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Review

New Techniques of Meat Quality Assessment for Detecting Meat Texture

Chang Liu [1,2], Yanlei Li [2,*], Wenming Sun [2], Feiyu Ma [2], Xiangwu Wang [2] and Zihao Yang [2]

[1] School of Mechanical and Materials Engineering, North China University of Technology, Beijing 100144, China; liuchang2470@163.com
[2] College of Mechanical and Electrical Engineering, Beijing Polytechnic College, Beijing 100042, China; swm@bgy.edu.cn (W.S.); mfy@bgy.edu.cn (F.M.); wxw020619@163.com (X.W.); yzh05201900729@163.com (Z.Y.)
* Correspondence: liyanlei2021@163.com; Tel.: +86-15600985511

Abstract: Meat, as an essential food source in people's lives, provides a wealth of nutrients. The physical properties of meat are directly related to its sensory caracteristics, such as elasticity, viscosity, and toughness. Food rheology, as a discipline that studies the deformation and flow behavior of food under force, can effectively characterize these physical properties of meat. The evaluation methods of rheological properties provide a more comprehensive and accurate means of detecting meat quality. This not only helps enhance the quality control level in the meat industry but also holds significant importance for safeguarding consumer rights. This paper reviews the assessment of rheological properties such as sensory evaluation, texture analyzers, and rheometers. The combined application of multiple technologies (such as the integration of hyperspectral imaging (HSI) with computer vision and the fusion of airflow and laser detection) and emerging technologies (such as nanotechnology and biosensor technology) shows potential in predicting the rheological properties of meat. It analyzes the current application status, advantages, and challenges faced by the assessment of rheological properties and provides an outlook on future development trends, offering theoretical references for the objective evaluation of meat quality.

Keywords: rheological properties; viscoelasticity; rheometer; texture analysis

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1. Introduction

Meat quality is one of the key factors in measuring the market competitiveness of meat products, directly affecting consumers' purchasing choices and eating experiences [1,2]. As an important dimension for assessment, rheology provides a theoretical framework for analyzing the dynamic mechanical behavior of meat by studying stress–strain relationships and time-dependent characteristics of materials under external forces [3]. In meat systems, rheological properties directly affect product tenderness, chewiness, and dynamic changes in mouthfeel through key indicators such as elastic modulus and viscoelastic parameters [4]. This dual role makes rheological analysis an important bridge connecting the physical properties of meat with sensory quality.

The rheological properties of meat are the result of the combined effects of muscle composition, structure, and processing conditions. They can provide a scientific basis for meat processing and quality control, helping companies optimize production processes and develop new products to enhance market competitiveness and improve consumer eating experiences [5,6]. Moreover, the development of the assessment of rheological properties plays a significant role in food safety regulation. It can be used to monitor

quality changes in meat during processing and storage, ensuring consumer health [7,8]. Research on meat rheological properties has injected new vitality into the traditional meat processing industry, enabling companies to achieve standardized and refined production and ensure meat quality control. This not only improves the stability of product quality but also meets the diverse needs of consumers.

Currently, the assessment of rheological properties such as sensory evaluation, mechanical testing, texture analyzers, and rheometers has been widely applied for the precise assessment of meat quality [9–14]. The combined application of multiple technologies (such as the integration of HSI with computer vision, the fusion of airflow and laser detection, and the combination of airflow pulse and 3D structured light imaging) [15–18] and emerging technologies (such as nanotechnology and biosensor technology) [19,20] has enabled more in-depth and comprehensive analysis of meat, providing a scientific basis and efficient means for meat processing and quality control. This paper aims to provide a comprehensive overview of the main technologies and research progress in the detection of the rheological properties of meat quality, offering valuable references for further promoting the development of the meat industry in terms of quality control, product innovation, and market expansion.

2. The Relationship Between Rheological Properties and Meat Quality

2.1. The Impact of Rheological Properties on Processing and Sensory Characteristics

The rheological properties of meat refer to the ability of the internal structure of meat to deform and flow under external forces, which include elasticity, viscosity, hardness, tenderness, and other mechanical properties. These properties not only determine the behavior of meat during processing operations such as cutting, mixing, and forming but also directly affect consumers' sensory experiences [9,21].

Purslow et al. [22] pointed out that changes in connective tissue within muscle can significantly affect the rheological properties of meat. Experimental data show that structural changes in connective tissue directly influence meat tenderness and texture. In addition, the type and orientation of muscle fibers, the degree of protein cross-linking, and the fat content within muscle also affect the mechanical properties of meat [23]. For example, the higher the intramuscular fat content, the better the tenderness and juiciness of the meat [24]. Processing methods, such as thermal and non-thermal treatments, can also significantly alter the rheological properties of meat. Thermal processing leads to protein denaturation and texture changes, while non-thermal processing techniques, such as high-pressure processing, can maintain the sensory properties of meat with higher energy efficiency [25].

