins with good solubility have good functional properties, such as emulsification, WHC, foaming, and dispersibility[25], and proteins with high solubility can have stronger processing effects[26]. Table 6 showed that the solubility and emulsifying ability of the WBMPs were significantly lower than those of the NBMPs ($P < 0.05$). The solubility, EAI, and ESI of mild WBMPs were (61.36 ± 1.47)%, (6.35 ± 0.72) m^2/g, and (71.68 ± 2.31)%, respectively. These results indicate that wooden breasts influence the functional characteristics of their myofibrillar proteins, which significantly affects their solubility and emulsification[27]. Furthermore, the solubility of severe WBMPs decreases to (42.36 ± 1.39)%, while EAI and ESI decrease to (2.44 ± 0.11) m^2/g and (45.12 ± 0.69)%, respectively. Amphiphilic biopolymer (proteins) aggregates protect droplets from flocculation and aggregation via a combination of spatial and electrostatic repulsion interactions[28]. However, the quality of WBMPs decreases, resulting in the deterioration of the emulsifying activity and stability of the emulsion[27]. Furthermore, the emulsification performance indicated that the functional properties of WBMPs were significantly reduced, and their emulsification ability and other protein functional properties weakened[29]. These phenomena resulted in significant damage to the quality of the protein emulsion products, which significantly affects the reuse of WBMPs[25].

3.2 Construction of a hierarchical model

3.2.1 Indicator traits and distribution

Significant differences were noted in the quality of the wooden breast meats collected, based on traditional grading strategies and functional characteristics of the WBMPs, and degradation occurred regularly according to the grading. These methods can be accurately applied to wooden breasts; However, the selection of weight indicators by principal component analysis is an important step. Following data collection, the screening of useless indicators to build a model more efficiently is essential. Therefore, this study used the coefficient of variation as a reference to extract effective quality indicators. When calculating the coefficient of variations of different quality indicators among different varieties, the determination of key indicators after principal component analysis can provide a basis for judgement. If the coefficient of variation is too small, it is unsuitable as a representative indicator. As presented in Table 7, the coefficient of variation (CV) of the physicochemical properties of different grades of wooden breast and myofibril proteins were calculated and compared. Various indicators exhibited varying degrees of deviations in the different grades of wooden breast, among which the CV of protein functional

Table 5 Texture characteristics and water holding capacity (WHC) of different grades of wooden breast myofibrillar protein (WBMP) gel.

Classification	Gel hardness (g)	Gel springiness	Gel cohesion	WHC (%)
Normal (n = 20)	85.62 ± 2.11[a]	0.67 ± 0.13[a]	0.78 ± 0.11[a]	83.79 ± 1.74[a]
Mild (n = 30)	67.20 ± 4.42[b]	0.55 ± 0.12[b]	0.54 ± 0.02[b]	80.58 ± 3.24[b]
Moderate (n = 30)	55.23 ± 6.72[c]	0.45 ± 0.11[c]	0.35 ± 0.04[c]	75.62 ± 3.39[c]
Severe (n = 30)	41.98 ± 4.31[d]	0.31 ±0.07[d]	0.21 ± 0.02[d]	70.11 ± 1.52[d]

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

Table 6 Solubility, emulsion activity index, and emulsion stability index of myofibrillar protein from different grades of wooden breasts (n = 30).

Classification	Solubility (%)	EAI (m^2/g)	ESI (%)
Normal	72.15 ± 2.01[a]	8.23 ± 1.03[a]	88.74 ± 2.20[a]
Mild	61.36 ± 1.47[b]	6.35 ± 0.72[b]	71.68 ± 2.31[b]
Moderate	55.25 ± 1.45[c]	4.12 ± 0.21[c]	65.62 ± 1.22[c]
Severe	42.36 ± 1.39[d]	2.44 ± 0.11[d]	45.12 ± 0.69[d]

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

characteristics was generally greater than that of raw meat. Notably, the CV of b^*, cohesion, and chewiness of wooden breast were less than 10%, indicating that the degree of lignification has little influence on these characteristics of chicken breast meat.

Table 7 Coefficient of variation (CV) of protein soluble indexes of different grades of wooden breasts and myofibrillar protein.

