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Research Article

Deep-learning classification of chicken woody breast based on bioelectrical impedance characteristics

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Abstract: As a serious threat to the broiler industry, woody breast (WB) requires precise classification that is theoretically aligned with the advantage of bioelectrical impedance detection. This research used normal chicken breast (NORM) and three levels of WB condition, namely, mild, moderate and severe (SEV), based on sensory evaluation. The basic objective quality indicators and impedance characteristics of the samples were detected, and then the various levels of WB were categorized by model-classification approach. At a consistent frequency, the impedance amplitude of samples decreased with increased WB level. Significant differences in the absolute value of the phase angle existed among different levels of WB. The increase in WB level led to a considerable increase in intracellular resistance (R_i) and in the characteristic frequency (f_c). However, four other indices including the radius of Cole-Cole curve arc, the extracellular resistance (R_e), the polarization coefficient (K), and the relaxation factor (α) substantially dropped with increased WB level. The accuracy of SEV training, NORM and SEV test samples achieved a perfect score of 100% according to the partial least squares (PLS) prediction model. The PLS model also exhibited an overall accuracy of 91.70% for training samples compared with the value of 88.35% from limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) deep-learning prediction model. However, the L-BFGS model achieved a higher overall correct rate for test samples (90.00%) than PLS model (80.00%). These results provided valuable information for the classification of WB based on the characteristics of bioelectrical impedance.

Keywords: woody breast; bioelectrical impedance; partial least squares; limited-memory Broyden-Fletcher-Goldfarb-Shanno; discriminant classification

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1 Introduction

The production and consumption of broilers are increasing because of advancements in poultry feeding management and genetic-breeding techniques. Nevertheless, the occurrence of chicken breast meat abnormalities is also rising with the increase in growth rate, yield, and breast size of broilers. This poses a serious threat to the broiler industry[1]. According to the study of Malila et al.[2], the occurrence of severely abnormal chicken breast meat rises by 61.0% for every 1% rise in broiler pectoral-muscle weight based on logistic-regression analysis. Woody breast (WB) is a chicken-breast defect receiving widespread attention in the industry. WB is characterized by an increase in hardness and thickness, with distinct ridges observed on the tail of the chicken breast[3–4]. According to a previous study by Wang et al.[5], the properties of WB myofibrillar proteins, such as solubility, emulsification, and gelation, were significantly deteriorated compared to healthy control[6]. Sihvo et al.[7] revealed that the incidence of WB under commercial conditions is as high as 48% to 73%. Xing et al.[8] found that the incidence of WB in broiler producers in China has reached 61.9%. Thus, if the broiler market continues to prioritize achieving high slaughter weight and meat yield, the prevalence and occurrence of WB may rise.

Contrary to the sensory characteristics of normal meat, the surface of WB may appear pale in color and have mucus present. In more severe cases, apparent blood seepage may occur, which can significantly reduce consumer willingness to purchase[9–11]. Certain consumers may also assess the tenderness of chicken breast by tactile perception and refrain from buying meat that is tough, which is considered as an important texture feature of WB. Simultaneously, WB myopathy significantly impacts the nutritional composition of chicken meat. This is primarily demonstrated by a rise in moisture, collagen, and fat content, along with a decline in crude protein content[12–15], resulting in a loss of nutritional value. Chickens with WB tissue exhibit also reportedly reduced water retention and lower marinade absorption during processing[16–18]. These adverse processing characteristics can also negatively impact on consumer-purchasing decisions. Processing enterprises often engage in the sale of WB at a reduced price or utilize it as a raw material for the processing of by-product, such as minced meat. Overall, WB significantly impacts the sensory attributes, nutritional value, and processing properties of chicken breast. It also diminishes consumer interest in purchasing and has a detrimental impact on the economic performance of broiler producers[19].

Given the threat that WB poses to the meat industry, classifying it correctly is crucial. The common method for WB identification and grading is manual palpation[20]. However, this approach has the drawbacks of low efficiency in determining quality and limited promotion. Bioelectrical impedance, as a detection method that relies on the movement of electrons to generate electrical signals, can be used for meat-quality monitoring and has yielded specific application outcomes[21–23]. Bioelectrical impedance measurement is a method that extracts biomedical information about an organism's physiological and pathological circumstances. It relies on the electrical properties of biological tissues and organs, as well as their changes[24]. The test samples are stimulated with delicate alternating current (or voltage) signals by applying driving electrodes on the surface of the biological tissues. The voltage or current signals are acquired by the measuring electrodes, and the related impedance is determined by analyzing the observed signals. The impedance of biological tissues is used to examine physiological and pathological information. Bioelectrical impedance testing technique has been applied to meat-quality analysis and other aspects owing to their advantages of simple instrumentation, convenient operation, and fast detection. By detecting the impedance and phase angle of beef tissues at different curing times during the diffusion of NaCl when curing beef. Zhao et al.[25] discovered a strong correlation ($R^2 > 0.98$) between the NaCl content in beef and the impedance value by measuring the impedance and phase angle of beef tissues at various curing times during the diffusion of NaCl. Sun et al.[26] utilized chemometrics and impedance properties to develop a comprehensive multi-quality index for Atlantic salmon. All three models have achieved a 100% accuracy in distinguishing Atlantic salmon from rainbow trout and differentiating chilled salmon from frozen-thawed salmon. Prior research has indicated that bioelectrical impedance can identify muscle degradation caused by aberrant muscle growth disorders in chicken breast meat[27]. However, further research is required to thoroughly understand how to differentiate between normal (NORM) chicken breast and mild (MILD), moderate (MOD), and severe (SEV) WB.