Offer et al. [26] revealed the impact of meat structure on rheological properties through research on water-holding capacity in meat. They found that the water-holding capacity of meat is closely related to muscle fiber structure and ion distribution, which together determine the rheological behavior of meat during processing. There is a significant correlation between water-holding capacity and shear rheological properties in meat; meat with a higher water-holding capacity exhibits lower viscosity and better elasticity in rheological tests. Bouton et al. [27] found, through experiments, that the rheological properties of meat, such as elasticity and viscosity, change with increasing heating time and temperature. These changes not only affect the processing properties of meat but also directly influence the mouthfeel and consumer experience of meat.

Flavor, as one of the key indicators of meat quality, includes taste and odor and is related to the composition of amino acids, fatty acids, and other substrates. Rheological properties can affect the binding and release of flavor compounds, thereby influencing the overall flavor experience of meat [28]. Xiong et al. [29] found that protein interactions and their effects on heating and pH-induced gelation significantly influence the flavor

and texture of meat. Additionally, recent advances in the mechanisms of flavor formation in meat products and the impact of processing methods on flavor have shown that the degradation of flavor precursors, the Maillard reaction occurring during meat processing, and interactions between key components contribute to the unique meat flavor [30]. The rheological properties of meat are key factors affecting meat processing and consumption quality, and they have complex interactions with meat quality [31].

2.2. The Impact of Rheological Properties on Texture and Mouthfeel

Heat treatment significantly affects the rheological properties of meat by altering the protein structure, thereby influencing meat texture and flavor. Experimental results by Tornberg et al. [32] show that most myofibrillar proteins aggregate between 40 and 60 °C, while the coagulation process of some myosin can extend to 90 °C. For myofibrillar protein solutions, unfolding begins at 30–32 °C, protein–protein associations occur at 36–40 °C, and gelation follows at 45–50 °C (at concentrations greater than 0.5% w/w). Collagen denatures in the temperature range of 53 °C to 63 °C, after which collagen fibers contract. If collagen fibers are not stabilized by heat-resistant intermolecular bonds, they will dissolve upon further heating and form gelatin. These changes significantly affect the gelation behavior and texture of meat products.

Funami et al. [33] studied the thermal and rheological properties of curdlan (CUD) in pork emulsion gels using differential scanning calorimetry (DSC) and dynamic viscoelastic measurements. Their research found that, upon re-scanning, the meat/CUD mixture did not exhibit endothermic behavior, which contrasts with the distinct single endothermic peak observed in meat/κ-carrageenan mixtures. This indicates that CUD underwent a relatively thermally irreversible gelation process during heating at 75 °C, a characteristic that confers good thermal stability in meat product processing. They also found that these properties vary with temperature, and as ionic strength increases, the rheological properties of the 75 °C gel become like those of the thermally irreversible 90 °C gel. This suggests that the rheological properties of CUD gels are significantly influenced by temperature and ionic strength, which is of great significance for controlling processing conditions and improving product quality in meat products.

Based on these studies, we can conclude that these findings provide a scientific basis for the development of new types of meat products. By adjusting the concentration of gelling polysaccharides and heating conditions, the texture and mouthfeel of meat products can be controlled to meet consumer demand for high-quality meat products. Moreover, these studies offer theoretical support for the optimization of meat product formulations and process improvements, which can enhance product market competitiveness. For example, by precisely controlling the amount of CUD added and the heating temperature, meat products with better elasticity and water-holding capacity can be produced. This is significant for extending product shelf life and increasing consumer acceptance. From a consumer perspective, the rheological properties of meat directly affect sensory perception. Consumers generally prefer meat that achieves an ideal balance of tenderness, juiciness, and flavor. Therefore, understanding and controlling the rheological properties of meat is crucial for optimizing processing techniques and improving consumer satisfaction.