Index	CV (%)	Index	CV (%)
Drip loss	30.71	Solubility	99.98
Cooking loss	14.45	Gel hardness	29.65
L^*	18.90	Gel springiness	30.83
a^*	33.18	Gel cohesion	52.55
b^*	7.21	Gel WHC	27.71
Shear force	15.92	EAI	47.94
pH	30.59	ESI	26.56
Hardness	39.2	Cohesion	2.79
Springiness	27.43	Chewiness	0.74

3.2.2 Index correlation analysis

The quality of the wooden breast meat affects the properties of its myofibrillar proteins; thus, there must be a positive or negative correlation between the two indicators. Furthermore, the correlation is an important basis for analyzing key indicators, owing to the sizes of, and differences in, the correlation. Table 8 shows that the drip loss of wooden breasts is negatively correlated with a^*, cohesion, solubility, gel WHC, and L^* and positively correlated with chewiness, cooking loss, pH, and hardness.

3.2.3 Principal component analysis

Generally, if the cumulative contribution rate of the principal component analysis results exceeds 80%, it can be used in the next step of the analysis[30]. The cumulative variance contribution rate of the first two principal components was 98.779%, reflecting the significance of the results. Based on the correlation analysis between different levels of wooden breast and the quality indicators, the final representative indicator of the corresponding principal component was selected from the representative wooden breast indicators with larger weights and CVs (Table 9). The contribution rate of the first principal component is 76.760% with representative indicators (Table 10), such as cooking loss, a^*, and pH. Furthermore, a^* was significantly negatively correlated with cooking loss and pH ($P < 0.01$), significantly positively correlated with solubility, gel springiness, gel WHC, and emulsification stability ($P < 0.01$), significantly positively correlated with L^*, b^*, springiness, cohesion, gel hardness, gel cohesion, and emulsification activity ($P < 0.05$), and significantly negatively correlated with dripping loss, shear force, hardness, and mastication ($P < 0.05$). Therefore, with a high CV of 33.18%, a^* was selected as the first representative indicator. The contribution rate of the second principal component was 22.019% with representative indicators, such as cooking loss, b^*, and pH. Among them, pH was significantly positively correlated with cooking loss and mastication ($P < 0.01$), significantly positively correlated with dripping loss, L^*, a^*, b^*, shear force, and hardness ($P < 0.05$), and significantly negatively correlated with springiness, cohesion, solubility, gel hardness, gel springiness, gel cohesion, gel WHC, emulsifying activity, and emulsifying stability ($P < 0.05$). Therefore, with a high coefficient of variation (30.59%), pH was selected as the second representative index. Therefore, the physicochemical indicators of the wooden breast were simplified to a^* and pH (P).

Table 8 Correlation between protein soluble quality indexes of different grades of wooden breast and myofibrillar protein.

	Drip loss	Cooking loss	L^*	a^*	b^*	Shear force	pH	Hardness	Springiness	Cohesion	Chewiness	Solubility	Gel hardness	Gel springiness	Gel cohesion	Gel WHC	EAI	ESI
Drip loss	1																	
Cooking loss	0.976*	1																
L^*	−0.999**	−0.967*	1															
a^*	−0.980*	−0.998**	0.974*	1														
b^*	−0.919	−0.974*	0.911	0.977*	1													
Shear force	0.921	0.983*	−0.907	−0.978*	−0.989*	1												
pH	0.989*	0.995*	−0.985*	−0.999**	−0.966*	−0.989*	1											
Hardness	0.961*	0.995**	−0.947	−0.986*	−0.958*	−0.978*	0.982*	1										
Springiness	−0.913	−0.979*	0.900	0.975*	0.993**	−0.907	−0.962*	−0.975*	1									
Cohesion	−0.956*	−0.976*	0.941	0.962*	0.909	0.983*	−0.962*	−0.990**	0.936	1								
Chewiness	0.998**	0.987*	−0.996**	−0.990**	−0.940	0.921	0.996**	0.973*	−0.935	−0.962*	1							
Solubility	−0.953*	0.989*	0.947	0.993**	0.995**	−0.987*	−0.987*	−0.974*	0.988*	0.935	−0.969*	1						
Gel hardness	−0.902	−0.968*	0.891	0.969*	0.998**	−0.956*	−0.956*	−0.957*	0.996**	0.908	−0.925	0.990*	1					
Gel springiness	−0.945	−0.991**	0.935	0.991**	0.998**	−0.982*	−0.982*	−0.982*	0.996**	0.947	0.962*	0.998**	0.993**	1				
Gel cohesion	−0.879	−0.958	0.866	0.956*	0.992**	−0.939	−0.939	−0.952*	0.996**	0.902	−0.905	0.979*	0.998**	0.987**	1			
Gel WHC	−0.954*	−0.996**	0.941	0.991*	0.979*	−0.984*	−0.984*	−0.996**	0.990**	0.975*	−0.969*	0.988*	0.978*	0.994**	0.974*	1		
EAI	-0.909	−0.978*	0.895	0.972*	0.988*	−0.958*	−0.958*	−0.978*	0.999**	0.942	−0.932	0.984*	0.993**	0.993**	0.995**	0.991**	1	
ESI	0.956*	−0.983*	0.953	0.991**	0.991**	−0.987*	−0.987*	−0.961*	0.977*	0.919	−0.970*	0.998**	0.982*	0.991**	0.969*	0.977*	0.971*	1