In general, the bioelectrical impedance properties of biological tissues can provide information about the nature of muscle tissue. The bioelectrical impedance approach has been used to analyze meat quality due to its advantage of simple instrumentation, convenient operation, and fast detection. However, comprehensive investigations into the application of equivalent circuits and the derivation of equivalent characteristic parameters are lacking. In the present study, high-accuracy method of classifying WB was established through partial least squares (PLS) and limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) deep-learning prediction model based on the impedance eigenvalues.

2 Materials and methods

2.1 Test materials

The sample was provided by Jiangsu Yike Food Group Co., Ltd. The chicken breast meat (*pectoralis major*) used in this study was obtained from 45-day-old white-feathered broilers that were slaughtered following standard procedures (NY/T 1174–2006). The slaughtering procedures involved the following steps: electric shock, bloodletting, hair removal, cutting, pre-cooling at 0–4 °C for 40 min, and segmentation. Segmented chicken breast was packaged in a water-resistant bag and transported immediately into the laboratory at 0–4 °C.

2.2 Classification of WB by sensory evaluation

The grading method of Sun et al.[28] was used with some modifications (Table 1). Excluding NORM, we classified chicken breast with different levels of myopathy to three degrees, namely, MILD, MOD, and SEV. A professionally trained sensory evaluation group of 16 persons was selected on the basis of gender[4]. The room temperature was maintained at 25 °C and the sensory evaluation criteria were shown in Table 1. For each WB level, 20 test samples were chosen to carry out following studies.

Table 1 Classification standard for woody breast (WB).

WB level	Description
Normal (NORM)	NORM breast is smooth and soft to the touch, with both ends sagging naturally when held in the hand
Mild (MILD)	MILD WB is soft on the whole, with a slight hardness and touch on the head
Moderate (MOD)	MOD WB can feel hardness tactility whole, but the hardness is mainly concentrated in the chicken head, tail there is a certain degree of bump, but carry in the hands of chicken breast is having some sense of prolapse
Severe (SEV)	SEV WB hardness rose obviously, from head to tail have a hard touch, specially the tail visible to the naked eye apars obvious uplift, carry in the hands without hanging feeling; the surface of chicken breast showed lignin-like texture and sticky secretions, and in some cases even oozing blood

2.3 Basic indicators measurement

2.3.1 Weight and characteristic dimensions

According to the method of Sun et al.[28], the weight (g) and characteristic dimensions of chicken breast samples were measured, including length (L, mm), width (W, mm), top thickness (H_1, mm) and bottom thickness (H_2, mm). L refers to the maximum distance between the top and bottom of the chicken breast, W refers to the maximum distance between the left and right end of the chicken breast, H_1 denotes the thickness at the top of the head of the chicken breast, and H_2 represents the thickness at a distance of 3 cm from the bottom of the chicken breast, as shown in Figure 1. The mean of each chicken breast sample was measured for three times, and the characteristic size of each WB level was the average of 20 samples.

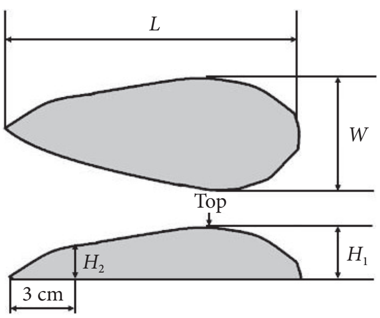

Figure 1 Schematic diagram of sample three-dimensional measurement.

2.3.2 Color

Referring to the method of Zhao et al.[29] with slight modifications, the connective tissue on the surface of the sample was removed before measurement. Three measuring points on the bone side of the chicken breast sample were selected to measure brightness (L^*), redness (a^*) and yellowness (b^*) values with chromatism meter (CR400, Konica Minolta Co., Tokyo, Japan). The mean of each chicken breast sample was taken for three times, and the meat color of each WB level was determined by calculating the average of 20 samples.

2.3.3 pH

Three measuring points with 1–2 cm intervals were selected in the front part of the chicken breast sample near the wing root. The measuring electrode of a pH meter (Testo 205, Testo AG, Lenzkirch, Germany) was inserted into the chicken breast sample for measurement about 2 cm deep. The pH of each chicken breast sample was the average of three measurements. The pH of each WB level was determined by calculating the average of 20 samples.