3. The Research Progress of the Assessment of Rheological Properties in the Field of Meat Quality Detection

The assessment of rheological properties, as a key means of assessing meat quality, has achieved significant research results in recent years and encompasses a variety of detection methods [34]. Sensory evaluation assesses various attributes of meat through different human perceptual methods, such as vision, olfaction, taste, and touch [10,35]. Specifically,

vision is primarily used to evaluate the color, size, and shape of meat products, while olfaction and taste are employed to assess the composition, odor, and flavor of meat [36]. Audition can determine the location, defects, and structural density of meat, and touch perceives the temperature, material properties, and texture of meat through contact [37]. Although these perceptual methods can provide qualitative data on key attributes such as meat quality, flavor, and mouthfeel, their subjectivity, poor reproducibility, and difficulty in quantification limit their application in scientific research [38,39]. Lawless et al. [39] emphasized the inconsistency of sensory evaluation results in their study, pointing out that different evaluators may have significant differences in their assessments of the same meat product, thereby affecting the reliability of the evaluation results.

Texture profile analysis (TPA) and the Warner–Bratzler shear test are the most used methods for mechanically assessing the rheological properties of meat. TPA measures meat hardness, springiness, cohesiveness, and chewiness by compressing a meat sample twice and analyzing the force–deformation curve, providing quantitative data for meat texture evaluation. However, TPA is limited to static or small deformation conditions and cannot fully simulate the dynamic mastication process in the mouth [40,41]. Rosenau et al. [42] suggested combining TPA with other rheological tests to gain a more comprehensive understanding of meat texture and its relationship with sensory attributes. The Warner–Bratzler shear test determines meat tenderness by measuring the force required to shear a meat sample and is particularly useful for assessing the tenderness of cooked meat products, but it is also limited to static conditions and cannot reflect dynamic changes during mastication [11,43]. Ruiz et al. [43] compared the strengths and weaknesses of Warner–Bratzler shear force and TPA in evaluating the textural properties of meat and meat products. The results showed that the coefficient of variation for Warner–Bratzler force was larger, while the coefficients of variation for TPA parameters were closer to, or even smaller than, those for sensory evaluation results. In predicting sensory parameters, TPA could better predict hardness, juiciness, greasiness, and number of chews, while springiness could only be effectively predicted by Warner–Bratzler shear force. These findings indicate that both TPA and Warner–Bratzler shear force have their own strengths, and the appropriate detection method can be chosen according to specific needs in practical applications.

Texture analyzers and rheometers have long been the cornerstone in the field of the assessment of meat's rheological properties. These instruments can quantitatively analyze the physical properties of meat and provide objective, accurate, and consistent descriptions of the textural characteristics of samples [44]. The Strain gage denture tenderometer, an early instrument for food texture measurement as shown in Figure 1, laid the foundation for the development of subsequent texture analyzers. Texture analyzers mainly consist of a main unit, testing software, probes, and a testing platform. Their working principle involves subjecting samples to compression, cutting, compressing, and stretching using various probes, with a focus on analyzing distance, time, and force to derive analytical results. The results reflect mechanical properties related to meat texture, such as hardness, springiness, adhesiveness, and breaking point, with high sensitivity and objectivity [45]. Specialized software is used for quantitative processing and precise quantification of these results, thereby providing an objective and comprehensive evaluation of meat products and reducing the impact of human factors on subjective assessments [46]. Wang et al. [47] used a texture analyzer to detect rheological property parameters of beef, such as viscosity and springiness. They initially screened the meat products through sensory evaluation and then further tested the screened meat products using a texture analyzer. The study found that rheological property parameters were significantly negatively correlated with tenderness, with correlation coefficients for springiness and springiness length reaching -0.92 and -0.939, respectively. In addition, researchers combined a self-organizing neural

network (SONN) model to classify and predict beef tenderness, with prediction accuracy as high as 90%. This study fully illustrates the close relationship between the rheological properties of meat and consumer sensory experience. Gallego et al. [12] further explored the use of texture analyzers to study the behavior of meat treated with proteolytic enzymes during simulated gastrointestinal digestion in elderly individuals. They found that the addition of different proteins and hydrocolloids significantly affected the rheological and viscoelastic properties of the meat samples, highlighting the potential for improving meat texture through specific ingredient modifications. This research underscores the importance of texture analyzers in understanding and enhancing meat quality.



Figure 1. Strain gage denture tenderometer (from the museum of MIT).

Rheometers measure rheological data by applying different loads and deformations to samples, such as shear rate, shear stress, oscillation frequency, and amplitude of stress–strain, thereby calculating rheological parameters like viscosity, storage modulus, and loss modulus [48]. Giménez-Ribes et al. [13] used a rheometer to study the rheological properties of beef and chicken. They sliced beef and chicken into 3 mm thick slices with fiber orientation either parallel or perpendicular to the cutting direction. The samples were further processed into 25 mm diameter disks to fit the geometry of the rheometer plate. Figure 2 shows a schematic diagram of the sample placement under the testing structure of the rheometer and the coordinates used in rheological studies. It was found that meat samples exhibited lower energy dissipation and higher strain hardening at small strains, while showing greater positive stress response at large strains. These characteristics are closely related to the elasticity of the meat fiber structure and have a significant impact on the textural properties of meat products.