Note: ** Significant correlation at the 0.01 level; * Significant correlation at the 0.05 level.

Table 9 Principal component analysis array load factors of quality indexes of different grades of wooden breasts.

Index	Component 1	Component 2
Drip loss	0.701	0.789
Cooking loss	0.975	0.882
L^*	−0.564	−0.820
a^*	−0.912	−0.760
b^*	−0.614	−0.883
Shear force	0.716	0.803
pH	0.841	0.922
Hardness	−0.672	−0.736
Springiness	0.808	0.812
Cohesion	−0.678	−0.689
Chewiness	0.750	0.614

Table 10 Principal component analysis of quality indexes of different grades of wooden breasts.

Item	Component 1	Component 2
Eigenvalue	7.612	2.404
Contribution rate (%)	76.760	22.019
Cumulative variance contribution rate (%)	76.760	98.779

3.2.4 Determination of key indicator weights

Representing a linear combination of other indicators is effective when the collinearity relationship between indicators is strong. Therefore, the weight should be considered. The weighted coefficient method was used to objectively determine the weight of each indicator. A regression model analysis was performed on the a^* and pH (P) of normal chicken breast meat and different grades of wooden breast meat (mild, moderate, and severe). The weights of the key indicators of wooden breast meat quality for different grades were obtained, and the eigenvalues of a^* and pH were 7.612, and 2.404, respectively, with weight coefficients of 0.353 and 0.219, respectively. The results indicated that the weight of a^* was the highest, followed by pH. This result also indicates that, among the quality indicators of wooden breasts, a^* and pH significantly change due to changes in the grade of the wooden breasts. Moreover, they can represent the relationship between wooden breast quality indicators and WBMP functional characteristics. Therefore, this weight also includes the various coefficients of the comprehensive evaluation calculation formula. Further, the calculation formula for the comprehensive evaluation score (y) of different grades of wooden breast quality was obtained as $y = 0.353a^* + 0.219P$.

3.2.5 Comprehensive quality and sensory evaluation scores

The key indicators of wooden breasts were standardized, and the comprehensive quality evaluation scores of different grades of wooden breasts, based on the abovementioned comprehensive evaluation score formula, were calculated. Table 11 shows that, as the degree of wooden breast increases, its comprehensive quality evaluation score significantly decreases from the initial total score of 0.92 (normal chicken breast) to 0.28 (severe wooden breast). According to the range of the comprehensive quality evaluation score, normal chicken breast meat ranges from 0.8 to 1.0, mild wooden breast ranges from 0.6 to 0.8, moderate wooden breast ranges from 0.3 to 0.6, and severe wooden breast ranges from 0.0 to 0.3. Comparing the quality decline trend of different grades of wooden breast samples with these data demonstrates that the two indicators of a^* and pH can accurately represent the differences between different grades of wooden breast, and the quantification of the differences are more convenient for further model validation.

Table 11 Comprehensive quality evaluation scores of different grades of wooden breasts.