2.3.4 Cooking loss (CL)

Referring to the measurement method of Barbanti et al.[30] with some modifications, each chicken breast was cut into 2 pieces of 2 cm × 2 cm × 4 cm with a mass of (20 ± 2) g. The mass of the chicken breast sample (m_1) was weighed and recorded before cooking. All breasts were wrapped in individual plastic bags to cook until the center temperature of the cranial area reached 70 °C in a 75 °C water bath. After the samples were cooled, they were weighed again and the mass m_2 of the chicken breast sample was recorded. The sampling site of each chicken breast was the same. The CL of each chicken breast sample was the average of its two pieces, and the CL of each WB level was the average of 20 pieces. The CL was calculated as follows:

$$\text{CL}\ (\%) = \frac{m_1 - m_2}{m_1} \times 100$$

2.3.5 Warner-Bratzler shear force

Following the measurement of CL, the cooked breasts were cut into five meat strips (3 cm × 1 cm × 1 cm) parallel to the muscle fibers. The meat strips were cut off for three times by using a tenderization analyzer (C-LM3B, Northeast Agricultural University, Harbin, China) to obtain shear force data. Shear force was measured three times, and the average was taken as the shear force of each piece of meat. The tenderness of each WB level was the average value of 20 samples.

2.3.6 Texture profile analysis (TPA)

Whole chicken breast sample was taken and subjected to TPA with a texture analyzer (TA.XT Plus, Stable Micro Systems Ltd., Godalming, UK). Parameters were set as follows: speed before test, 3 mm/s; test speed, 2 mm/s; speed after test, 3 mm/s; shape variable, 50%; time interval between two presses, 5 s; trigger force, 5 g; and probe type, P50. Through the TPA test, numbers of physical properties of the samples including hardness, springiness, cohesiveness, resilience, and gumminess were obtained.

2.4 Impedance measurement

Impedance eigenvalues, including impedance amplitude and phase angle, were measured based on the method of Damez et al.[31] with a LCR electric bridge (AT2827-1, Applent Electricity Technology Co., Ltd., Changzhou, China). The external part consisted of two rows of six copper needles (diameter = 2 mm), which were twined by copper wires. The distance between the rows was 3 cm, and that between the pins in the same row was 1 cm. The direction of test current was perpendicular to the muscle-fiber direction of the chicken breast sample, and the measurement position was selected as the front and exterior of the chicken breast sample. A total of 15 frequency points ranging from 0.06 to 200 kHz were chosen, with frequencies of 0.06, 0.08, 0.1, 0.12, 0.15, 0.2, 0.25, 0.4, 0.8, 1.5, 5, 15, 50, 100, and 200 kHz. The impedance characteristic value of each chicken breast sample was determined by conducting six tests and calculating the average value of the measurements. The impedance characteristic value of each WB level at each frequency point was calculated as the mean of 20 samples.

2.5 Data processing

Matlab R2016b software (MathWorks, USA) was used to fit the equivalent characteristic parameters of bioelectrical impedance of chicken breast samples. Classification by nonlinear least squares was conducted. The deep-learning classification of chicken WB was also adopted using L-BFGS algorithm. Data normalization with min-max scaler was performed to stabilize our training process. We used a network with two hidden layers. The hidden-layer size of the neural network was set to 64 and 32. The model was trained with Pytorch[32], one of the most extensively used deep-learning framework. ANOVA in SPSS 25.0 software (IBM Co., USA) was used to test the significance of the data based on Duncan's multiple comparative analysis. Results are expressed as the mean ± standard deviation. A P value of < 0.05 was considered statistically significant. Origin Pro 2021 software was used for visualization.

3 Results and discussion

3.1 Weight and characteristic size of different levels of WB

Table 2 demonstrates that weight rose significantly (P < 0.05) with increased myopathy level. The effect of myopathy on chicken breast length was not clearly visible because no significant difference in L for chicken breast length existed across all groups (P > 0.05). The W, H_2, and H_1 of chicken breast increased with increased WB level, and the W, H_2, and H_1 of SEV were significantly higher than those of NORM (P < 0.05). This finding indicated that the occurrence of WB in chicken may be an important factor leading to the abnormal increase in top thickness.

Using logistic regression, Bordignon et al.[33] discovered that WB occurrence was associated with breast weight. Zotte et al.[10] also proposed that the occurrence of WB is closely related to the

Table 2 Measurement results of weight and characteristic size of different levels of woody breast (WB).

WB level	Weight (g)	L (mm)	W (mm)	H_1 (mm)	H_2 (mm)
NORM	204.41 ± 26.89^{D}	155.90 ± 5.49^{A}	85.58 ± 5.17^{B}	36.54 ± 7.05^{C}	19.99 ± 2.38^{B}
MILD	266.18 ± 32.84^{C}	158.55 ± 8.17^{A}	87.92 ± 5.57^{AB}	39.05 ± 3.15^{BC}	20.45 ± 2.70^{AB}
MOD	290.82 ± 25.69^{B}	158.61 ± 9.30^{A}	88.70 ± 4.54^{AB}	40.39 ± 2.54^{AB}	22.11 ± 5.08^{AB}
SEV	320.27 ± 31.59^{A}	155.70 ± 7.09^{A}	89.36 ± 5.51^{A}	42.44 ± 3.32^{A}	22.38 ± 2.85^{A}

Note: Different superscript letters in the same column indicate significant differences (P < 0.05).

increase in the weight of chicken breast. According to the study of Sun et al.[28], a significant correlation exists between the thickness of chicken breast and the WB level, i.e., the top and bottom thicknesses rise significantly with increased WB level. In line with our study, Mudalal et al.[17] found that the weight and top thickness of WB increase significantly compared with those of NORM. Nevertheless, using weight or thickness alone to assess chicken breast is insufficient due to the inhomogeneity of WB muscle[34].