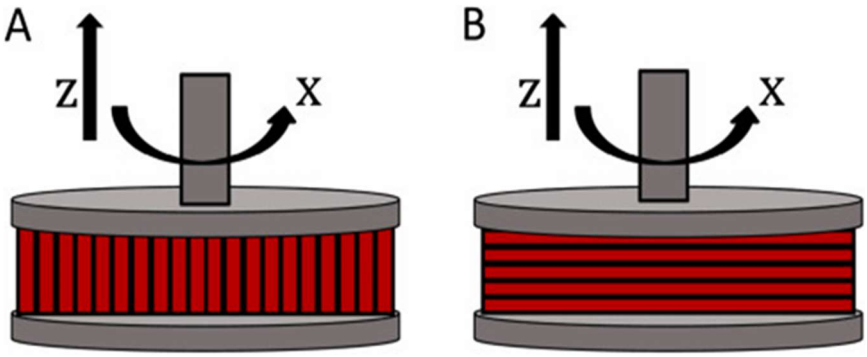


Figure 2. Schematic diagram of fibers with different orientations. Figure (**A**) shows fibers perpendicular to the shear direction, while Figure (**B**) shows fibers parallel to the shear direction. The x-axis represents the orientation (shear) direction, and the z-axis represents the shear gradient direction.

Dong et al. [49] developed a classification algorithm for pork breeds based on the rheological properties of meat. In this study, a universal testing machine was used to conduct stress relaxation experiments on pork from different cuts, including rib and belly, front shoulder, loin, and hind leg. The relaxation characteristics of the pork were identified by combining a genetic algorithm with a third-order Maxwell model, with the model and experimental apparatus illustrated in Figures 3 and 4. The data were then subjected to dimensionality reduction and classification using Principal Component Analysis (PCA) and Fisher's Linear Discriminant Analysis (FLDA). The results showed that the classification accuracy for rib and belly meat compared to the other three types of meat was 98%, 96%, and 95%, respectively. This indicates that the method has high accuracy in distinguishing different cuts of pork and can efficiently classify pork breeds. This approach not only provides a solid theoretical basis for the identification and classification of meat quality but also offers a new pathway for meat classification.

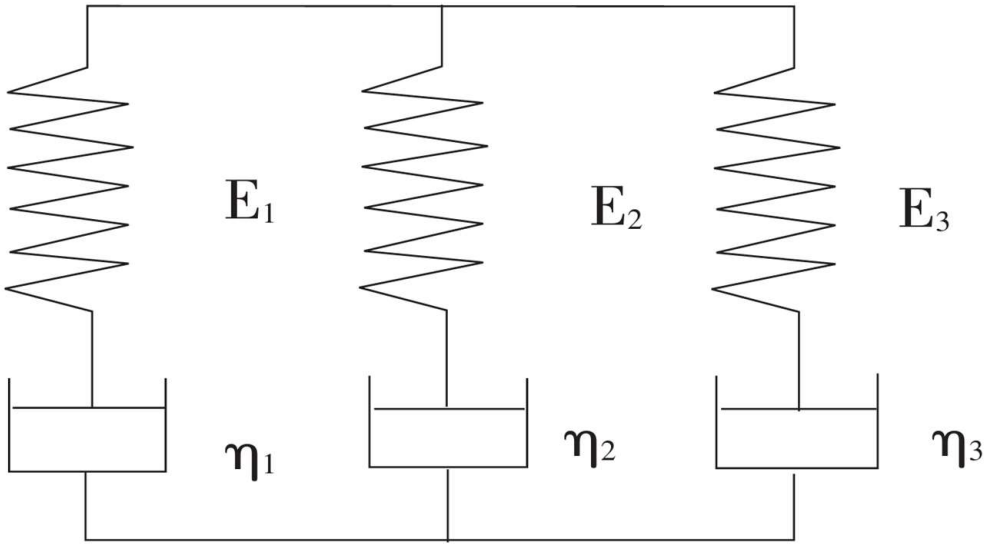


Figure 3. Generalized Maxwell model of pork.



Figure 4. Experimental machine.