Classification	a^* Score	pH Score	Total score
Normal	0.57	0.35	0.92
Mild	0.46	0.31	0.77
Moderate	0.33	0.22	0.55
Severe	0.13	0.15	0.28

To verify the accuracy and practicality of the model, 12 evaluators involved in meat product research performed sensory evaluations on different grades of wooden breasts. According to the sensory evaluation results listed in Table 12, the appearance and hardness scores of mild wooden breast meats begin to decrease, with the total score decreasing from 90.33 ± 1.53 (normal breast meat) to 68.34 ± 3.00. Subsequently, the decline in quality was not significant, particularly manifesting as a dark and yellow color, small number of bleeding points and connective tissue, and slight changes in the head and near the tail of the breast. Few negative evaluations were from consumers regarding mild wooden breast meats. Moderate wooden breast meats are characterized by the presence of bleeding and infiltration on the chicken breast surface. The entire breast exhibits hard characteristics, however, springiness occurs from the middle of the breast to the tail. Moderate wooden breast meats obtained a total score of 50.66 ± 2.08, which was significantly lower than the normal breast meat score. The color and hardness scores of the severe wooden breast meats significantly decreased. Compared to that of moderate wooden breasts, the surface of severe wooden breast meats is accompanied by bleeding and infiltration, and the entire breast is hard. The total score was 26.00 ± 3.06, indicating that the meat is no longer acceptable to consumers.

Table 12 Sensory evaluation of different grades of wooden breasts.

Classification	Appearance	Hardness	Total score
Normal	45.33 ± 1.15^a	45.00 ± 0.00^a	90.33 ± 1.53^a
Mild	33.67 ± 0.58^b	34.67 ± 1.15^b	68.34 ± 3.00^b
Moderate	25.33 ± 0.58^c	25.33 ± 1.15^c	50.66 ± 2.08^c
Severe	13.67 ± 0.58^d	12.33 ± 0.58^d	26.00 ± 3.06^d

Note: Significant differences are noted between letters in the same column ($P < 0.05$).

3.2.6 Verification of hierarchical models

Linear regression was used as the correlation analysis between the sensory and comprehensive quality evaluation scores of different grades of wooden breasts to verify the applicability of the established wooden breast grading models. R^2 is the judgment coefficient, and the value range of R^2 is 0–1. When R^2 is greater than 0.75, the fit of the model is good and has a high degree of interpretability. When R^2 is less than 0.5, the model fitting is poor and should not be used for regression analysis. First, the sensory evaluation results of different levels of wooden breast tissue were standardized, with the sensory evaluation scores on the vertical axis and comprehensive quality evaluation scores on the horizontal axis. Using verification, the equation was y = 2.407 1x + 0.034 3 (R^2 = 0.988 3), with R^2 > 0.8. This result indicates that the sensory evaluation scores can be accurately predicted, and the quality differences of different grades of wooden breasts can be effectively reflected. Thus, the usefulness of the different wooden breast grading models was verified. Using a^* and pH as the main weight indicators to determine the grade of wooden breasts have improved the accuracy compared to that of traditional manual grading. In addition, this method has greatly increased the convenience and reduced the cost of grading compared to that of currently unpopular and complex machine recognition techniques.

4 Conclusion

Compared to that of normal chicken breast meats, the quality of chicken wooden breast meats significantly declined in the increasing order of mild, moderate, and severe. The functional properties of the WBMPs were also affected, and their physicochemical and functional properties (gel and emulsifying properties) were sharply reduced. Hence, the qualities of the gel and emulsion formed by WBMPs were poorer, and water retention, textural properties, and emulsifying properties were severely reduced. In comparing and analyzing the quality indicators of different grades of wooden breast and their WBMPs, two key quality indicators were selected for the construction of the model: a^* and pH (P). A comprehensive evaluation model for the quality of different levels of wooden breasts was then obtained as follows: $y = 0.353a^* + 0.219P$. Using verification, the equation was y = 2.407 1x + 0.034 3 (R^2 = 0.988 3), with a fitting coefficient > 0.8. This result indicates that the presented method can accurately predict the sensory evaluation scores and effectively reflect the quality differences of different grades of wooden breasts. The selection of mild, moderate, and severe levels of wooden breast tissue via a grading model can help achieve rapid detection and grading in combination with new equipment.

Conflict of interest

The authors declare no conflict of interest.

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