3.2 Color, pH, CL and shear force of different levels of WB

The most logical way for people to assess the meat quality and freshness is by its color. Table 3 shows that the L^* value of WB was significantly higher than the NORM (P < 0.05), and the L^* value increased significantly with increased level (P < 0.05). The a^* value of WB was significantly higher than the NORM (P < 0.05), and the a^* value of WB except the SEV group showed an overall upward trend with the increased level. The b^* value of WB was significantly higher than NORM (P < 0.05), but no significant difference in b^* value existed among different levels of WB (P > 0.05). Cai et al.[13] also discovered that the pH, L^*, a^*, b^*, and CL of WB increased. Similarly, as stated by Tijare et al.[20], WB exhibited increased hardness, lighter color, and higher pH and CL than NORM.

Pan et al.[35] found that the L^* and b^* values of WB were significantly higher than those of NORM, which was consistent with the findings in this experiment. WB causes the transformation of non-liquid water into free water within the chicken breast, which raises surface exudate and light reflection and gives the breast its pale color[29]. Muscle fibers may be type I (slow twitch-red) or type II (fast-twitch-white). Myoglobin primarily exists in type I fiber. NORM muscle fiber is almost entirely composed of type II fiber. We hypothesized that type II fiber cell death, type I fiber regeneration, and the overexpression of the myoglobin gene may occur throughout a myopathy process[36–37]. Thus, with increased WB myoglobin concentration, a^* value was higher than that of a typical chicken breast[38–39]. Griffin et al.[38] found that broiler chickens are severely woody at 30 days of age, with a large number of white stripes covering their surfaces and pale flesh. This finding may explain the significantly lower a^* value of the SEV group than MOD in this study. Compared with the NORM group, the b^* value of the WB increased significantly (P < 0.05), which may be related to the light yellow viscous exudate on the muscle surface[1]. Zhuang et al.[39] noted that the skin side of the breast muscle is more affected by myopathy than the bone side, indicating the impracticality of determining WB in chicken through color.

As shown in Table 3, the pH values of MOD and SEV were significantly higher than those of NORM (P < 0.05). The pH of WB is reportedly significantly higher than that of NORM[40–41]. Livingston et al.[42] also proposed that pH increases gradually with increased WB level. The oxidative stress of WB[40] also leads to increased muscle-glycogen consumption. Meanwhile, the gluconeogenesis and glycolysis pathways of WB are down-regulated[43]. The above factors may jointly cause the increase in terminal pH of WB, but some studies suggest that no significant difference in pH exists between WB and NORM[38]. Some studies have found that the pH of the tail of ipsilateral chicken breast is lower than that of the head[44], so different measurement sites may lead to varied results. Although the pH of WB was higher, it remained within the normal range. Therefore, different levels of WB cannot be determined based on pH values.

Water retention is one of the most important indices of meat quality evaluation. It is closely related to the economic benefit of enterprises and the acceptance degree of consumers[45]. SEV had the largest CL and the lowest water retention. The occurrence of myopathy also makes chicken breast lose moisture more easily during cooking, greatly affecting its edible quality. The water retention of meat directly affects its mouthfeel, taste, nutrition, and color, which are common basic indices for meat quality evaluation. Relevant studies have shown that the CL of chicken breast increases significantly with increased WB level[17,20], consistent with our results. Soglia et al.[46] observed that severely WB had elevated levels of CL, elasticity, and cohesiveness. Myopathy disrupts the integrity of the muscle cell membrane, alters the shape of the muscle fiber, moves water from the muscle-fiber interior to the myofibrillary-network exterior, thereby worsening water loss. Consequently, a higher level of water binding in chicken breast leads to a greater extent of water retention. Sihvo et al.[45] conducted histological examination and discovered that WB muscle fibers undergo degradation and necrosis. Intermuscular adipose tissue continues to accumulate, fat content increases with increased hydrophobicity, and the muscle's ability to retain water is further impaired.

The observed shear force of WB in this test was significantly lower than that of NORM (P < 0.05). It also generally exhibited a decreasing pattern with increased WB level, consistent with the findings of Brambila et al.[44]. The unequal distribution of connective tissue and intramuscular fat in WB, along with thermal instability, resulted in decreased shear force[46]. Nevertheless, the shear force of WB reportedly does not exhibit a significant change when compared with regular chicken breast. We hypothesized that the selection of chicken breast samples may have an affected test outcomes.

3.3 Texture characteristics of different levels of WB

Table 4 clearly demonstrates that the hardness of WB considerably exceeded that of NORM (P < 0.05), and it grew with increased WB level. This can be attributed to the excessive growth of connective tissue in WB[47]. No statistically significant variations in springiness and cohesiveness were observed between NORM and different levels of WB (P > 0.05). The resistance of chicken breast flesh exhibited a positive correlation with increased in WB level, with MOD and SEV values being significantly greater than NORM (P < 0.05). The gumminess of WB was substantially higher than that of NORM (P < 0.05).