4. Integrated Application of Rheological Characterization and Emerging Technologies

4.1. Advantages and Disadvantages of Different Assessments of Rheological Properties

The evaluation of meat rheological properties has a history of several decades, but these techniques continue to evolve and improve. Precise detection of rheological properties provides important insights into meat quality. Future research should focus on further refining existing technologies and exploring new application areas to enhance the correlation between meat quality assessment and rheological properties. Sensory evaluation and simple mechanical tests (such as TPA and Warner–Bratzler shear tests) do not require complex equipment, are easy to operate, and have low costs [50]. Sensory evaluation can directly reflect consumer perceptions and is significant for assessments that need to incorporate consumer experience [51]. However, it relies on subjective human judgment, and results can be influenced by the evaluator's personal experience, cultural background, emotional state, and physiological conditions. Significant differences may exist among different evaluators, and even the same evaluator might give different assessments of the same meat product at different times [52]. Although it is easy to operate, there are certain limitations [2]. For example, research by the American Meat Science Association (AMSA) indicates that sensory evaluation should be combined with instrumental measurements to comprehensively assess meat quality [53]. Traditional mechanical tests (such as TPA and Warner–Bratzler shear tests) are usually limited to measurements under static or small deformation conditions and cannot fully simulate the complex movements of the human mouth. Therefore, they are insufficient for evaluating the dynamic rheological behavior of meat during actual consumption [8]. Moreover, these tests typically require a certain amount of sample for accurate measurements, which may be a limiting factor for some precious or hard-to-obtain meat products [54].

Texture analyzers and rheometers provide more sensitive and objective detection methods, avoiding interference from human factors [55]. These technologies enable more accurate assessment of meat texture, rheological properties, and other related indicators through digital and quantitative analysis. Texture analyzers simulate chewing and deformation processes to precisely measure key parameters such as hardness, elasticity, adhesiveness, and breaking point, which directly affect consumer eating experiences [46]. As a precision instrument, texture analyzers must be operated strictly according to the manual, with rigorous requirements for sample preparation, control of the testing environment, and standardization of the testing process [56]. Their complex structure, incorporating numerous precision sensors and electronic components, demands high standards for maintenance and care. In the event of a malfunction, the cost of repair can be high [57]. Rheometers measure rheological data such as shear rate, shear stress, oscillation frequency, and stress–strain amplitude by applying different loads and deformations to samples, calculating rheological parameters like viscosity, storage modulus, and loss modulus [58]. The operation and data processing of rheometers are relatively complex, requiring operators to have a high level of professional knowledge and skills. Familiarity with rheological theory and the working principle of the instrument is necessary to correctly set experimental parameters, conduct tests, and analyze data, which to some extent limits their widespread application [59]. In summary, different assessments of rheological properties have their own advantages and disadvantages. The choice of technology should be based on specific detection needs, budgets, and the skill levels of operators. However, there are still some limitations and challenges in practical applications that require further research and technological innovation to overcome.

4.2. Possibilities and Effects of Combined Application of Multiple Technologies

4.2.1. Combination of Hyperspectral Imaging (HSI) and Computer Vision Techniques

In the field of meat rheological property detection, the integrated application of multiple techniques can provide a more comprehensive and precise analysis of material properties. For example, the combination of HSI and computer vision techniques can provide detailed information on meat color, texture, and chemical composition at the same time, which is valuable for the assessment of meat freshness and maturity [15].

A study by Wang et al. [15] pioneered the combination of visible near-infrared HSI technology with artificial neural networks for monitoring the color change in rhubarb fish fillets during cryogenic storage. By developing a nonlinear quantitative analytical model based on a feed-forward neural network (FNN) combined with leaky rectified linear units (Leaky–Relu), the study was able to accurately predict the changes in fillet color, where the prediction models achieved coefficients of determination (R^2_P) of 0.908, 0.915, and 0.977 for the values of L*, a*, and b*, respectively, as well as 1.062, 3.315 and 0.082 root mean square error (RMSEP). In the experiment, 15 large yellow croakers were cut into fillets after being beheaded, gutted, skinned and cleaned, and labeled according to their different locations on the fish body to reflect the natural variations in the shape and thickness of the fillets. Through extensive statistical data analysis of L*, a*, and b* values, the study developed a robust model, which is essential to ensure the accuracy and predictive power of the model. Ultimately, the study confirms that the HSI technique is not only capable of assessing color changes in dorado fillets during storage but also serves as a rapid, non-destructive alternative to traditional color measurement tools for accurately determining the spatial distribution of fillet color. This technique provides a new perspective for quality control of aquatic products, especially dorado, during storage and marketing, especially in monitoring color changes in real time, which is significant for maintaining product quality and enhancing consumer experience.

4.2.2. Airflow and Laser Fusion Detection Technology

Airflow and laser fusion technology is also a novel technique for meat quality inspection, which combines the impact force of airflow and the high-precision measurement of a laser to obtain viscoelasticity information, which is essential for predicting the texture and tenderness of meat. Tenderness is a comprehensive indicator of meat quality and is influenced by various factors, among which rheological properties, such as elasticity, viscosity and hardness, are important physical indicators for predicting meat texture [60].

A viscoelasticity–tenderness assay has been studied using chicken and beef as test samples, and this method has the potential for multi-technology integration. However, there are shortcomings, i.e., the non-uniformity of samples subjected to the impact of the airflow, as well as their susceptibility to environmental disturbances [61]. Li et al. [16] utilized a meat viscoelasticity testing device based on airflow and laser technology to collect data and developed a model for predicting the content of TVB-N through the application of statistical methods, such as multivariate linear regression (MLR), principal component regression (PCR), and partial least squares regression (PLSR). The PLSR model using 12 eigen parameters performed the best among the models developed, with correlation coefficients (Rc and Rp) of 0.847 and 0.821 in the calibration and prediction sets, respectively, and root mean square errors (RMSEC and RMSEP) of 1.750 mg/100 g and 2.560 mg/100 g in the calibration and prediction sets, respectively. The study demonstrated that the effectiveness of the airflow and laser techniques of viscoelasticity combined with chemometrics has the potential to predict chilled beef-quality. Xu et al. [17] used airflow pulses and laser ranging techniques to obtain deformation data from chicken meat samples. By controlling the strength of the airflow and the precision of the laser, it was possible

to accurately measure the degree of deformation of chicken meat after being subjected to airflow impact. The collected data were processed by denoising, segmentation, profile analysis and deformation region extraction to extract parameters such as depth, mapped area, surface area and volume of the deformed region of chicken meat. Prediction models based on LS-SVR, Backpropagation neural network (BP), and GRNN were developed for predicting the sheer force of chicken meat, and the results of the study showed that the GRNN model performed the best in predicting the tenderness of chicken meat. For tender and moderately tender chicken meat, the prediction results can reach 100% accuracy; for older chicken meat, the prediction set correlation coefficient is 0.975 and the root mean square error is 5.307 N.

In order to overcome the defects of single-point data collection, which is prone to errors, He et al. [62] used the airflow–multipoint laser method to detect beef quality, i.e., the airflow exerts pressure on the sample, and the viscoelastic information of the sample manifests itself as a change in the deformation information, which is ultimately obtained by multiple laser sensors and used to detect the deformation data of the sample, and the hardware device is shown in Figure 5 (the air compressor is not shown in the figure). This method can effectively avoid the research assumption of "consistent sample displacement", and the collected data were subjected to S-G convolutional smoothing, first-order derivative processing, and first-order derivative processing combined with S-G convolutional smoothing preprocessing, and a beef quality prediction model was established. The best prediction model (FD + S-G preprocessing) had a correction set correlation coefficient of 0.891 and a root mean square error of 1.071 mg/100 g, and a prediction set correlation coefficient of 0.859 and a root mean square error of 1.337 mg/100 g. The feasibility of the detection method was proved, and the potentials of the fusion of the airflow and laser technologies in the detection of tenderness and rheological characteristics of beef were demonstrated, and future research can further explore how to improve the detection accuracy of the rheological properties by improving the algorithm and enhancing the data processing capability, so as to predict the quality of meat more accurately.