Table 3 Color, pH, CL, and shear force results of different levels of woody breast (WB).

WB level	L^*	a^*	b^*	pH	CL (%)	Shear force (N)
NORM	51.19 ± 1.72^{C}	0.28 ± 0.29^{C}	1.14 ± 1.48^{B}	5.87 ± 0.12^{B}	12.59 ± 1.65^{C}	38.00 ± 4.48^{A}
MILD	53.85 ± 2.19^{B}	0.37 ± 0.59^{B}	3.99 ± 0.86^{A}	5.94 ± 0.13^{AB}	13.80 ± 2.33^{BC}	20.73 ± 2.15^{C}
MOD	56.53 ± 2.23^{A}	0.90 ± 0.47^{A}	3.91 ± 1.32^{A}	5.99 ± 0.11^{A}	14.45 ± 1.63^{B}	24.43 ± 1.55^{B}
SEV	57.74 ± 2.32^{A}	0.35 ± 0.55^{B}	4.23 ± 1.52^{A}	5.98 ± 0.15^{A}	22.51 ± 2.45^{A}	21.59 ± 0.96^{C}

Note: Different superscript letters in the same column indicate significant differences (P < 0.05).

Table 4 Measurement results of texture characteristics of different levels of woody breast (WB).

WB level	Hardness (g)	Springiness (cm)	Cohesiveness	Resilience	Gumminess (g·s)
NORM	2 336.67 ± 981.58^{C}	0.77 ± 0.07^{A}	0.67 ± 0.04^{A}	0.36 ± 0.05^{C}	1 629.86 ± 744.27^{B}
MILD	3 133.52 ± 985.38^{B}	0.73 ± 0.07^{A}	0.66 ± 0.06^{A}	0.38 ± 0.04^{BC}	2 256.30 ± 1 033.49^{A}
MOD	3 517.11 ± 1 094.60^{AB}	0.73 ± 0.05^{A}	0.66 ± 0.05^{A}	0.40 ± 0.05^{AB}	2 396.54 ± 833.82^{A}
SEV	3 922.04 ± 1 052.56^{A}	0.76 ± 0.04^{A}	0.66 ± 0.03^{A}	0.42 ± 0.04^{A}	2 587.66 ± 596.62^{A}

Note: Different superscript letters in the same column indicate significant differences ($P < 0.05$).

Previous studies have found that the hardness of WB is much greater than that of NORM[41,48], consistent with our own findings. Chicken breast hardness is greatly enhanced by the presence of myopathy, which can be attributed to connective-tissue hyperplasia[49]. Nevertheless, some studies indicate that no substantial disparity in hardness exists between WB and regular chicken breast. The observed variations in the results may be attributed to the distinct textural properties of the skin side and bone side of breast muscle, as stated in literature[44]. Disparities among sampling sites may account for such discrepancies. Mudalal et al.[17] and Chatterjee et al.[47] discovered that the presence of WB may not have a substantial impact on the elasticity and stickiness of chicken breast, consistent with our findings. The viscosity of WB markedly exceeds that of regular chicken breast potentially due to the elevated intramuscular fat content[42].

3.4 Impedance characteristics and classification of chicken WB

3.4.1 Amplitude of different levels of WB

The impedance amplitudes of different levels of WB are shown in Figure 2. The impedance amplitudes of NORM and different levels of WB decreased with increased frequency. The impedance amplitude of chicken breast decreased with increased WB level, which may be due to the destruction of tissue structure and cell membrane of muscle during the defective condition of chicken breast. Thus, the electrical conductivity was enhanced and the cell-membrane resistance and capacitance were reduced. The impedance amplitudes of NORM and different levels of WB tended to be consistent at high frequencies. When the electric-field frequency was high, the current can directly penetrate the cell membrane and flow through the whole biological tissue, thereby reflecting the overall electrical conductivity of biological tissue[49].

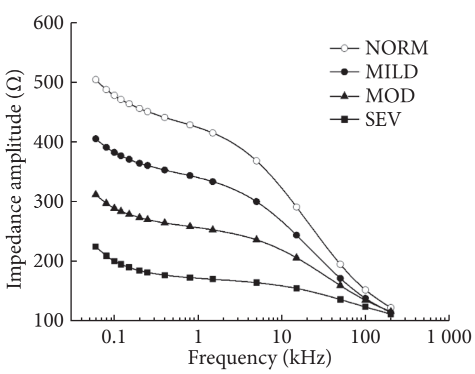

Figure 2 Amplitude-frequency curve of different levels of woody breast (WB).

The impedance properties of various levels of WB were analyzed. Within the frequency range of 0.06–200 kHz, the amplitude of impedance in NORM was consistently larger than that of WB, except at 200 kHz at which the difference was not significant. With increased WB degree, the impedance amplitude of chicken breast in the middle- and low-frequency bands dramatically decreased. This observation indicated that myopathy reduced the muscular tissue's ability to withstand electrical current. Degeneration, necrosis, fibrosis, and other lesions in the WB tissue damaged the structure of the cell membrane, leading to decreased in the resistance and capacitance characteristics of the cell membrane. Conversely, the intracellular fluid exited and combined with the tissue fluid to create electrolyte solutions that possessed enhanced conductivity. With increased severity of the WB degree, damage to the tissue structure increased and impedance underwent a higher decrease. These alterations can be considered a significant foundation for WB categorization. Compared with regular chicken breast, the muscular tissue of WB decreased, whereas the fat tissue increased[49]. Muscle tissue had significant levels of moisture and electrolytes, resulting in robust electric conductivity. By contrast, adipose tissue had low water and electrolyte content, leading to poor electrical conductivity. In theory, a lower proportion of muscular tissue and a higher proportion of adipose tissue result in a higher bioelectrical impedance of the whole body. Thus, alterations in the tissue structure and tissue composition of WB had a collective impact on its bioelectrical impedance characteristics. The influence of damaged cell membrane on impedance was found to be more significant than that of reduced muscle tissue and increased adipose tissue. However, further investigations are required to determine the specific underlying causes.

3.4.2 Phase angle of different levels of WB

In addition to impedance amplitudes, phase angle is a significant parameter that indicates the bioelectrical impedance properties of components in an AC electric field. Phase angle is a measure of the relationship between the cell interior and exterior, as well as the cell-membrane stability. It is frequently used in medical research to evaluate the integrity of the cell membrane and the distribution of water inside and outside the cell. With increased phase angle, cellular function increased in robustness and nutritional status improved. Figure 3 displays the phase angles of different levels of WB. The absolute value of phase angle initially decreased and then increased before finally decreasing again when the test frequency increased within the range of 0.06–200 kHz. The minimum absolute value of the phase angle occurred at nearly 5 kHz. In the high-frequency region, the phase angle of NORM, MILD, and MOD exhibited a consistent drop, whereas the phase angle of SEV remained rather stable. In the medium- and high-frequency range (1.5–200.0 kHz), the magnitude of the phase angle of NORM was substantially greater than that of WB. Significant differences in the magnitude of the phase angle existed across different levels of WB. The tissue structure of NORM was relatively intact, and the cell-membrane capacitance was basically constant when the electric-field frequency was high. Thus, a certain phase angle always existed between current and voltage. However, serious lesions in WB muscle tissue especially SEV destroyed the cell-membrane structure, which increased its overall conductivity. Therefore, the absolute phase angle of WB at high frequency tended to be stable and significantly lower than that of NORM with increased frequency. The phase-angle data at middle and high frequencies were useful for differentiating NORM from different levels of WB.

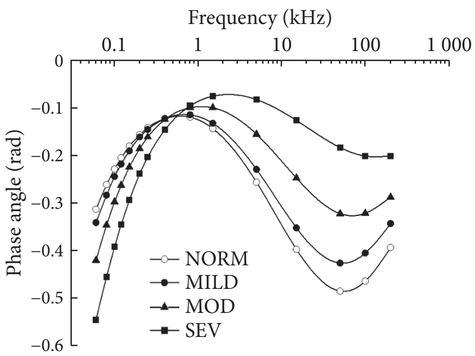

Figure 3 Phase frequency curves of different levels of woody breast (WB).

3.4.3 Complex bioelectrical impedance curves of different levels of WB

Muscle impedance is a complex number usually described by the Cole–Cole impedance equation, i.e., $Z = R_\infty + (R_0 - R_\infty)/[1 + (j\omega\tau)^\alpha]$, where Z is the muscle bioelectrical impedance (Ω); R_0 is the bioelectrical impedance (Ω) at frequency 0; R_∞ is the bioelectrical impedance (Ω) at infinite frequency; j is the complex operator; ω is the angular frequency (rad/s); and τ is a time constant. The plot corresponding with the impedance value is the complex bioelectrical impedance curve (Cole–Cole curve), whose abscissa is the real part of impedance and the ordinate is the imaginary part of impedance. This curve can reflect the life state of muscle tissue to a certain extent. Figure 4 displays Cole–Cole curves for various levels of WB. Specifically, Figure 4a exhibits Cole–Cole curves for different levels of WB across the entire frequency range of 0.06–200 kHz. Figure 4a shows that the Cole–Cole curve of the chicken breast sample was composed of two sections. The right was a straight line, representing the complex impedance at a lower frequency; the left was a semi-ellipse, representing the complex impedance at medium and high frequencies. These impedance characteristics were consistent with those typically observed in biological tissues. Figure 4b depicts the Cole–Cole curve for the frequency range of 1.5–200 kHz, specifically focusing on the intermediate and high frequency bands. Figure 4b demonstrates a notable drop in the real and imaginary impedance components of chicken breast samples in each group at a low frequency. Conversely, minimal alterations were observed at a high frequency. Within the same frequency range, the decrease in NORM was greater than that of WB. The semi-elliptic curve of chicken breast gradually decreased in size with increased WB level. This was due to the destruction of the cell membrane in the muscle tissue of WB, which weakened its capacity-resistance property and significantly reduced the impedance value of the muscle tissue. These findings revealed that monitoring the bioelectrical impedance characteristics of chicken breast meat can facilitate the real-time evaluation and categorization of WB.