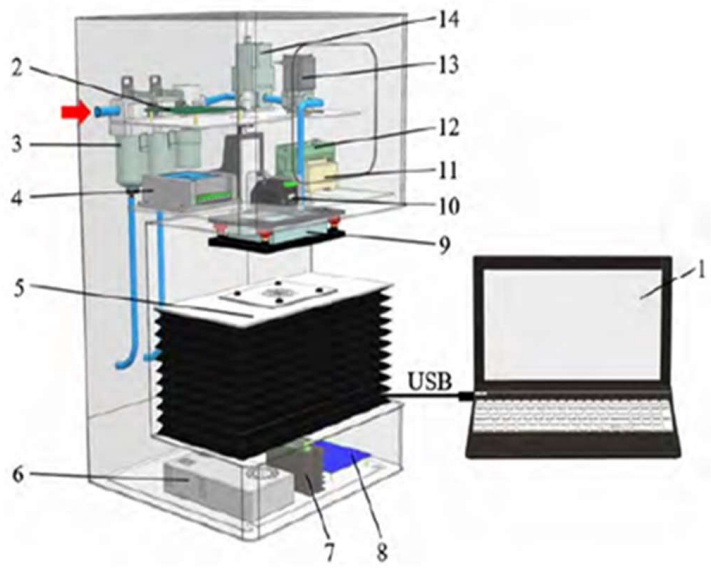


Figure 5. Hardware schematic of beef freshness testing device. 1. Microcomputer. 2. Air flow control board. 3. Two-stage air filter. 4. Analog voltage output. 5. Motorized displacement elevator. 6. Switching power supply. 7. Driver. 8. Motion control card. 9. Air chamber. 10. Laser sensor. 11. RS-232 communicator. 12. Signal amplifier. 13. Solenoid valves. 14. Electrical proportional valves. (The red arrow indicates the direction of airflow acting on the sample).

4.2.3. Fusion of Airflow Pulse and 3D Structured Light Imaging

Airflow pulse and 3D structured light imaging is an emerging technology for meat quality inspection, which is like the principle of airflow and laser fusion technology. This method uses airflow pulses to apply an impact force to the meat surface, while 3D structured light imaging is used to obtain meat deformation images, build a shear force prediction model, and compare the model prediction results to achieve rapid and nondestructive detection of quality characteristics such as meat tenderness [16,18]. This technique has an important application value in the field of meat processing and quality control because it can provide detailed information about the rheological properties of meat, which include the deformation, recovery, and rupture behaviors of meat after being subjected to force and are closely related to the sensory evaluation of meat such as tenderness, juiciness, and mouthfeel.

Lu et al. [18] used airflow pulse and structured light imaging to detect beef tenderness, and the airflow pulse and structured light imaging inspection system is shown in Figure 6. This method impacts the surface of beef by pulsed airflow; uses Gray-coded structured light 3D imaging technology to obtain the depression data on the surface of beef; adopts a series of algorithms such as denoising, segmentation, profiling, deformation region extraction, etc., to analyze and process the obtained data; extracts the parameters of the beef deformation region such as the depth, the mapping area, the surface area and the volume; and establishes the LS-SVR based on the LS-SVR, BP neural network, and GRNN beef shear force prediction model to predict beef tenderness. Shear force was measured on beef samples using a traditional shear force instrument and compared with the prediction results of the constructed model, which showed that the GRNN prediction model was the best, with 100% prediction of tenderness and medium tenderness, and the correlation coefficient of the prediction set of older beef was 0.975 and the mean square deviation (MSD) was 5.307 N. The study demonstrated the validity and accuracy of the technique for meat quality testing. With airflow pulsing and 3D structured light imaging, these rheological properties can be evaluated non-invasively, providing important information for meat processing and quality control. The application of this technology will not only improve the efficiency of meat processing and product quality but will also provide consumers with meat that better meets their expectations.

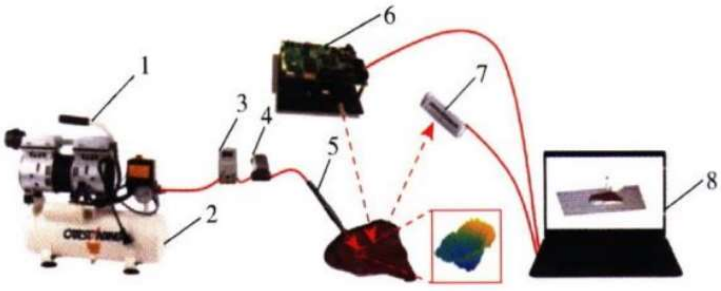


Figure 6. Airflow pulse and structured light detection system. Note: 1. Small air compressor; 2. air storage tank; 3. SMC proportional valve; 4. pneumatic solenoid valve; 5. ventilation pipe and nozzle; 6. DLP digital projector; 7. camera; 8. portable computer. (The lines and arrows indicate the path of airflow or the projection path of structured light).

4.3. The Potential Applications of Emerging Technologies in the Detection of Rheological Properties of Meat

4.3.1. Nanotechnology

In the research field of the assessment of rheological properties for meat quality, emerging technologies such as nanotechnology and biosensors have shown great potential. These technologies can not only enhance the sensitivity and specificity of detection but also

feature real-time, non-destructive characteristics, which can better ensure the safety and quality of meat products [63,64].

Nanotechnology has achieved research progress in meat preservation. Lamri et al. [19] summarized in their study that nanomaterials can achieve antibacterial preservation of food by interfering with bacterial metabolic processes or inhibiting growth and reproduction. Common nanoscale antimicrobial agents include silver nanoparticles (AgNPs), copper nanoparticles (CuNPs), titanium dioxide (TiO_2) nanoparticles, and zinc oxide (ZnO) nanoparticles. These nanomaterials can effectively inhibit microbial growth and extend the shelf life of meat products [65].