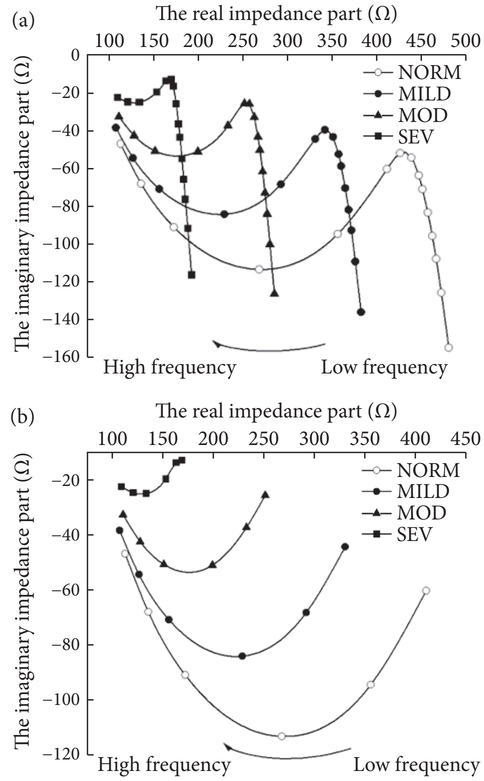

Figure 4 Complex bioelectrical impedance curves of different levels of woody breast (WB). (a) Cole-Cole curves of different levels of WB in full frequency band; (b) Cole-Cole curves of different levels of WB at medium and high frequencies.

3.4.4 Impedance equivalent parameters of different levels of WB

The polarization phenomenon of the electrode itself can occur at low frequencies, causing polarization resistance unrelated to the cell structure. This can result in a relatively substantial fitting error of impedance equivalent parameters. Thus, impedance within the frequency range of 1.5–200 kHz was chosen for parameter fitting in this part. Table 5 displays the impedance parameters equivalent to various levels of WB. The intracellular resistance (R_i) is an indicator of the conductivity of the fluid inside the cell. With increased intensity of intracellular ions, the R_i decreased, resulting in a smaller cell impedance and higher conductivity. A positive correlation existed between the R_i of chicken breast and the WB level, and a statistically significant difference was observed between the groups ($P < 0.05$). The extracellular resistance (R_e) can be utilized as a means to quantify the conductivity of the extracellular fluid. With increased intensity of extracellular ions, the R_e decreased, resulting in decreased cell impedance and increased conductivity. The R_e of chicken breast decreased with increased degree of WB, and the difference between groups was statistically significant ($P < 0.05$). The membrane capacitance (C_m) served as an indicator of the cell membrane's integrity. A higher value of C_m suggested a stronger integrity of the cell membrane. In the case of WB, the C_m of MILD and MOD was notably greater than that of SEV, with a statistically significant difference ($P < 0.05$). The relaxation factor (α) is indicative of the dimensions and structure of macromolecules in biological systems. Herein, the α of chicken breast significantly decreased with increased WB level ($P < 0.05$). This suggested that myopathy had a major impact on the size and spatial structure of macromolecules in muscular tissues. The characteristic frequency, denoted as f_c, is the frequency at which the imaginary part of the impedance reaches its maximum value. This characteristic frequency is present in all biological tissues. Table 5 shows that the

Table 5 Calculation results of impedance equivalent parameters of different levels of woody breast (WB).

WB level	R_i (Ω)	R_e (Ω)	C_m (pF)	α	f_c (kHz)	K
NORM	94.85 ± 10.43^C	457.46 ± 74.83^A	79.20 ± 7.98^B	0.69 ± 0.01^A	36.98 ± 2.23^C	4.14 ± 0.51^A
MILD	97.58 ± 10.43^C	366.30 ± 32.41^B	87.61 ± 6.92^A	0.67 ± 0.01^B	39.43 ± 1.21^C	3.56 ± 0.18^B
MOD	113.36 ± 15.84^B	272.03 ± 37.09^C	88.03 ± 8.36^A	0.64 ± 0.02^C	47.53 ± 4.86^B	2.71 ± 0.33^C
SEV	134.60 ± 25.26^A	180.42 ± 14.95^D	81.01 ± 12.04^B	0.58 ± 0.03^D	63.68 ± 8.16^A	2.02 ± 0.11^D

Note: Different superscript letters in the same column indicate significant differences (P <0.05).

f_c of WB was significantly greater than NORM (P < 0.05), and it increased significantly with increased WB level (P < 0.05). Analyzing Figure 3 in conjunction with the data revealed that with increased WB level, the frequency point shifted toward the right when the imaginary component of impedance reached its maximum, and it shifted noticeably toward higher frequencies. The polarization coefficient (K) was indicative of cellular vitality. During the process of cell death, the ability to polarize was diminished, resulting in a commensurate decrease in K. The reduction from the highest value to the value of 1 indicated the full destruction of the dielectric structure of biological tissues. The K of NORM was the highest. With increased degree, K dropped with significant variations among groups (P < 0.05). Results showed that with increased WB level, muscle fibers decomposed and damage intensified[42]. The life qualities of biological tissue gradually disappeared, and the difference in impedance amplitude between high and low frequencies steadily decreased.

3.4.5 Discrimination of different levels of WB based on PLS and L-BFGS method

PLS discriminant analysis was used to train and evaluate the impedance amplitude and phase-angle data at 15 frequency points ranging from 0.06 kHz to 200 kHz for the aforementioned four groups of chicken breast samples. This resulted in the classification of NORM and three distinct classes of WB. Out of the 80 sets of data (each set including 20 subsets), 75% were assigned randomly to the training sample and 25% to the validation sample. Table 6 demonstrates that the accuracy of SEV training samples, test samples, and NORM test samples all achieved a perfect score of 100%. The overall accuracy of the instruction achieved a rate of 91.7%. As a result of the low precision of the MOD test samples, the overall percentage of accurate predictions was 80%. NORM and various levels of WB were effectively differentiated using PLS discriminant analysis. The similar impedance characteristics of MILD and MOD implied a low likelihood of accurately determining the quality of chicken-breast samples from these two levels. To enhance the precision of distinguishing among various levels of WB, numerous repetitive tests should be conducted to gather substantial data, establish a comprehensive database, and thus facilitate the development of a more refined discriminating model.

Due to the relatively limited size of our data, we used the L-BFGS algorithm to train the deep-learning model. The neural network took the impedance amplitude and phase-angle values within the frequency range of 0.06–200 kHz as input features. The neural network's hidden-layer size was specified as 32, and the learning rate was set to 0.000 1. We used random selection to allocate 75% of the 80 samples for training, whereas the remaining samples were reserved for testing. The classification results are presented in Table 7 and Figure 5. Table 7 demonstrates that the accuracy of the SEV training samples, MILD test samples, and MOD test samples

Table 6 Training and test results of different levels of woody breast (WB) classification model based on PLS.

Sample	WB level	Number					Accuracy (%)
		Total	NORM	MILD	MOD	SEV	
Train	NORM	15	13	2	0	0	86.7
	MILD	15	1	13	1	0	86.7
	MOD	15	0	1	14	0	93.3
	SEV	15	0	0	0	15	100.0
Test	NORM	5	0	0	0	0	100.0
	MILD	5	1	4	0	0	80.0
	MOD	5	0	3	2	0	40.0
	SEV	5	0	0	0	5	100.0

Table 7 Training and test results of different levels of woody breast (WB) classification model based on deep learning.

Sample	WB level	Number					Accuracy (%)
		Total	NORM	MILD	MOD	SEV	
Train	NORM	15	14	1	0	0	86.7
	MILD	15	2	13	0	0	80.0
	MOD	15	1	0	14	0	86.7
	SEV	15	0	0	0	15	100.0
Test	NORM	5	4	1	0	0	80.0
	MILD	5	0	5	0	0	100.0
	MOD	5	0	0	5	0	100.0
	SEV	5	0	0	1	4	80.0

achieved a perfect score of 100%. The average accuracy of the entire training set achieved 88.35%, whereas the average accuracy for the test samples was 90%. PLS exhibited a superior overall accuracy in predicting training samples compared with L-BFGS, but L-BFGS outperformed PLS in terms of overall accuracy in predicting test samples.

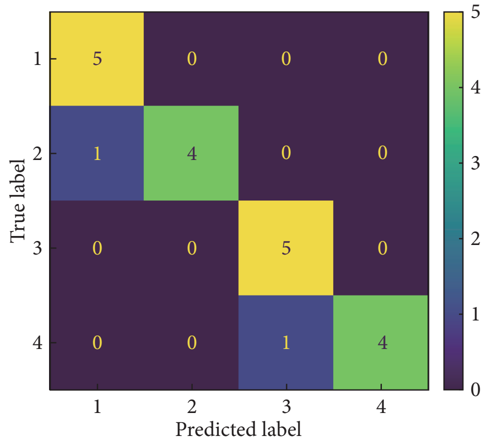

Figure 5 Confusion matrix of deep learning method.

4 Conclusion

With increased WB level, the weight, top thickness, pH, and hardness of chicken breast decreased, whereas color deteriorated and water retention decreased. The magnitude of impedance decreased with increased WB level, and the disparity between NORM in the middle- and low-frequency ranges and WB chicken breast in various levels became more pronounced. The absolute value of phase angle in NORM in the middle- and high-frequency bands was higher than that in WB. With increased WB level, R_i and f_c increased; conversely, the radius of the arc of the Cole-Cole curve, R_e, K, and α decreased. These impedance characteristics can be used for the bioelectrical impedance identification of different levels of WB. The PLS analysis model can classify and judge NORM and different levels of WB, whereas the L-BFGS model had a higher prediction rate for test samples. Based on our experimental conclusions, different levels of WB were more accurately classified, which avoids the shortcomings of manual palpation, such as low determination efficiency and poor diffusion, and is of great significance in promoting rapid and accurate quality detection of chicken breast meat and safeguarding the economic benefits of enterprises.

Conflict of interest

The authors declare no conflict of interest.

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