In terms of rheological properties, the application of nanotechnology is also of great significance. For example, Zhang et al. [66] prepared nano-encapsulated dill essential oil and combined it with chitosan–gelatin to make edible coatings. Coating pork slices with this coating can effectively delay color changes in the samples, indicating that dill essential oil treated with nanotechnology can significantly delay browning and fading in pork slices. This treatment not only improves the appearance and color of meat products but also indirectly affects their rheological properties, such as hardness, elasticity, and viscosity, by reducing oxidation reactions. Nanotechnology helps to improve meat texture and enhance the stability of odor and nutrients in packaged foods.

In addition, the application of nanotechnology in meat preservation also includes antibacterial applications, such as using nanoscale antibacterial materials to disrupt cell membranes and block the transfer of electrons and protons, causing cell contents to coagulate. These characteristics not only help extend the shelf life of meat products but also indirectly affect their rheological properties by reducing microbial growth and metabolic activities, allowing them to maintain better texture and mouthfeel during processing and storage.

4.3.2. Biosensor Technology

Biosensor technology, due to its high sensitivity, specificity, reproducibility, and stability, has shown significant advantages in monitoring and controlling the quality (freshness and sensory characteristics such as tenderness) and safety (metabolites, contaminants, pathogens, drug residues, etc.) of muscle foods and is gradually becoming a promising tool [67,68]. For example, Sionek et al. [20] discussed in their review the applications of biosensors in the safety testing of meat and meat products, including the detection of microorganisms and other contaminants, as well as quality assessment, such as meat freshness, beef tenderness, and pork quality defects. Since biosensors rely on the type of receptor, a thorough understanding of the metabolic transformations occurring in meat helps to develop new potential biomarkers and indicators. For example, the use of surface plasmon resonance (SPR) technology to assess calpain activity in beef samples achieved the highest correlation coefficient r = 0.597 ($p \leq 0.01$) compared to the traditional Warner–Bratzler shear force (WBSF) method, with a modified R^2 = 0.6058 at 48 h post-slaughter. These data and conclusions support the effectiveness of biosensors as a non-destructive predictive tool and demonstrate their potential application value in the meat industry.

Biosensors can not only monitor rheological changes in meat during processing and storage in real-time but also provide more accurate quality control and prediction in a non-destructive manner. For example, a colorimetric biosensor based on CRISPR/Cas12a has been developed to detect Pseudomonas in meat, a bacterium closely associated with meat spoilage. The sensor, which provides a colorimetric response, can rapidly and accurately detect microbial content in meat, thereby indirectly reflecting changes in the rheological properties of meat [69]. Studies have shown that the sensor exhibits good accuracy and

sensitivity in detecting meat freshness, helping to better control quality during meat processing and storage, extend shelf life, and enhance consumer satisfaction.

5. Conclusions

The innovation in meat quality assessment technology is advancing towards a more intelligent, precise, and diversified direction. Rheological property detection, as a core evaluation tool, has the unique advantage of dynamically analyzing the microstructural evolution of muscle tissue under processing stress. In particular, the quantitative correlation established between parameters such as the elastic modulus and viscosity coefficient and key quality indicators like myofibrillar protein denaturation and endomysium integrity provides a new theoretical basis for tenderness prediction and water-holding capacity assessment. This cross-scale characterization of physical and chemical properties also offers significant support for the development of new meat processing technologies, thereby enhancing product market competitiveness.

However, with the continuous development of the meat industry, current rheological detection technologies are increasingly unable to meet the growing demands. Future development trends will focus more on the integration of multiple technologies. For example, multimodal detection technologies that combine HSI, computer vision, and dual sensors can capture the physical and chemical properties of meat from multiple perspectives, thereby improving the accuracy and reliability of detection. This multi-technology integration approach can provide a more comprehensive assessment of the rheological properties of meat and offer meat processing enterprises more precise quality control tools. At the same time, innovations in nanotechnology and biosensors will provide more sensitive and specific methods for the early detection of changes in meat quality. These new technological developments will further improve the precision and efficiency of meat quality assessment and provide strong support for the sustainable development of the meat processing industry. Nevertheless, to enhance the comparability and reliability of detection results, further research is needed on standardized sample preparation methods, as well as considerations of environmental impacts and cost-effectiveness. In summary, the sustainable development of rheological property technology holds significant practical significance for the meat industry.

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